

Quality assessment and comparison of two merged sea surface height products: ALT MUL and AVISO

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Abstract

Merged satellite altimeter products are widely used in ocean-related fields. Currently, the altimeter merged products of archiving validation and interpretation of satellite oceanographic (AVISO) data are widely used internationally. Chinese National Satellite Ocean Application Service also released merged altimeter products (ALT MUL) in 2023. However, there are few studies on the quality assessment of ALT MUL. Based on the data of AVISO merged products, Jason3 satellite, tide gauge and drifter buoy, the quality assessment and effect analysis of ALT MUL merged products were carried out by means of error evaluation index, interpolation along rails, velocity inversion and power spectrum. The result shows that the average sea level anomaly (SLA) of ALT MUL is about 2 cm smaller than that of AVISO. And they are consistent with the large-scale characteristics and spatial distribution. These two SLA products are both in accordance with normal distribution. Results indicate a lesser congruence between ALT MUL and Jason3 satellite compared to AVISO. This difference may be attributed to the fact that AVISO products use Jason3 satellite as cross-calibrated reference satellite during the merged process. Comparing the matching effect of the two merged products with the tide gauge and drifter buoy, ALT MUL merged products are superior to AVISO in general. The energy spectral density was calculated by using Jason3 satellite data along the orbit, and the two merged products were interpolated to the data points along the orbit. The effective resolution of AVISO and ALT MUL merged products was 180 km and 210 km respectively through spectral calculation, indicating that AVISO merged products have higher effective resolution.

Key words satellite altimeter, ALT MUL merged products, sea level anomaly, quality assessment

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1 Introduction

Abundant marine field observations (such as tide gauges, drifter buoys, Argo buoys, etc.) have greatly promoted the progress of oceanography and are a traditional way to study the ocean (Abdalla et al., 2021; Elipot et al., 2016; Liu et al., 2023; Ubelmann et al., 2021; Wang et al., 2022). Owing to the limitation of sparse field observation (Dieng et al., 2021; Hu et al., 2023), the satellite altimeter, functioning as an active spaceborne microwave radar system, has increasingly been recognized as a sophisticated

tool for oceanographic exploration, enabling the comprehension and detection of oceanic phenomena with centimeter-level accuracy (Stammer and Cazenave, 2017; Sun et al., 2022). The measurement of regional and global absolute dynamic topography (ADT) and sea level anomaly (SLA) offers the advantages of extensive coverage, rapid data updates, and resilience to weather conditions (Yu et al., 2018).

The origins of the satellite altimetry research program can be traced back to the Solid Earth and Ocean Physics Conference held in Williamstown in 1969. Following the

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proposal of satellite altimetry, NASA utilized the altimeter S-193 on Skylab to conduct the initial ocean satellite radar altimetry test. Subsequently, a series of satellites including GEOS-3, Seasat, Geosat, ERS-1, ERS-2, Topex/Poseidon, Cryosat-2 and others have been launched worldwide, yielding a wealth of valuable altimetry data (Eito-Brun, 2018; Fu et al., 1994). China has successfully launched the HY-2A, HY-2B, HY-2C, and HY-2D satellites in succession. Currently, a three-satellite network consisting of HY-2B/C/D has been established, indicating the maturity of dynamic environment satellites in China (Liu et al., 2022). In December 2022, the surface water and ocean topography (SWOT) satellite with interferometric imaging altimetry was successfully launched, achieving a precise observation of sea surface height with an accuracy of 1 cm (Altenau et al., 2021).

However, the observation data obtained by a single satellite equipped with an altimeter are along-orbit satellite observations, resulting in non-full coverage of observation, irregular observation networks, difficulties in direct assimilation, and variations in observations between different satellites (Lopez-Radenceno et al., 2019). Merged satellite altimetry products mitigate these limitations by utilizing sophisticated merged algorithms to amalgamate datasets from multiple satellites, culminating in the generation of a gridded products that provides a cohesive and regular observational network.

Nonetheless, there exists a paucity of research concerning merged satellite altimeter products and their associated quality assessment metrics. In ocean sciences, the quality of merged products obtained by the merged of multiple satellite altimeters will be significantly improved from the perspective of research (Fu et al., 2003; Pascual et al., 2006; Le Traon and Dibarboure, 1999). In previous work, the T/P satellite served as benchmark observation to evaluate merged products (Le Traon et al., 2003). When assessing the discrepancies between near-real-time and offline products, satellite along-track data were used as ground truth for comparison (Lillibridge et al., 2011). When investigating the accuracy of the HY-2A altimeter in retrieving sea surface height (SSH), the bias derived from along-track SLA statistics and its crossover difference with Jason2 were employed (Cui et al., 2018; Jiang et al., 2018). Based on variational principle, Liu et al (2020) fused the along-track data of five satellite altimeters, and the accuracy of their products is verified by wavenumber spectrum and independent data. In evaluating the precision of the HY-2B satellite altimetry data products, they were juxtaposed with the level 2 GDR data from Jason2/3, underscoring the high measurement accuracy of the Jason2/3 satellite series (Jia et al., 2020).

On March 23, 2023, NSOAS released merged sea surface height products (ALT MUL). It covers the entire global marine area with a global resolution of $0.25^\circ \times 0.25^\circ$, and the resolution in key marine areas reaches $0.125^\circ \times 0.125^\circ$. However, there is currently no research

that comprehensively assesses the quality of this merged products.

Based on the aforementioned foundation, to gain a comprehensive understanding of the error distribution characteristics of the ALT MUL products and to expand subsequent marine research and assimilation applications, this paper conducts a quality assessment of this merged products.

The structure of this paper is as follows: The second section provides a brief introduction to the data and methods. The third section carries out a comparative analysis between the ALT MUL and archiving validation and interpretation of satellite oceanographic (AVISO) merged products. The summary is presented in the last section.

2 Data and method

2.1 ALT MUL and AVISO merged products

ALT MUL products were released by NSOAS. It has a temporal resolution of 1 d, and the spatial resolution is divided into global $0.25^\circ \times 0.25^\circ$ and regional $0.125^\circ \times 0.125^\circ$, which can be accessed from the NSOAS website (<https://osdds.nsoas.org.cn/OceanDynamics>). One advantage of the ALT MUL products is the public release of a sea surface height product with a higher resolution of $0.125^\circ \times 0.125^\circ$, while AVISO products only publicly release a sea surface height product of $0.25^\circ \times 0.25^\circ$. ALT MUL is based on domestic HY-2 series satellite altimeter data and foreign Jason3, Sentinel-3A/3B and other altimeter data. Its primary products include SLA and ADT. SLA and ADT are both variables that describe sea level. Their relationship can be described by the following formula.

$$\text{SLA} = \text{ADT} - \text{MDT}. \quad (1)$$

Among them, MDT is the mean dynamic topography on the geoid. ALT MUL products uses the MDT-CNES-CLS18 model (Mulet et al., 2021b), which is based on estimates of average sea surface heights above the geoid over the period 1993–2012.

The basic principle of the generation of ALT MUL products is based on the orbital sea surface height data with irregular temporal and spatial distribution observed by multiple satellite altimeters. After pre-processing such as data quality control and unification, the irregular multi-source satellite altimetry data is fused to generate SLA, ADT and other grid data with a uniform grid size at a specified time.

AVISO products (Archiving, Validation, and Interpretation of Satellite Oceanographic data) integrates altimeter data from multiple satellites including Jason3, Sentinel-3A, HY-2A, Saral/AltiKa, Cryosat-2, Jason2, Jason1, T/P, ENVISAT, GFO, ERS1/2. It is worth noting that the manual description of AVISO products mentions that Jason3 is the reference mission used for the altimeter

inter-calibration processing.

AVISO products can be obtained from the Copernicus Data Center (<https://marine.copernicus.eu/>). Its products include SLA and ADT and it also uses the MDT-CNES-CLS18 model. AVISO boasts a temporal resolution of 1 d, and spatial resolution measuring at $0.25^\circ \times 0.25^\circ$. AVISO includes near real-time (NRT) products with a delay ranging from several hours to one day, as well as delayed time (DT) products with a delay spanning several months (Chen and Cao, 2023). Since May 2015, the system has fallen under the purview of the European Copernicus Program; subsequently leading to the production and release of DT2018 merged products by both the Copernicus Marine Service (CMEMS) and Copernicus Climate Change Service (C3S), respectively. The specific differences between these aforementioned products are detailed in Taburet et al. (2019).

For this paper, in order to be consistent with the temporal resolution of AVISO, we utilized the $0.25^\circ \times 0.25^\circ$ ALT MUL products. Due to the limited field observation data, we chose a time span from January 2021 to September 2023. Because of the abundance of tide stations and drifter buoys in the northern Indian and western Pacific Oceans (40° – 170° E, 10° S– 50° N), we chose this area as our research area. The primary data utilized in this study consist of the SLA and ADT, with the calculation of geostrophic currents based on the geostrophic relationship derived from ADT inversion (Knudsen et al., 2011) :

$$u = -\frac{g}{f} \frac{\partial h}{\partial y}, \quad v = \frac{g}{f} \frac{\partial h}{\partial x}, \quad (2)$$

where, h is the ADT (unit: m), g is the acceleration of gravity (unit: m/s^2), $f = 2\Omega \sin\varphi$ is called the Coriolis parameter. Ω represents the angular velocity of the rotation of the earth and φ is the latitude.

2.2 Verification and evaluation data

These data are mainly for the analysis, verification and evaluation of the two merged products of ALT MUL and AVISO. They mainly include Jason3 satellite orbiting data, tide gauge data and drifting buoy data. The following will be introduced separately.

2.2.1 Jason3 Satellite orbiting data

The Jason3 satellite SLA data utilized in this paper covers the period from January to December 2021. The release products have a temporal resolution of 1 d, and it takes 10 d for the satellite to orbit the Earth. The measurement accuracy is high, making it a commonly used reference for evaluating grid products in scientific research (<https://data.marine.copernicus.eu/>). In this paper, we first extract the trajectory scanned by the Jason3 satellite over a 10-d period, obtaining all latitude and longitude coordinates as well as SLA data along its orbit. We then interpolate the gridded ALT MUL and AVISO SLA products on-

to the Jason3 orbit for comparison and analysis.

2.2.2 Tide gauge (UHSLC)

Tidal gauges are observation stations equipped with instruments such as tide gauges or water gauges to record water level changes at specific locations (<https://uhslc.soest.hawaii.edu/opendap/hyrax/fast/daily/contents.html>). Due to the limited data from tide station, we chose a time range from January 2021 to August 2023. The temporal resolution of this data is 1 d. The measured SLA can be used to verify and evaluate ALT MUL and AVISO products. To minimize land influence, we select sites far away from the coast for specific analysis. These selected site locations are labeled as Station 1 through Station 6 (as shown in Fig. 1).

Using the SLA measured by the tide gauge as ground truth, we interpolate ALT MUL and AVISO SLA into the same time and space range at each tide gauge site. Subsequently, relevant errors are calculated to evaluate the quality of the two products.

