



Article

Inter-Calibration and Limb Correction of FY-3D/E MWTS for Long-Term Gridded Microwave Brightness Temperature Dataset

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Abstract: The Microwave Temperature Sounder-3 (MWTS-3) onboard the Chinese FengYun-3E (FY-3E) satellite is the third generation of Chinese microwave temperature sounder. Based on MWTS-2, the number of MWTS-3 channels has been increased from 13 to 17, which can observe the atmospheric temperature and water vapor profiles from the surface to the lower stratosphere. In this study, two generations of MWTSs onboard FY-3D/3E were inter-calibrated by the Double Difference (DD) method to eliminate bias. The results showed that the biases of tropospheric channels were stable (within 1 K) and the biases of stratospheric channels were relatively large (over 2 K). In addition, the weighting functions of all MWTS channels varied with fields of view (FOVs) due to different optical paths, causing the brightness temperature (TB) observations to display strong scan-dependent features, i.e., the limb effect. This work used a limb correction method to remove scan-dependent patterns so that the underlying weather signals could be uncovered. After inter-calibration and limb correction, this work converted the TB observations from MWTS-2/3 onto a global gridded dataset at $0.5^\circ \times 0.5^\circ$ latitudinal and longitudinal resolutions using a method of nested interpolation. Based on this research, more long-term FengYun series satellite climate datasets can be established in the future.

Keywords: microwave temperature sounder; inter-calibration; limb correction; climate datasets



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1. Introduction

Microwave temperature sounders (MWTSs) onboard satellites can measure the radiance related to the global vertical atmospheric temperature under all-weather conditions, and have been widely used in numerical weather prediction and climate research. Since the first generation of FengYun-1 was launched in 1988, the Chinese satellite industry has developed rapidly in the following decades. So far, twenty-two FengYun series satellites have been launched, eight of which are now in operation. The first generation of MWTS with four channels was carried on the FY-3A satellite launched in 2008. Based on the first generation of MWTS, the MWTS-2 onboard FY-3C (launched in 2013) increased the number of channels near the 50–60 GHz oxygen absorption band from 4 to 13 [1]. The number of channels of MWTS-3 (onboard FY-3E, launched in 2022) has increased to 17, further improving the detection capability and performance of MWTSs. MWTS-3 has 15 sounding

channels with center frequencies at 50–57 GHz (the oxygen absorption band), providing information on the global vertical atmospheric temperature profiles. The two window channels (23.8 and 31.4 GHz) of MWTS-3 can be used for the retrieval of the total amount of atmospheric water vapor and cloud water content [2]. Data from MWTS-3 have been widely applied to climate research and numerical weather prediction [3–7].

During the design of spaceborne microwave radiometers, laboratory calibration needs to be completed to guarantee that their operating parameters meet working requirements. However, while satellites orbit the earth, the instruments carried on them will be influenced by the external environment and some unpredictable factors, which will lead to certain biases in TB observations. Therefore, bias estimation and calibration need to be carried out prior to the utilization of satellite observations. Bias estimation for satellite microwave radiometers typically employs inter-calibration methods. Particularly when data from multiple satellites need to be fused in climate research, it is essential to inter-calibrate these observations to eliminate biases among instruments. Commonly utilized microwave inter-calibration methods comprise the following four: (1) comparisons of satellite observations and ground-based observations [8]; (2) comparisons of satellite-observed TBs with simulated TBs under clear skies [9]; (3) comparisons of observations from two radiometers with the same observation times in fixed areas [10]; and (4) statistical analyses of observations from two radiometers based on observations of cold earth targets [3]. Bindlish et al. (2017) [11] compared Soil Moisture and Ocean Salinity (SMOS) and Soil Moisture Active Passive (SMAP) TBs from simultaneous overpasses within a maximum time window of 30 min with footprint distances of less than 1 km. Schmitt and Kaleschke (2018) [12] used a two-step regression fitting method to calibrate the TBs of SMOS and SMAP over sea ice, finding that the SMOS and SMAP TBs agreed very well, with correlations exceeding 0.99 over sea ice, but showed an intensity bias of about 2.7 K over both ocean and sea ice regions. Wang et al. (2022) [13] compared different inter-calibration methods for TBs from FY-3D and Advanced Microwave Scanning Radiometer 2 (AMSR2) and found that the pixel-based global linear regression method performed best. Simultaneous Nadir Overpass (SNO) is a method based on finding crossover observations between two instruments, which was successfully used for the inter-sensor calibration of Advanced Microwave Sounding Unit-A (AMSU-A) observations from multiple satellites [14,15]. Zou et al. (2009) [16] also used the SNO method to calibrate the MSU carried by the TIROS-N to NOAA-14 series of satellites. Due to high matching requirements, satisfactory observations obtained by the SNO method are always rare. Especially when the data length is short, it is difficult for SNO to obtain enough matching observations. The DD method facilitates inter-comparison between sensors of interest (SOIs) that do not have the optimal temporal or spatial coincidence to allow for direct inter-comparison [17]. This method depends on a stable sensor reference standard (SRS) of characterized uncertainty that can be directly inter-compared with two or more SOIs with similar radiometric characteristics as the reference standard. The directly inferred radiometric biases between each SOI and the SRS (SOI–SRS) comprise the elements used to compute the DD radiometric bias values. Microwave instruments that are well characterized and with an understood uncertainty can be used as a benchmark for inter-comparison using the SNO method [18]. Studies have shown that, when the same data amount is used, the calibration results obtained by the DD method are consistent with the SNO method [19]. Many studies have shown that the DD method can well eliminate observation biases caused by different instrument center frequencies and incident angles [20–22].

For a cross-track scanning microwave radiometer, as the field of view (FOV) varies from the nadir to both sides, the scanning angle increases correspondingly. Owing to the increase in the optical path at the edge of the FOV, the attenuation effect of the atmosphere

on electromagnetic waves intensifies, leading to variations in the height of the weighting function. Consequently, in contrast to the observed TB of the nadir FOV, the observational biases of other FOVs expand with an increase in the scanning angle, and this phenomenon is called the limb effect. For the AMSU-A window channels 1–2, the scanning angle bias for edge observations reached a range of -4 to 2 K [23]. To address this issue, Goldberg et al. (2001) [23] proposed a limb correction method suitable for AMSU-A, which effectively eliminated the scanning angle bias. Zhang et al. (2017) [24] applied this method to the scanning angle bias correction of data from the Advanced Technology Microwave Sounder (ATMS). Xiaoxu et al. (2018) [25] employed the linear regression relationship of TBs from adjacent channels to carry out limb corrections for all channels of FY-3C MWTS-2.

