

Article

Estimation of Significant Wave Height Using Wave-Radar Images

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Abstract: Characteristics of random ocean waves have been measured by different devices, and X-band marine radar is one of the typical devices. This study proposes an enhanced methodology for estimating the significant wave height of ocean waves through the analysis of X-band radar images, particularly leveraging the shadowing characteristics inherent within radar images. The enhancement of the shadowing-based algorithm is achieved by incorporating three different key physical properties of ocean waves. These include the spatial autocorrelation function (SACF) in the Smith function, the orthogonal property of mean surface slopes, and the relationship of high-order spectral moments. The enhanced algorithm is complementarily integrated with fast Fourier transform (FFT)-based spectral analysis, facilitating the determination of significant wave height without the necessity for supplementary reference measurements. Numerical tests have been conducted using synthetic and real radar images corresponding to various sea states to validate the accuracy and reliability of the proposed methodology. The results demonstrate that the proposed techniques consistently improve the estimation accuracy of significant wave heights for both synthetic and real radar images. Even though the measured real radar images used for validation are not exhaustive in terms of the amount of dataset and range of sea state severity, considering that the proposed technique is in its early development stage, it is inspiring that its effectiveness and physical validity have been demonstrated through the present study.



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Keywords: wave radar; estimation of significant wave height; shadowing effect; fast Fourier transform

1. Introduction

Obtaining reliable ocean wave information is critical for the design and operation of marine facilities and vehicles. A classic way to observe the ocean environment is by using a wave rider buoy, which delivers a point measurement of time variation in the wave elevation. A relatively long history of buoy records is necessary to determine statistically meaningful sea state parameters. Unlike in situ measurements, marine radars are suitable for real-time monitoring of sea state parameters because they can simultaneously collect wave information within a large area. Indeed, owing to the benefits of marine radar and the advancements in remote-sensing technology, a sophisticated digital twin system has been developed to support marine operations through real-time measurement and analysis of marine radar images [1]. The statistical parameters, spectral information, and phase-resolved wave data derived from radar image analysis are valuable for offshore activities, contributing to a substantial enhancement in the safety and efficiency of maritime operations.

Marine radars measure the intensity of backscattered microwaves caused by Bragg scattering, which is a result of the resonant interactions of microwaves emitted from radars

with ocean surface ripples of similar wavelengths, with a high spatial resolution (5–10 m) in a 2–5 km radius. Because the remote sensing mechanism entails nonlinear modulation effects, mainly driven by shadowing, tilting, and hydrodynamic effects, several nonphysical components are involved in radar images [2,3]. Moreover, the radar intensity is bounded within a positive grayscale (0~256), unlike the ocean wave elevation. Hence, it is imperative to incorporate diverse post-processing methods to eliminate nonphysical components inherent in radar imaging mechanisms. Furthermore, ensuring a reliable estimation of significant wave height is essential, as it plays a crucial role in accurately adjusting the total energy of the wave spectrum.

Conventionally, spectral domain analysis is conducted to remove nonphysical components from radar images. In this approach, a sequence of radar images is first transformed into the spectral domain using a three-dimensional (3D) fast Fourier transform (FFT), and post-processing that involves filtering and multiplication of the modulation transfer function (MTF) is applied later [3,4]. Various efforts have been made to enhance the conventional spectral analysis procedure. Empirical parameters related to spectral-domain treatments can be optimized using phase-resolved simulations with the high-order spectral method [5]. A radar intensity modification technique was introduced to mitigate the characteristic differences in the shape of spatial/temporal variations in radar intensity and ocean wave elevation [6]. Recently, an energy-level calibration procedure was proposed to attenuate the uneven energy distributions caused by shadowing effects [7].

It is imperative to accurately determine significant wave height from X-band marine radar images because of the scaling between wave elevation and radar intensity. For several decades, significant efforts have been dedicated to accurately and efficiently estimating significant wave heights. The signal-to-noise ratio (SNR)-based empirical regression technique is a classical approach, but it requires extensive external data from in-situ measurements to establish a reliable SNR curve for applications [8,9]. Recently, artificial intelligence methods, such as multilayer perceptrons [10], support vector regression [11], and convolutional neural networks [12,13], have demonstrated their capability for estimating significant wave height. However, these techniques still require large amounts of ground truth wave height data obtained from weather forecasts or wave buoys for training purposes. To overcome the dependency on external calibration or training data, various alternative methods, such as shadowing-based estimation algorithms [14,15] and surface particle velocity measurements using coherent marine radars [16], have been proposed.

Among these methods, shadowing-based H_S estimation is highly promising owing to the low computational cost and independence of the reference measurement. The shadowing-based method takes advantage of established knowledge of the stochastic characteristics of geometric shadowing by a rough surface. On a Gaussian random surface with purely geometric shadowing, the probability of observation, known as the “Smith function”, can be computed theoretically [17–19]. The mean slope of the ocean surface can be assessed using a Smith function-based fitting technique. Thereafter, the H_S is computed from the physical relationship with the mean surface slope and mean wave period [14]. Despite its advantage that additional (reference) measurements are not required, the shadowing-based method has not been studied extensively.

In this study, an enhanced H_S estimation methodology that exploits the shadowing characteristics of marine radar images has been developed. To achieve this, three different ocean wave properties have been introduced: the spatial autocorrelation function (SACF) in the Smith function, the orthogonal property of mean surface slopes, and the interrelation between spectral moments. By integrating the developed method with FFT-based spectral analysis, the determination of significant wave height is feasible without the necessity for supplementary reference measurements. Numerical tests were conducted using synthetic and real radar images corresponding to diverse sea states to validate the accuracy and reliability of the proposed methodology. The results consistently demonstrate that the introduced techniques enhance the accuracy of significant wave height estimation for both synthetic and real radar images.

The remainder of this paper is organized as follows: In Section 2, the proposed shadowing-based method for H_S estimation is described. The setup for the numerical tests on synthetic radar images and the corresponding results and discussion are presented in Section 3. This section also presents the H_S estimation results for radar images collected in real seaways. Finally, conclusions are presented in Section 4.

