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Preliminary Evaluation and Correction of Sea Surface Height from Chinese Tiangong-2 Interferometric Imaging Radar Altimeter

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Abstract: In this study, we performed preliminary comparative evaluation and correction of two-dimensional sea surface height (SSH) data from the Chinese Tiangong-2 Interferometric Imaging Radar Altimeter (InIRA) with the goal of advancing its retrieval. Data from the InIRA were compared with one-dimensional SSH data from the traditional altimeters Jason-2, Saral/AltiKa, and Jason-3. Because the sea state bias (SSB) of distributed InIRA data has not yet been considered, consistency was maintained by neglecting the SSB for the traditional altimeters. The results of the comparisons show that the InIRA captures the same SSH trends as those obtained by traditional altimeters. However, there is a significant deviation between InIRA and traditional altimeter SSHs; consequently, systematic and parametric biases were analyzed. The parametric bias was found to be related to the incidence angles and a significant wave height. Upon correcting the two biases, the standard deviation significantly reduced to 8.1 cm. This value is slightly higher than those of traditional altimeters, which typically have a bias of ~7.0 cm. The results indicate that the InIRA is promising in providing a wide swath of SSH measurements. Moreover, we recommend that the InIRA retrieval algorithm should consider the two biases to improve SSH accuracy.

Keywords: Tiangong-2 Interferometric Imaging Radar Altimeter (InIRA); sea surface height (SSH); evaluation; correction

1. Introduction

Sea surface height (SSH) has an important role in studies on ocean circulation, mesoscale eddies, and marine gravity fields [1–5]. Conventional measurement methods include tide gauges, Global Positioning System (GPS) buoys, and traditional spaceborne altimeters. Tidal gauges and GPS buoys are typically used for monitoring small areas near the shore by utilizing a long time series of observational data. As remote sensing tools, traditional altimeters are more suitable for global SSH measurements and have been widely used in the fields mentioned above [6–9].

The traditional altimeter measures SSH at the nadir angle using the difference in distance between satellite altitude (i.e., through precise orbit determination such as GPS, Doppler Orbitography, and Radiopositioning Integrated by Satellite (DORIS)) and range (i.e., using the two-way propagation time between satellite and sea surface) [10]. The traditional altimeter footprint is sampled linearly along the ground track. The standard SSH product is given approximately every 1 s along the track

(about every 6 km for Jason-2). In practice, traditional altimeter SSH products are usually merged for several days and over multiple acquisitions to obtain complete coverage. However, the merged products have a low spatial and temporal resolution, rendering them insufficient for capturing ocean phenomena with submesoscale or shorter periods. More importantly, the traditional altimeter SSH is not suitable for nearshore monitoring because of the waveform tracking problem at the sea–land boundary as well as coarse spatial resolution [11].

To overcome the limitations of traditional altimeter SSH measurements, new concepts have been proposed to achieve high resolution and wide swath. These new concepts include scanning altimeters, Doppler altimeters, dual-antenna altimeters, synthetic aperture radar (SAR) altimeters, and interferometric SAR imaging altimeters [12–16]. The SAR altimeter works at nadir and has a high resolution in azimuth, but with no imaging capacity. Interferometric SAR imaging altimeters work at low incidence angles and thus have a high-resolution imaging capacity in both azimuthal and range directions. Among these concepts, only interferometric SAR imaging altimeters consider both resolution and swath.

In 2009, the surface water and ocean topography (SWOT) plan was proposed by the National Aeronautics and Space Administration/Jet Propulsion Laboratory (NASA/JPL) and National Centre for Space Studies (CNES) for accurate monitoring of local sea-level changes at the land–sea interface. The radar used by SWOT is an interferometric SAR at low incidence angles with an across-track. It deviates from the concept of traditional altimeters by using the interferometric phase to measure SSH rather than the propagation time of the electromagnetic wave, thus allowing wide swath [17–19]. However, the SWOT satellite has not yet been launched. On 15 September 2016, the Chinese Tiangong-2 space laboratory with an onboard interferometric imaging radar altimeter (InIRA) was launched. This InIRA continues to use wide-swath interferometric technology to estimate the SSH. The SAR technology has also been adopted for improving the azimuthal resolution. Moreover, owing to its short baseline, it achieves a good accuracy (i.e., 0.1°) for the interferometric phase measurement on a single-pulse basis [20–22].

The InIRA is a scientific experimental spaceborne sensor. Its main tasks include (1) validation of the SSH measurement capability with high accuracy and wide swath by interferometric technology at low incidence angles; (2) testing of some key technologies such as high-power solid-state power amplifiers; and (3) typical applications such as SSH, wind, and wave measurements. At present, studies on InIRA data mostly focus on backscattering characteristics. As InIRA can provide the normalized radar cross-section (NRCS) in addition to the interferometric phase, it has the potential to extract sea states and detect targets, similar to conventional SAR with medium incidence angles. Some studies have been performed using InIRA data in these application areas; for example, the sea surface wind speed was retrieved from the InIRA NRCS at a resolution of 1 km. The Ku-band low incidence model-2 (KuLMOD2) was used and developed from the Tropical Rainfall Measuring Mission Precipitation Radar data. The root mean square error (RMSE) of the retrieved wind speed was found to be within 2 m/s as compared to that of the Advanced Scatterometer winds [23–25]. Moreover, the ship wakes on the InIRA image exhibit apparent symmetrical features that are stronger than the background of the sea surface [26].

Studies regarding the InIRA altimetry are also in progress. Some studies [27,28] performed simulations to explore the InIRA altimetric precision, thereby theoretically demonstrating the feasibility of the InIRA SSH measurements. Meanwhile, a first retrieval algorithm for the InIRA SSH has been proposed [29]. However, the algorithm should be continuously improved to advance the SSH accuracy and account for the many factors that may cause errors in SSH products, such as path delay, instrument drift, and short baseline configuration. In order to further advance the development of InIRA SSH retrieval, we evaluated the preliminary InIRA SSH measurements to identify possible future improvements to the retrieval algorithm. In traditional altimeter evaluations, the main methods include specific calibration fields, tide gauges, transponders, and cross-over with other traditional altimeters. Owing to its simplicity and regional diversity, cross-over evaluation by traditional altimeters

is a commonly used method [30–35]; thus, it was adopted in this study to evaluate the InIRA SSH accuracy. Moreover, the bias in the evaluation was analyzed and corrected, which helps to determine the error source and the accuracy that can be achieved by the InIRA SSH.

2. Data

In this study, the InIRA, traditional altimeter, and European Center for Medium-Range Weather Forecasts (ECMWF) data were collected. The InIRA SSH data were evaluated by comparison with the traditional altimeter SSH data. The ECMWF significant wave height (SWH) was used to analyze the parametric bias. These data are briefly described below.

2.1. InIRA Data

InIRA is a Ku-band (13.58 GHz) side-looking radar at low incidence angles (1° – 8°). It measures SSH in normal interferometric mode by using two antennas and two receivers. Moreover, the height tracker used in traditional altimeters is also used by the InIRA to deal with variations in orbit height and backscatter coefficient, as well as the short time window for receiving. In this regard, InIRA belongs to the category of altimeters. It has two important features. The first is the aperture synthesis function similar to conventional SAR, which allows high spatial resolution in the azimuthal direction. Thus, InIRA can image land or ocean surface. The second is the interferometric function, which provides the capability for height measurements. By combining these two features, InIRA can measure SSH at a high resolution and cover wide swaths. The measured SSH uses the World Geodetic System 1984 ellipsoid as a reference system. The SSH data used in this study had an original spatial resolution of $30\text{ m} \times 30\text{ m}$. However, the 30-m SSH data varied significantly in space. To reduce the variation, it was filtered down to a 5 km scale, which is comparable to the spatial resolution of traditional altimeters and helps to maintain the consistency in comparisons. Thus, the actual spatial resolution is $5\text{ km} \times 5\text{ km}$. Moreover, incidence angles from 2.5° to 7.5° were used, while minor data at the beam edge were removed owing to the known uncertainties. The chosen range of incidence angles corresponds to a changing swath from 33.437 km to 35.197 km when the satellite orbit altitude varies between 380 km and 400 km. Moreover, the distributed InIRA SSH product was not final, and its sea state bias (SSB) had not yet been corrected. This means that the InIRA SSH product only encompassed the corrections of the wet and dry troposphere and ionospheric effects, while its SSB was temporarily not considered.

2.2. Traditional Altimeter Data

The traditional altimeter technology is very mature. To date, the SSH measurement technology has reached a high accuracy of the order of a few centimetres. In this study, the traditional altimeter SSH data were used as a reference for evaluating the InIRA SSH accuracy. Specifically, we used the traditional altimeter data from Jason-2, Saral/AltiKa, and Jason-3. The reference ellipsoids for these traditional altimeters are the same as those used by the InIRA. All SSH data were provided as geophysical data records, version D (GDR-D) standard product files, and Ku-band (for Jason-2 and Jason-3) and Ka-band (for Saral/AltiKa). We directly used these products without extra corrections, assuming that good quality control was performed for these products. The data had a 1-Hz along-track sampling rate and was colocated to InIRA data within a 1-h and 2-km window. Figure 1 shows the data location of the InIRA and traditional altimeters, while Table 1 lists the data acquisition times. Based on the parameters recorded in the files, the traditional altimeter SSH data can be estimated using Equation (1) [10]:

$$SSH = ALT - CR \quad (1)$$

where ALT is the satellite altitude and CR is the corrected range (R) between the satellite and the sea surface. We considered that the InIRA data used in this study had no SSB correction. For consistency, the traditional altimeter should also maintain the same correction level. Thus, the SSB correction

of the traditional altimeter was neglected, and the CR was corrected for the remaining three effects highlighted in Equation (2) [10]:

$$CR = R + WTC + DTC + IC \quad (2)$$

where WTC is the wet troposphere correction, DTC is the dry troposphere correction, and IC is the ionosphere correction.

Figure 1. Location of Interferometric Imaging Radar Altimeter (InIRA) and colocated traditional altimeter data. The red circles represent the centre location of InIRA data, while the blue lines represent the ground track of colocated traditional altimeter data.

Table 1. Data acquisition time (i.e., start time) for the Interferometric Imaging Radar Altimeter (InIRA) and three types of colocated traditional altimeter data.

Number	Traditional Altimeter Type	InIRA Time (UTC)	Traditional Altimeter Time (UTC)
1	Jason-2	2018-02-12 12:36:34	2018-02-12 13:20:23
2	Jason-2	2017-07-22 08:24:36	2017-07-22 08:26:50
3	Jason-2	2017-10-20 12:11:04	2017-10-20 12:38:25
4	Saral/AltiKa	2018-03-23 13:40:23	2018-03-23 13:44:47
5	Saral/AltiKa	2018-02-12 07:35:18	2018-02-12 08:09:06
6	Saral/AltiKa	2017-10-17 18:29:38	2017-10-17 18:43:19
7	Jason-3	2018-03-23 13:40:23	2018-03-23 13:56:21

2.3. ECMWF Data

ECMWF is a numerical forecast model. In addition to forecast data, it can also provide multiple global atmospheric and oceanic re-analysis data such as wind and wave parameters. These re-analysis data have been widely used as the colocation reference for remote sensing data to explore data trend characteristics. In a previous study [36], the wind speed and SWH parameter played an essential role in the SSB correction of traditional altimeter SSH measurements. The two parameters were also used in this study for the error analysis. The SWH data were extracted from the ECMWF using linear interpolation according to coincident time and location.

3. Evaluation

In the evaluation, the InIRA SSH was compared to the validation data from the colocated traditional altimeter SSH. A case study and total colocations were described. In these comparisons, the differences between the InIRA and traditional altimeter SSH were quantitatively analyzed. The statistical analysis included mean bias (BIAS, Equation (A1)), root mean square error (RMSE, Equation (A2)), and standard deviation (STD, Equation (A3)). These equations are described in Appendix A.

3.1. Case Study

This case study compared the InIRA data and colocated Saral/AltiKa altimeter data (see Figure 2). Figure 2a shows the map of the two SSH estimates, in which the linear Saral/AltiKa ground track coincided with a rectangular InIRA footprint. As shown in the figure, both SSH data exhibited apparent variations on the map. Moreover, the InIRA and Saral/AltiKa SSH measurements exhibited the same change trend. Both showed a significant decrease from left to right on the map. This shows the similarity between the InIRA and traditional altimeters in capturing SSH changes. In particular, the wide-swath InIRA exhibits a more detailed SSH compared to Saral/AltiKa. Figure 2b shows a quantitative comparison of the colocated SSH profile of the map. From this figure, it is apparent that the InIRA SSH was close to the Saral/AltiKa SSH. It was precisely the same at higher SSH, while there was a difference at lower SSH. Figure 2c shows that the InIRA SSH had a systematic bias (BIAS) of 13.1 cm and an RMSE of 18.5 cm when compared to Saral/AltiKa SSH. A systematic bias between different traditional altimeter SSH estimates has been reported in a previous study. Thus, a systematic bias between the InIRA and Saral/AltiKa was expected in this study. When the systematic bias was removed, the RMSE reduced to an STD value of 13.0 cm. This STD was higher than that of the conventional traditional altimeter SSH (~ 7.0 cm). However, it demonstrated (in a preliminary way) the feasibility of this new InIRA SSH measurement technology in terms of the captured change trend. To determine the InIRA SSH accuracy more comprehensively, we analyzed additional collocations.

Figure 2. Comparison of sea surface height (SSH) measurements between the Interferometric Imaging Radar Altimeter (InIRA) and colocated Saral/AltiKa altimeter. (a) SSH map from the InIRA (large rectangle) and Saral/AltiKa (small circles), (b) SSH profile along the Saral/AltiKa track, and (c) SSH difference along the Saral/AltiKa track.

3.2. Total Colocations

As shown in Table 1, seven sets of collocations were collected, including three sets of collocations using Jason-2 and Saral/AltiKa and one set using Jason-3. Figure 3 shows the remaining SSH maps of the collocations. These maps show that each traditional altimeter ground track coincided with the InIRA footprint. In this case, a series of SSH collocations along a traditional altimeter track was obtained. In these collocations, the InIRA and traditional altimeter SSHs exhibit the same SSH change trend, although each set is at different SSH intervals.

The statistics of the SSH difference between the InIRA and traditional altimeters are shown in Figure 4. We considered three types of traditional altimeters that likely had different biases with respect to the InIRA SSH estimate. Thus, we present the collocation statistics separately according to the traditional altimeter type (i.e., Jason-2, Saral/AltiKa, or Jason-3). The consideration of different biases was confirmed in Figure 4, which shows that the different biases with Jason-2, Saral/AltiKa, and Jason-3 are -14.7 cm, 5.9 cm, and 45.3 cm, respectively. Here, the bias for Jason-3 was more significant than it was for the other two traditional altimeters. The RMSE values for the three types

of traditional altimeters were 20.0 cm, 14.3 cm, and 45.7 cm for Jason-2, Saral/AltiKa, and Jason-3, respectively. A larger RMSE corresponds to a larger BIAS. This finding indicates that systematic bias is an essential factor affecting the magnitude of the RMSE. Moreover, the STDs (i.e., with no bias consideration) for Jason-2, Saral/AltiKa, and Jason-3 were 13.6 cm, 13.1 cm, and 6.1 cm, respectively. From the statistics, the STDs of Jason-2 and Saral/AltiKa were more similar; however, their RMSEs were significantly different. This finding implies that the deviations between the InIRA and Jason-2 and between the InIRA and Saral/AltiKa are consistent in the case of no systematic bias. Note that the STD of InIRA and Jason-3 is better than those of the other two traditional altimeters. However, due to the fewer collocations from Jason-3, we believe that the statistics with Jason-2 and Saral/AltiKa can better reflect reality.

Figure 3. All collocated sea surface height (SSH) maps of the Interferometric Imaging Radar Altimeter (InIRA) and traditional altimeters, except for the case described in Figure 2. (a, c, e) show collocations with Jason-2, (b, d) show collocations with Saral/AltiKa, and (f) shows collocations with Jason-3.

Figure 4. Sea surface height (SSH) comparisons between the Interferometric Imaging Radar Altimeter (InIRA) and each type of traditional altimeter, (a) for all Jason-2 passes, (b) for all Saral/AltiKa passes, and (c) for a single Jason-3 pass.

4. Bias Correction

Figure 4 demonstrates that the InIRA STDs with both Jason-2 and Saral/AltiKa were ~13.0 cm. This STD is higher than that for the conventional traditional altimeter SSH, implying that there are other factors affecting the accuracy besides a systematic bias. To further improve the accuracy, parametric bias analysis and correction were performed. Before the parametric bias analysis, the systematic bias was first removed to unify the three kinds of collocations.

4.1. Systematic Bias Correction.

The systematic bias is easily corrected by subtracting the mean bias from the original InIRA SSH measurements. Here, the mean bias is equal to the BIAS values shown in Figure 4, which are different for the three types of traditional altimeters. For example, the InIRA SSH data collocated with Jason-2 should be corrected by subtracting the BIAS of −14.7 cm, while the data collocated with Saral/AltiKa is corrected by subtracting the BIAS of 5.9 cm. After systematic bias correction, statistics were recomputed using all collocations. Figure 5 shows that the BIAS reduced to −1.2 cm, which means that the systematic bias was removed. Consequently, the STD of 12.7 cm is similar to the RMSE of 12.8 cm.

Figure 5. Statistics of the sea surface height (SSH) difference between the Interferometric Imaging Radar Altimeter (InIRA) and all traditional altimeters after systematic bias correction.

4.2. Parametric Bias Correction.

After the systematic bias correction, parametric bias was analyzed by relating the difference between the InIRA and traditional altimeter SSH estimates to some parameters. Here, the parametric bias was defined as a bias varying with the parameters. The difference between the systematic and parametric bias results from the fact that the former does not change with parameters, while the latter changes with a few parameters. The parametric bias can be generally described by Equation (3):

$$bias_p = f(p_1, p_2, \dots, p_n), n \in N \quad (3)$$

where $bias_p$ is the parametric bias, f is the function, and $p_1, p_2, \dots, p_n$ are the possible parameters. The parametric bias is not directly involved in previous traditional altimeter SSH correction; however, it has a behavior similar to that of the SSB. That is, both the biases change with respect to some parameters. The SSB changes with wind speed and SWH. Next, the parameters causing the parametric bias change were analyzed.

Based on the interferometric altimetry principle, the SSH estimation is a function of the incidence angle. This means that the incidence angle deviation may induce an SSH estimate error. For traditional altimeters, it is reduced to a unique 0° incidence angle. In this case, the error induced by the incidence angle can be seen as a systematic bias. However, InIRA has a wide range of incidence angles. If there are distinctive biases at different incidence angle bins, the biases will change with the incidence angle. In this case, the biases related to the incidence angles meet the definition of parametric bias. Thus,

the incidence angle was the first parameter to be used in the parametric bias. Moreover, both the InIRA and traditional altimeter SSH estimates used in this study had no SSB correction. If they had precisely the same SSB, there would be no parametric bias induced by the sea state. In contrast, the parametric bias will vary with the sea state if their SSBs are different. According to previous studies, the main factors affecting SSB are wind speed and SWH. Thus, these two parameters were also considered in the parametric bias analysis. Here, the incidence angle information was recorded in the InIRA product file, and the SWH was provided by the ECMWF data. The wind speed was estimated from the InIRA NRCS using the KuLMOD2 model [23].

Figure 6 shows the InIRA SSH parametric bias analysis for the three parameters. The BIAS between the InIRA and the traditional altimeter was plotted along with the parameter bins. As shown in Figure 6a, the BIAS first decreased and then increased in reverse with the incidence angle. The BIAS ranged from 13 cm to 8 cm. When the incidence angle was approximately 5° , the BIAS approached zero. This finding reveals that the biases exhibit an evident trend change with the incidence angle bins. Hence, we believe that there was a parametric bias related to the incidence angle. In Figure 6b, a similar analysis was performed for the wind speed. As shown in Figure 6b, the BIAS fluctuated around zero with wind speed, and there was no significant monotonic change. This finding implies that there is no apparent parametric bias related to the wind speed. In Figure 6c, a similar analysis was performed for the SWH. The results show that the bias significantly increased with an increase in SWH from 0.5 m to 2.5 m, and then it remained unchanged for larger SWHs. This finding indicates a parametric bias related to the SWH, especially for low SWHs.

Figure 6. Sea surface height (SSH) parametric bias analysis for (a) incidence angle, (b) wind speed, and (c) significant wave height.

According to the above analysis, the InIRA SSH data exhibit parametric biases for both the incidence angle and SWH. To correct the biases, we developed a bias model for the two parameters by fitting the BIAS trends within four different SWH bins. The model structure was designed as a piecewise polynomial. Thus, the general expression in Equation (3) can be rewritten as Equation (4). To determine the best fitting degree, the fitting residual with the degree is shown in Figure 7a in terms of RMSE. This indicates that degree three corresponds to a minimum RMSE. Thus, a third-order polynomial was chosen for the parametric model. The model fitting is shown in Figure 7b, and the model coefficients are listed in Table 2. From the figure, the model exhibits clear dependence on the incidence angle and SWH. In particular, the higher the SWH, the stronger the dependence on the

incidence angle. The error bar of the model is shown in Figure 7c. The model errors in the middle part (smaller than 15 cm and larger than −5 cm) are slightly better than those at both ends. Overall, the model is consistent with the InIRA SSH parametric bias data, with a BIAS of −0.5 cm and an RMSE of 8.1 cm.

$$bias_p(\theta, SWH_{bin}) = \sum_{i=0}^n a_i(SWH_{bin}) \cdot \theta^i \quad (4)$$

where θ is the incidence angle, n is the fitting degree, and a_i is the model coefficient within a certain SWH bin (SWH_{bin}).

Figure 7. Parametric model details of (a) residual evolution with fitting degree, (b) fitting, and (c) error bars. For (b), the colours represent the different SWH bins. The dashed line represents the Interferometric Imaging Radar Altimeter (InIRA) sea surface height (SSH) mean bias (BIAS), while the solid line represents the fitting.

Table 2. Parametric bias model coefficients for Interferometric Imaging Radar Altimeter (InIRA) sea surface height (SSH).

SWH_{bin} (m)	Model Coefficient			
	a_0	a_1	a_2	a_3
(0.5, 1.5]	−178.94196323	103.3807699	−20.09269648	1.24252407
(1.5, 2.5]	−84.53051983	51.72502079	−8.80839698	0.42226203
(2.5, 3.5]	21.70346396	−11.44348505	4.25720119	−0.46318078
(3.5, 4.5]	21.46840233	6.79459699	−3.26950451	0.25112205

Based on the developed model, each incidence angle and SWH were substituted into Equation (4) to estimate the parametric biases. Then, the biases were subtracted from the InIRA SSH. After removing the parametric bias, we plotted the BIAS along with the three parameters in Figure 8a,c,e. As shown in the figure, all BIAS values were significantly reduced along with the three parameter bins. Here, all absolute BIAS values were within 4.0 cm. Moreover, the RMSE and the three parameters are plotted in Figure 8b,d,f to aid in determining the best observation conditions. As shown in Figure 8b, the RMSE at central 5° was more significant than that at the edge angles. In contrast, the 5° angle corresponds to the minimum BIAS in Figure 6. This contrast shows that the edge angle has a better SSH accuracy than the central angle in the case of no bias. This finding was unexpected. Generally, the central angle performs better because of the higher signal-to-noise ratio. We attribute this observation to the baseline incline angle (the angle between the baseline and the horizontal direction). Based on the conventional interferometric SAR measurement principle, the theoretical interferometric phase error ($\Delta\phi$) of the

InIRA SSH can be deduced from the relationship between the interferometric phase (φ) and the SSH, and it is expressed as Equation (5) [37]:

$$\Delta\varphi = \frac{2\pi B \cos(\alpha - \theta)}{\lambda R \sin\theta} \Delta z \quad (5)$$

where B is the baseline length, α is the baseline incline angle, θ is the incidence angle, λ is the radar wavelength, R is the slant range, and Δz is the variation in SSH. From Equation (5), when α equals θ , the maximum $\Delta\varphi$ is obtained. Since $\Delta\varphi$ can be converted into the SSH error, the SSH error in this case is also at a maximum. We know that the InIRA baseline incline angle is 5° . Thus, the largest RMSE occurs at an incidence angle of 5° , which is reasonable and consistent with Equation (5).

Figure 8. Error analysis after further parametric bias correction. Mean bias (BIAS) plotted against (a) incidence angle, (c) wind speed, and (e) significant wave height. Root mean square error (RMSE) plotted against (b) incidence angle, (d) wind speed, and (f) significant wave height.

The results in Figure 8d indicate that the RMSE first decreased and then increased with the wind speed. When the wind speed was in the 10 m/s bin, the best RMSE was achieved, with a value of 5.7 cm. This finding indicates that the InIRA SSH measurements perform better around a wind speed of 10 m/s. Figure 8f indicates that the RMSE exhibited a similar trend to that shown in Figure 8d. The SWH bins of 1.5 m and 2.5 m correspond to the best RMSE of 6.0 cm. This finding indicates that the InIRA SSH measurements perform better around an SWH of 2.0 m.

The results (Figure 9) show all error statistics between the InIRA and the traditional altimeter after removing the systematic and parametric biases. The BIAS, RMSE, and STD were 0.5 cm, 8.1 cm, and 8.1 cm, respectively. On the other hand, the RMSE decreased to the same level as the STD. More importantly, the STD significantly improved by 4.6 cm after the parametric bias correction, making the STD of the InIRA SSH (8.1 cm) comparable to those of traditional altimeters (~ 7.0 cm).

Figure 9. SSH difference statistics between the Interferometric Imaging Radar Altimeter (InIRA) and traditional altimeter after further parametric bias correction.

5. Discussion

The InIRA is a new spaceborne sensor. Its most important task is to measure the two-dimensional SSH. Currently, the InIRA SSH retrieval algorithm is continuously being improved to achieve an SSH accuracy close to that of the traditional altimeter. Thus, it is essential to find the accuracy gap between the InIRA and traditional altimeter SSH measurements, which would guide future improvements of the algorithm. This was the motivation for the current study, which comparatively evaluated the InIRA SSH and standard traditional altimeter SSH products. The results of the evaluations showed that the InIRA could capture the same SSH change trend as those obtained by traditional altimeters. Moreover, the STD reduced to ~ 8.1 cm through two-bias correction. These results show that the InIRA is promising in SSH measurement; further, the two biases, systematic and parametric, should be considered in the InIRA SSH retrieval algorithm.

This study follows the same cross-over evaluation method used to evaluate traditional altimeters. In the InIRA evaluation, the STD reduced to 12.7 cm when a systematic bias correction was applied and further reduced to 8.1 cm when a parametric bias correction was applied. Previous evaluations of the traditional altimeter reported a satisfactory STD of ~ 7.0 cm. Faugere et al. [30] showed that the STD of the Envisat SSH cross-over difference was between 7.5 cm and 7.7 cm when compared with Jason-1. Labroue et al. [31] assessed Cryosat-2 SSH measurements, which have an STD of ~ 6.5 cm when compared to Jason-2. Bao et al. [32] estimated that HY-2A SSH measurements have an STD of 6.98 cm when compared with Jason-2. Though the InIRA STD after correction is still higher, it is comparable to that of the traditional altimeters. The deviation in the estimation of the baseline incline angle is probably an important source of the remaining error, which is induced by the satellite roll angle. This problem is expected to be solved by using a new baseline incline angle estimation method [37].

The InIRA SSH is a two-dimensional mapping, while the traditional altimeter SSH is sampled along the ground track; this highlights the former's focus on high resolution and wide swath. However, these capabilities consume more power, thereby limiting the number of continuous working hours. Thus, we believe that the InIRA is more suitable for the observation of specific areas and periods, such as offshore and known mesoscale eddy locations. Owing to their low power consumption, traditional altimeters are more suited for continuous global monitoring. However, the limited sampling area remains as a limitation to their application. Therefore, the SSH estimates derived from the two altimeter types can be used complementarily. For example, when a traditional altimeter finds a possible observation target, the InIRA instrument can be tasked to observe the target with a high resolution in space and time. Moreover, by combining the InIRA and traditional altimeter SSHs, the global SSH map can be developed within a shorter period of time.

The spatial resolution of the InIRA SSH used in this study is $5\text{ km} \times 5\text{ km}$, which is comparable to the resolution of traditional altimeters. At this scale, both the InIRA and traditional altimeter data can be used to study mesoscale ocean phenomena. However, with the development of processing technology, it is expected that the InIRA SSH resolution will increase. When the resolution is refined down to $\sim 1\text{ km}$, sub-mesoscale (1–10 km) ocean phenomena can be observed. However, for now, the InIRA SSH data only have the advantages of a wide swath; the high resolution is not yet available.

This study has two limitations. First, the InIRA SSH product used in this work is not the final standard product. This product is only corrected for three effects, not including SSB. Therefore, methods to model the SSB are urgently required. The SSB is usually modelled using wind speed and SWH as model inputs. In the bias analysis of this study, we found a parametric bias related to the incidence angle and SWH. The latter indicates that the SSB of the InIRA and traditional altimeters are probably different. This is supported by the SWH-related differences observed between them. Therefore, a new InIRA SSB model needs to be developed. Moreover, the parametric bias related to the incidence angle inspired us to consider its effect on the InIRA SSB. In addition to the conventional wind speed and SWH parameter, the incidence angle could be an additional SSB model input.

Second, this study lacks adequate collocations. Seven sets of collocations were used to evaluate the InIRA SSH. These collocations were chosen from a large amount of data within 1 h and 2 km windows. Compared to previous evaluations between traditional altimeters, the amount of data used in this study remains insufficient. There are two reasons for this small amount of data. First, the InIRA sensor onboard Tiangong-2 is not fully operational, which limits data availability. Second, the measured InIRA SSH was significantly affected by the SSB and geophysical effects (i.e., tidal and inverse barometers, which are usually used for sea-level anomaly correction). Therefore, the time and spatial window must be sufficiently narrow to avoid the effects of these rapidly changing factors. This issue may be resolved after performing the SSB and geophysical effect corrections. This is because the fully corrected SSH product does not change dramatically in a few days. In this case, we can extend the time window from 1 h to a few days to match more collocations.

6. Conclusions

The Chinese Tiangong-2 Interferometric Imaging Radar Altimeter (InIRA) is a new sensor, designed to measure two-dimensional sea surface height (SSH). To advance the InIRA SSH retrieval work, we evaluated the product with respect to colocated traditional altimeter SSH estimates.

The traditional altimeter data used include Jason-2, Saral/AltiKa, and Jason-3. Seven sets of collocations were collected. Each set consisted of a coincidental traditional altimeter ground track with a rectangular footprint of InIRA. The colocated SSH maps from these altimeters were then compared. The traditional altimeter data were matched to that from the InIRA, and we neglected the sea state bias (SSB) correction for consistency at the correction level. The results of the comparisons show that the InIRA captured the same SSH change trends as those captured by traditional altimeters. However, there was a significant bias between them.

The InIRA SSH results were first corrected for systematic bias by directly subtracting the mean bias from the original product. Here, the systematic correction was performed separately with different traditional altimeters. This allowed the removal of the mean bias from the SSH. However, decreased biases were still apparent. For this, a parametric bias analysis of the incidence angle, wind speed, and SWH was added. The analysis revealed that the parametric bias was related to the incidence angle and SWH. Then, a parametric bias model was developed for the incidence angle and SWH. The parametric bias correction significantly reduced the standard deviation (STD) from 12.7 cm to 8.1 cm.

After the two bias corrections, the final STD was slightly larger than but comparable to that of the traditional altimeters. This shows that InIRA is promising for two-dimensional SSH measurements. Future work will focus on the SSB correction for the InIRA SSH measurements.

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Appendix A

$$BIAS = \frac{1}{N} \sum_{i=1}^N (x_i - y_i) \quad (A1)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2} \quad (A2)$$

$$STD = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i - BIAS)^2} \quad (A3)$$

where x_i is the SSH from InIRA and y_i is the SSH from the traditional altimeter.

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