After a series of bias corrections, long-term satellite microwave radiometer data from multiple years can be integrated to span a long-term satellite microwave TB dataset. Since the 1990s, the United States has established several working groups dedicated to satellite microwave datasets. The teams led by Spencer and Christy from National Aeronautics and Space Administration (NASA) and the University of Alabama in Huntsville (UAH) were among the first to undertake research on the integration of MSU and AMSU-A TB data, obtaining a global tropospheric microwave TB sequence from 1979 to 1984 [26]. Subsequently, Christy et al. (1995) [27] further conducted noise reduction processing and bias correction on TB observations, encompassing errors caused by factors such as inter-instrument observation biases, orbital drifts, and variations in the warm blackbody temperature, and developed a real-time and uniformly gridded middle tropospheric temperature dataset [28]. As the meteorological satellite industry in China began relatively late, there is currently a deficiency in long-time-series microwave TB data products from FengYun satellites. In this study, inter-satellite calibration and limb correction were performed for the MWTS-2 and MWTS-3 instruments onboard FY-3D and FY-3E, and a set of globally uniformly gridded microwave TB data from the FengYun satellites was formed through interpolation.

The organization of this paper is as follows: Section 2 presents the characteristics of MWTSs, the DD method, and the limb correction algorithm. Section 3 shows the inter-calibration and limb correction results, and presents the final formed microwave TB dataset. Section 4 provides a conclusion and discussion.

2. Data and Methods

2.1. MWTS Data

The MWTS-2 onboard FY-3D is a cross-track microwave sounder that encompasses 13 channels with weighting functions distributed from the lower troposphere to the lower stratosphere. The scanning swath of MWTS-2 is approximately 2600 km, and each scan line consists of 90 FOVs, with a spatial resolution of around 32 km at the nadir point. The MWTS-3 onboard FY-3E is based on MWTS-2, with the number of channels increased to 17 and the number of FOVs per scan line increased to 98 with a resolution of 33 km at the nadir point. It is capable of detecting atmospheric information from the surface to the lower stratosphere, and its sensitivity and calibration accuracy have been significantly enhanced. Detailed channel information for MWTS-2 and MWTS-3 is presented in Table 1.

Figure 1 shows the distribution of the weighting functions for the 17 channels of MWTS-3 with respect to pressure. Among them, 13 black dashed lines correspond to the weighting functions of the 13 channels of MWTS-2, and the colored lines represent the 4 newly added channels of MWTS-3. The newly added channels encompass two window channels (channels 1–2) for enhanced water vapor measurement, as well as temperature measurements at altitudes of 4 km and 6 km in the troposphere (channels 6 and 8). This research utilizes FY-3D MWTS-2 data from 1 January 2019 to 30 June 2023, and FY-3E MWTS-3 data from 15 March 2022 to 30 June 2023.

Table 1. Channel number, center frequency, bandwidth, and noise equivalent differential temperature (NEDT) of MWTS-2 and MWTS-3 from FY-3D and FY-3E, respectively.

Channel Number		Frequency (GHz)		Bandwidth (MHz)		NEDT (K)	
MWTS-2	MWTS-3	MWTS-2	MWTS-3	MWTS-2	MWTS-3	MWTS-2	MWTS-3
-	1	-	23.8	-	270	-	0.4
-	2	-	31.4	-	180	-	0.45
1	3	50.30		180	180	1.5	0.45
2	4	51.76		400	400	0.9	0.3
3	5	52.80		400	400	0.9	0.3
-	6	-	53.246 ± 0.08	-	2×140	-	0.35
4	7	53.596 ± 0.115		400	2×170	0.9	0.3
-	8	-	53.948 ± 0.081	400	2×142	-	0.35
5	9	54.40		400	400	0.9	0.3
6	10	54.94		400	400	0.9	0.3
7	11	55.50		330	330	0.9	0.3
8	12	$57.29 (f_0)$		330	330	0.9	0.7
9	13	$f_0 \pm 0.217$		78	2×78	1.5	0.9
10	14	$f_0 \pm 0.3222 \pm 0.048$		36	4×36	1.5	0.9
11	15	$f_0 \pm 0.3222 \pm 0.022$		16	4×16	2.3	1.3
12	16	$f_0 \pm 0.3222 \pm 0.01$		8	4×8	3.0	1.6
13	17	$f_0 \pm 0.3222 \pm 0.0045$		3	4×3	4.5	2.8

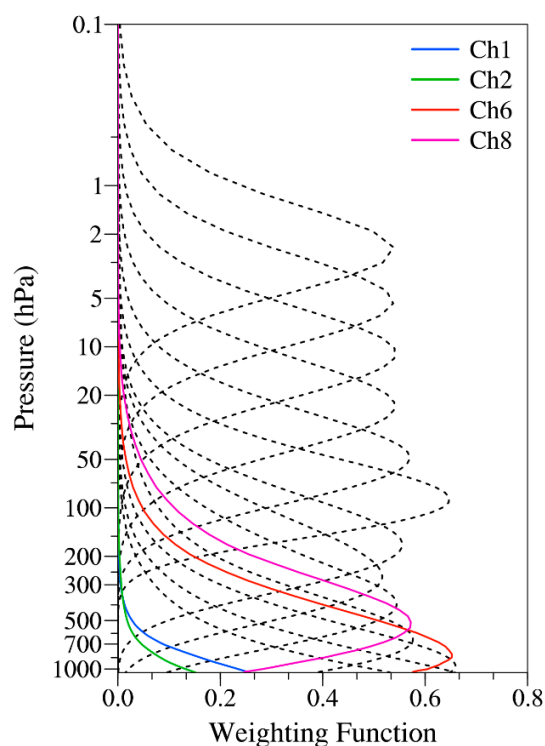


Figure 1. Weighting functions (WFs) of FY-3E MWTS-3 channels 1–17 (including 13 channels same as MWTS-2 shown in black curves), calculated using Radiative Transfer for TOVS (RTTOV) with the U.S. standard atmosphere profile at nadir.

2.2. DD Method

The DD method is an inter-calibration method that can eliminate inter-instrument biases by utilizing the matching of SNO observations and comparing the statistical differences between the observed and simulated TBs of two instruments. Figure 2 shows the monthly average local equator-crossing time (LECT) variations for the polar-orbiting satellites FY-3D and FY-3E from January 2019 to June 2023. It can be seen that FY-3D has undergone a slight orbital drift since 2021, while the orbit of FY-3E remains relatively stable.

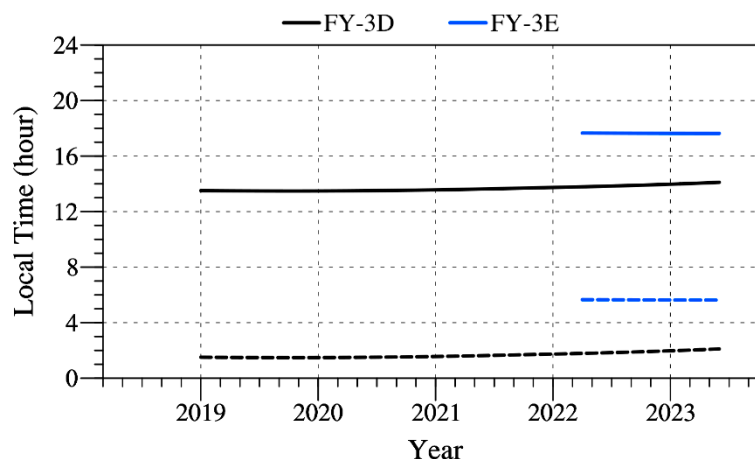


Figure 2. Monthly mean local equator-crossing times of FY-3D and FY-3E calculated from nadir observations on ascending (solid curves) and descending (dashed curves) nodes from January 2019 to June 2023.

Considering the time length of the data and the number of channels, this study adopts FY-3E MWTS-3 as the reference standard. Before inter-calibration, the spatiotemporal matching of observations from the two instruments is requisite. The spatiotemporal matching criteria used in this study are as follows: (1) the observation distance is less than 5 km and (2) the time difference between observations is less than 10 min [29]. To avoid uncertainties related to cloud cover and surface emissivity, we only select nadir-point observations over the ocean under clear-sky conditions for matching and inter-calibration. Clear-sky conditions are defined as a liquid water path (LWP) of ≤ 0.01 kg/m² [30], with the LWP obtained from ERA5 reanalysis [31].

After matching the observational data, it is necessary to simulate these TBs. The radiative transfer model used for TB simulation in this study is Radiative Transfer for TOVS (RTTOV). RTTOV is a fast radiative transfer model developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) in the early 1990s [32]. By providing atmospheric profiles with a specified temperature, concentrations of absorbing gases, cloud information, and surface data, it can simulate the radiative TBs of hundreds of meteorological satellite instruments worldwide, including the ultraviolet, visible, infrared, and microwave channels. This study utilizes version 13.0 of RTTOV. Saunders et al. (2018) [33] demonstrated the variables necessary for RTTOV clear-sky microwave radiation simulation, mainly including satellite self-information, surface information, and atmospheric profile information, as detailed in Table 2.

Table 2. Input variables for calculating MWTS clear-sky radiances with RTTOV (Version 13.0).

Category	Variable Name	Unit
Atmosphere variables	Pressure levels	hPa
	Temperature	K
	Water vapor mixing ratio	ppmv
Surface variables	Surface pressure	hPa
	2 m temperature	K
	2 m water vapor	ppmv
	10 m wind U, V	m/s
	Surface type	Land = 0, sea = 1, sea ice = 2
	Surface skin temperature	K
	Elevation	km
Satellite variables	Satellite zenith angle	deg
	Satellite azimuth angle	deg
	Solar zenith angle	deg
	Solar azimuth angle	deg
	Latitude	deg
	Longitude	deg

Once all the observed and simulated TBs have been obtained, inter-calibration can be performed. Below, the principles of the DD calibration method will be specifically introduced. For brevity, we will use O to represent the TB observation and B to represent the TB simulation, as follows:

$$O_{\text{sat}} = O_{\text{sat, true}} + \mu_{O_{\text{sat}}} \quad (1)$$

$$B_{\text{sat}} = B_{\text{sat, true}} + \mu_{B_{\text{sat}}} \quad (2)$$

Here, “sat” refers to MWTS data from the FY-3D or FY-3E satellites. It is important to note that they both represent the true values of TB, i.e., $O_{\text{sat, true}} = B_{\text{sat, true}}$. $\mu_{O_{\text{sat}}}$ and $\mu_{B_{\text{sat}}}$ represent the observation bias and simulation bias, respectively, considering the following relationship:

$$\overline{O_{\text{FY-3D}}} - \overline{B_{\text{FY-3D}}} = \overline{\mu_{O_{\text{FY-3D}}}} - \overline{\mu_{B_{\text{FY-3D}}}} \quad (3)$$

$$\overline{O_{\text{FY-3E}}} - \overline{B_{\text{FY-3E}}} = \overline{\mu_{O_{\text{FY-3E}}}} - \overline{\mu_{B_{\text{FY-3E}}}} \quad (4)$$

By taking the difference between both sides of Equations (1) and (2) and Equations (3) and (4), we obtain the following:

$$\overline{O_{\text{FY-3D}}} - \overline{B_{\text{FY-3D}}} - \overline{O_{\text{FY-3E}}} - \overline{B_{\text{FY-3E}}} = (\overline{\mu_{O_{\text{FY-3D}}}} - \overline{\mu_{O_{\text{FY-3E}}}}) - (\overline{\mu_{B_{\text{FY-3D}}}} - \overline{\mu_{B_{\text{FY-3E}}}}) \quad (5)$$

Since the reanalysis data (ERA5) input during the simulation process are the same for different instruments and the systematic biases of the RTTOV radiative transfer model and the ERA5 dataset are stable, the long-term simulation error, denoted as $\mu_{B_{\text{sat}}}$, is the same for all instruments [34], i.e., $\overline{\mu_{B_{\text{FY-3D}}}} = \overline{\mu_{B_{\text{FY-3E}}}}$. Thus, Equation (5) can be simplified to the following:

$$\overline{O_{\text{FY-3D}}} - \overline{B_{\text{FY-3D}}} - \overline{O_{\text{FY-3E}}} - \overline{B_{\text{FY-3E}}} = \overline{\mu_{O_{\text{FY-3D}}}} - \overline{\mu_{O_{\text{FY-3E}}}} \equiv \mu_{\text{DD}} \quad (6)$$

In this equation, μ_{DD} represents the observation bias between the FY-3D and FY-3E microwave radiometers. The essence of this method is to utilize the characteristics of constant model systematic biases, allowing for the observation bias between instruments to be transformed into a function of TB observations and simulations, even without knowing the true values.

Although the inter-sensor biases have been eliminated, each instrument still has its own scanning angle bias. Hence, before creating the MWTS dataset, limb correction of the instruments is necessary to remove scan-dependent patterns, which will be discussed in the next section.