2. Methodology

2.1. Overall Procedure

The estimation of significant wave height is conducted based on consecutive marine radar images to consider the spatial/temporal evolution of the ocean surfaces. The X-band radar measures backscattered image intensity, and the data acquisition is repeatedly performed to construct a sequence of images with the time interval Δt , which is determined according to the rotation period of the antenna. Because marine radar intensity has a characteristically different scale from the wave elevation and is influenced by various physical and nonphysical factors, it does not correspond to a one-to-one mapping of the original sea surface deformation. Therefore, proper algorithms are required to retrieve physically meaningful wave data from the radar intensity images. Figure 1 depicts a flowchart of the overall procedure for the proposed significant wave height estimation. For a given time sequence of radar intensity images, the estimation of the significant wave height consists of two coupled operations that utilize the shadowing characteristics in radar images: shadowing-based H_S estimation and 3D-FFT-based spectral analysis to recover the spatially and temporally varying wave elevation.

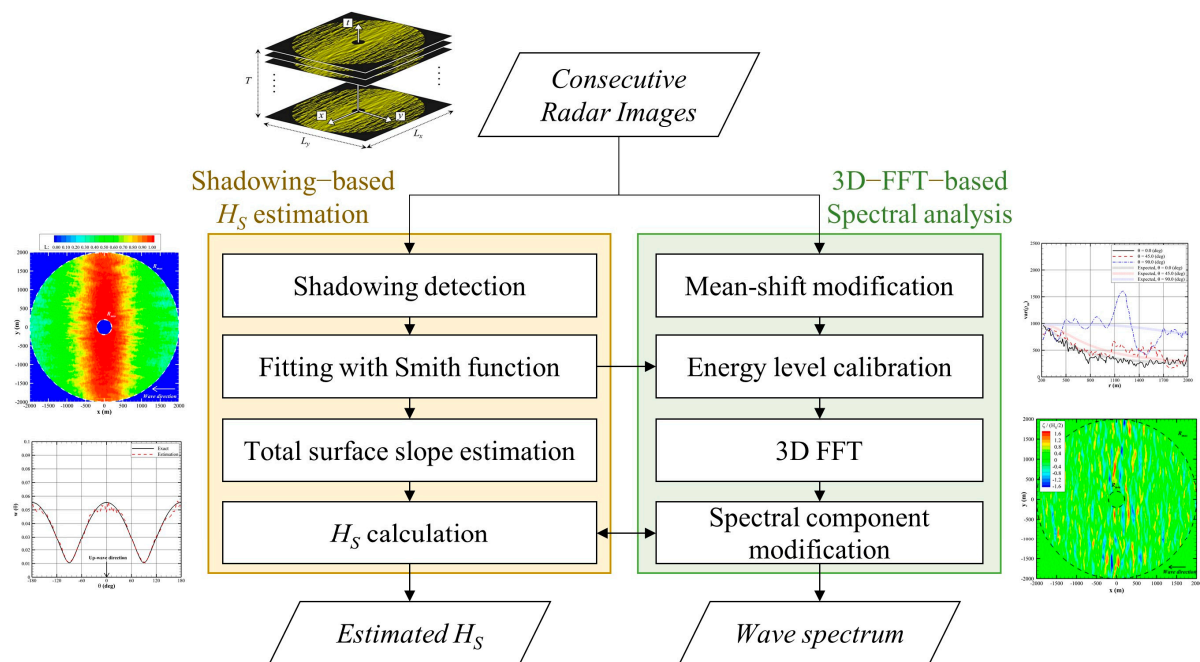


Figure 1. Flowchart of the H_S estimation procedure based on incoherent marine radar images.

The shadowing-based H_S estimation technique is favorable for practical applications as it eliminates the need for additional external observation data [14,15]. In this scheme, the H_S is estimated based on the assessment of the mean surface slope of the wave field using the theoretically computed probability of illumination (i.e., a non-shadowed place) of a Gaussian random surface, the Smith function [17]. Given that high-order spectral moments play a crucial role in the final stage of H_S estimation, it is essential to carry out spectral analysis during the shadowing analysis simultaneously. To retrieve the wave spectrum and the associated spectral moments, a 3D-FFT-based spectral analysis is employed. In the literature, various efforts have been made to acquire and enhance spectral information from

measured-wave radar images. However, the conventional spectral analysis procedure [3], applied with the mean-shift modification [6] and energy level calibration [7], is introduced in this study. In other words, the shadowing-based H_S estimation algorithms and the 3D-FFT-based spectral analysis procedure are complementarily applied to estimate H_S without external calibration data.

2.2. Shadowing-Based Significant Wave Height Estimation

In this study, significant wave height is estimated based on the stochastic characteristics of the geometric shadowing on the ocean surface. The geometric shadowing phenomenon occurs when the emitted radar ray from the X-band radar is obstructed by higher sea surface elevations. Figure 2 shows a schematic diagram of the geometric shadowing effect for a certain azimuthal direction θ . A radar ray with a slope of μ is assumed to be emitted from a radar located at the origin of the coordinate system. Wave elevation ζ and wave slope q are assumed to be two zero-mean Gaussian random processes with standard deviations of σ and w , respectively. Moreover, the visibility function $\Omega(r, \theta, t)$ is defined to represent whether the shadowing occurs at a certain measurement point; the visibility function is zero for the shadowed area and one for the non-shadowed area.

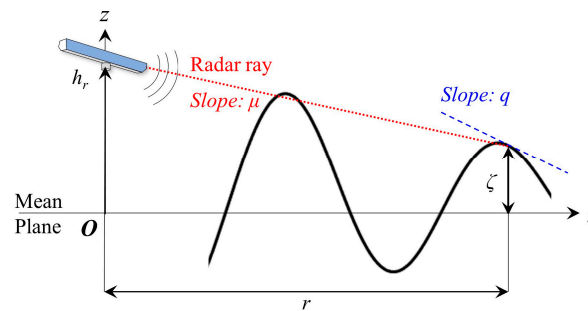


Figure 2. Schematic diagram for the occurrence of the geometric shadowing effect.

Shadowing-based H_S estimation from consecutive radar images consists of four major steps: (1) distinction of the shadowed area, (2) fitting with the Smith function, (3) total mean surface slope estimation, and (4) H_S calculation. In this study, the first step, that is, the distinction of the shadowed area, is based on the threshold-value-based shadowing distinction technique [14]. Since the original measured data may have unexpected noise, this step is to distinguish the shadow and non-shadow areas. To this end, the edge pixels located at the border of the shadowed and non-shadowed areas were detected based on the discontinuity index, which means the severity of the discontinuity of intensity. The shadow area is determined when the intensity is over a thresholding value, which is defined as the mode of the histogram of the edge intensity. In this paper, the details of this step are not described since the same technique presented by [14] is used.

