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On-Orbit Calibration Method for Correction Microwave Radiometer of the HY-2 Satellite Constellation

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Abstract: The HY-2D satellite was successfully launched in 2022, which marks the first phase of the HY-2 satellite constellation. In order to reduce the deviation of wet path delay (WPD) between different satellites in the HY-2 satellite constellation and increase precision in the correction microwave radiometer (CMR) products, on-orbit calibration must be performed to the brightness temperature (BT) of the CMR in this constellation. This study describes the principle and process of on-orbit calibration for CMR in detail. For the three satellites of the HY-2 satellite constellation, after cross-matching with each other within a limited spatio-temporal range, the HY-2B satellite with sounding on the global ocean is selected to the calibration source, calibrating BT from the CMR of the HY-2C and HY-2D satellites to the BT dimension of the HY-2B satellite CMR. To check on-orbit calibration, a retrieval algorithm is built using atmospheric profile data from ECMWF and BT data, obtained from the CMR of the HY-2B satellite; this is used to calculate the atmospheric water vapor (AWV) and WPD from the HY-2 satellite constellation. After on-orbit calibration to the CMRs of the HY-2 satellite constellation, the deviation between the CMR products of different satellites is significantly reduced by over 20%, and the RMS of WPD for the same type of products from the Jason-3 satellite is less than 1 cm. It may be concluded that on-orbit calibration improves the accuracy of AWV and WPD by normalizing the BT dimension for CMRs of the HY-2 satellite constellation, so this calibration method is effective and credible for enhancing the quality of altimeter products in the HY-2 satellite constellation.

Keywords: on-orbit calibration; correction microwave radiometer; the HY-2 satellite constellation; brightness temperature; crossovers; reference satellite



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1. Introduction

The correction microwave radiometer (CMR) is a fixed-beam pointing microwave radiometer, which is a payload on each satellite of the HY-2 (HaiYang-2) constellation. Its main function is to provide error correction for the wet path delay (WPD) from the radar altimeter to the satellite. WPD is a distance error caused by the influence of atmospheric water vapor (AWV) and other relative substances in the troposphere during the transmission of electromagnetic waves in the atmosphere; it ranges from zero (dry and cold air) to around 40 cm (wet and hot air) [1,2]. Because the distribution and change are unpredictable due to water vapor and other substances in the spatio-temporal range, the most accurate method is to load a microwave radiometer together with the radar altimeter, to measure and produce the WPD quantitatively [3,4].

Since WPD is one of the most critical terms in a satellite radar altimeter error budget, all modern altimetry satellites are equipped with special microwave radiometers for wet

tropospheric correction. For example, on 10 August 1992, the United States and France jointly launched the TOPEX/Poseidon (TP) satellite for sea-surface topography; it carries a special microwave radiometer (TMR, 18 GHz, 21 GHz, 37 GHz) for WPD, with an accuracy of 1.2 cm [5,6]. As a follow-up satellite, the Jason-1 satellite was launched and changed the observed frequency of the microwave radiometer (JMR, 18.7 GHz, 23.8 GHz, 34 GHz) on board [7]. Subsequently, the Jason-2 and Jason-3 satellites were successfully launched, carrying advanced microwave radiometers (AMR, 18.7 GHz, 23.8 GHz, 34 GHz) with the same mechanism [8,9]. On 21 November 2020, the United States and Europe jointly launched the Sentinel-6MF (Jason-CS) satellite with the advanced microwave radiometer for climate (AMR-C, 18.7 GHz, 23.8 GHz, 34 GHz); it carried a new measurement system (Poseidon-4) combining dual-frequency synthetic aperture radar (SAR) and traditional altimeter radar [10]. The microwave radiometers of these satellites all have three frequencies for wet tropospheric correction.

The HY-2 satellite constellation consists of three satellites for the marine dynamic environment; they all carry CMRs to measure WPD and include the HY-2B, HY-2C, and HY-2D satellites. In this constellation, every CMR has three channels for ocean observation: the 23.8 GHz channel is for the AWV absorption line, the 37 GHz channel is for cloud liquid water (CLW), and the 18.7 GHz channel is for observing sea-surface wind contributions [11]. Table 1 details their main specifications.

Table 1. Main parameters of correction microwave radiometers (CMRs) for the HY-2 satellite constellation.

Marker	Frequency (GHz)	Bandwidth (MHz)	Footprint (km)	Beamwidth (3 dB) (°)	Antenna Aperture (mm)
HY-2B	18.7, 23.8, 37	250, 250, 500	24, 19, 10	1.4 ± 0.2 , 1.1 ± 0.2 , 0.6 ± 0.1	920 ± 10
HY-2C HY-2D	18.7, 23.8, 37	250, 250, 500	21, 19, 13	1.25 ± 0.2 , 1.15 ± 0.2 , $0.2, 0.75 \pm 0.2$	920 ± 10

The HY-2B, HY-2C and HY-2D satellites were successfully launched on 25 October 2018, 21 September 2020 and 19 May 2021, respectively. HY-2B runs on a sun-synchronous orbit (inclination of 99.34°), and HY-2C and HY-2D are designed with non-sun-synchronous inclined orbits (inclination of 66°) [12]. Although both HY-2C and HY-2D have the same orbit inclination, they are not on the same orbital plane and there is a fixed angle between the orbital planes of the two satellites, to maintain a fixed-phase difference between the ground tracks of the two satellites and produce a denser ground-track grid than a single satellite. Because HY-2C and HY-2D are different from HY-2B in terms of orbit character, it is impossible for HY-2C and HY-2D to produce a fixed-phase difference with HY-2B [13]. However, the dual-satellite system that consists of HY-2C and HY-2D (with the same orbit character) can achieve fixed-cycle (about 10 days) observation coverage, so their ground tracks are evenly spaced on the Earth, with a spacing of about 146.3 km for the grid formed by the tracks [14]. When HY-2B (fixed-cycle: about 14 days) is joined to this system, this grid can reduce the average spacing to about 100 km, and the density is increased significantly. These grids are shown in Figure 1.

The radiometer must be calibrated before launch via on-ground calibration. The calibration equation of the receiver shows the relationship between the output voltage and antenna temperature, which extends from the mechanism to the receiver [15]. The calibration result of every CMR achieves satisfactory accuracy on the ground for the HY-2 satellite constellation; however, post-launch, the brightness temperature (BT) deviation still exists between them, for multiple reasons:

- As time increases in satellite operation, the decline of CMR performance will cause the observed BT to drift [16].
- For the CMR antenna and feed, the ambient temperature will change after launch, meaning calculation from on-ground calibration formulas can deviate from real BT values [17].

- The CMR of HY-2B has three feed sources that correspond to three channels for observations; the CMRs of HY-2C and HY-2D satellites have only one feed source to three channels respectively. This is shown in Figure 2.

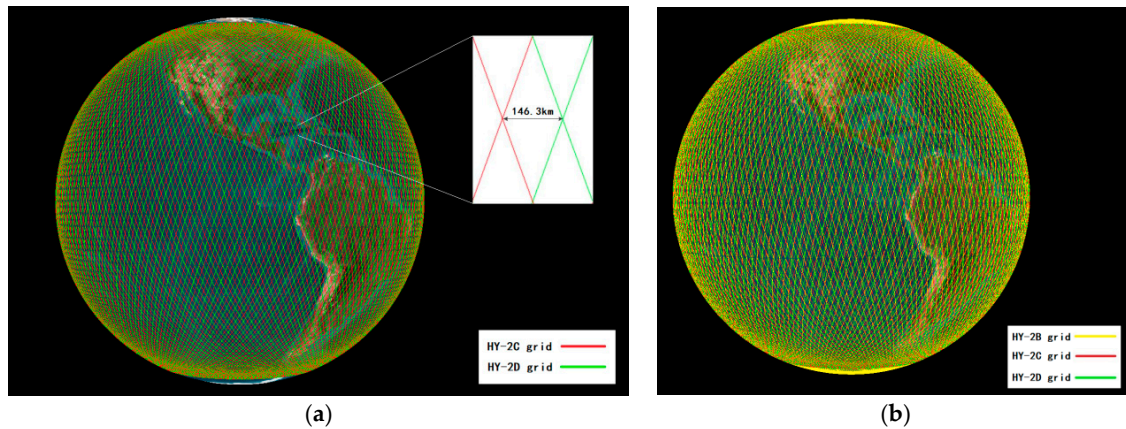


Figure 1. The HY-2 satellite constellation ground tracks. (a) A dual-satellite grid including HY-2C and HY-2D, with symmetrical tracks. (b) A constellation grid including HY-2B, HY-2C and HY-2D; it is an uneven grid due to the HY-2B orbit differing from that of HY-2C and HY-2D, but its tracks cover polar regions.

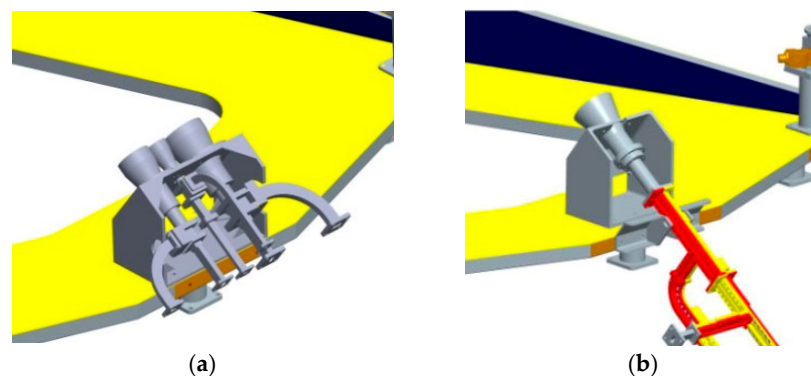


Figure 2. The CMR feed sources of the HY-2 satellite constellation. The HY-2B satellite flies forward along the $+x$ axis; (a) shows its CMR and has three feed sources at three frequencies; these are arranged in a straight line along the flight direction, and the centers of the three-channel footprint are collinear. Both the HY-2C and HY-2D satellites fly on the yaw, which no longer stays flying forward along the $+x$ axis. (b) The resulting CMRs, which have only one feed source to the three frequencies.

Therefore, every CMR must be calibrated after launch; this is on-orbit calibration. It is customary to revise the calibration equation for stable satellites, which improves the accuracy of WPD. In 1992, Jason-1 was cross-calibrated by TOPEX in the “verification tandem phase” [18]. In wetter conditions, the bias of WPD between JMR and TMR before calibration is 5–7 mm; after on-orbit calibration, the bias is approximately zero; in dry atmospheric conditions, this bias before calibration is 15 mm, and it drops to 5 mm after calibration. In 1997, ERS-2 was cross-calibrated by TOPEX and ERS-1, which improved the WPD [19]. The objective of the present study is to normalize the BT values obtained from the on-ground calibration equations for the CMRs of the three satellites, and to minimize the bias among BT values of different CMRs, so as to further improve the accuracy and consistency of the WPD for the HY-2 satellite constellation.

2. Datasets

On-orbit calibration must be supported with sufficient data; one portion of these are used to build models for calibration and inversion, and the other is used to verify them. The

observed times for the three sets of data must be different, to prevent data for calibrating or modeling being used to verify them [20,21]. Therefore, all experimental datasets used for this on-orbit calibration should be divided into three parts: verification, retrieval algorithm, and calibration equation. The datasets are given in Table 2.

Table 2. The datasets for on-orbit calibration.

Dataset	Function	Level	Volume	Satellite	Timeframe
1st group	Verification	L2B	2.52 GB	HY-2B, HY-2C, HY-2D	27 December 2021–27 January 2022 21 March 2022–21 April 2022
2nd group	Retrieval algorithm	L1B	14.24 GB	HY-2B	1 January 2021–1 March 2021 1 April 2021–1 June 2021 1 July 2021–1 September 2021 1 October 2021–1 December 2021
3rd group	On-orbit calibration	L2B	13.68 GB	HY-2B, HY-2C, HY-2D	1 May 2022–1 May 2023

The first group is used to cross-check on-orbit calibration. In order to normalize the BT of the three CMRs in the HY-2 satellite constellation, it is necessary to select one of them as the reference. The reference satellite should have more crossovers than the other two satellites in the constellation, to provide as many samples as possible for on-orbit calibration [22,23]. The task that checks the effect of on-orbit calibration includes two steps: one observes the change of differences for CMR products in the crossovers of two satellites before and after calibration [24], and the other checks the accuracy of products after calibration. In this experiment, the CMR products of the HY-2 satellite constellation for two discontinuous months are selected to cross-match and compare, and after on-orbit calibration, the AMR products of Jason-3 are compared with CMR products to verify.

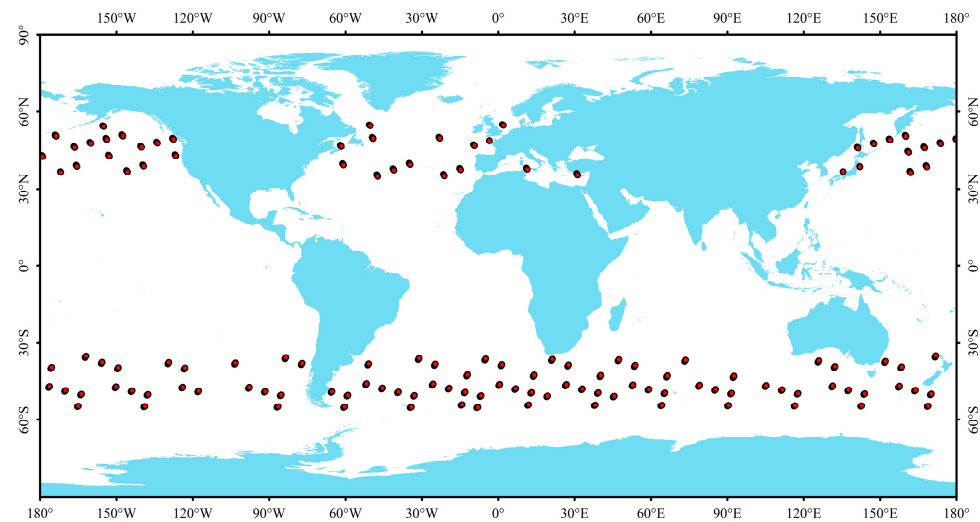
The second group is used to build a new retrieval algorithm. The current operational algorithm for the CMRs of the HY-2 satellite constellation is from the HY-2A satellite; it was fitted using WPD (AWV) data from the AMR and TB data of CMR, as obtained from the HY-2A satellite [25]. The WPD and AWV of the HY-2 satellite constellation were validated by comparing them with the synchronous data from in-situ observations of the ocean or the AMR of Jason-3, which all show minor deviations [26]. In this on-orbit calibration, new models and coefficients are tried experimentally.

The third group is used to establish an on-orbit calibration equation. After selecting the reference satellite, the BT data of the other two satellite CMRs are calibrated to the BT data's dimension of the reference satellite CMR. In order to ensure the accuracy of BT data, this calibration must be performed when every satellite of the constellation is running stably [27]. The HY-2D was sufficiently stable after April 2022. This experiment accumulated datasets for about 1 year until 2023, which was enough to determine whether the on-orbit calibration method had an optimal effect.

3. Cross-Checking in the HY-2 Satellite Constellation

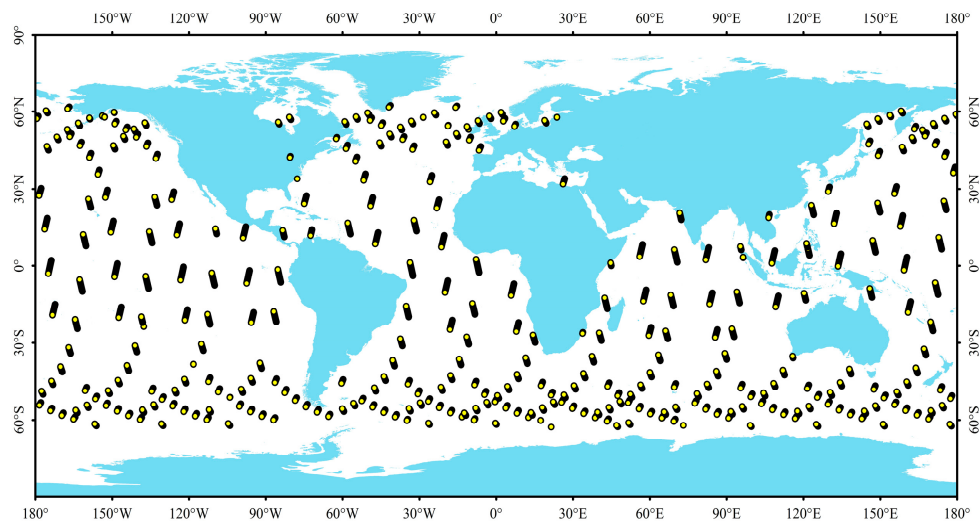
The constraints for selecting crossovers for on-orbit calibration are as follows: they are all more than 50 km from the coastline, the temporal range is less than 30 min, and the spatial range is a radius of 15 km across a circular area. The data for one month (see Table 2 from 27 December 2021 to 27 January 2022) are extracted from the datasets used for on-orbit calibration, and any two of three satellites in the HY-2 satellite constellation are cross-matched according to the above constraints. Among them, there are 1254 crossovers between HY-2B and HY-2C; 10,898 points are between HY-2B and HY-2D and have no points between HY-2C and HY-2D. We take data for another month (see Table 2 from 21 March to 21 April 2022) to cross with each other under the same constraints in the HY-2 satellite constellation; HY-2B crosses HY-2C and HY-2D, respectively, for 4424 and 3050 points, though we still have no crossovers between HY-2C and HY-2D.

The distribution of crossovers is shown in Figure 3a–d. It can be shown in two durations: HY-2B has the most crossing points with HY-2D, with the second-most being between HY-2B and HY-2C. However, the distribution and number of crossovers varies in different months between HY-2B and HY-2C (shown in Figure 3a,c) as well as HY-2B and HY-2D (shown in Figure 3b,d). Therefore, long-term data accumulation can ensure sufficient points for on-orbit calibration, but there are no points between HY-2C and HY-2D. These are mainly determined from the orbit characteristics of the three satellites in the constellation (see paragraph 4 in Section 1). Therefore, the HY-2B satellite can be used as the reference satellite for this on-orbit calibration.



crossovers between HY-2B and HY-2C (from 27 December 2021 to 27 January 2022)

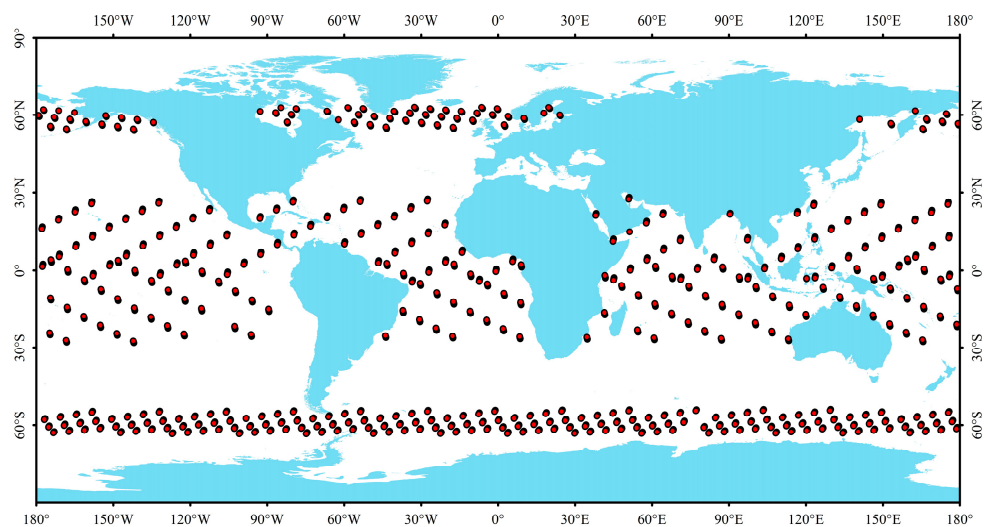
(a)



crossovers between HY-2B and HY-2D (from 27 December 2021 to 27 January 2022)

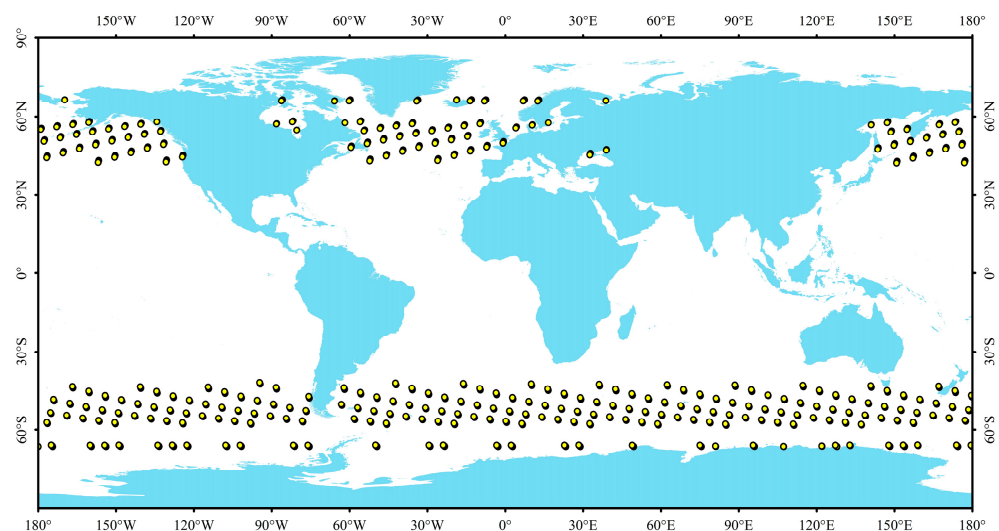
(b)

Figure 3. *Cont.*



crossovers between HY-2B and HY-2C (from 21 March 2022 to 21 April 2022)

(c)



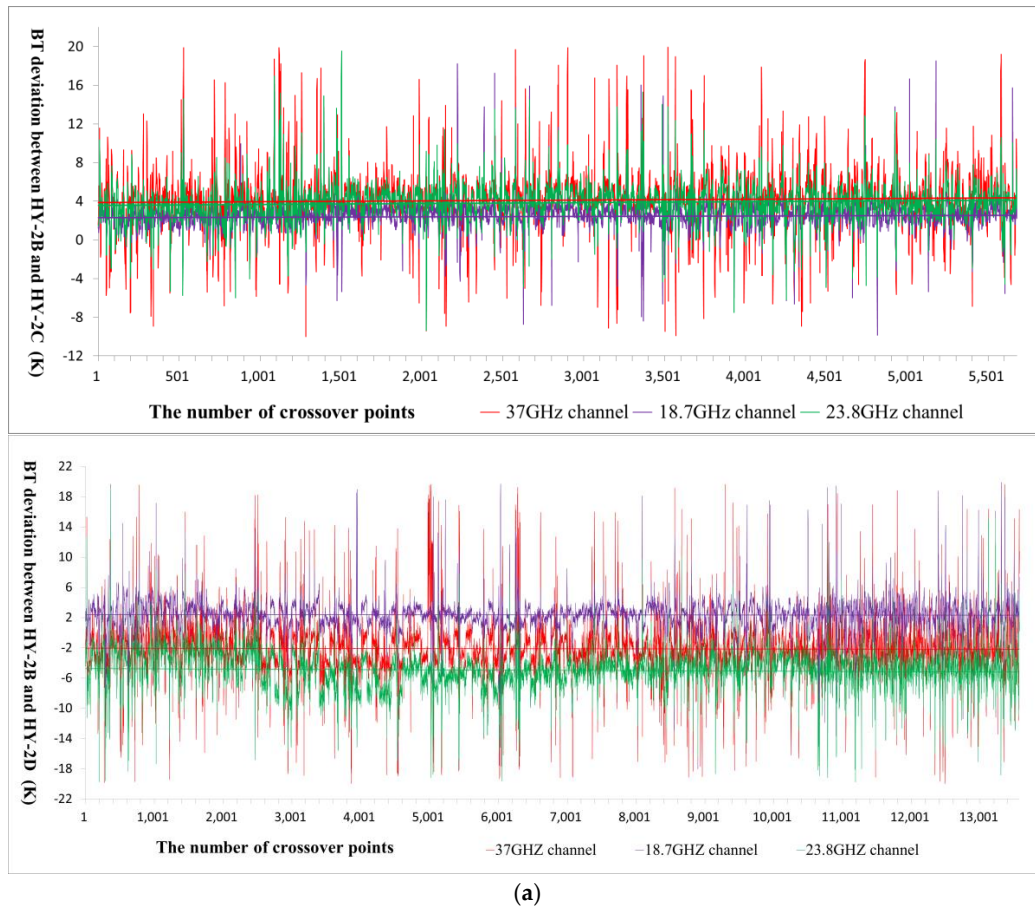
crossovers between HY-2B and HY-2D (from 21 March 2022 to 21 April 2022)

(d)

Figure 3. The distribution of crossovers with each other in the HY-2 satellite constellation; (a,b) are within the same time period and (c,d) are within another time period. (a,c) Crossovers between HY-2B and HY-2C and (b,d) crossovers between HY-2B and HY-2D. (a,d) Crossovers from 30° to 60° at south and north latitudes, respectively, and (b,c) crossovers where HY-2B crosses HY-2C and HY-2D, distributed on the globe from 60° of the north and south latitudes to the equator.

We compare the BT data of the above crossovers between the satellites and take three channels from this constellation; as shown in Figure 4a, their deviations are quite obvious. It may be seen that their BT differences are all concentrated on a fixed threshold and the trend line of their BT differences is very straight, indicating that the relative stability of BT is excellent between them [28] from 2021 to 2022. Therefore, it may be deduced that if crossovers conform to the above constraints between HY-2C and HY-2D, these stable differences must also occur for them. For two satellites with crossovers, we removed the BT data contaminated by sea ice and rainfall from all points; the invalid data for HY-2B and HY-2C accounted for 1.92% of the total, and the invalid data for HY-2B and HY-2D accounted for 1.86%. In Figure 4b, the BT data of crossovers for the same frequency channels

from two satellites are linearly correlated, indicating that the CMRs of the three satellites have consistency and inheritance, which is also a prerequisite for on-orbit calibration in the HY-2 satellite constellation.



(a)

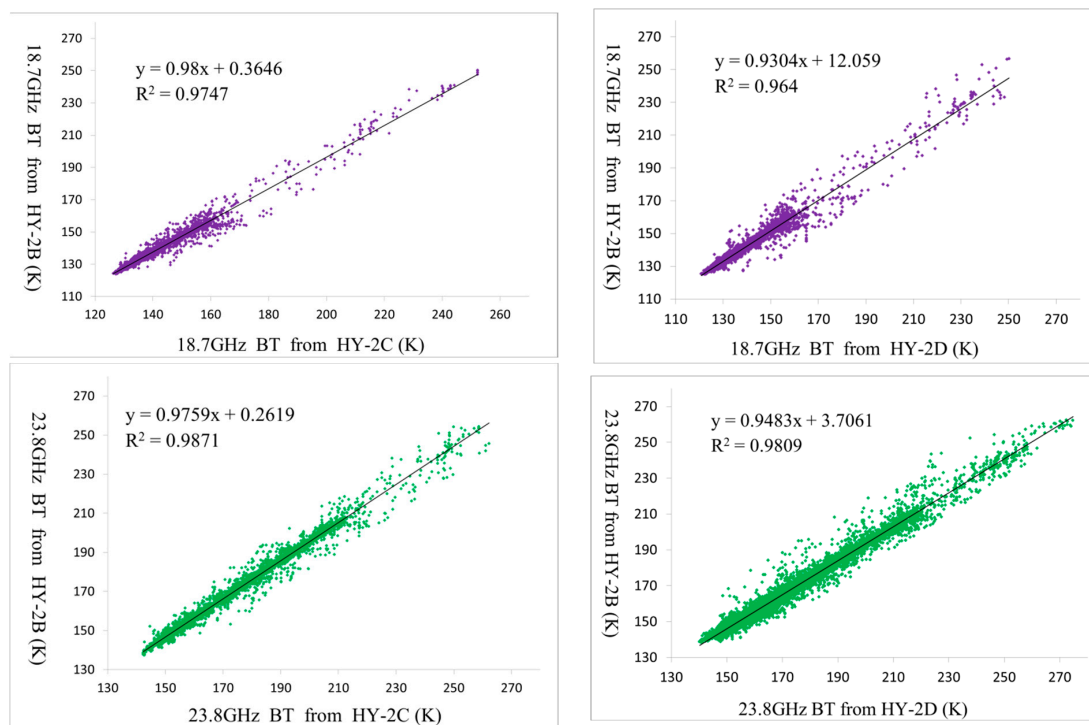


Figure 4. Cont.

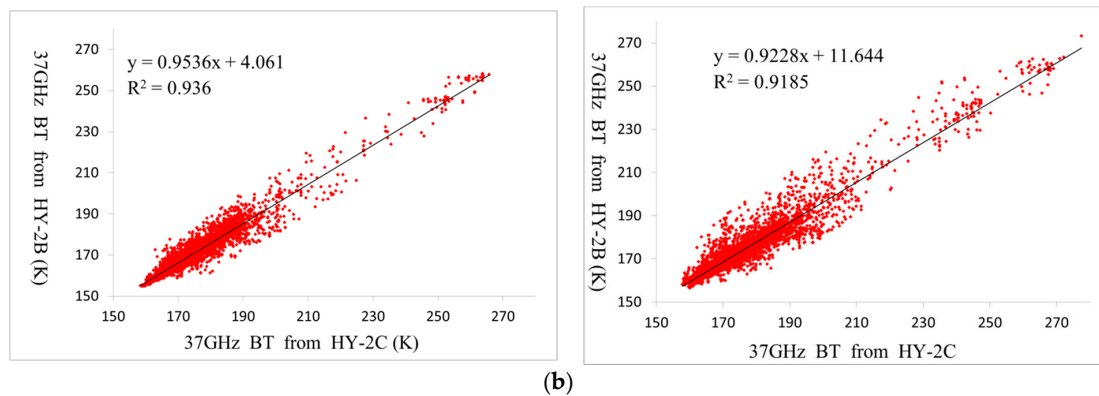


Figure 4. Comparing brightness temperature (BT) differences of three channels in crossovers for two satellites: (a) BT differences between HY-2B and HY-2C, concentrated from -10 K to 20 K, and BT differences between HY-2B and HY-2D, concentrated from -20 K to 20 K, as obtained from three channels. (b) Correlation between any two groups of BT data at crossovers between two satellites.

Although products of all CMRs in the HY-2 satellite constellation meet specifications, the BT differences between different CMRs still leads to differences in AWP or WPD in close spatio-temporal ranges. In statistics, normalization can unify singular sample data to the same dimension, which may improve the accuracy of the retrieval model's output results [29]. Therefore, the next study will normalize the BT data dimension for the CMRs of the HY-2 satellite constellation, to reduce the difference of the observed BT for different CMRs.

4. Calibration in the HY-2 Satellite Constellation

In the restricted spatio-temporal range, there are crossovers between the HY-2B satellite and the other two satellites in the HY-2 satellite constellation. In theory, the BT deviation is small from different satellites at the intersection of channels of the same frequency, but this is not certain from the above when cross-checking for BT (see Figure 4). On-orbit calibration aims to revise BT data in the HY-2 satellite constellation, minimizing the root mean square error (RMS) to BT data from three different CMRs.

In order to obtain enough effective data for on-orbit calibration, this experiment selected the third group data (see Table 2) during 12 months in the HY-2 satellite constellation. A total of 53,664 crossovers between HY-2B and HY-2C and 51,386 crossovers between HY-2B and HY-2D were necessary to calibrate HY-2C and HY-2D to HY-2B, respectively. The distribution of crossovers is shown in Figure 5. It can be seen that, within one year, the distribution map of crossovers between the HY-2B satellite and other two satellites is very similar, with high-density points in high-latitude regions and points distributed uniformly in global mid-low-latitude regions. In terms of distribution or quantity, crossovers can guarantee accuracy for on-orbit calibration equations.

In-situ observation is the most accurate method for obtaining atmospheric water vapor data at present [30]. During the on-orbit test, every satellite of the constellation cooperates with the observation ship to produce in-situ data. When the satellite flies over the ship, it releases sounding balloons to obtain the integral amount of atmospheric water vapor, measured to validate observations from the CMR. The in-situ points used to observe are shown in Figure 6. For atmospheric water vapor, the RMS is small between CMR and scene: it is 2.55 mm for HY-2C and 2.45 mm for HY-2D, and the RMS of HY-2B is 2.23 mm, which is less than those of HY-2C or HY-2D. Lower errors may occur because the CMR of HY-2B has three feed sources for three channels, and exclusive waveguides can be more beneficial for measuring radiation. The HY-2B satellite altimeter observes the sea level reasonably well and within its specifications, which shows BT from the HY-2B satellite CMR is also credible [31].

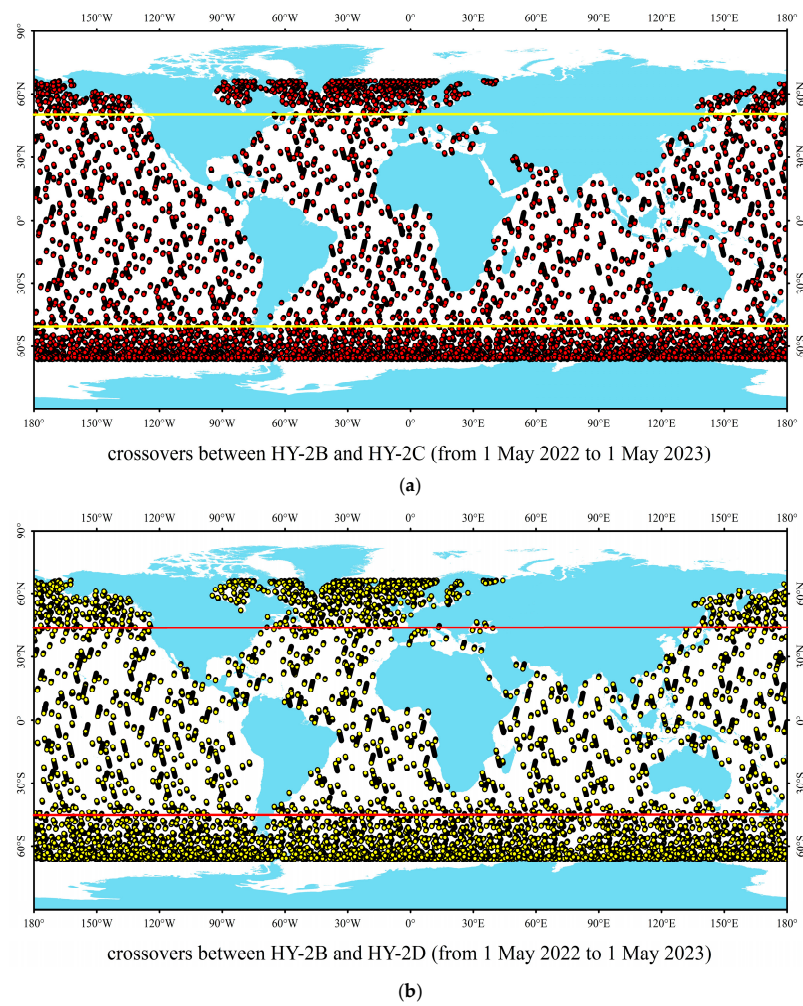


Figure 5. The distribution of crossovers for on-orbit calibration. Comparing the position of yellow lines in (a) and red lines in (b), more uniform crossovers are distributed between HY-2B and HY-2C on mid-low-latitudes, and crossovers between HY-2B and HY-2D have larger areas than between HY-2B and HY-2C at high latitudes.

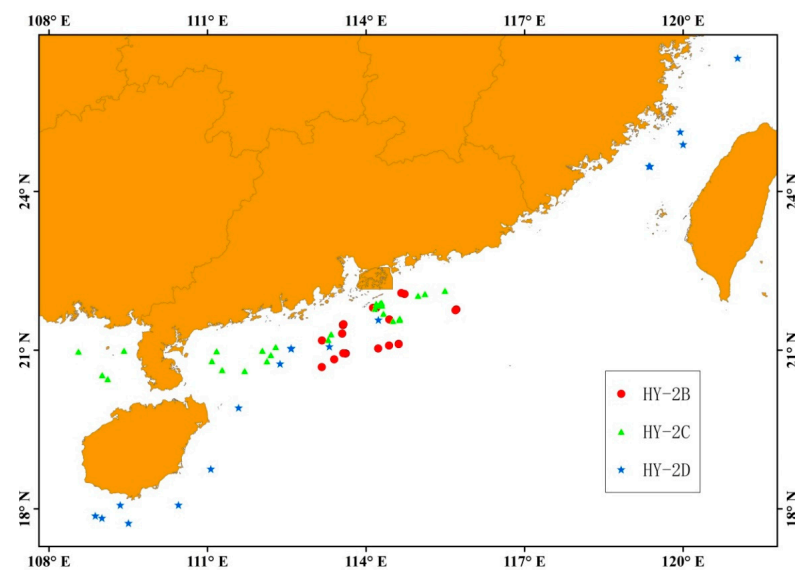


Figure 6. In-situ observation at sea.

The HY-2B satellite is selected as a reference satellite for on-orbit calibration in the HY-2 satellite constellation, and its BT datasets are regarded as a benchmark; on-orbit calibration equations are established by ordinary least squares and one year's worth of datasets [32]. The BT datasets of the HY-2C and HY-2D satellites are calibrated to the HY-2B satellite to minimize BT differences between the same channels of any two satellites. The on-orbit calibration equation for HY-2C and HY-2D can be obtained using the 23.8 GHz channel, as follows:

$$T_{RC_238} = 0.967 \cdot T_{C_238} + 0.7984 \quad (1)$$

$$T_{RD_238} = 0.9236 \cdot T_{D_238} + 7.3746 \quad (2)$$

The variables are as follows: T_{C_238} and T_{D_238} are, respectively, the BT of HY-2C and HY-2D for the 23.8 GHz channel of the CMR; T_{RC_238} and T_{RD_238} are the corrected BT. For the 23.8 GHz channel, BT differences between the HY-2C and HY-2D satellites and the HY-2B satellite before and after on-orbit calibration are shown in Figure 7. It can be seen that after on-orbit calibration, the overall trend of BT differences between them and the HY-2B satellite in the 23.8 GHz channel is close to zero.

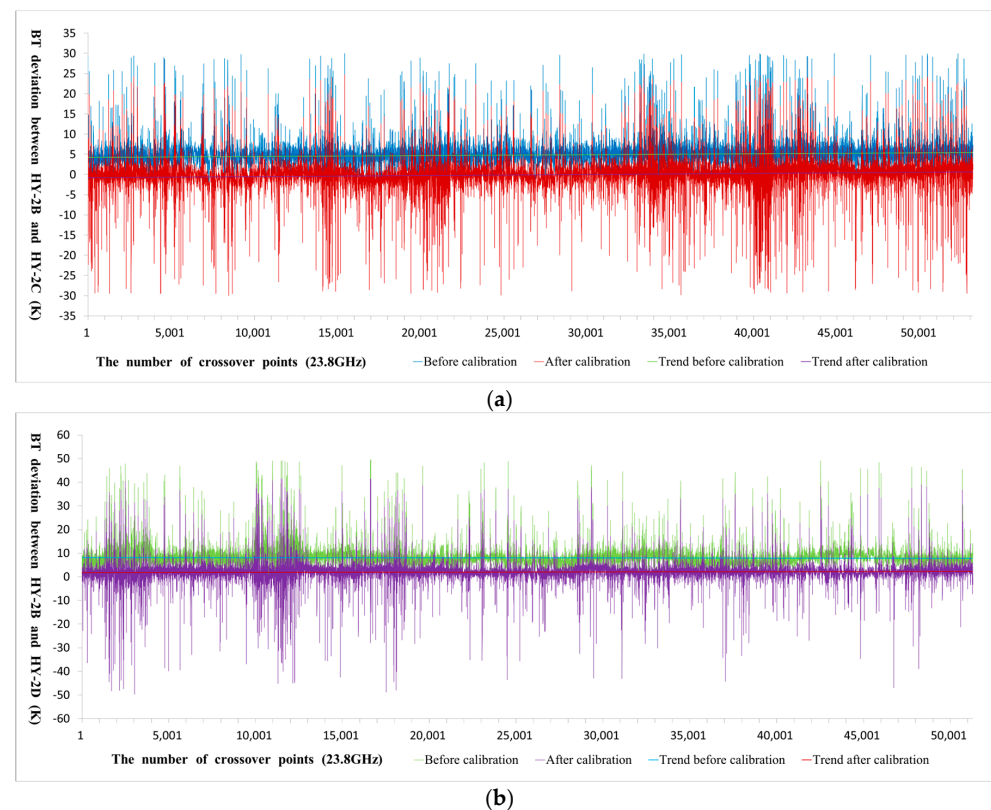


Figure 7. Comparing BT differences for 23.8 GHz in crossover: (a) BT differences, which fall from about 5 K to 0 K between HY-2B and HY-2C; (b) BT differences, which fall from about 10 K to 0 K between HY-2B and HY-2D.

Similarly, BT values from 18.7 GHz and 37 GHz can be also corrected using this method. The plots in Figures 8 and 9 illustrate the comparison between the HY-2B and HY-2C satellites as well as the HY-2D satellites, showing the differences in their BT before and after on-orbit calibration. Furthermore, the on-orbit calibration equations can be derived from these comparisons:

$$T_{RC_187} = 0.9562 \cdot T_{C_187} + 3.4183 \quad (3)$$

$$T_{RD_187} = 0.9306 \cdot T_{D_187} + 11.065 \quad (4)$$

$$T_{RC_37} = 0.9079 \cdot T_{C_37} + 11.37 \quad (5)$$

$$T_{RD_37} = 0.9227 \cdot T_{D_37} + 8.4048 \quad (6)$$

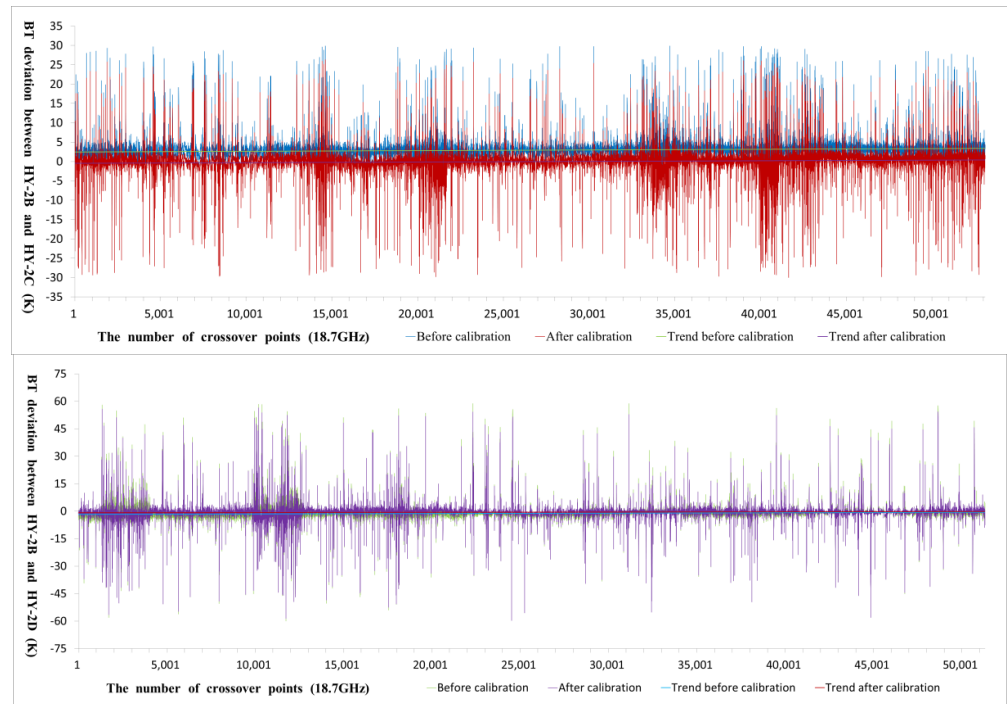


Figure 8. Comparing BT differences for 18.7 GHz in crossovers.

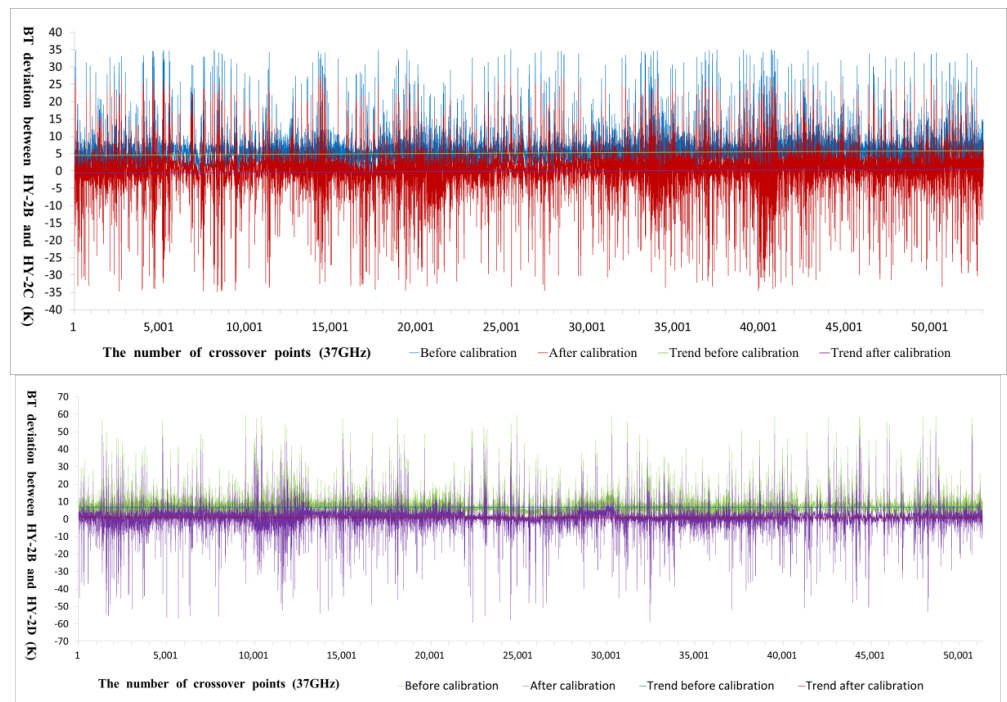


Figure 9. Comparing BT differences for 37 GHz in crossovers.

For the CMRs of the HY-2C and HY-2D satellites, the corrected three-channel BT data may be used to retrieve new AWW and WPD values, which differ from uncalibrated products and must be checked for accuracy.

5. Inversion and Verification

The better way to fit the retrieval model is to use BT data from the radiometer and synchronously observed atmospheric parameters, but at present there are no sufficient on-site observation datasets from the atmosphere. This experiment used ECMWF reanalysis atmosphere data to match the second group dataset (see Table 2) from the HY-2B satellite and obtain coefficients. The new retrieval models are of the form [33]:

$$AWV = a_0 + a_{187}\ln(280 - TB_{18.7}) + a_{238}\ln(280 - TB_{23.8}) + a_{37}\ln(280 - TB_{37}) \quad (7)$$

$$WPD = c_0 + c_{187}\ln(280 - TB_{18.7}) + c_{238}\ln(280 - TB_{23.8}) + c_{37}\ln(280 - TB_{37}) \quad (8)$$

Ordinary least squares can determine the coefficients; $TB_{18.7}$, $TB_{23.8}$ and TB_{37} represent BT, respectively, from the three channels of the CMR; the fitted coefficients are given in Table 3. Both AWV and WPD are products of CMR, AWV is the most important contribution to WPD, and there is a specific mathematical relationship between them [34]. Different retrieval algorithms are built for AWV and WPD in this study, in order to verify the reliability of the on-orbit calibration method for two groups of results.

Table 3. Coefficients in the retrieval algorithm of atmospheric water vapor (AWV) and wet path delay (WPD).

Product	Coefficient			
AWV	a_0	a_{187}	a_{238}	a_{37}
	20.9824976853874	91.5293174061542	−129.146718974558	33.5602960484433
WPD	c_0	c_{187}	c_{238}	c_{37}
	0.08414570	0.57683177	−0.78380061	0.19110949

After on-orbit calibration, BT values of the first dataset (see Table 2) were reprocessed and compared. The operational algorithm for the HY-2 satellite constellation processes the BT dataset before and after calibration. Compared results are shown in Table 4. Both mean bias and RMS decrease significantly between the HY-2C or HY-2D satellite and the HY-2B satellite after calibration. With the new retrieval algorithm for Equations (7) and (8), the BT datasets are processed and compared again; there are similar changes in the differences between satellite products. The operational algorithm and new algorithm are respectively used for the BT datasets of the HY-2B satellite; the difference between the two products is relatively small. According to the above compared results, it can be seen that similar algorithms from different data sources have little impact on products, while BT values are the key factor in determining the accuracy of products.

Table 4. Cross-checking for CMRs before and after on-orbit calibration.

Algorithm	Content	Reference	Compared	Mean Bias (mm)	RMS (mm)
				Before/After	Before/After
Operational	HY-2C	HY-2B	AWV	−0.320/−0.274	1.447/0.932
			WPD	−1.849/−1.722	8.451/5.877
	HY-2D		AWV	−0.731/0.451	1.980/1.346
			WPD	−4.361/2.807	11.832/7.521
HY-2B (operational vs new)			AWV	−0.189	0.780
			WPD	−1.214	4.832
New	HY-2C	HY-2B	AWV	0.509/0.378	1.632/1.218
			WPD	3.172/2.212	9.831/7.427
	HY-2D		AWV	−0.802/0.461	2.040/1.422
			WPD	−4.577/2.857	12.028/8.764

In the distribution of crossovers (see Figure 5), it can be seen that the density of crossovers at high latitudes is significantly greater than that at low latitudes. In fact, HY-2B and HY-2D also have more crossovers than between HY-2B and HY-2C at high latitudes, and observations at high latitude contain more uncertainty. Therefore, RMS is always greater between HY-2D and HY-2B than between HY-2C and HY-2B. In this study, the AWV and WPD of crossovers are divided into two parts by high and low latitude, which are bounded by the 45° north–south latitude. The products are reprocessed by the new retrieval algorithm presented in Equations (7) and (8). In Table 5, it can be seen that after on-orbit calibration, mean bias and RMS for products of the HY-2 satellite constellation at low latitudes is smaller than that at high-latitudes, but the reduction of RMS for high-latitude products is greater than that for low-latitude products after calibration. This shows that on-orbit calibration is more effective for improving the relative accuracy of high-latitude products and the absolute accuracy of low-latitude products.

Table 5. Cross-checking before and after on-orbit calibration for products separated by the 45° north-south latitude.

Latitude	Content	Reference	Compared	Mean Bias (mm)	RMS (mm)	RMS Reduction
				Before/After	Before/After	
≥45°	HY-2C	HY-2B	AWV	−0.617/−0.454	1.824/1.263	0.561
			WPD	−3.512/−2.833	10.631/ 7.287	3.344
	HY-2D		AWV	−0.815/−0.512	2.104/1.663	0.441
			WPD	−5.161/−3.414	12.111/9.645	2.466
<45°	HY-2C	HY-2B	AWV	0.471/0.341	1.513/1.178	0.335
			WPD	2.925/2.364	9.142/7.011	2.131
	HY-2D		AWV	−0.680/−0.453	1.712/1.422	0.290
			WPD	−4.182/−2.857	10.138/8.155	1.983

The deviation between products from different CMRs has a significantly decreased after-orbit calibration in the HY-2 satellite constellation, but the absolute accuracy of products must be also validated. Since too few in-situ measurement points can be matched with the HY-2 satellite constellation, AMR products of the Jason-3 satellite are used as a reference for validation. The AMR in Jason-3 is a radiometer with a similar mechanism as CMR, and its BT data have a good accuracy after long-term and systematic on-orbit calibration [35]. After on-orbit calibration to the HY-2 satellite constellation, the CMR products of HY-2C and HY-2D (the first group in Table 2), obtained by the operational algorithm, are compared with AMR products to check AWV and WPD. For HY-2B, the CMR products of the operational algorithm and new algorithm are compared with AMR products. The checking result is shown in Table 6. The RMS between CMR products and AMR products is decreased, but the variation is less than the reduction of RMS before and after calibration inside the HY-2 satellite constellation.

Table 6. Cross CMR and advanced microwave radiometers (AMR) to check before and after on-orbit calibration.

Content	Marker	Number	Mean Bias (mm)	RMS (mm)
			Before/After	Before/After
HY-2C	AWV	3863	0.421 / −0.215	1.290/1.087
	WPD		2.411 / −1.197	7.736/6.842
HY-2D	AWV	5823	1.087/1.345	1.887/1.446
	WPD		6.563/7.831	11.056/9.121
			Operational/New	Operational/New
HY-2B	AWV	4983	0.471 / −0.779	1.442/1.172
	WPD		2.859 / −4.675	8.278/7.061

For the first dataset (see Table 2) in cross-checking, Figure 10 shows a very different distribution of crossovers, to match the three satellites to the Jason-3 satellite at the same

time. HY-2C satellite has more points than the other two satellites, to match the Jason-3 satellite at low latitude; meanwhile, HY-2B and HY-2D satellites have more crossovers with the Jason-3 satellite at high latitudes. Since observation errors of the space-borne radiometer are greater at high latitudes than at low latitudes, the increase in the proportion of high-latitude crossovers will lead to larger errors for cross-checking [36]. In Tables 4–6, it can also be found that the results of cross-checking between the HY-2C satellite and other satellites are better than those of the HY-2D satellite, which is affected by the uneven distribution of crossovers from the test dataset; the HY-2C satellite has more crossovers at low latitudes than other satellites. However, the above cross-checking shows that those differences between different satellite products after on-orbit calibration are all less than before calibration.

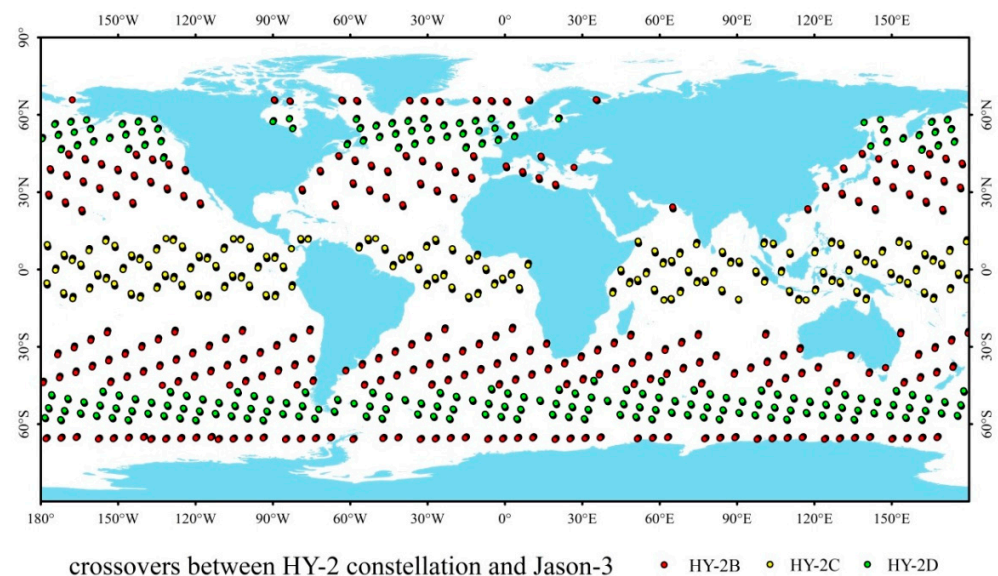


Figure 10. The distribution of crossovers between the HY-2 satellite constellation and Jason-3 satellite. For two-month datasets for all satellites, crossovers distributed on mid–high latitudes for HY-2B are concentrated at high latitudes for HY-2D and near the equator for HY-2C.

6. Summary and Conclusions

This calibration selects the CMRs of the HY-2B satellite as a reference and calibrates the CMRs of the HY-2C and HY-2D satellites so that the BT data of all CMRs are normalized to the same level. It greatly reduces differences between the three satellite observation products in the HY-2 satellite constellation. By cross-checking to AMR products from the Jason-3 satellite, it can be shown that the accuracy of CMRs products from the HY-2 satellite constellation is almost the same as that of similar satellites, and this on-orbit calibration also decreases the differences in similar radiometer products between the HY-2 satellite constellation and Jason-3 satellite.

In this on-orbit calibration, it can be shown that normalization to the BT of CMRs can effectively improve the accuracy of products for the HY-2 satellite constellation. This also indicates, for a fixed retrieval algorithm, that there must be a unique set of BT values from the calibration equation that can make the AWV and CLW from CMR as close as possible to the true values in the atmosphere. For the ground segment, it is better method to use a weather radar to measure the atmospheric element and a satellite to synchronously observe atmospheric BT, and to construct the retrieval algorithm from these two datasets as the core algorithm; other methods for revision are based on this. For the satellite segment, it is an important task for satellite platforms to minimize the differences of working environments for CMR between the ground and space after determining the coefficients of the calibration equation from on-ground calibration, in order to ensure the stability of the observed BT.

Although good quality can be obtained for CMR products compared with AMR products, CMR products may still be further improved. Firstly, there is still room for improvement in the quality of BT data for the 18.7 GHz and 37 GHz channels. From the above comparison, it can be seen that the correlation between the BT data of the 23.8 GHz channels from different satellites is excellent, but the correlation between BT data of the other two channels is relatively low. This indicates that wind speed and cloud liquid water accuracy are not optimal, and the calibration equations of these two channels can still be optimized to improve WPD. Secondly, the retrieval algorithm can be improved based on the different geographical locations. The HY-2B satellite can observe polar areas, but the accuracy of CMR products in high-latitude regions is lower than that in low-latitude regions; for the three satellites, the accuracy of products in coastal waters is lower than that in distant sea waters; all of these can be solved by using different retrieval algorithms for different sea areas. Finally, standard BT data for on-orbit calibration can be further improved. WPD estimates are from the retrieval algorithm, which is built from atmosphere data and BT data obtained from the forward model. Therefore, acquiring more accurate BT data is the most critical step to improving the accuracy of WPD; the superior method is on-orbit calibration using BT obtained from field observation data and the forward model. However, due to the high cost and long period taken to acquire and accumulate effective field data, the main method of on-orbit calibration is still cross-calibration between two satellites or between satellite and model.

The on-orbit calibration described in this study is one method to improve the accuracy of BT data for CMRs in the HY-2 satellite constellation. In order to improve the accuracy of products in the HY-2 satellite constellation, the task of optimizing calibration equations and retrieval algorithms to WPD from multiple directions must continue, including on-orbit calibration, adapting retrieval algorithms to various latitudes or different wind speeds, building special retrieval algorithms for inshore products, etc. Improving CMR products is a systematic project; in the future, special retrieval algorithms will be used according to wind speed or pertinent regions. Though the constellation has operated for a short time and some effective data are missing, this study has proved the effectiveness of on-orbit calibration, and the current calibration equations can still be further optimized. With more data, this method will further improve the accuracy of WPD in the HY-2 satellite constellation.

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References

1. Fu, L.L.; Christensen, E.J.; Yamarone, C.A., Jr.; Lefebvre, M.; Menard, Y.; Dorrer, M.; Escudier, P. TOPEX/Poseidon mission overview. *J. Geophys. Res. Ocean.* **1994**, *99*, 24369–24381. [\[CrossRef\]](#)
2. Boudouris, G. On the index of refraction of air the absorption and dispersion of centimeterwaves by gases. *J. Res. Natl. Bur. Stand.* **1963**, *67*, 631–684. [\[CrossRef\]](#)
3. Keihm, S.J.; Janssen, M.A.; Ruf, C.S. TOPEX/Poseidon Microwave Radiometer (TMR). Part 3: Wet troposphere range correction algorithm and pre-launch error budget. *IEEE Trans. Geosci. Remote Sens.* **1995**, *33*, 147–161. [\[CrossRef\]](#)
4. Jourdan, D.; Boissier, C.; Braun, A.; Minster, J.F. Influence of wet tropospheric correction on mesoscale dynamic topography as derived from satellite altimetry. *J. Geophys. Res.* **1990**, *95*, 17993–18004. [\[CrossRef\]](#)
5. Keihm, S.J.; Zlotnicki, V.; Ruf, C.S. TOPEX microwave radiometer performance evaluation. *IEEE Trans. Geosci. Remote Sens.* **2000**, *38*, 1379–1386. [\[CrossRef\]](#)

6. Ruf, C.S.; Keihm, S.J.; Janssen, M.A. TOPEX/Poseidon Microwave Radiometer (TMR). Part 1: Instrument description and antenna temperature calibration. *IEEE Trans. Geosci. Remote Sens.* **1995**, *33*, 125–137. [\[CrossRef\]](#)
7. Niedzielski, T.; Kosek, W. Forecasting sea level anomalies from TOPEX/Poseidon and Jason-1 satellite altimetry. *J. Geod.* **2009**, *83*, 469–476. [\[CrossRef\]](#)
8. Ablain, M.; Philipps, S.; Picot, N.; Bronner, E. Jason-2 global statistical assessment and cross-calibration with Jason-1. *Mar. Geod.* **2010**, *33* (Suppl. 1), 162–185. [\[CrossRef\]](#)
9. Liang, G.; Yang, J.; Wang, J. Accuracy Evaluation of CFOSAT SWIM L2 Products Based on NDBC Buoy and Jason-3 Altimeter Data. *Remote Sens.* **2021**, *13*, 887. [\[CrossRef\]](#)
10. Scharroo, R.; Bonekamp, H.; Ponsard, C.; Parisot, F.; von Engeln, A.; Tahtadjiev, M.; de Vriendt, K.; Montagner, F. Jason continuity of services: Continuing the Jason altimeter data records as Copernicus Sentinel-6. *Ocean Sci.* **2016**, *12*, 471–479. [\[CrossRef\]](#)
11. Wilheit, T.T.; Chang, A.T.C. An algorithm for retrieval of ocean surface and atmospheric parameters from observations of the scanning multichannel microwave radiometer. *Radio Sci.* **1980**, *15*, 525–544. [\[CrossRef\]](#)
12. Chen, C.; Zhu, J.; Ma, C.; Lin, M.; Yan, L.; Huang, X.; Zhai, W.; Mu, B.; Jia, Y. Preliminary calibration results of the HY-2B altimeter's SSH at China's Wanshan calibration site. *Acta Oceanol. Sin.* **2021**, *40*, 129–140. [\[CrossRef\]](#)
13. Lin, M.; Jia, Y. Past, Present and Future Marine Microwave Satellite Missions in China. *Remote Sens.* **2022**, *14*, 1330. [\[CrossRef\]](#)
14. Ju, M.; Fangjie, Y.; Zhiyuan, Z.; Juanjuan, Q.; Ge, C. Quality analysis of sea level height data of HY-2C satellite. *Acta Oceanol. Sin.* **2022**, *44*, 173–181.
15. Zhao, J. *Calibration of Spaceborne Microwave Radiometer with Fixed Beam Pointing*; The Center for Space Science and Applied Research, Chinese Academy of Sciences: Beijing, China, 2010.
16. Bernard, R.; Le Cornec, A.; Eymard, L.; Tabary, L. The microwave radiometer aboard ERS-1. 1. Characteristics and Performances. *IEEE Trans. Geosci. Remote Sens.* **1993**, *31*, 1186–1198. [\[CrossRef\]](#)
17. Imaoka, K.; Fujimoto, Y.; Kachi, M.; Takeshima, T.; Shiomi, K.; Mikai, H.; Mutoh, T.; Yoshikawa, M.; Shibata, A. Post-launch calibration and data evaluation of AMSR-E. In Proceedings of the 2003 IEEE Geoscience and Remote Sensing Symposium, IGARSS 2003, Toulouse, France, 21–25 July 2003; pp. 666–668.
18. Menard, Y.; Haines, B. *Jason-1 CALVAL Plan*; Ref: TP2-J0-PL-974-CN; CNES: Paris, France, 2001.
19. Stum, J. A Comparison of the Brightness Temperatures and Water Vapor Path Delays Measured by the TOPEX, ERS-1, and ERS-2 Microwave Radiometers. *J. Atmospheric Ocean. Technol.* **1998**, *15*, 987–994. [\[CrossRef\]](#)
20. Keihm, S.J.; Ruf, C.S. Role of water vapor radiometers for in-flight calibration of the TOPEX microwave radiometer. *Mar. Geod.* **1995**, *18*, 139–156. [\[CrossRef\]](#)
21. Bobylev, L.P.; Zabolotskikh, E.V.; Mitnik, L.M.; Mitnik, M.L. Atmospheric Water Vapor and Cloud Liquid Water Retrieval Over the Arctic Ocean Using Satellite Passive Microwave Sensing. *IEEE Trans. Geosci. Remote Sens.* **2010**, *48*, 283–294. [\[CrossRef\]](#)
22. Liu, Y.; Zhang, Y.; Lin, M.; Tang, J. A preliminary crossover calibration result for HY-2. In Proceedings of the 2014 IEEE Geoscience and Remote Sensing Symposium, IGARSS 2014, Quebec City, QC, Canada, 13–18 July 2014; pp. 688–691.
23. Jiang, M.; Xu, K.; Liu, Y. Global Statistical Assessment and Cross-Calibration with Jason-2 for Reprocessed HY-2 A Altimeter Data. *Mar. Geod.* **2018**, *41*, 289–312. [\[CrossRef\]](#)
24. Xiaomin, Y.; Mingsen, L.; Qingjun, S. Research on validation methods of satellite radar altimeter retrieved sea surface wind speed and significant wave height using in-situ data. *Remote Sens. Technol. Appl.* **2014**, *29*, 26–32.
25. Zheng, G.; Yang, J.; Ren, L. Retrieval Models of Water Vapor and Wet Tropospheric Path Delay for the HY-2A Calibration Microwave Radiometer. *J. Atmos. Ocean. Technol.* **2014**, *31*, 1516–1528. [\[CrossRef\]](#)
26. Jia, Y.; Yang, J.; Lin, M.; Zhang, Y.; Ma, C.; Fan, C. Global Assessments of the HY-2B Measurements and Cross-Calibrations with Jason-3. *Remote Sens.* **2020**, *12*, 2470. [\[CrossRef\]](#)
27. Mertikas, S.P.; Donlon, C.; Femenias, P.; Mavrocordatos, C.; Galanakis, D.; Guinle, T.; Boy, F.; Tripolitsiotis, A.; Frantzis, X.; Tziavos, I.N.; et al. Absolute Calibration of Sentinel-3A and Jason-3 Altimeters with Sea-Surface and Transponder Techniques in West Crete, Greece. In *Fiducial Reference Measurements for Altimetry*; Springer: Cham, Switzerland, 2019; pp. 41–47.
28. Fernandes, M.J.; Clara, L. Wet Tropospheric Corrections over Inland Water—Getting Ready for Sentinel-3. In Proceedings of the Sentinel-3 for Science Workshop 2015, Venice, Italy, 2–5 June 2015.
29. Mackman, T.; Allen, C.; Ghoreyshi, M.; Badcock, K. Comparison of Adaptive Sampling Methods for Generation of Surrogate Aerodynamic Models. *AIAA J.* **2013**, *51*, 797–808. [\[CrossRef\]](#)
30. Liu, Z.; Wu, X.; Xu, J.; Li, H.; Lu, S.; Sun, C.; Cao, M. China Argo project: Progress in China Argo ocean observations and data applications. *Acta Oceanol. Sin.* **2017**, *36*, 1–11. [\[CrossRef\]](#)
31. Mertikas, S.P.; Lin, M.; Piretzidis, D.; Kokolakis, C.; Donlon, C.; Ma, C.; Zhang, Y.; Jia, Y.; Mu, B.; Frantzis, X.; et al. Absolute Calibration of the Chinese HY-2B Altimetric Mission with Fiducial Reference Measurement Standards. *Remote Sens.* **2023**, *15*, 1393. [\[CrossRef\]](#)
32. Roithmayr, C.M.; Lukashin, C.; Speth, P.W.; Kopp, G.; Thome, K.; Wielicki, B.A.; Young, D.F. CLARREO Approach for Reference Intercalibration of Reflected Solar Sensors: On-Orbit Data Matching and Sampling. *IEEE Trans. Geosci. Remote Sens.* **2014**, *52*, 6762–6774. [\[CrossRef\]](#)
33. Brown, S.; Ruf, C.; Keihm, S.; Kitiyakara, A. Jason Microwave Radiometer Performance and On-Orbit Calibration. *Mar. Geod.* **2004**, *27*, 199–220. [\[CrossRef\]](#)

34. Fernandes, M.J.; Lázaro, C.; Vieira, T. On the role of the troposphere in satellite altimetry. *Remote Sens. Environ. Interdiscip. J.* **2021**, *252*, 112149. [[CrossRef](#)]
35. Tapley, B.D.; Ries, J.C.; Davis, G.W.; Eanes, R.J.; Schutz, B.E.; Shum, C.K.; Watkins, M.M.; Marshall, J.A.; Nerem, R.S.; Putney, B.H.; et al. Precision orbit determination for TOPEX/POSEIDON. *J. Geophys. Res. Ocean.* **1994**, *10*, 239–247. [[CrossRef](#)]
36. Zhang, Z.; Dong, X. Sea Level Pressure Retrieval in Mid-to-low Latitude Regions Using FY-3C/MWHTS Data. *Chin. J. Space Sci.* **2020**, *40*, 364–375. [[CrossRef](#)]

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