2.2.3 Drifter buoy

The Global Drifter Program (GDP) is a global array of sea surface drifters tracked by more than 1 000 satellites. Its data sets are widely used to study small-scale high-frequency ocean dynamic processes and are part of the NOAA Global Ocean Observing System (<https://www.aoml.noaa.gov/global-drifter-program/>). The data has a temporal resolution of 6 hours and can measure current velocity in the ocean with high accuracy. In this study, all buoys from January 2021 to September 2023 were searched in the target area, resulting in a total of 400 buoys being found. Using the geostrophic formula, the ADT of ALT MUL and AVISO falling within this circle area was calculated through deduction. The flow velocity calculated by ADT is geostrophic velocity, while the flow velocity measured by buoys includes geostrophic flow, wind-generated flow, and stokes flow, etc. Studies have shown that wind-induced drift is called downwind “sliding” (the movement of a drifter relative to water at a depth of 15 m), which is only 0.1% of the wind speed when the wind speed is as high as 10 m/s (Niiler et al., 1995; Wang et al., 2020). There is a difference between the two flow velocities, but the error is small in low-latitude areas and

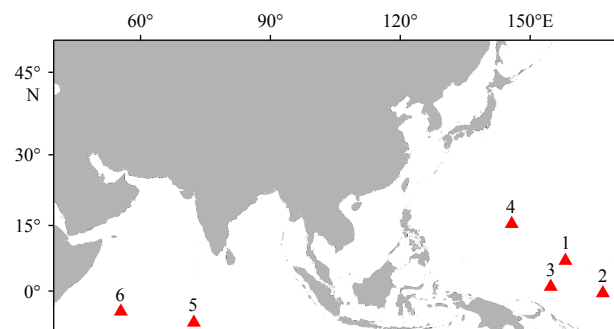


Fig. 1. Location of tide station.

can be used as an indicator for evaluating ADT products (Zhao et al., 2021). By interpolating the velocity to the location of each buoy and matching it with corresponding time data, we were able to compare the velocity of both merged products with that measured by each drifter buoy for further analysis and evaluation (Mulet et al., 2021a).

2.3 Data analysis method

Statistical parameters such as Bias, STD, RMSE, and correlation coefficient (R) were utilized for analyzing and evaluating ALT MUL and AVISO products against true value data.

$$\text{Bias} = \frac{1}{N} \sum_{i=1}^N (S_i - B_i), \quad (3)$$

$$\text{STD} = \sqrt{\frac{\sum_{i=1}^N (S_i - B_i - \bar{S} - \bar{B})^2}{N-1}}, \quad (4)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (S_i - B_i)^2}{N}}, \quad (5)$$

$$R = \frac{\sum_{i=1}^N (S_i - \bar{S})(B_i - \bar{B})}{\sqrt{\sum_{i=1}^N (S_i - \bar{S})^2 \sum_{i=1}^N (B_i - \bar{B})^2}}, \quad (6)$$

Where N represents number of samples, B_i is field measurement value, S_i is the satellite products measurement value. These parameters effectively describe error distribution characteristics within merged products.

Furthermore, SLA power spectral density (PSD) was calculated from along-track SLA measurements using periodogram method. Gridded data was also interpolated or extrapolated using merged algorithm to cover any unmeasured areas. However, it should be noted that spatial scale limitations still exist within these products which can be quantified by ER. Different from the grid spacing, ER is defined as the spatial and temporal scale of the structure that the gridded data can correctly parse. The specific formula is expressed as (Ballarotta et al., 2019) :

$$NSR(\lambda_s) = \frac{S_{diff}(\lambda_s)}{S_{obs}(\lambda_s)}, \quad (7)$$

where $S_{diff}(\lambda_s)$ is the PSD of the $ADT_{obs} - ADT_{map}$, ADT_{obs} is along-track ADT, and ADT_{map} is the ADT interpolated onto the same along-track segment. $NSR(\lambda_s)$ is the ratio at λ_s , where λ_s is the wavelength. If the $NSR(\lambda_s)$ at the λ_s is greater than 0.5, then it is considered that the signal at that scale can be resolved. We can determine the ER of satellite products by analyzing the slope of the

wavenumber spectrum and comparing the spectral energy (Olmedo et al., 2016; Yan et al., 2019). By computing the ER using the wavenumber spectrum, we can further analyze the ALT MUL and AVISO merged products to assess their performance in reflecting oceanographic phenomena.

3 Result

3.1 Comparison of SLA products between ALT MUL and AVISO

Both ALT MUL and AVISO merged products include ADT, SLA, MDT, U, V and other merged products, among which SLA merged products reflect the change of sea surface height, which is of great significance to Marine research. In order to have a more comprehensive and macro understanding of the SLA of ALT MUL merged products, compare and analyze the SLA of ALT MUL merged products with that of AVISO merged products widely used in the world, make a difference between them, analyze the distribution, and explore the commonalities and differences between them. Figure 2 shows the SLA field distribution of ALT MUL and AVISO merged products in the study area.

Figures 2a and b show the average SLA fields for the ALT MUL and AVISO merged products from January 2021 to September 2023. The selected region spans from 10°S to 50°N and from 40°E to 170°E. In terms of large-scale features of SLA, the spatial distribution is consistent between the two merged products. To the southeast of the Japanese archipelago, both products exhibit significant positive SLA values, forming a striped pattern along the longitudinal direction. A nearly circular area south of Kyushu Island shows substantial negative SLA values. In other regions, the SLA is close to 0. Notably, overall, the SLA values of the AVISO are slightly larger. Figure 2c displays the spatial distribution of the SLA difference between the AVISO and ALT MUL products, indicating that the AVISO SLA values are generally higher than those of ALT MUL by an average of 2.03 cm. However, in certain areas south of Kyushu Island, the ALT MUL products have larger SLA values compared to AVISO.

In order to compare and analyze the specific distribution of SLA values of ALT MUL and AVISO, the histogram distribution of SLA of the two merged products is drawn as shown in Fig. 3 below.

Figures 3a and b respectively depict the SLA histograms for the ALT MUL and AVISO products. The figures reveal that the SLA of both products follows a normal distribution. The maximum frequency of SLA products corresponds to the SLA value of 0.107 m for ALT MUL and 0.110 m for AVISO.

In order to more clearly see the SLAs distribution of the two products, the SLAs of ALT MUL and AVISO are drawn in the density distribution diagram, as shown in

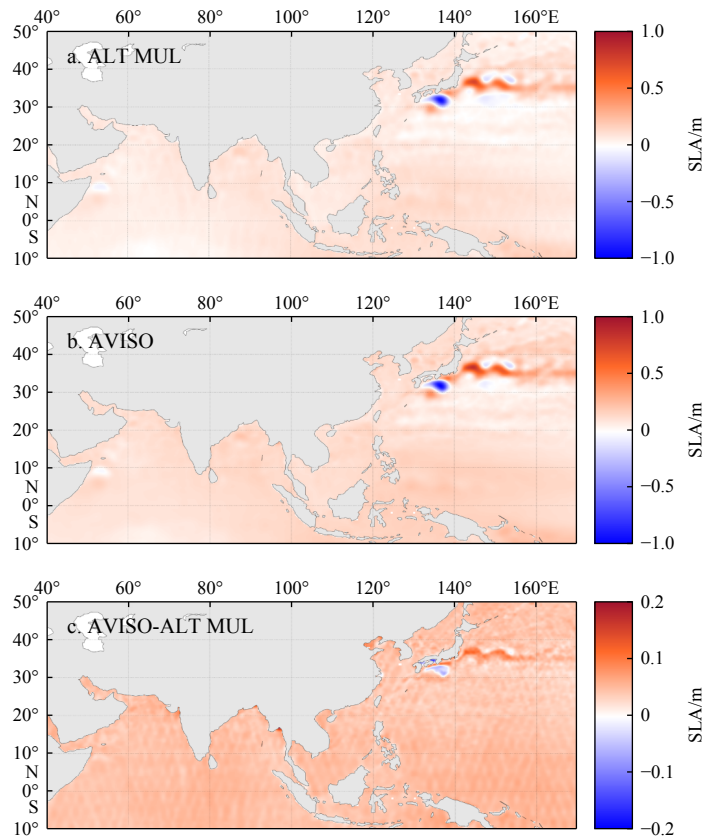


Fig. 2. ALT MUL (a), AVISO SLA (b) and (AVISO-ALT MUL) (c) SLA spatial distribution.

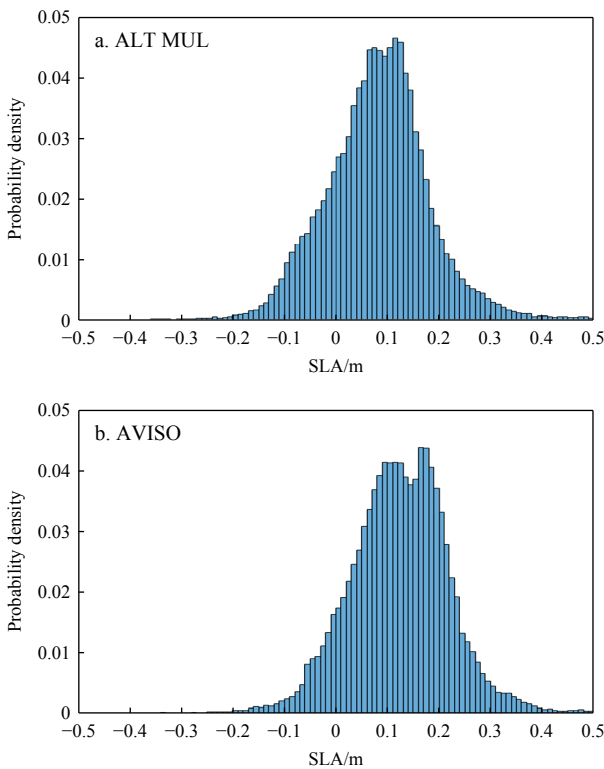


Fig. 3. ALT MUL (a) and AVISO SLA (b) square distribution.

Fig. 4 below.

Figure 4 illustrates the average SLA density distribu-

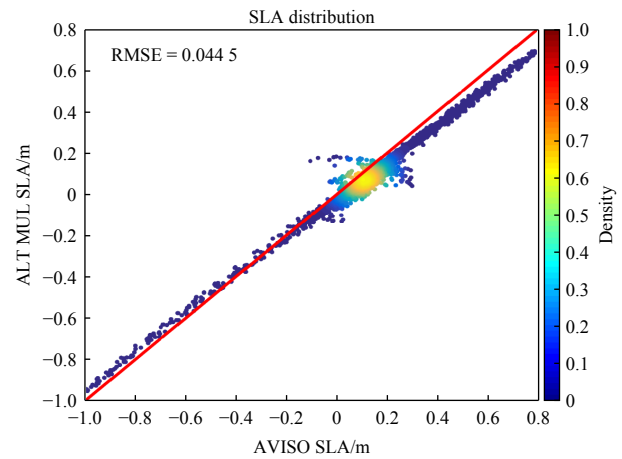


Fig. 4. The density distribution map of the values of ALT MUL and AVISO SLA products. The color code indicates the density of this point on the map.

tion for the ALT MUL and AVISO products from January 2021 to September 2023. From the figure, it is evident that when the SLA values range between -1 m and -0.2 m, the ALT MUL products have higher SLA values compared to the AVISO products. Conversely, within the range of -0.2 m to 0.8 m, the SLA values of the ALT MUL products are smaller than those of AVISO. This shows that for the same SLA value, the SLA change of ALT MUL is smaller than that of AVISO. The highest density of SLA for both products occurs within the inter-

val [0, 0.2] m, where the SLA values of the ALT MUL products are slightly lower than AVISO. The average RMSE of approximately 4.5 cm shows that there is a certain discrepancy between the SLA of the ALT MUL products and that of AVISO.

3.2 Satellite orbit data inspection

Previous studies have shown that the measurement of SSH by Jason series satellites is more accurate and can be used as a theoretical reference (Jia et al., 2020). So in this paper, we evaluate the accuracy of the products by interpolating the SLA values of ALT MUL and AVISO products into the orbit of Jason3 satellites. Then, the average RMSE for the entire year of 2021 is calculated, with its distribution shown in Fig. 5.

Figure 5a and b respectively show the average RMSE distribution maps for the SLA of ALT MUL and AVISO products. The results indicate that larger RMSE are observed in the Bohai Sea and near coastal areas. In most regions, the ALT MUL has a higher RMSE than the AVISO products, with an average RMSE approximately 3 cm greater for ALT MUL compared to AVISO.

In order to compare and analyze the average RMSE size of SLA interpolation from two merged products to each orbit of Jason3 satellite, the curve change of RMSE with orbit is plotted, as shown in Fig. 6 below.

As is shown in Fig. 6, the error distribution trends for both are relatively consistent, with the overall RMSE for AVISO being less than that of ALT MUL. The average difference in RMSE between the two is 3.60 cm, indicating that the SLA of AVISO matches better with the Jason3 satellite data. This discrepancy may be due to the fact that ALT MUL primarily integrates satellites such as HY-2B/C/D, with less merged of Jason3 data, whereas AVISO products use Jason3 data as the reference mission used for the altimeter inter-calibration processing, poten-

tially leading to a higher compatibility and lower error with Jason3 satellite data.

3.3 Independent observational data testing

This section involves comparing and evaluating the ALT MUL and AVISO products separately against independent observational data, which includes tide gauge (UHSLC) and drifter buoys.

First of all, we analyzed and tested the merged products of ALT MUL and AVISO with the tide gauge data. The tide gauge was used as the measured data, and the SLA measured could be used as the reference value. By interpolating the SLAs of ALT MUL and AVISO merged products into a single station location and further comparing them with the SLA measured by the tide station, the SLA of the two merged products can be analyzed and evaluated. Since the SLA in the nearshore sea area is greatly affected by many aspects, this paper selected 6 tide stations in the open ocean, interpolated the SLA of the two merged products into each tide station, and compared the SLA time series of the 6 stations, as shown in Fig. 7 below. The time series is from January 2021 to August 2023.

As shown in Fig. 7, Figs 7a–f are 6 open tide measuring stations respectively. Figure 7 shows that both the ALT MUL and AVISO products SLAs closely follow the trends of the tide gauge data. The ALT MUL products SLA mostly exhibits a negative bias compared to the tide gauges, whereas the AVISO products SLA typically shows a positive bias. Overall, the ALT MUL products SLA has a better matching effect with the tide gauge data than the AVISO products. Table 1 lists the Bias, RMSE, and R for Stations 1–6.

From Table 1, it can be seen that the bias of the SLA of the ALT MUL products is less than that of the AVISO products. The RMSE of the ALT MUL products is gener-

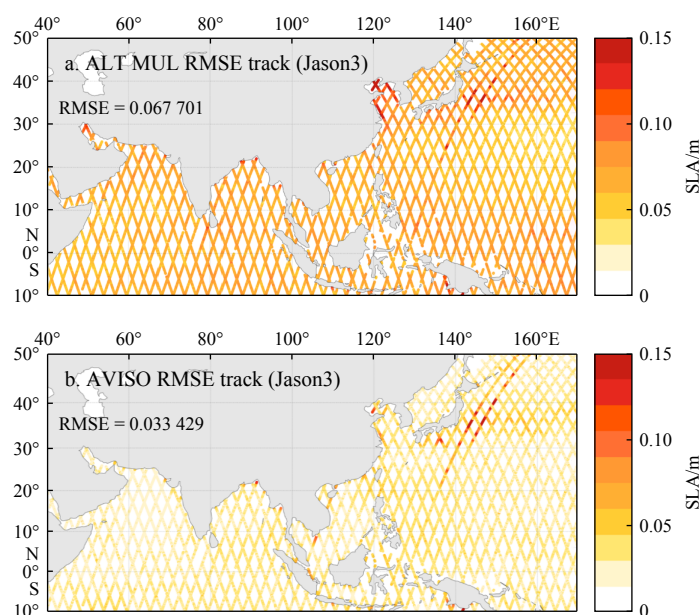


Fig. 5. ALT MUL (a), AVISO (b) and Jason3 satellite RMSE spatial distribution.

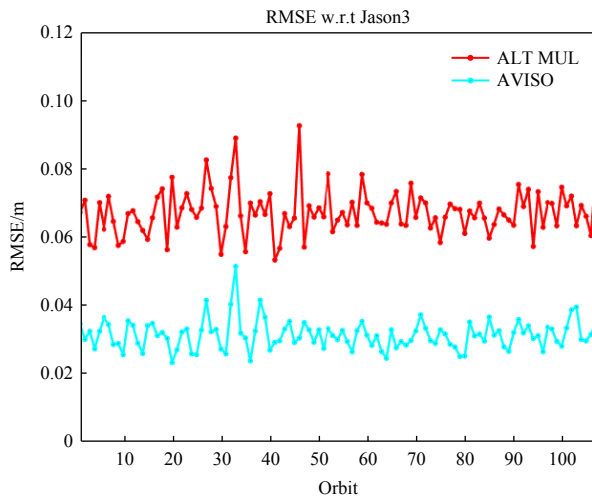


Fig. 6. RMSE variation for ALT MUL and AVISO SLA products against Jason3 satellite SLA.

ally smaller than that of the AVISO, indicating that the SLA from the ALT MUL products match better with the

actual data from the tide gauge. Because we select these six tide gauge stations in open seas, it can be explained to a certain extent that the SLA of the ALT MUL products in open seas are better than AVISO, which also provides a basis for the selection and use of data in future operational applications. In terms of correlation coefficient, there is not much difference between the two products.

Due to the high accuracy of flow velocity measured by drifting buoys, it can be compared with the flow velocity inversion of ADT products of merged products. Although there are some errors in this method, some studies have shown that the errors are small, and it is also a method to evaluate the effect of ADT products in merged products, while the effect of SLA products is closely related to ADT products. The first step in the validation analysis is to calculate the inverse velocity using the Eq. (2) from the ADT product of the ALT MUL and AVISO merged products, and then compare it with the measured velocity of the drifting buoys, using 10 buoys as an average. The curve changes of the measured flow velocity of the drifting buoy and the inversion velocity of the two merged products are

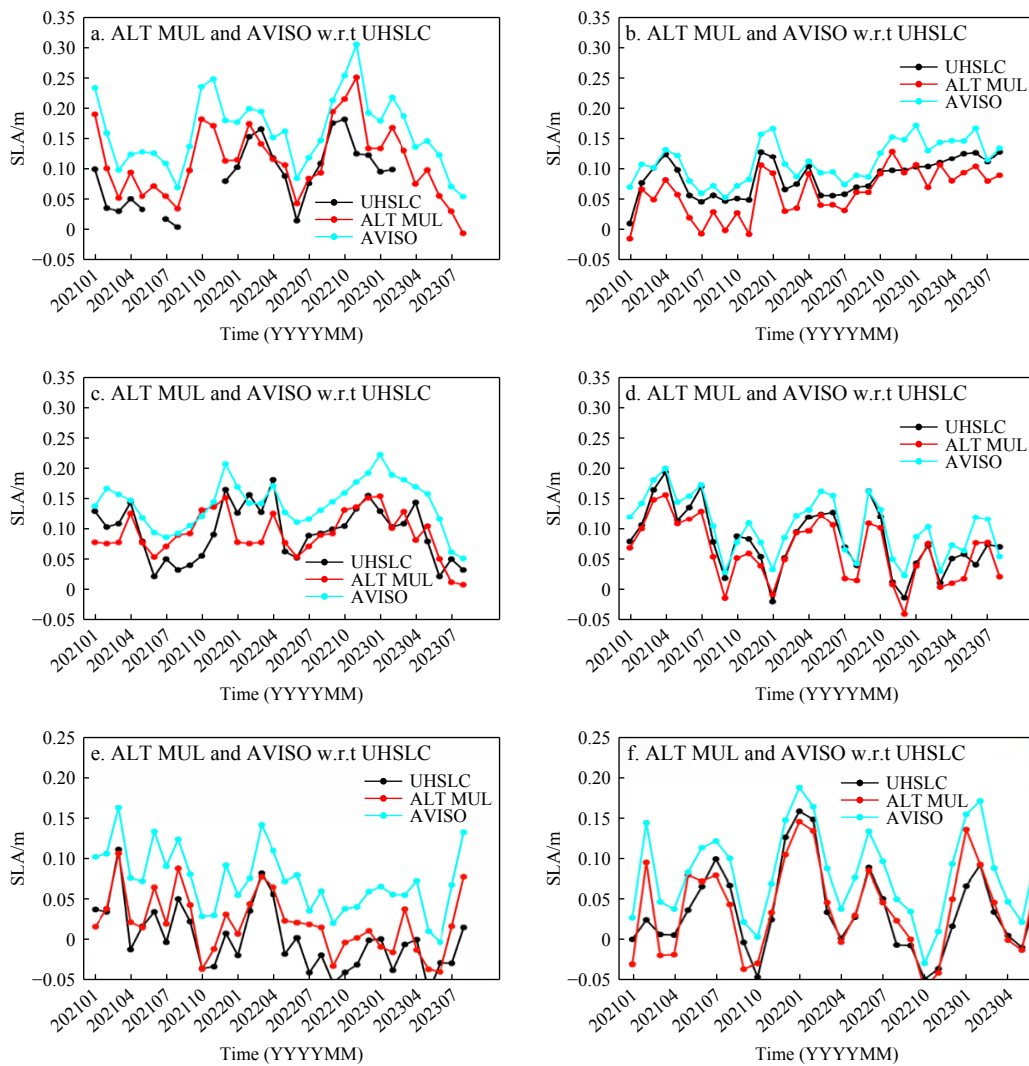


Fig. 7. SLA time series comparison for ALT MUL and AVISO at six stations. a. Station 1, b. Station 2, c. Station 3, d. Station 4, e. Station 5, f. Station 6.

Table 1. Comparison of SLA from different tide gauge stations with ALT MUL and AVISO products. Unit: cm

Station	Station 1		Station 2		Station 3		Station 4		Station 5		Station 6	
Products	ALT MUL	AVISO	ALT MUL	AVISO	ALT MUL	AVISO	ALT MUL	AVISO	ALT MUL	AVISO	ALT MUL	AVISO
Bias	2.17	7.14	-2.52	2.74	-0.34	4.52	-1.83	2.29	1.96	7.21	0.74	5.03
RMSE	4.53	8.61	3.14	3.23	3.73	5.30	2.70	3.00	2.85	7.21	2.60	5.08
R	82.4%	78.0%	87.3%	86.7%	58.8%	78.4%	92.7%	92.9%	85.2%	89.4%	88.8%	91.8%

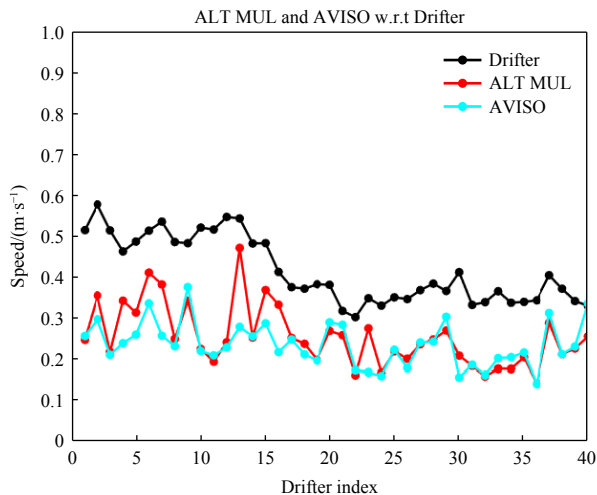
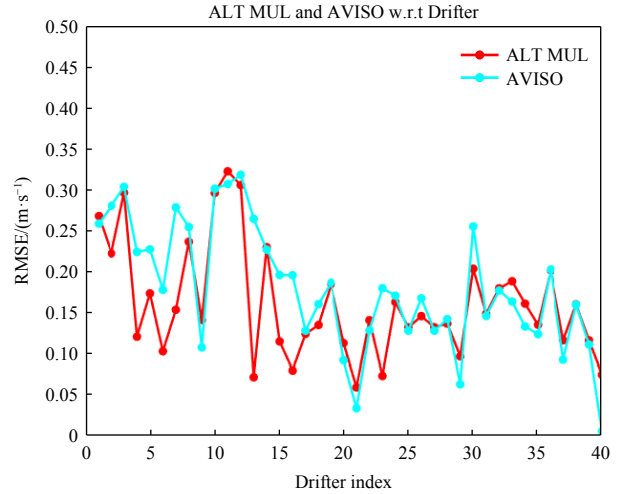
plotted as shown in Fig. 8 below.

From Fig. 8, it is evident that the speed of both products is mostly less than the measured speed, with a consistent trend. This is because the measured velocities include both geostrophic flows and smaller wind-driven flows, whereas the velocities represent only the geostrophic currents, which are smaller than the measured velocities. The ADT from ALT MUL shows velocities that are generally larger than those from the AVISO products, and the ALT MUL speed is closer to the actual measured velocities from the drifting buoys.

In order to further compare the error distribution between the inversion velocity of the two merged products ADT and the velocity measured by the drifting buoy, Fig. 9 is drawn as shown in the following:

Figure 9 shows the RMSE of the speed from both ALT MUL and AVISO products compared to the measured speed from drifting buoys. As can be seen from the figure, the RMSE for both are very similar, but overall, the RMSE for the speed performed by the ADT products in ALT MUL is smaller than that of the AVISO. Specific data are shown in Table 2.

From Table 2, it can be observed that both the ALT MUL and AVISO speed show a negative bias. Bias, STD and RMSE of ADT product inversion speed in ALT MUL are smaller than those in AVISO, indicating that the ADT product inversion speed in ALT MUL is more accurate than that in AVISO. This indicates that the ADT product in ALT MUL is superior to AVISO in retrieving geostrophic speed, indicating its potential for wider appli-

**Fig. 8.** Comparison of speed from ALT MUL and AVISO with drifting buoy data.**Fig. 9.** RMSE comparison of speed from ALT MUL and AVISO with drifter data.**Table 2.** Comparison of measured speed from drifting buoys with speed from ALT MUL and AVISO products. Unit: m/s

Products	ALT MUL	AVISO
Bias	-0.161 5	-0.179 8
Std	0.067 8	0.077 3
RMSE	0.174 8	0.195 4

cation in the future.

Further comparison is made between the direction of the velocities from both products and the measured velocity directions from the drifting buoys, with the deviations plotted as shown in Fig. 10.

Figure 10 shows the bias of the velocity direction from ALT MUL and AVISO products compared to the measured velocity direction from drifting buoys. From Fig. 10 it is evident that the inversion velocity of the two products has a large deviation compared to the drifter current observations in terms of direction. The average ocean current direction bias is approximately 90 degrees. This indicates that ALT MUL products still have some shortcomings in the inversion of velocity direction and need to be improved in the future.

3.4 Power spectrum

In order to compare and analyze the energy distribution of the two merged products ALT MUL and AVISO in the frequency domain, the SLA of the two merged products is interpolated onto the Jason3 track, and the

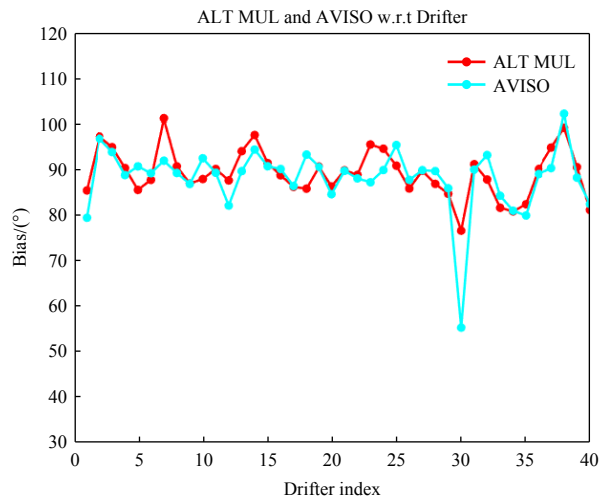


Fig. 10. Bias between ALT MUL and AVISO and drifting buoy data for the velocity direction.

PSD comparison diagram is drawn as shown in Fig. 11 below.

As shown in Fig. 11, between wavelengths of 125 km to 200 km, the energy spectral density ranks as Jason3 along-track data, AVISO, and then ALT MUL products, suggesting that both AVISO and ALT MUL have smoothed the data during the merging process, with ALT MUL showing more significant smoothing. At scales larger than 200 km, the spectral densities of Jason3 along-track data, AVISO, and ALT MUL are similar, which indicates that both AVISO and ALT MUL have retained the original energy well above the 200 km scale.

In order to further compare the effective resolution of the two merged products, the two merged products are interpolated into the orbit of Jason3 satellite, and the spectral calculation is carried out. The scale of the ratio of energy spectral density between the merged product and the orbital data is 1/2, which is the effective resolution of the merged product. Figure 12 shows the ratio of average or-

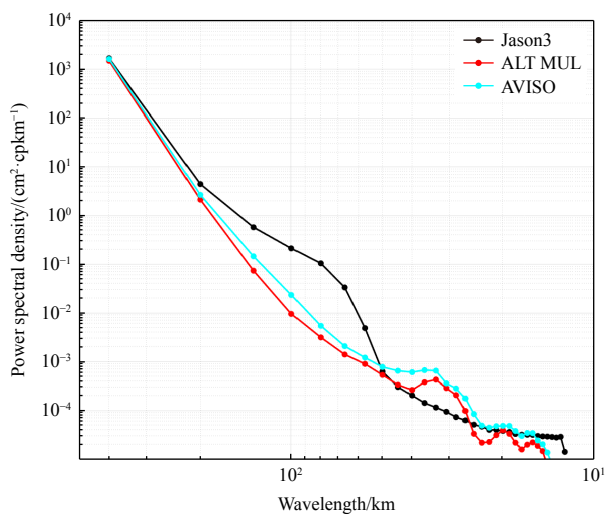


Fig. 11. Power spectral density of the merged products from ALT MUL and AVISO.

bit energy spectral density:

Interpolating the two merged products to the along-track points of the Jason3 satellite and performing spectral calculations, we obtain the scales at which the energy spectral density ratio of the merged products to the along-track data is 1/2, which is referred to as the ER of the merged products. Figure 12 shows the energy spectral density ratios. From the figure, it can be seen that compared with Jason3 along-track data, the ER of AVISO is about 180 km, and that of ALT MUL is 210 km. This shows that AVISO has greater resolution than ALT MUL. This reflects that the effective resolution of ALT MUL products is not as good as that of AVISO and there is a need for enhancement in characterizing smaller effective signals.

4 Conclusions

To address the insufficient quality assessment of the ALT MUL altimetry merged products, a comparative validation evaluation was conducted using *in-situ* data and power spectral methods against the internationally recognized AVISO altimetry merged products, leading to a deeper understanding of the ALT MUL merged products.

For the two merged satellite altimetry products, ALT MUL and AVISO, comparison of their SLA series revealed that the overall SLA values of the ALT MUL products are about 2 cm less than those of AVISO, yet their large-scale features and spatial distributions are consistent with each other and both conform to a normal distribution.

By treating the along-track SLA from the Jason3 satellite as the true theoretical value, a comparative analysis between the two merged products was performed. The results showed that both have smaller RMSE in offshore areas, and overall, the SLA products from ALT MUL has a worse matching effect with the Jason3 satellite than AVISO does, probably because AVISO uses Jason3 as a refer-

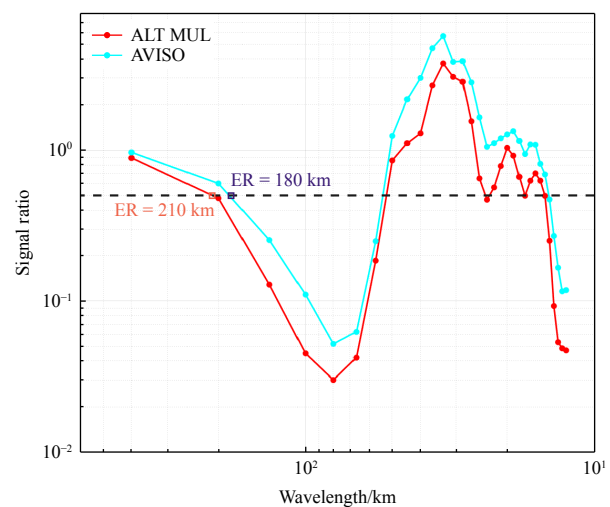


Fig. 12. The energy spectral density ratio of the merged products from ALT MUL and AVISO.

ence mission used for the altimeter inter-calibration processing.

Comparisons between tide gauge and drifting buoys with both merged products indicate that, overall, the ALT MUL products have a better matching effect than AVISO.

Calculation of the power spectra for the SLA products of ALT MUL and AVISO shows that the AVISO products have a higher resolution.

In summary, based on the validation and evaluation analysis presented in this study, ALT MUL, as newly released satellite altimetry merged products, still has room for development and improvement. Moving forward, there is a need to further integrate more observational data and enhance fusion methods to enhance the accuracy of off-shore sea surface height in ALT MUL products. Additionally, future considerations could include evaluating the impact of sea surface temperature on sea surface height fusion. Furthermore, there is a need to explore the innovative fusion techniques that bridge low resolution traditional radar altimeter observations and high-resolution interference imaging radar altimeter observations. On the whole, the overall quality of ALT MUL merged products currently has reached certain accuracy and precision standards, there is potential for enhancement to provide robust data support for scientific research.

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