The details and improvements proposed for the next three steps are described below.

2.2.1. Fitting of the Illumination Ratio with the Smith Function

The illumination ratio $L(r, \theta)$, which is the probability of non-shadowing, is evaluated based on consecutive radar images. In this study, $L(r, \theta)$ is estimated as the ratio of the non-shadowed time to the entire time window of the radar image sequence as follows:

$$L(r, \theta) = \frac{1}{T} \sum_t \Omega(r, \theta, t) \Delta t, \quad (1)$$

where T represents the duration of the time window. The theoretical estimation of the illumination ratio $L(r, \theta)$ is expressed using the Smith function $S(\mu(r); w(\theta))$, which depends on the slope of a radar ray and the mean surface slope.

The Smith function can be computed using the following integration [19]:

$$S(\mu(r); w(\theta)) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \hat{S}(\zeta, q, \mu(r); \sigma, w(\theta)) \frac{1}{2\pi\sigma w} \exp\left(-\frac{\zeta^2}{2\sigma^2} - \frac{q^2}{2w^2}\right) d\zeta dq \quad (2)$$

where $\mu(r) = \frac{h_r}{r}$,

here, the shadowing probability density function $\hat{S}(\zeta_0, q_0, \mu(r); \sigma, w(\theta))$ denotes the probability density, which represents how much shadowing will occur at the measurement point.

There are two different ways to compute the shadowing probability density function: with and without considering the spatial autocorrelation properties of the ocean surface. A simple computation that does not account for the SACF effect was derived by [17]. In this simple computation, the “uncorrelated” Smith function $S_u(\mu(r); w(\theta))$ can be computed based on a simple analytic integration. However, when the SACF effect is considered, the “correlated” Smith function $S_c(\mu(r); w(\theta))$ must be numerically evaluated [19]. A closed form of the SACF for the given wave field must be known beforehand to compute the correlated Smith function. The fixed form of the SACF can be assumed to be such that

$$\text{SACF}(l) = \sigma^2 (1 + c_1 l + c_4 l^4) \exp(-c_1 l) \cos(c_2 l) \quad (3)$$

where $l = \frac{wr}{\sigma}$, $c_1 = \sqrt{\frac{l_0^2 - \pi^2}{l_0^2}}$, $c_2 = \frac{\pi}{l_0}$, $c_4 = \frac{1}{l_0^4} (p_0 e^{\sqrt{l_0^2 - \pi^2}} - 1 - \sqrt{l_0^2 - \pi^2})$,

here, l_0 and p_0 are the empirical fitting parameters. These parameters can be determined either by directly applying the inverse 3D-FFT or by using an empirical database for the target ocean wave spectrum. In the present study, based on numerical tests for synthetic long-crested wave fields generated from the ITTC wave spectra, $l_0 = 7.0$ and $p_0 = 0.3$ have been selected to emulate the first overshooting behavior of SACF for various sea states, as depicted in Figure 3.

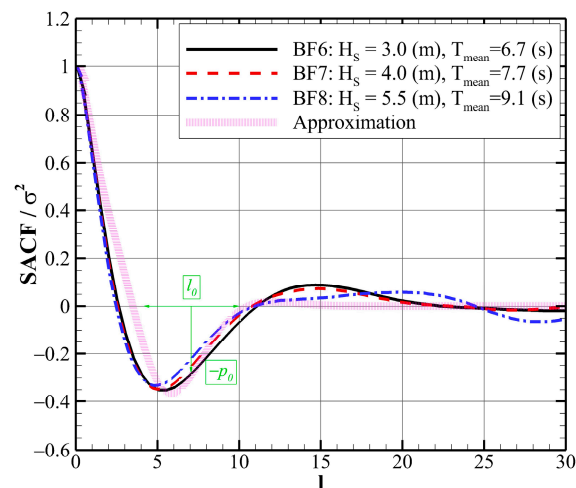


Figure 3. Comparison of the exact numerical values of the spatial autocorrelation functions with the results estimated using the approximate formula for three different sea states.

Figure 4 presents the comparison between the correlated Smith function and the uncorrelated Smith function. It can be seen that the correlated Smith function is slightly smaller than the uncorrelated Smith function. This is because the uncorrelated Smith function generally underestimates the occurrence of the shadowing effect. Because the theoretical value of the illumination ratio is the Smith function, the mean surface slope in each direction $w_{est}(\theta)$ of the wave field can be obtained via optimization to minimize the error between the illumination ratio and the Smith function.

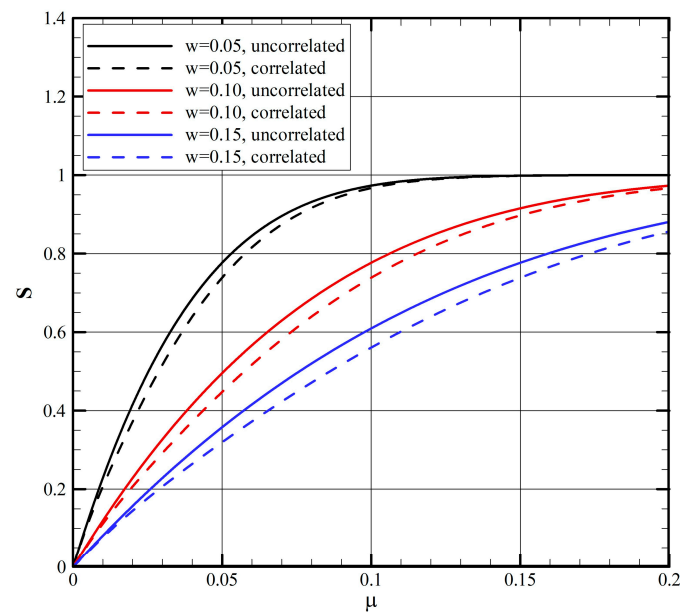


Figure 4. Comparison of uncorrelated and correlated Smith functions for three different w values.

2.2.2. Total Mean Surface Slope Estimation

After obtaining the mean surface slope in each direction $w_{est}(\theta)$ via fitting the illumination ratio with the Smith function, the total mean surface slope w_{total} is computed. A simple way to evaluate w_{total} is to take the root mean square (RMS) average of the $w_{est}(\theta)$ for various azimuthal angles [14] as follows:

$$w_{total} = \text{RMS}\{w_{est}(\theta)\}, \quad (4)$$

in this study, the total mean surface slope is estimated by considering the orthogonality of the mean surface slope. The physical background for the orthogonality of the mean surface slope can be found in [20]. For linear gravity waves, w_{total} , which is theoretically independent of θ , can be computed using only two mean surface slopes in the perpendicular directions. To avoid numerical uncertainties, the final value of the total mean surface slope is evaluated by the RMS averaging of the estimated (total mean surface slope) values based on various azimuthal angles as follows:

$$w_{total} = \text{RMS}\{\hat{w}_{total}(\theta)\} \quad (5)$$

$$\text{where } \hat{w}_{total}(\theta) = \sqrt{w_{est}^2(\theta) + w_{est}^2(\theta + \frac{\pi}{2})},$$

2.2.3. Significant Wave Height Calculation

Finally, an enhanced formula for estimating significant wave height is proposed based on the physical relationship between sea state parameters. Generally, under the assumption that ocean waves follow a narrow-banded random Gaussian process, the significant wave height and the zeroth-order spectral moment have the following relationship: $H_S = 4\sqrt{m_0}$. Furthermore, according to [20], the total mean surface slope of ocean waves can be expressed in terms of the fourth-order spectral moment based on the Fourier-Stieltjes integral and linear dispersion relations.

$$w_{total} = \sqrt{\frac{m_4}{g^2}} \quad (6)$$

Here, m_0 and m_4 are the zeroth and fourth-order spectral moments of the wave spectrum, respectively. Therefore, if the wave spectrum and associated spectral moments

are provided, the relationship between H_S , w_{total} , and the period based on the fourth-order spectral moment (T_4) can be derived as follows:

$$H_S = \frac{gw_{total}T_4^2}{\pi^2} \quad (7)$$

In this study, the wave spectrum and T_4 are obtained from the 3D-FFT analysis, and w_{total} is acquired from the aforementioned shadowing analysis procedure.

2.3. FFT-Based Spectral Analysis

As previously mentioned, 3D-FFT-based spectral analysis is indispensable for the shadowing-based algorithm, as it facilitates the utilization of high-order spectral moments in the final stage of H_S estimation. The 3D-FFT-based spectral analysis consists of the following steps: (1) mean-shift modification, (2) energy-level calibration, (3) 3D-FFT, (4) filtering, and (5) spectrum adjustment by the MTF.

2.3.1. Mean-Shift Modification

The mean-shift modification [6] is performed to mitigate distinctive differences in the shapes of spatial/temporal variations in radar intensity and ocean wave elevation. The following mean shift in the radar image intensity ρ_s yields a wave-like intensity ρ_m :

$$\rho_m(x, y, t) = \begin{cases} \rho_s - \beta_{mean}\rho_{mean} & \text{when } \Omega(x, y, t) = 1 \\ 0 & \text{when } \Omega(x, y, t) = 0 \end{cases} \quad (8)$$

where $\rho_{mean} = \text{mean}[\rho_s(x, y, t)]$ for $\Omega(x, y, t) = 1$,

here, β_{mean} is an empirically determined mean-shift parameter. In general, the optimal β_{mean} obtained from the numerical tests is less than 1.0 because more shadowing occurs at the troughs than at the crests of the wave field, further resulting in the intensity corresponding to the mean sea level being lower than ρ_{mean} . In the present study, we set $\beta_{mean} = 0.9$, which is similar to that reported in a previous study by [6].

2.3.2. Energy-Level Calibration

Unlike the ocean wave field, the radar intensity image has an uneven variance distribution (i.e., energy distribution), owing to the inhomogeneous occurrence of the shadowing effect. This uneven variance distribution produces nonphysical spectral components in FFT analysis. Therefore, the energy-level calibration procedure is introduced based on the shadowing characteristics of radar images to improve the accuracy of spectral analysis.

Assuming that only the shadowing effect modulates the radar images, the expected variance of the modified intensity ρ_m and the Smith variance $V(\mu(r); w(\theta))$ can be theoretically evaluated because the mean-shift modification converts the radar image intensity proportional to the shadowed wave field ζ_s [21]. The Smith variance can be computed using the following numerical integration:

$$V(\mu(r); w(\theta)) = \frac{\text{var}(\zeta_s)}{\text{var}(\zeta)} = \frac{1}{\sigma^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \zeta^2 \hat{S}(\zeta, q, \mu(r); \sigma, w(\theta)) \frac{1}{2\pi\sigma w} \exp\left(-\frac{\zeta^2}{2\sigma^2} - \frac{q^2}{2w^2}\right) d\zeta dq \quad (9)$$

where $\zeta_s(r, \theta, t) = \begin{cases} \zeta(r, \theta, t) & \text{no shadowing} \\ 0 & \text{shadowing} \end{cases}$,

subsequently, the following energy-level calibration is conducted according to the estimated mean surface slope in each direction ($w_{est}(\theta)$) and radar ray slope ($\mu(r)$):

$$\rho_C(r, \theta, t) = \frac{\rho_m(r, \theta, t)}{\sqrt{V(\mu(r); w_{est}(\theta))}}. \quad (10)$$

2.3.3. Three-Dimensional Fast Fourier Transform (3D-FFT)

3D-FFT is performed to obtain the complex amplitude of each spectral component $A(k_x, k_y, \omega)$. Here, k_x and k_y denote the wave numbers along the x - and y -axes, and ω stands for the wave frequency. Moreover, the 3D power spectrum S_{3D} is obtained from the complex amplitude as follows:

$$S_{3D}(k_x, k_y, \omega) = \frac{1}{2dk_x dk_y d\omega} |A(k_x, k_y, \omega)|^2. \quad (11)$$

2.3.4. Spectral Component Modification

Because radar images contain several nonphysical effects, the high-pass filter and the dispersion-relation-based bandpass filter are applied to extract physical components from the measured spectrum. First, the high pass filter eliminates the nonphysical low-frequency components whose frequency is lower than $\kappa_1 \Delta\omega$. Subsequently, dispersion relation-based bandpass filtering has been conducted to extract physical components [4]:

$$S_f(k_x, k_y, \omega) = \begin{cases} S_{3D}(k_x, k_y, \omega) & \omega \in [\omega(k_x, k_y) \pm \kappa_2 d\omega] \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

where $\omega(k_x, k_y) = \sqrt{gk \tanh(kh)} + k_x u_c + k_y v_c$, $k = \sqrt{k_x^2 + k_y^2}$,

here, κ_1 and κ_2 denote the empirical parameters for the filtering range of the high-pass filter and dispersion filter, respectively; (u_c, v_c) is the surface current velocity; and h is the water depth.

Despite filtering, the nonphysical overestimation of high-frequency components remains in the measured spectrum. To mitigate this overestimation, ref. [3] introduced the MTF in the form of a power function of the wavenumber:

$$S_f^{(MTF)}(k_x, k_y, \omega) = S_f(k_x, k_y, \omega) M(k)^2 \quad (13)$$

where $M(k)^2 = \alpha_{MTF} k^{-\beta_{MTF}}$,

here, α_{MTF} is a scaling coefficient determined according to the H_S (the total energy of a wave field), and β_{MTF} is the exponent of the MTF that represents the extent of high-frequency components to be adjusted.

Finally, Table 1 summarizes the empirical parameters involved in the spectral analysis based on marine radar images and the values selected for this study.

Table 1. Parameters used in the spectral analysis based on marine radar images.

Designation	Value
Mean-shift parameter, β_{mean}	0.9
High-pass filtering range, κ_1	1.0
Dispersion filtering range, κ_2	2.0
Exponent of MTF, β_{MTF}	0.3

2.4. Originality of the Proposed H_S Estimation Procedure

In this study, several significant improvements have been made to enhance the efficacy and accuracy of the existing methods by incorporating the physical characteristics of the ocean wave field. In particular, the relationship between the spatial autocorrelation function (SACF) and stochastic characteristics of the shadowing effect is considered [18,19]. Moreover, improved calculation formulas for total mean surface slope, w_{total} , and H_S are proposed to rigorously reflect the physical characteristics of ocean gravity waves. In summary, various aspects of the shadowing-based H_S estimation technique have been modified from the existing method [14], as summarized in Table 2.

Table 2. Comparison of the major properties (or assumptions) in the existing method and the present method for shadowing-based H_S estimation.

Designation	Existing Method [14]	Present Study (Enhancement)
Fitting with the Smith function	- No effect of SACF - Using the uncorrelated Smith function [17] as a fitting function	- Considering the effect of SACF - Using the correlated Smith function [19] as a fitting function
Total mean surface slope estimation	Direct RMS average of the mean surface slope for each direction	Based on the orthogonal property of the mean surface slopes
H_S calculation	Based on the dispersion relation between the sea state parameters, which is valid for the narrow-banded wave spectrum only	Based on the definitions of the sea state parameters in terms of the spectral moments

3. Results and Discussion

3.1. Validation Using Synthetic Radar Images

3.1.1. Generation of Synthetic Radar Images

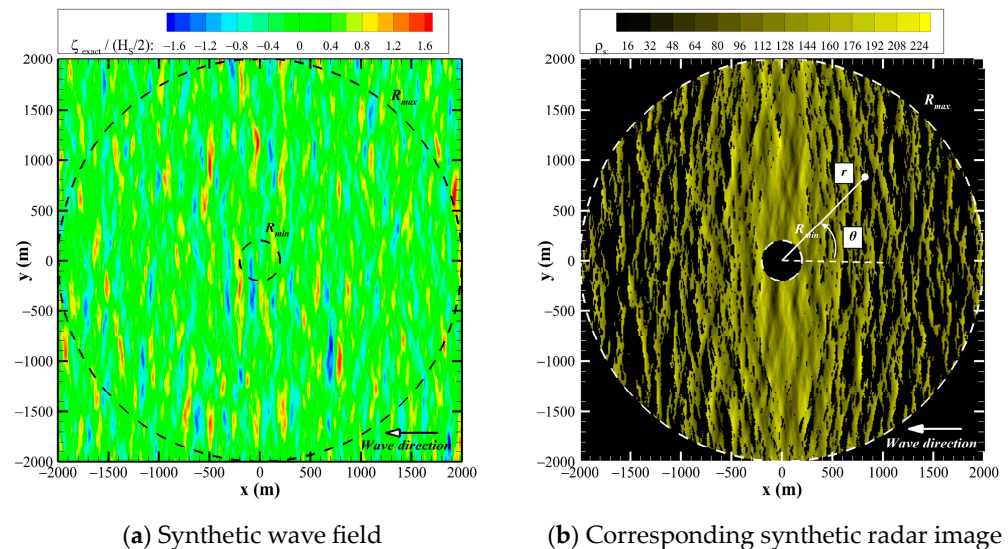
In this study, synthetic radar images have been used to validate the proposed shadowing-based significant wave height estimation algorithm. For this purpose, irregular short-crested wave elevation data $\zeta_{exact}(x, y, t)$ were synthesized based on the linear superposition of random wave components. The directional wave spectrum is given by the ITTC spectrum with a $\cos^2$ directional spreading function. For a sea state defined by the H_S , T_{mean} (mean wave period), and χ_s (spreading angle), the wave spectrum is discretized into 650 wave components. The main wave direction is set along the negative x -direction ($\chi_M = 180.0$ deg). The sea states chosen for numerical studies are summarized in Table 3. For the selected sea states, the maximum steepness $\varepsilon = \frac{2\pi H_S}{g T_m^2}$ in irregular waves was calculated, and the wave-breaking criterion was examined to investigate whether the wave-breaking phenomenon occurs [22]. The calculated maximum steepness values range between 0.01 and 0.05, indicating that all the sea states covered in this study do not exceed the wave-breaking constraint. Nevertheless, the proposed H_S estimation procedure should be carefully applied to more severe sea state conditions, where wave-breaking phenomena and the nonlinearity of ocean waves become significant. Subsequently, the synthetic radar images $\rho_s(x, y, t)$ were synthesized based on the generated wave data by considering the geometric shadowing effect [23,24]. The parameters and their values used to create the synthetic radar images are listed in Table 4. Moreover, Figure 5 illustrates samples of the synthetic wave elevation data and the corresponding synthetic radar image.

Table 3. Sea state parameters used in the generation of synthetic radar images.

Mean Period, T_{mean} (s)	Spreading Angle, χ_s (deg)	Significant Wave Height, $H_{S,exact}$ (m)
9.0	60.0	2.0~6.0
	90.0	2.0~6.0
12.0	60.0	2.0~6.0
	90.0	2.0~6.0
15.0	60.0	2.0~6.0
	90.0	2.0~6.0

Table 4. Parameters used in the generation of synthetic radar intensity images.

Designation	Value
Radar height, h_r (m)	40.0
Minimum sensing radius, R_{min} (m)	200.0
Maximum sensing radius, R_{max} (m)	2000.0
Spatial resolution, $dx = dy$ (m)	10.0
Length of the time window, T (s)	100.0
Time interval, dt (s)	1.0

**Figure 5.** Synthetic wave-field and corresponding radar image at the instant $t = T/2$ for the sea state with $H_{S,exact} = 6.0$ (m), $T_{mean} = 9.0$ (s), and $\chi_S = 60.0$ (deg).

3.1.2. Results of Significant Wave Height Estimation

To validate the proposed H_S estimation technique, numerical studies have been conducted for synthetic radar images corresponding to the various sea states. First, the illumination ratio is computed based on the generated synthetic radar images. Figure 6 depicts the illumination ratio corresponding to the radar image shown in Figure 5b. The illumination ratio is lower in the main wave direction than it is in the cross-wave direction because the shadowing effect is generally severe in the up- and down-wave directions.

Then, the mean surface slope is estimated via fitting with the illumination ratio evaluated from the radar images and the Smith function. Figure 7 depicts the observed illumination ratio and fitting curves as a function of the radar ray slope μ in each direction: $\theta = 0.0$ deg (up-wave direction) and 90.0 deg (cross-wave direction). Here, “w/o SACF” indicates the uncorrelated Smith function [17], and “w/SACF” indicates the correlated Smith function [19]. The figure confirms that the measured illumination ratios fit well with both Smith functions.

The estimated mean surface slopes based on fitting with the uncorrelated and correlated Smith functions in each direction are compared in Figure 8. Moreover, the exact mean surface slope obtained by the analytic integration of the given spectrum presented in [20] is presented for comparison. Figure 8a confirms that the fitting based on the uncorrelated Smith function generally overestimates the mean surface slope. This is because the uncorrelated Smith function underestimated the shadowing effect, which leads to a larger mean surface slope to represent the same extent of shadowing. The mean surface slope estimation is more accurate using the correlated Smith function, as depicted in Figure 8b.

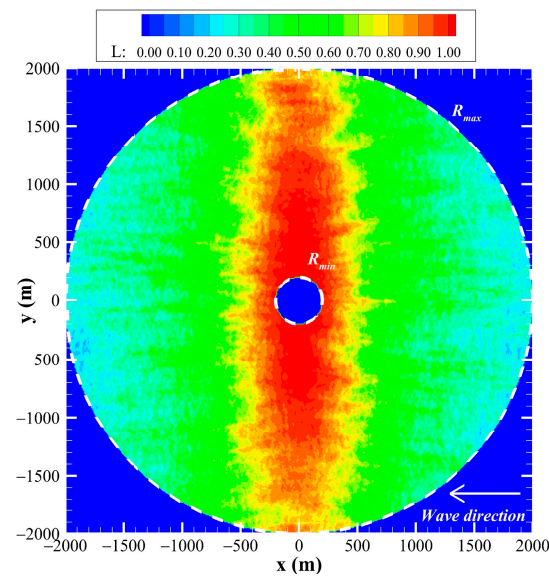


Figure 6. Estimated illumination ratio for the radar image depicted in Figure 5b for the sea state with $H_{S,exact} = 6.0$ (m), $T_{mean} = 9.0$ (s), and $\chi_S = 60.0$ (deg).

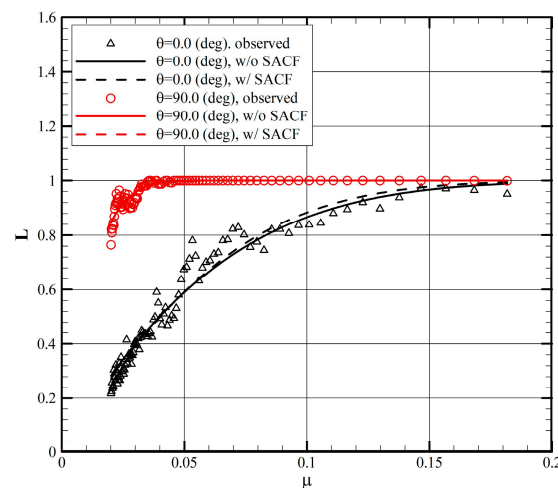


Figure 7. Fitting with the Smith function for the sea state with $H_{S,exact} = 6.0$ (m), $T_{mean} = 9.0$ (s), and $\chi_S = 60.0$ (deg).

The total mean surface slope has been evaluated using two estimation equations. The first equation (Equation (4)) computes the RMS average of the mean surface slopes in all directions, whereas the second equation (Equation (5)) considers the orthogonality of the mean surface slope. As presented in Figure 9, the estimated w_{total} agrees well with the exact value when the SACF effect in the Smith function, and the orthogonality property are both considered. These results indicate that rigorous reflection of the physical characteristics of ocean waves is required for accurate w_{total} estimation. Figure 10 compares the estimated H_S , which has been computed based on the relationship between w_{total} , T_4 , and H_S (Equation (7)). As aforementioned, 100 consecutive radar images were used for each analysis case. A total of 30 validation cases (Table 3) are shown in Figure 10. Because the proposed formula for the H_S can accurately reflect the overall properties of the wave spectrum, the results are in good agreement with the exact values.

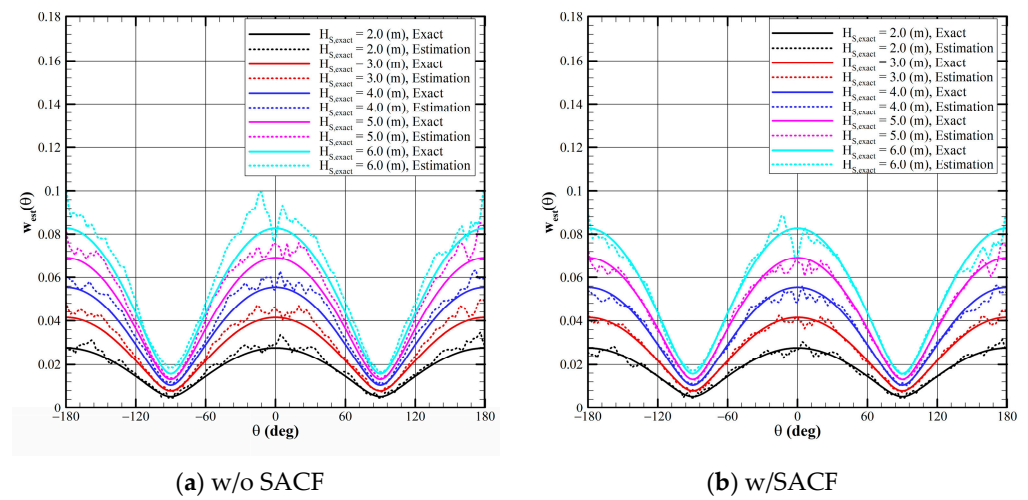


Figure 8. Mean surface slope estimation in each direction for sea states with different H_S : $T_{mean} = 9.0$ (s) and $\chi_S = 60.0$ (deg).

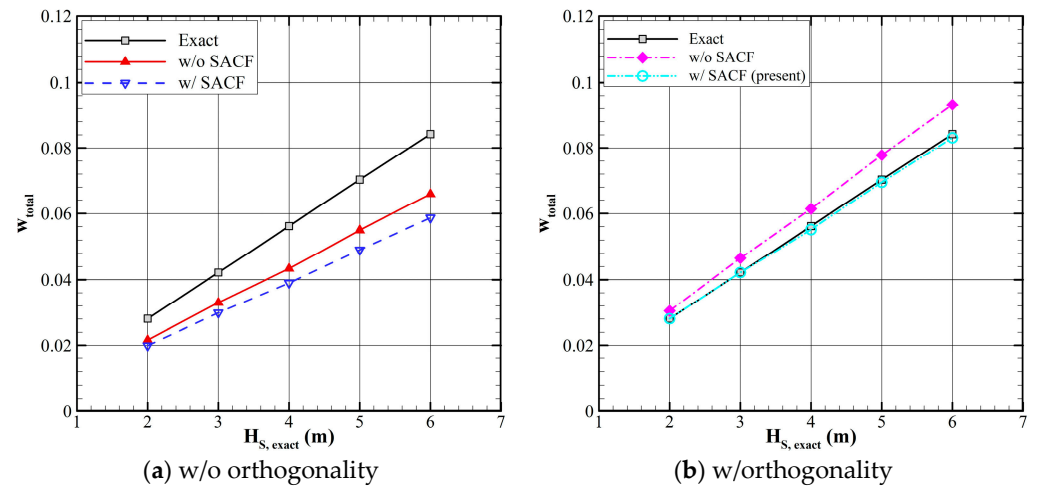


Figure 9. Examples of the estimated total mean surface slope: $T_{mean} = 9.0$ (s) and $\chi_S = 60.0$ (deg).

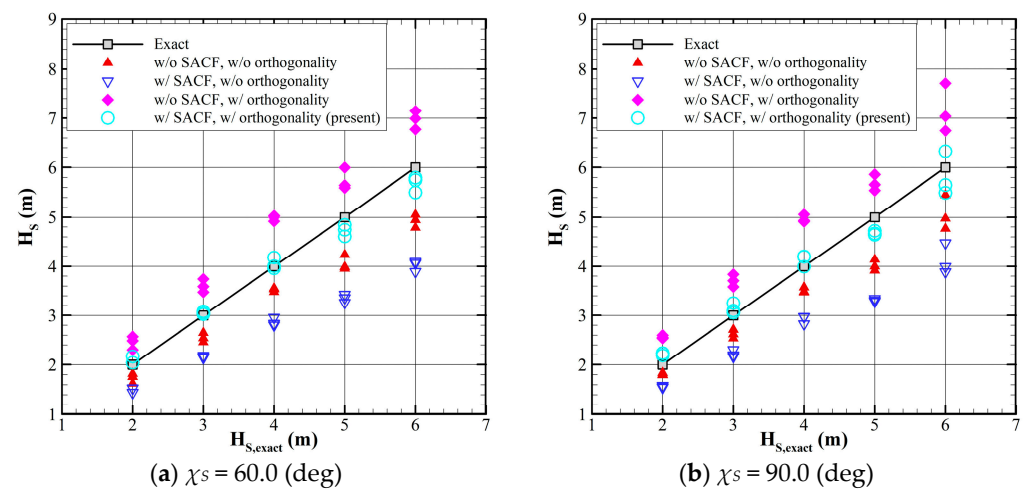


Figure 10. H_S estimation result for various sea states (total of 30 cases).

By applying the present method (i.e., w/SACF and Equation (5)), further numerical studies were conducted to confirm the validity of the H_S estimation technique for various sea states. Figure 11 illustrates the error rate with respect to the exact value ($H_{S,exact}$) for various spreading angles (χ_s) and mean wave periods (T_{mean}). The H_S estimation accuracy slightly depends on the exact significant wave height because a fixed MTF exponent was used regardless of the sea state when the 3D-FFT-based analysis was conducted for the spectral moment computation. This dependence is less apparent when T_{mean} increases. Overall, the estimation results demonstrate a good correspondence with the exact values within an error bound of approximately $\pm 8\%$.

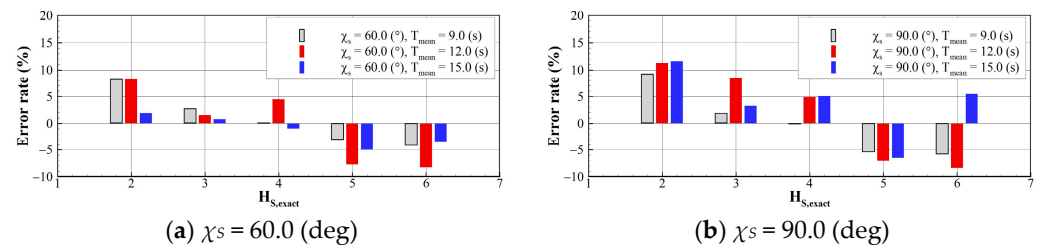


Figure 11. Error rate of significant wave height estimation for various sea states (total of 30 cases).

3.2. Application for Real Radar Images

3.2.1. Dataset of Real Radar Images

The proposed techniques have been applied to two real radar image datasets: the dataset measured at Ieodo Ocean Research Station and the dataset of the National Institute of Meteorological Sciences (NIMS, Republic of Korea). The Ieodo dataset includes a total of 72 sets of X-band radar measurements, which were collected at the Ieodo Ocean Research Station (Figure 12), located 150 km from Jeju, every 20 min on 15 June 2008 [25]. A radar-type tide gauge mounted at the station measured the H_S independently, which is used as a reference value to examine the accuracy of the proposed methodology for H_S estimation. On the other hand, the NIMS dataset was collected at the research vessel Gisang No. 1 (IMO: 9588550, [26]) every 5 min from 18:00 on 16 October 2022, to 12:30 on 17 October 2022. The H_S measurements collected from the wave buoy 1.5 km apart from the ship and the computed H_S values from a commercial radar system are used to validate the proposed technique. The specifications of real radar image datasets are presented in Table 5.

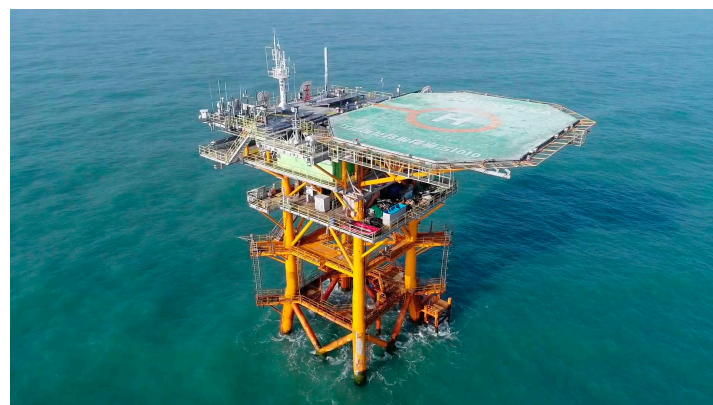


Figure 12. Illustrations of the Ieodo Ocean Research Station [27].

Table 5. Specification of real radar image datasets.

Designation	Ieodo Dataset	NIMS Dataset
Measurement location	32.1250° N, 125.1830° E	36.2500° N, 126.2085° E
Collecting time	15 June 2008, 00:00 ~15 June 2008, 23:00	16 October 2022, 18:00 ~17 October 2022, 12:30
Radar height, h_r (m)	35.0	11.5
Sensing distance (R_{min} and R_{max}) (m)	[400.0, 2050.0]	[300.0, 1264.8]
Azimuth range (θ_{min} and θ_{max}) (deg)	[−100.0, 90.0]	[90.0, 280.2]
Spatial resolution, $dx = dy$ (m)	6.0	5.0
Antenna rotation speed (rpm)	47.0	24.0
Number of images for each sequence	64	32
Water depth, h (m)	41.0	16.0

3.2.2. Results of Significant Wave Height Estimation: Ieodo Dataset

As mentioned above, the threshold-based shadowed region distinction [14] has been conducted before applying the proposed H_s estimation technique because noise obscures the distinction between shadowed and non-shadowed areas. Figure 13 illustrates the input radar image and the corresponding shadowed region (shadow mask) obtained after the distinction. Based on the comparison between the detected shadowing area and the input radar image, it can be confirmed that the shadowed region is conservatively evaluated in the near-radar region ($r < \sim 800.0$ m). This is because the radar intensity is large in the near-radar area owing to the range dependence, resulting in a significant underestimation of the shadowing region based on the threshold-based distinction technique. Figure 14 illustrates the illumination ratio obtained from the estimated shadowing region and the corresponding fitting function. In the present study, only data with a low grazing angle (i.e., $\mu < 0.03$) are used for fitting with the Smith function to avoid undesirable effects owing to the range dependency of the radar intensity.

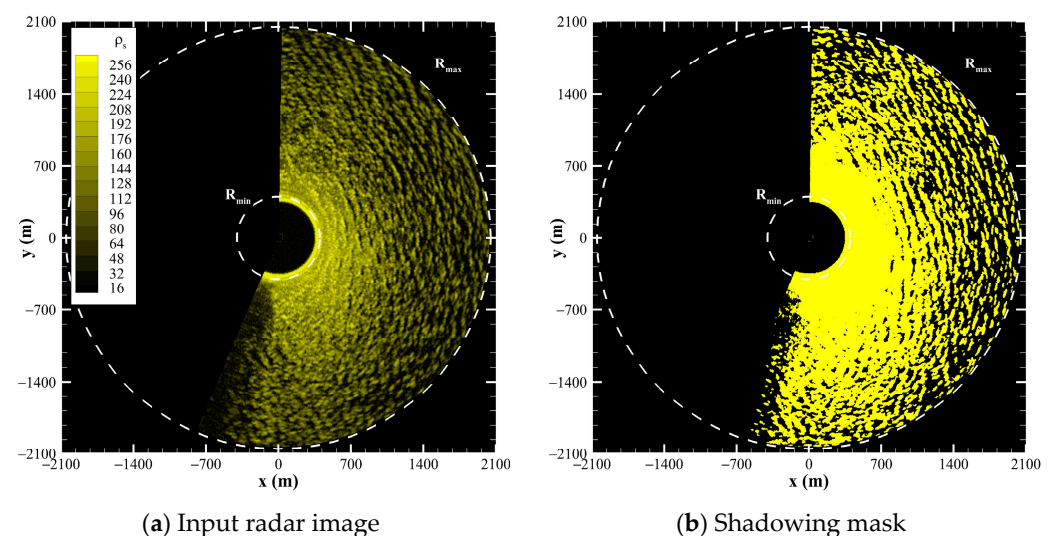


Figure 13. Real radar image and the corresponding shadowing mask: Ieodo dataset at 03:40 on 15 June 2008.

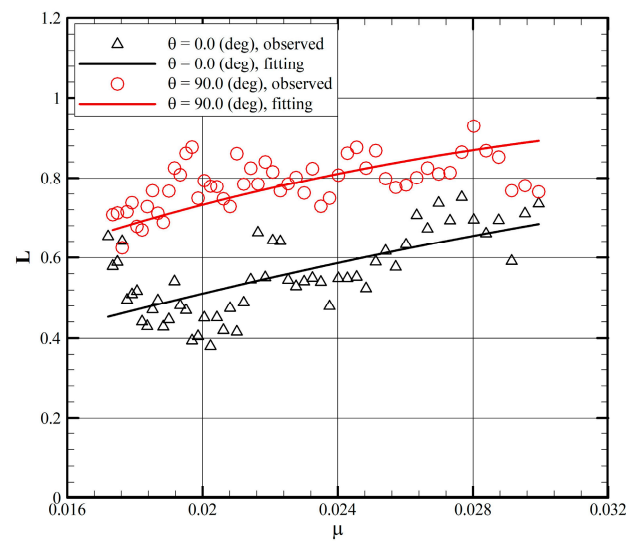


Figure 14. