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DETERMINATION OF SIGNIFICANT WAVE HEIGHT FROM SENTINEL-3B SATELLITE ALTIMETRY DATA IN THE EAST SEA

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Abstract
The purpose of this paper is to present the results of determining significant wave height (SWH) from satellite altimetry data in the East Sea and to evaluate the accuracy of the obtained values of SWH. To achieve this, the paper introduces the method for determining significant wave height, in which significant wave height is derived from the leading-edge slope of the return signal waveform. Accuracy is assessed based on the deviation between significant wave heights determined from the Ku- and C-band measurements at the same location. The experiment was conducted in the East Sea using Sentinel-3B satellite data from cycle 96. The results show that 4,856 significant wave height values were obtained, with a maximum of 1.962m, a minimum of 0.030m, and an average of 0.830m. The deviations of significant wave height generally follow a random distribution; however, 80 anomalous points, located near islands and coastal areas, needed to be excluded. The accuracy of the determined wave heights is estimated at ±0.378m. The processing results for 84 cycles indicate that the SWH accuracy ranges from ±0.315m to ±0.440m, with an average of ±0.402m.

Keywords: *Significant wave height, Sentinel-3B, Altimetry, East Sea.*

1. Introduction

Satellite altimetry is one of the key technologies in remote oceanographic research. It enables the collection of data on sea surface height, significant wave height (*SWH*), and ocean currents on a global scale. Over the past few decades, *SWH* derived from satellite altimetry has become a valuable data source for both scientific research and practical applications, including marine weather forecasting, offshore engineering design, wave energy potential assessment, and climate change impact studies.

The fundamental principle of satellite altimetry lies in transmitting radar signals from the satellite to the ocean surface and measuring the return time of the reflected signals to determine the distance between the satellite and the sea surface. The shape of the return waveform carries information about the state of the sea surface. Wave height can be inferred from the slope of the leading edge and the temporal dispersion of the return signal [1]. Waveform retracking models, such as the Brown model, have been widely used to extract *SWH* from raw satellite data.

One of the pioneering studies in this field was conducted by Walsh et al. (1984) [2], in which the authors introduced a method for analyzing satellite radar signals to estimate wave height. Their results showed that wave heights could be accurately determined under relatively stable sea conditions with low signal noise. Since the 1990s, with the launch of TOPEX/Poseidon, the estimation of wave height from space has become significantly more accurate. Callahan et al. (1994) demonstrated that *SWH* data from TOPEX/Poseidon had an average error of about ±0.3 m compared with in-situ buoy measurements. Following this, the Jason satellite series (Jason-1, Jason-2, Jason-3) has maintained a long-term, consistent dataset for global wave monitoring [3]. Envisat (2002-2012) also provided high-resolution altimetry data, particularly useful in coastal regions. Abdalla and Hersbach (2004) compared Envisat-derived data with wave model outputs and found strong correlations, especially under stormy sea conditions [4].

In the Asia-Pacific region, Hwang et al., (2010) utilized data from Jason-1, Envisat, and ERS-2 satellites to construct maps of wave height distribution and analyze the seasonal variability of waves in the East Sea and the western Pacific. Their results revealed pronounced seasonal changes in wave height associated with monsoon winds, particularly the Northeast Monsoon [5].

In Vietnam, research employing satellite altimetry data for wave analysis remains limited but is gradually expanding. Nguyen et al., (2018) used Jason-2 data to

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evaluate wave fields in the Central Vietnam waters, showing that average winter wave heights were 1.5-2 times higher than in summer, consistent with the characteristics of the monsoon climate [6].

These findings highlight that the determination of *SWH* from satellite altimetry has been successfully applied worldwide, and its application to the East Sea is both relevant and necessary. This paper presents the results of determining *SWH* in the East Sea using Sentinel-3B satellite data. Furthermore, the accuracy of the derived *SWHs* is assessed based on the deviations between Ku-band and C-band measurements. The paper is organized into the following sections: Section 1 provides the introduction; Section 2 presents the research methodology; Section 3 reports the results and discussion; Section 4 summarizes the conclusions; and finally, the references are listed.

2. Research Methodology

2.1. Method for Determining Wave Height from Satellite Altimetry Data

The basic principle of determining *SWH* from satellite altimetry data is illustrated in Figure 1. At time t_1, the satellite transmits a radar pulse toward the sea surface. Upon reaching the surface, the signal is reflected back to the satellite. Between t_1 and t_2, no return signal is received, and thus the signal power is zero. This time interval represents the signal's two-way travel time from the satellite to the sea surface and back. The difference $\Delta t = t_2 - t_1$ is used to calculate the distance from the satellite to the sea surface. At time t_2, the satellite begins receiving the return signal, and the signal power gradually increases until reaching a maximum at time t_3. After t_3, the signal power decreases. The plot of signal power over time is called the return waveform. The rising portion of

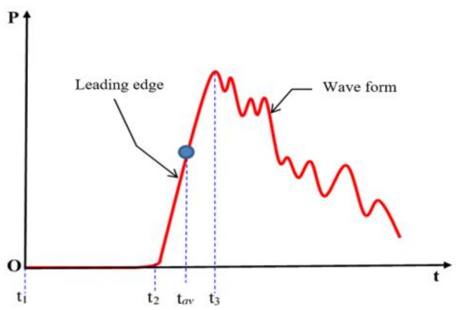

Figure 1. Principle of determining SWH from satellite altimetry data (P is the return signal power, expressed in dBW, and t denotes time in nanosecond) [7]

the return waveform between t_2 and t_3 is referred to as the leading edge [7].

When the sea surface is calm (no waves), most signals are reflected almost instantaneously and return to the satellite at the average time (t_{av}). The return power increases abruptly, and the leading edge of the waveform is nearly vertical. In this case, t_2, t_3, and t_{av} nearly coincide (differing only due to pulse length τ and correction factors).

When waves are present, signals reflected from wave crests arrive earlier than those from troughs, causing the leading edge of the waveform to have a slope. The wave height can be estimated from this slope, i.e., the time difference ($t_3 - t_2$) [7].

2.2. Accuracy Assessment of Significant Wave Height

The most accurate way to validate wave heights derived from satellite altimetry is by comparison with in-situ measurements, such as buoy observations. However, buoy measurements are costly, logistically difficult, and not always available. To overcome this limitation, we propose assessing accuracy by comparing wave heights derived from Ku-band and C-band signals.

In radar altimetry satellites (e.g., Sentinel-3B), the Synthetic Aperture Radar Altimeter (SRAL) operates simultaneously in two frequency bands: Ku-band and C-band, in order to improve measurement accuracy and reliability. The Ku-band operates at ~13.575 GHz and is the primary frequency used for sea surface height, wave height, and ocean current measurements. Ku-band signals are highly sensitive to sea surface conditions, providing high-resolution and high-accuracy data, especially effective in rough seas. The C-band operates at ~5.41 GHz, with longer wavelengths that are less affected by atmospheric water vapor and precipitation. C-band data are primarily used to correct for ionospheric and atmospheric errors in Ku-band signals, thereby improving measurement accuracy [8].

Both frequency bands can be used to derive *SWH*. By comparing Ku-band and C-band SWH values at the same observation point, deviations can be calculated to assess measurement accuracy and detect anomalous values.

Let SWH_i^{Ku} and SWH_i^{C} denote the wave heights derived from Ku-band and C-band at point i, respectively. The deviation of SWH at point i is:

Table 1. SWH results from Sentinel-3B altimetry in the East Sea

Nº	Pass	date	month	year	hour	min	second	*B*(°)	*L*(°)	*SWH_Ku* (m)	*SWH_C* (m)	*SWH_Ku-C* (m)
1	21	30	7	2024	16	4	30.320	5.558877	106.455828	0.405	0.757	-0.352
2	21	30	7	2024	16	6	5.376	5.617977	106.442658	0.677	0.475	0.202
3	21	30	7	2024	16	7	41.432	5.677076	106.429486	0.558	0.736	-0.178
4	21	30	7	2024	16	9	18.488	5.736176	106.416312	0.485	0.165	0.320
5	21	30	7	2024	16	10	56.544	5.795276	106.403136	0.624	0.000	0.624
6	21	30	7	2024	16	12	35.600	5.854375	106.389959	0.450	1.138	-0.688
…	…	…	…	…	…	…	…	…	…	…	…	…
2408	363	11	8	2024	16	47	40.167	7.452354	108.842436	0.901	0.480	0.421
2409	363	11	8	2024	16	49	47.256	7.511451	108.829200	0.831	0.436	0.395
2410	363	11	8	2024	16	54	4.434	7.629645	108.802718	0.859	1.111	-0.252
2411	363	11	8	2024	16	56	14.523	7.688741	108.789474	0.714	0.000	0.714
2412	363	11	8	2024	16	58	25.612	7.747837	108.776227	0.736	0.325	0.411
2413	363	11	8	2024	17	0	37.701	7.806933	108.762978	0.847	1.411	-0.564
2414	363	11	8	2024	17	2	50.790	7.866029	108.749726	1.010	0.494	0.516
2416	363	11	8	2024	17	5	4.879	7.925125	108.736471	1.110	0.808	0.302
…	…	…	…	…	…	…	…	…	…	…	…	…
4847	705	24	8	2024	6	57	19.778	20.883507	108.531044	0.404	0.381	0.023
4848	705	24	8	2024	7	3	15.600	20.942471	108.516669	0.351	0.176	0.175
4849	705	24	8	2024	7	9	12.422	21.001435	108.502285	0.480	0.068	0.412
4850	705	24	8	2024	7	15	10.244	21.060398	108.487894	0.471	0.000	0.471
4851	705	24	8	2024	7	27	8.888	21.178320	108.459087	0.626	1.106	-0.480
4852	705	24	8	2024	7	33	9.710	21.237280	108.444672	0.458	0.834	-0.376
4853	705	24	8	2024	7	39	11.532	21.296238	108.430248	0.263	0.000	0.263
4854	705	24	8	2024	7	45	14.354	21.355196	108.415816	0.319	0.000	0.319
4855	705	24	8	2024	7	51	18.176	21.414153	108.401376	0.560	0.211	0.349
4856	705	24	8	2024	7	57	22.998	21.473108	108.386928	0.251	0.474	-0.223

$$\Delta SWH_i = SWH_i^{Ku} - SWH_i^{C} \qquad (1)$$

If no systematic bias is present, the root mean square (*RMS*) deviation is given by Gauss' formula [9]:

$$RMS_{\Delta SWH} = \pm\sqrt{\frac{[\Delta SWH.\Delta SWH]}{n}} \qquad (2)$$

According to the principle of error propagation [9]:

$$RMS^2_{\Delta SWH} = RMS^2_{Ku} + RMS^2_{C} = 2RMS^2_{SWH} \qquad (3)$$

Combining (2) and (3) we have:

$$RMS_{SWH} = \frac{RMS_{\Delta SWH}}{\sqrt{2}} = \pm\sqrt{\frac{[\Delta SWH.\Delta SWH]}{2n}} \qquad (4)$$

If systematic bias exists, the standard deviation is computed as [9]:

$$STD_{SWH} = \pm\sqrt{\frac{[vv]}{2(n-1)}} \qquad (5)$$

where: $v_i = \Delta SWH_i - \overline{\Delta SWH}$, and $\overline{\Delta SWH}$ is the mean deviation.

3. Results and Discussion

3.1. Results of Significant Wave Height Determination

This study employed altimetry data from the Sentinel-3B satellite, cycle 96, measured over the East Sea during the period from July 30, 2024, to August

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24, 2024. The dataset was provided by AVISO [10].

Based on Sentinel-3B satellite altimetry data, SWH values were determined. A total of 4,856 measurement points were obtained across the East Sea. A brief statistical summary of SWH derived from Ku-band measurements is as follows: the maximum wave height was 1.962m, the minimum was 0.030m, and the average was 0.830m.

Table 1 presents a subset of the results for selected measurement points. Each record includes: pass number, observation time, measurement location, sea level anomaly (SLA), *SWH* derived from Ku-band (*SWH_Ku*), *SWH* derived from C-band (*SWH_C*), and the deviation between Ku- and C-band *SWH*.

The significant wave heights derived from the Ku-band are presented in Figure 2, where the magnitude of the wave height is represented by the length of the arrow symbols.

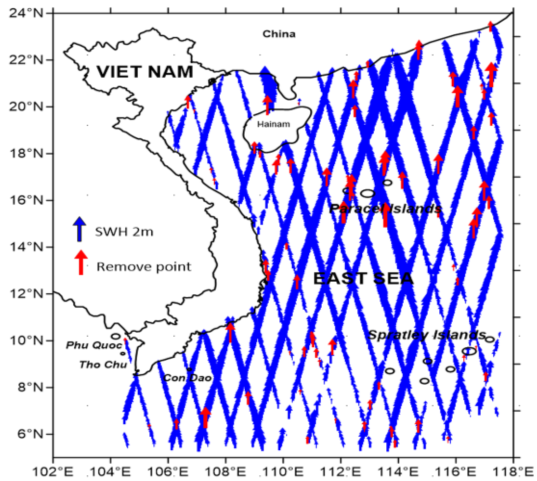

Figure 2. Location and magnitude of significant wave heights

3.2. Results of Accuracy Assessment of Significant Wave Height

According to the methodology described above, significant wave heights derived from Ku-band and C-band measurements at the same observation points were compared to assess accuracy. A summary of the statistical results is presented in Table 2.

The comparison indicates that the maximum deviation was 1.665 m, the minimum deviation was -6.989 m, the mean deviation was 0.219m, the root mean square (*RMS*) deviation was 0.433m, and the standard deviation was 0.404m.

The statistics on the number and percentage of deviations relative to the root mean square deviation are presented in Table 3.

Table 2. Summary statistics of Ku- and C-Band SWH comparison

	Max. (m)	Min. (m)	Mean (m)	RMS (m)	STD (m)
Before removing	1.665	-6.989	0.219	±0.433	±0.404
After removing	1.289	-1.293	0.249	±0.378	±0.334

Table 3. Distribution of deviations with respect to RMS

Statistical characteristic	Number of deviations	%
Less than 1 × *RMS*	2564	52.80%
Less than 2 × *RMS*	4267	87.87%
Less than 3 × *RMS*	4776	98.35%
Greater than 3 × *RMS*	80	1.65%

From Table 3, it can be observed that the deviations generally follow a random distribution; however, 80 points exhibit deviations greater than three times the *RMS*. These points are considered anomalous and should be removed from the dataset before further use. The removed outlier SWH values may be attributed to the effects of specific oceanographic and meteorological conditions—such as currents, storms, and tides—that were not fully corrected in the SWH retrieval process. Further investigation of these factors is required to improve the accuracy of SWH estimates in the East Sea region.

In Figure 2, these anomalous points are represented by red arrow symbols. They are mainly concentrated around islands and coastal areas, where the accuracy of satellite altimetry measurements is typically lower. Further research is needed to identify the causes of the discrepancies and improve the accuracy at these points.

After excluding the anomalous points, the revised summary statistics of deviations are presented in row 3 of Table 2. The frequency distribution of deviations is shown in Figure 3, which again confirms that the deviations follow a random distribution. Accordingly, the accuracy of the significant wave height determination is estimated at ±0.378m. However, this is only the evaluation result by comparing SWH determined from Ku-Band and C-Band. For higher

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reliability, it is necessary to evaluate by comparing with directly measured SWH (for example, buoy).

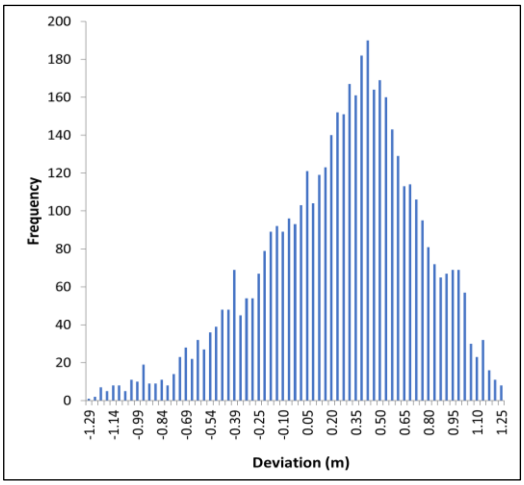

Figure 3. The frequency distribution of deviations

Compared with Jason-3 and Envisat, SWH derived from Sentinel-3B exhibit a higher spatial density due to its advanced radar footprint and SAR mode, whereas Jason-3 provides sparser coverage but benefits from a stable 10-day repeat cycle and well-validated accuracy through calibration sites. Envisat, with its longer repeat cycle (35 days) but older sensor technology, offers lower spatial density and reduced accuracy.

Using the same processing approach as for cycle 96, we obtained SWH estimates from 84 Sentinel-3B altimetry cycles (from cycle c009 to cycle c096, some cycles have no data), covering the period from June 2018 to August 2024, with a total of 458,402 data points. A summary of the results is presented in Table 4. The table shows that the SWH accuracy ranges from ±0.315m to ±0.440m, with an average of ±0.402m.

Table 4. Summary of SWH estimates from 84 Sentinel-3B satellite cycles

N	Cycle	Total Points	Removed points	RMS (m)
1	c009	4564	84	0.315
2	c010	5396	87	0.361
3	c011	5569	79	0.395
4	c012	5326	82	0.378
5	c013	5493	76	0.386
6	c014	376	12	0.375
6	c014	376	12	0.375
7	c019	4897	47	0.405
8	c020	5530	49	0.416
9	c021	5783	39	0.411
10	c022	5829	41	0.440
11	c023	5673	32	0.424
12	c024	5455	39	0.417
13	c025	5382	57	0.409
14	c026	5299	61	0.405
15	c027	5646	63	0.402
16	c028	5545	60	0.402
17	c029	5642	59	0.405
18	c030	5301	47	0.402
19	c031	5539	58	0.404
20	c032	5763	62	0.409
21	c033	5831	53	0.420
22	c034	5891	71	0.402
23	c035	5792	64	0.404
24	c036	5824	89	0.398
25	c037	5615	83	0.395
26	c038	5507	85	0.386
27	c039	5355	87	0.399
28	c040	5520	72	0.403
29	c041	4905	81	0.391
30	c042	5442	85	0.397
31	c043	5024	79	0.393
32	c044	5472	47	0.421
33	c045	5575	52	0.418
34	c046	5658	61	0.410
35	c047	5642	51	0.423
36	c048	5834	43	0.402
37	c049	5864	71	0.406
38	c050	5709	82	0.399
39	c051	5422	83	0.409
40	c052	5510	87	0.401
41	c053	5305	91	0.406
42	c054	5332	88	0.400
43	c055	5721	89	0.403
44	c056	5036	81	0.392
45	c057	5163	65	0.406
46	c058	5631	61	0.410
47	c059	5514	49	0.413

N	Cycle	Total Points	Removed points	RMS (m)
48	c060	5771	74	0.421
49	c061	5814	84	0.402
50	c062	5836	91	0.396
51	c063	5649	59	0.405
52	c064	5398	57	0.404
53	c065	5409	66	0.403
54	c066	5551	62	0.402
55	c067	5353	64	0.396
56	c068	5093	74	0.404
57	c069	5373	72	0.404
58	c070	5138	78	0.401
59	c071	5548	57	0.415
60	c072	5689	54	0.414
61	c073	5630	48	0.406
62	c074	5668	79	0.419
63	c075	5667	77	0.413
64	c076	5874	53	0.407
65	c077	5810	46	0.393
66	c078	5353	34	0.393
67	c079	5604	91	0.407
68	c080	5590	78	0.407
69	c081	5447	71	0.404
70	c082	5712	79	0.406
71	c083	5642	74	0.401
72	c084	5261	64	0.399
73	c085	5317	58	0.401
74	c086	5701	78	0.405
75	c087	5697	56	0.418
76	c088	5846	43	0.403
77	c089	5875	74	0.404
78	c090	5798	38	0.400
79	c091	5799	56	0.395
80	c092	5482	85	0.386
81	c093	5341	83	0.400
82	c094	5648	77	0.400
83	c095	5060	73	0.399
84	c096	4856	80	0.378

4. Conclusion

This study presented the results of significant wave height determination from Sentinel-3B satellite altimetry data over the East Sea. During cycle 96, the wave heights in the study area ranged from a minimum of 0.030m to a maximum of 1.962m, with an average value of 0.830m.

The Ku-band and C-band derived wave heights were compared to assess accuracy. The results indicate that the deviations generally follow a random distribution; however, several anomalous points with unusually large deviations were identified and excluded. After removing these points, the accuracy of significant wave height determination was estimated at ±0.378 m. Using the same processing procedure, the paper also presents a summary of the SWH results derived from 84 Sentinel-3B satellite cycles over the East Sea. The results indicate that the SWH accuracy ranges from ±0.315 m to ±0.440 m, with an average of ±0.402 m.

The findings demonstrate that Sentinel-3B satellite altimetry provides a reliable source of significant wave height data for the East Sea. Satellite altimetry data can be considered for application in marine weather forecasting, offshore engineering design, wave energy resource assessment, and studies on climate change impacts. Moreover, the methodology established in this study contributes to enhancing the quality of satellite-based wave observations in coastal and island regions, where conventional in-situ measurements are limited.

Due to the lack of in situ observations, the accuracy of SWH in this study is assessed solely by comparing the results derived from the Ku-band and C-band. For higher reliability, accuracy should be evaluated against direct measurements (e.g., buoy data). In addition, further investigation is required to identify the causes of large discrepancies observed near the coast and around islands, in order to improve accuracy in these areas.

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