2.3. Limb Correction

MWTSs adopt a cross-track scanning mode. In comparison with the nadir point, the atmospheric radiation received from the edge of the FOV has a longer optical path and the observations along the scan line reflect temperature information from different altitudes. Figure 3 depicts the weighting function distribution for four different FOVs of MWTS-3 channel 7. It can be seen that the weighting function for FOV-1 is located at 451 hPa, while that for FOV-45 drops to 661 hPa. This indicates that, as the scanning angle decreases, the altitude of the weighting function peak also decreases and the altitude of the weighting function peak at the nadir point is lowest. The influence of varying scanning angles on TB observations is referred to as the limb effect. The consequence of this effect is that true weather features are obscured by the dominant TB scanning patterns. For instance, in Figure 4, the global TB distribution of MWTS-3 channel 7 is predominantly influenced by the limb effect, especially in tropical regions. TB observations near the nadir point are approximately 10 K higher than those at larger scanning angles, which is a combined outcome of the atmospheric temperature decreasing with altitude in the troposphere and the weighting function peak increasing with altitude.

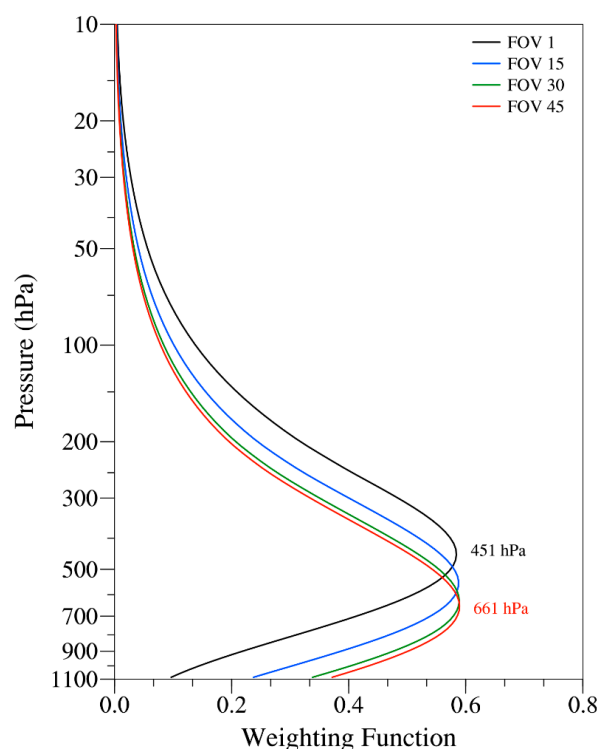


Figure 3. Weighting functions of MWTS-3 channel 7 at different scan angles of FOVs 1 (black), 15 (blue), 30 (green), and 45 (red) calculated by RTTOV using the U.S. standard atmosphere, 1976 (COESA 1976) profile.

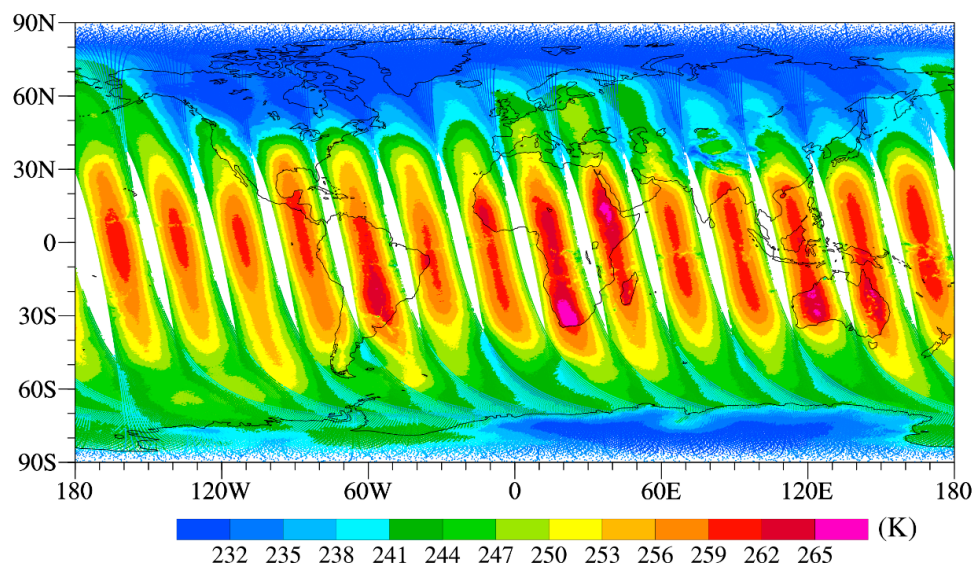


Figure 4. MWTS-3 channel 7 TBs observed on the ascending nodes on 1 January 2023.

Goldberg et al. (2001) [23] proposed a limb correction method for AMSU-A that effectively removes scanning angle bias. The limb effect in a targeting channel is removed by a linear regression of a few neighboring channels whose weight functions are right above and below the weighting function of the targeting channel. Xiaoxu et al. (2018) [25] described specific mathematical methods for correcting MWTSs, and Table 3 presents the auxiliary channels used for the limb correction of MWTS-3, along with their corresponding frequencies and weighting function information.

Table 3. Predictor channels and peak weighting functions of the 17 MWTS-3 channels.

Channel	Frequency (GHz)	Predictor Channels	Weighting Function (hPa)
1	23.8	1, 2	surface
2	31.4	1, 2, 3	surface
3	50.30	2, 3, 4	950
4	51.76	3, 4, 5	950
5	52.80	4, 5, 6	850
6	53.246 ± 0.08	5, 6, 7	850
7	53.596 ± 0.115	6, 7, 8	700
8	53.948 ± 0.081	7, 8, 9	500
9	54.40	8, 9, 10	400
10	54.94	9, 10, 11	250
11	55.50	10, 11, 12	200
12	$57.29 (f_0)$	11, 12	100
13	$f_0 \pm 0.217$	12, 13, 14	50
14	$f_0 \pm 0.3222 \pm 0.048$	13, 14, 15	25
15	$f_0 \pm 0.3222 \pm 0.022$	14, 15	10
16	$f_0 \pm 0.3222 \pm 0.01$	14, 15, 16	5
17	$f_0 \pm 0.3222 \pm 0.0045$	16, 17	2

A specific introduction of the limb correction algorithm is presented below, and the training equation of the correction coefficient is defined as follows:

$$\overline{T_{k,nadir}(j_2)} = b_i + \sum_{k_p=k-1}^{k+1} a_{k_p,i} [T_{k_p}(i,j_2) - \overline{T_{k_p}(i)}] \quad (7)$$

Here, $\overline{T_{k,nadir}(j_2)}$ represents the mean TB observation at the nadir point (FOVs 49 and 50) of MWTS-3 channel k in every 2° latitudinal band, and j_2 is the index for every 2° latitudinal band. The variable $T_{k_p}(i,j_2)$ is the mean TB at the predictor channel k_p of FOV position i , also estimated at every 2° latitudinal band, while $\overline{T_{k_p}(i)}$ is estimated globally. The coefficients $a_{k_p,i}$ and b_i are regression coefficients to be trained.

Once all regression coefficients are obtained, the limb correction formula can be expressed as follows:

$$T_{k,LC}(i, j) = b_i + \sum_{k_p=k-1}^{k+1} a_{k_p,i} [T_{k_p}(i,j) - \overline{T_{k_p}(i)}] \quad (8)$$

Here, $T_{k,LC}(i, j)$ represents the limb-corrected TB of channel k at FOV position i and scan line j . Considering the impact of surface emissivity instability on near-surface channels, the calculation process for MWTS-3 channels 1–7 only uses data over oceans, while for channels 8–17, no surface-type separations are made.

3. Results

3.1. Inter-Calibration Results

Figure 5a shows a schematic of the orbital distribution of FY-3D and FY-3E on 1 January 2023. Their ascending nodes' local equator-crossing times are 05:36 and 01:28, respectively. It is worth noting that FY-3E is the first dawn–dusk orbit meteorological satellite among the FengYun series satellites, and it is also the world's first sun-synchronous meteorological satellite to achieve operational status in a dawn–dusk orbit. The orbital paths of the two satellites intersect near the poles, and we exploit this feature for the spatiotemporal matching of the observation points. Figure 5b presents the matching results for the Northern Hemisphere, revealing that most of the matched observation points are located near the poles (at latitudes of around $\pm 80^\circ$). Because the orbit inclination of FY-3D and FY-3E is not exactly 90 degrees, but 98.75 degrees [2], the nadir FOV of these two satellites will not pass through the polar regions, but near $\pm 81.25^\circ$.

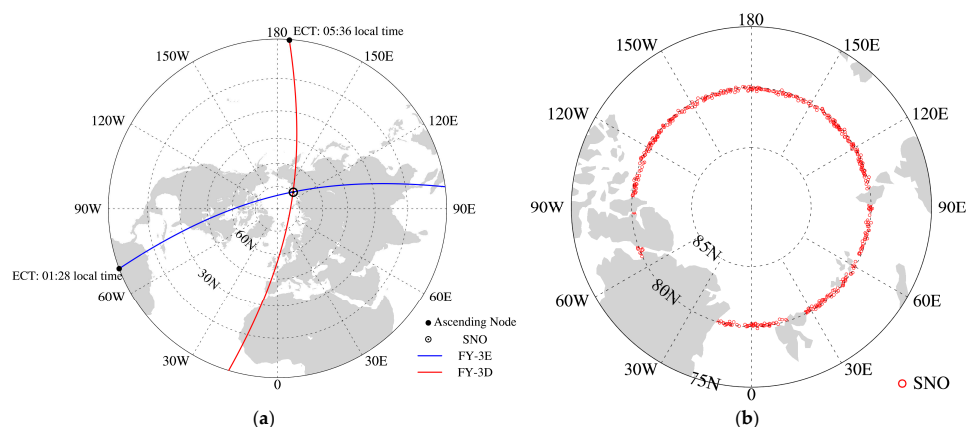


Figure 5. (a) Ascending nodes from FY-3D (blue curve) and FY-3E (red curve) swaths on 1 January 2023 shown under a north-polar stereographic projection. (b) All SNO points between FY-3D and FY-3E from March 2022 to June 2023.

After matching the observation data from the two satellites, the subsequent step is to employ the DD method introduced in Section 2.2 to estimate the observation biases between MWTS-2 and MWTS-3 for each channel. Figure 6 shows the distribution of biases for all channels. It can be seen that the variance of bias is larger for the lower channels (channels 3 and 4, Figure 6a), while the bias for the higher channels (channels 7, 9, 11, and 13, Figure 6b,c) is relatively stable. The main reason for this phenomenon is determined by the NEDTs of the channels themselves [35]. The NEDT for a channel describes the precision of the measured antenna brightness temperatures at the frequency of this channel. Therefore, for channels with a low measured precision (large NEDT), the observational bias between them will be large.

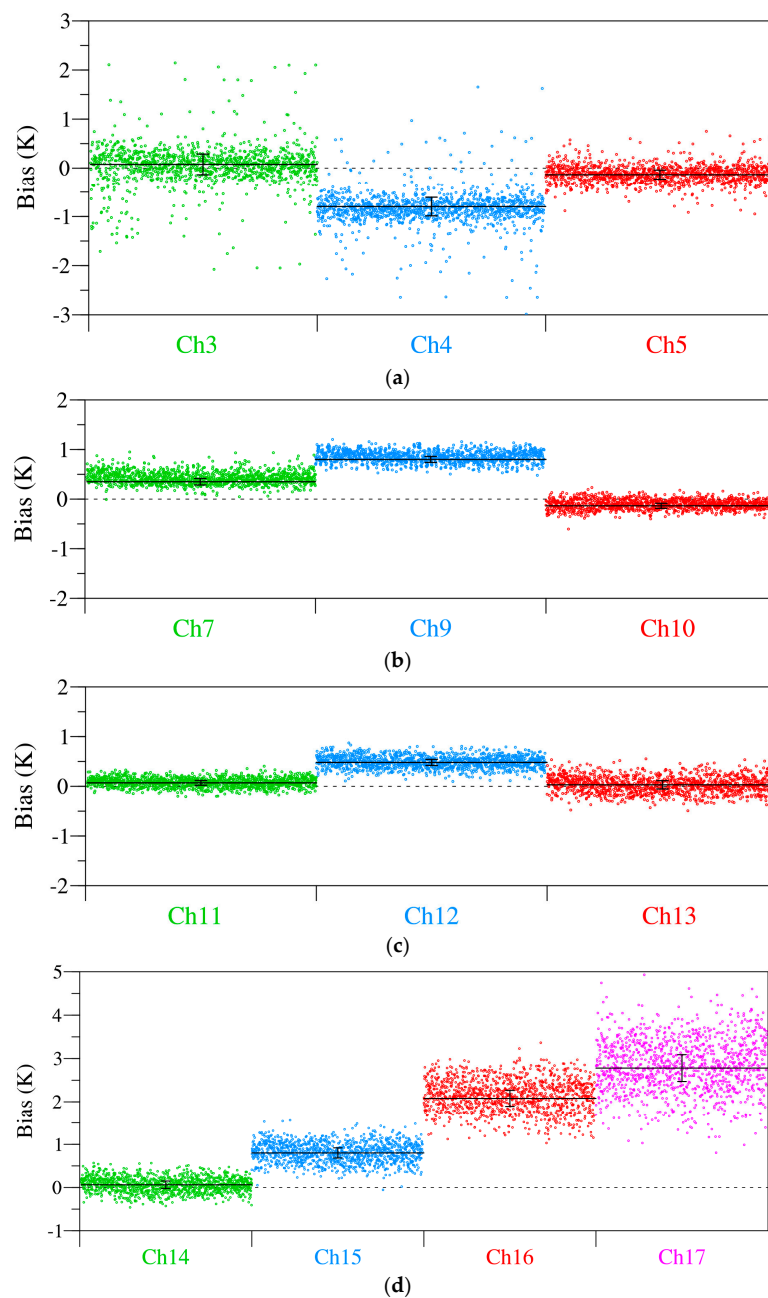


Figure 6. DD bias for all channels between MWTS-2 and MWTS-3 (mean value and standard deviation are indicated by black curves). Channel numbers in the figure are all from MWTS-3. (a) channels 3, 4, 5; (b) channels 7, 9, 10; (c) channels 11, 12, 13; (d) channels 14, 15, 16, 17.

Figure 7 shows the distribution of bias between channels of MWTS-3 and MWTS-2 with the same center frequency. We find that the biases for all tropospheric channels are within 1 K, with only channels 16 (5 hPa) and 17 (2 hPa) exhibiting larger biases, exceeding 2 K. The standard deviations of the biases for channels 5–15 are all less than 1 K, indicating that the biases between the remaining tropospheric channels, apart from the near-surface channels, are relatively stable. Based on these results, we can eliminate the observational bias between MWTS-3 and MWTS-2, so that the microwave data from FY-3D and FY-3E can be merged for use. Equation (9) shows how the bias adjustment is performed. Figure 8 shows a flowchart of the inter-calibration between MWTS-2 and MWTS-3.

$$TB_{DD}^{FY-3D, Ch_k} = TB_0^{FY-3D, Ch_k} - \mu_{DD}^{Ch_k} \quad (9)$$

Here, TB_0^{FY-3D, Ch_k} (TB_{DD}^{FY-3D, Ch_k}) is the raw (after bias adjustment) TB observation of MWTS-2 channel k from FY-3D. $\mu_{DD}^{Ch_k}$ represents the observation bias of channel k between the FY-3D MWTS-2 and FY-3E MWTS-3 (as reference mission).

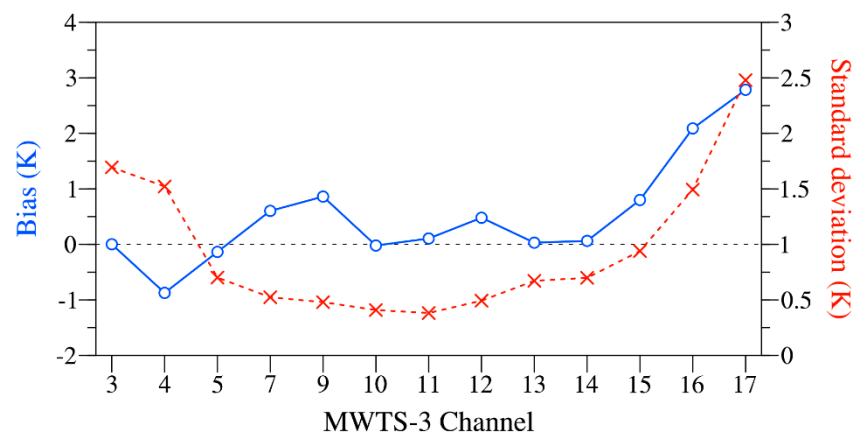


Figure 7. Inter-sensor DD bias (blue solid curve) with standard deviation (red dashed curve) of MWTS channels between FY-3D and FY-3E.

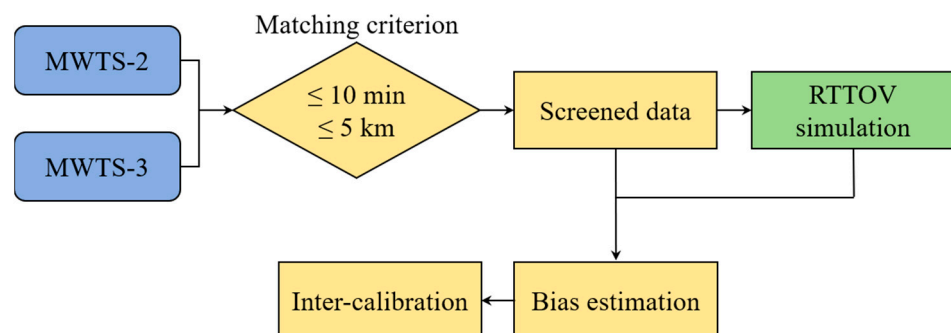


Figure 8. Flowchart of inter-calibration between MWTS-2 and MWTS-3.

3.2. Limb Correction Results

Figure 9 shows the mean TB for MWTS-3 channel 7 at every 2° latitudinal band over global oceans in January 2023, corresponding to $T_{kp}(i, j_2)$ in Equation (7). From the figure, we can see the following: (1) the TB observations exhibit a “high in the center, low on the sides” pattern across all latitude bands and (2) the maximum TB observations occur at approximately 10° north and south of the equator.

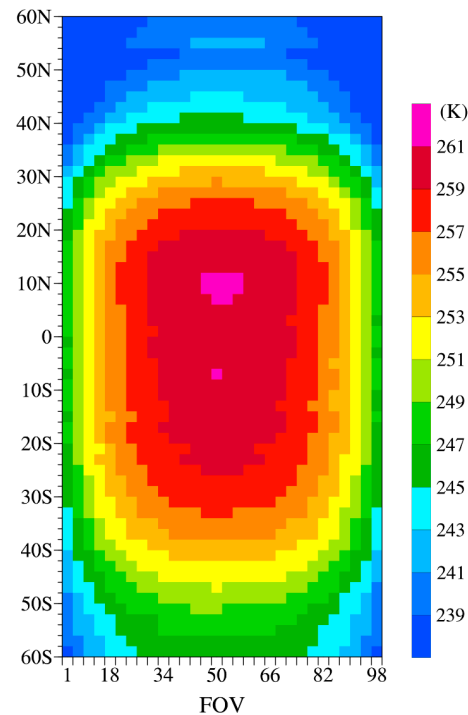


Figure 9. MWTS-3 channel 7 mean TBs averaged at every scan position and in every 2° latitudinal band over global ocean. Data are from January 2023.

Subsequently, we still take the TB observation of MWTS-3 in January 2023 as an example to calculate the values required for Equation (7) and obtain all the required coefficients through linear regression. Finally, these coefficients are substituted into Equation (8) for correction. Figure 10 shows the distributions of the mean TB observations for MWTS-3 channels 3, 7, 10, and 12 across all FOVs before (solid-colored lines) and after (dashed colored lines) limb correction within $\pm 60^\circ$ latitude. It can be seen that there are nearly no differences among the nadir observations before and after correction, while the differences are larger for those observations at FOV edges.

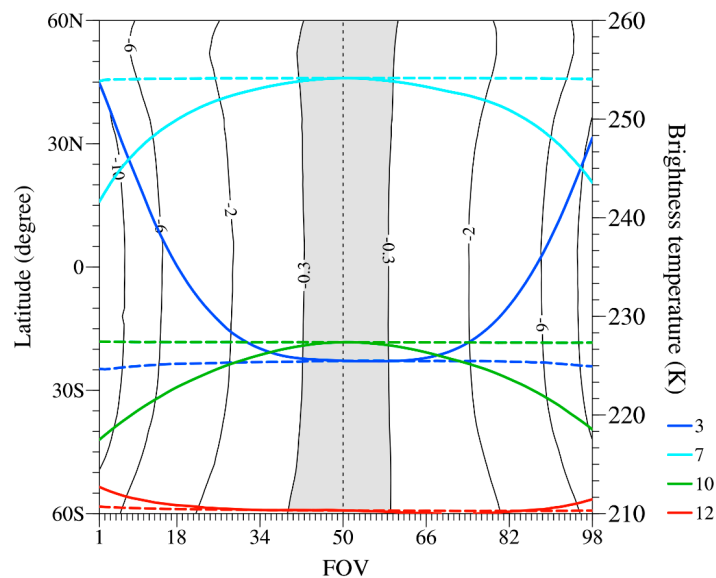


Figure 10. Limb-corrected values of MWTS-3 channel 7 $[T_b^{\text{Ch7}}(i, j) - T_{b, \text{LC}}^{\text{Ch7}}(i, j)]$ TBs (black contour lines at 2 K intervals) as a function of scan position and latitude at 2° intervals, as well as scan variations in the global mean TBs of channel 3, 7, 10, and 12 before (solid-colored curves) and after (dashed colored curves) the limb correction. MWTS-3 observations are collected from January 2023.

Figure 11 shows the TB distributions of MWTS-3 channel 7 before and after limb correction on ascending nodes on 15 January 2023. It is apparent that limb correction effectively removes scan-dependent patterns from the observations, resulting in a more uniform and coordinated TB distribution across the different orbits, and the TB field after limb correction begins to reflect large-scale weather features. The limb-corrected TBs at the conjunction of two neighboring swaths are coherent. This coherence is physically realistic, because the MWTS-3 is sampling a globally continuous temperature field in separate swaths that are about 100 min apart. The results above indicate the significant importance of limb correction for the application of polar-orbiting TB observations.

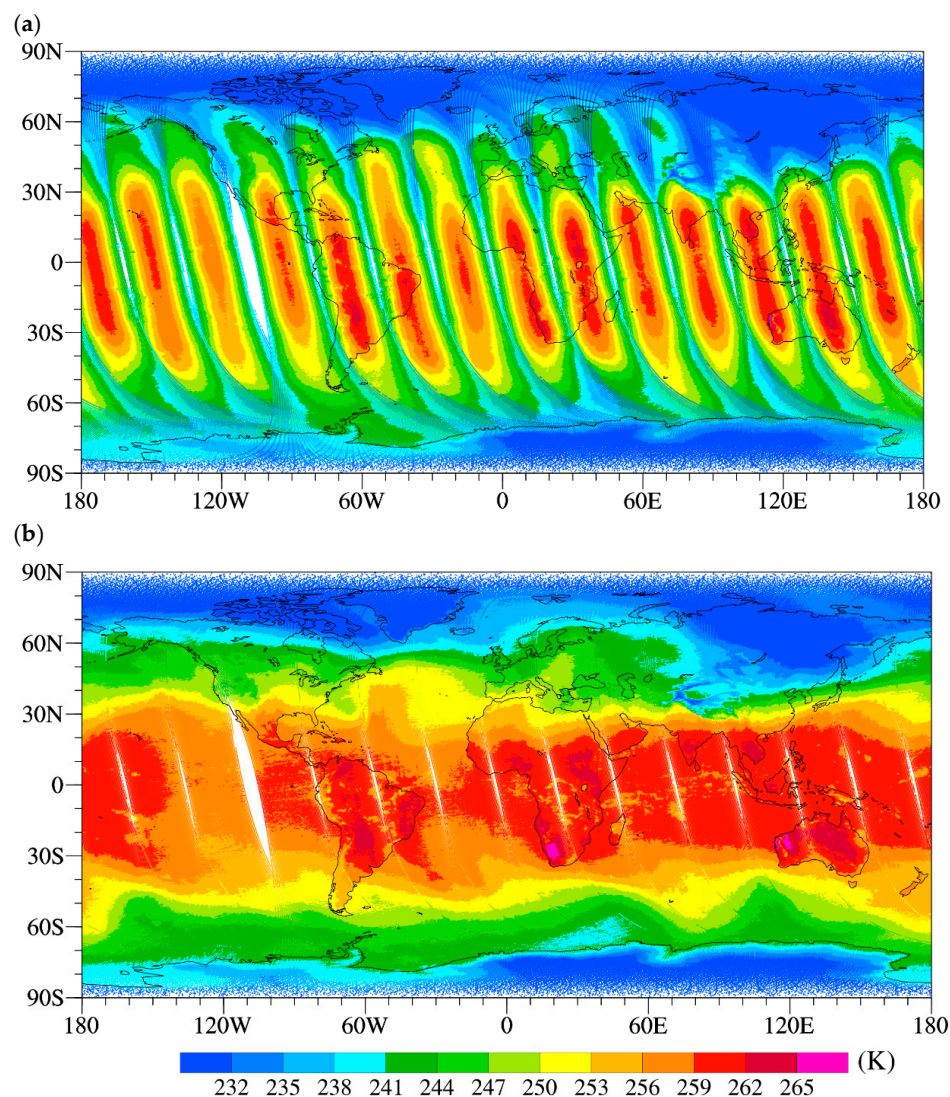


Figure 11. MWTS-3 channel 7 TBs observed on the ascending nodes on 15 January 2023 (a) before and (b) after the limb correction.

3.3. Data Gridded Results

After the completion of the inter-satellite calibration and limb correction of the MWTS data, the next step is to interpolate them to obtain a gridded dataset. Firstly, we divide the Earth into grids at the three following horizontal resolutions: $0.5^\circ \times 0.5^\circ$, $3^\circ \times 3^\circ$, and $9^\circ \times 9^\circ$. For each grid, we average the ascending and descending TB observations contained therein, resulting in three gridded datasets. Only a small number of grids at $0.5^\circ \times 0.5^\circ$ and $3^\circ \times 3^\circ$ near the equator may not contain observations. Missing grid points at the $0.5^\circ \times 0.5^\circ$ resolution will be obtained from the $3^\circ \times 3^\circ$ resolution, and the missing

grid points at the $3^\circ \times 3^\circ$ resolution will be obtained from the $9^\circ \times 9^\circ$ -resolution gridded dataset. This nested interpolation method generates a daily MWTS TB dataset at a global resolution of $0.5^\circ \times 0.5^\circ$ from January 2019 to June 2023. Taking MWTS-3 channel 7 as an example, Figure 12 shows the global TB distribution on 15 January 2023. It reveals a uniform and regular distribution of TB with latitude, and no observational gaps are present. The advantage of this dataset lies in its composition of TB data obtained from direct observations, covering the globe with a high vertical resolution, making it applicable for various climate studies in the future.

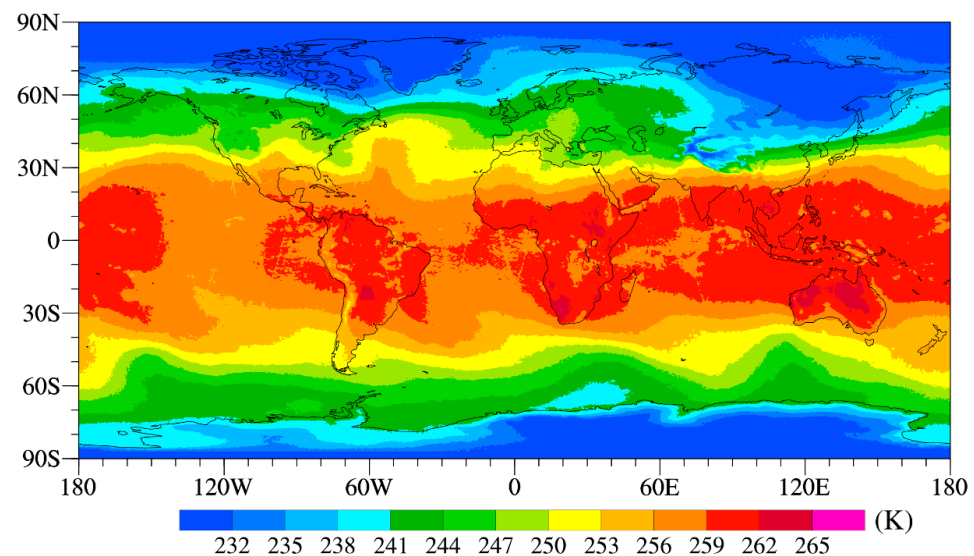


Figure 12. Global distributions of gridded MWTS-3 channel-7 TB after nested interpolation on 15 January 2023.

4. Conclusions and Discussion

This study accomplished the inter-satellite calibration and fusion of the microwave temperature sounders aboard the Chinese FY-3D and FY-3E polar-orbiting satellites, obtaining a global gridded microwave TB dataset. Firstly, we used the DD method to calculate and eliminate inter-sensor bias. By performing the spatiotemporal matching of over a year of MWTS-2 and MWTS-3 data, we found that the matched data were primarily located near the North and South Poles. The inter-calibration results indicated that the observational biases for all tropospheric channels were within 1 K, with only MWTS-3 channel 16 (5 hPa) and 17 (2 hPa) showing larger biases exceeding 2 K. Excluding the near-surface channel, the observational biases among the remaining tropospheric channels were relatively stable (with a standard deviation of less than 1 K). Secondly, after inter-calibration, a few statistical methods were used to perform limb correction on the raw observations, removing the scan-dependent patterns present in each channel. It was shown that limb correction effectively removed scan-dependent patterns from the observations, resulting in a more uniform and coordinated TB distribution across the different orbits, and the TB field after limb correction began to reflect large-scale weather features. Finally, we used the nested interpolation to convert the original MWTS orbital TB observations into a daily MWTS TB dataset with a global resolution of $0.5^\circ \times 0.5^\circ$. The steps for producing the MWTS gridded dataset can be summarized in the flowchart below (Figure 13).

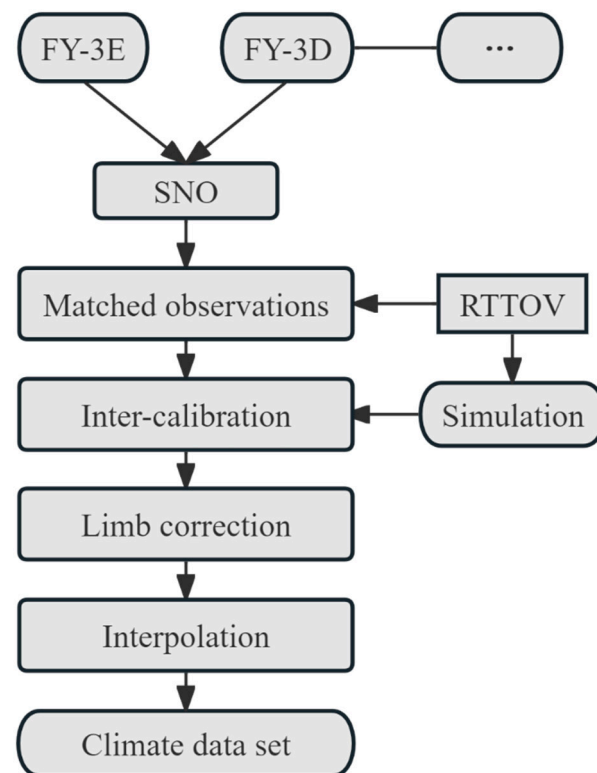


Figure 13. Flowchart for establishing multi-satellite MWTS gridded dataset.

The dataset established in this study is the first global microwave TB gridded dataset based on MWTS observations, consisting of 17 detection channels that provide atmospheric temperature information from the surface to the lower stratosphere. In the future, as more FengYun series satellites are launched, additional MWTS data can be integrated to create a long-term time series of microwave TB climate datasets. This dataset can be used for studying long-term trends in the atmospheric temperature at various altitudes, the distribution and trends of liquid water paths over global oceans, as well as various climate research topics such as El Niño and atmospheric teleconnections. In the future, based on the research of this paper, we will continue to correct and integrate data from other instruments (such as infrared instruments) onboard FengYun series satellites to form more long-term satellite observation products.

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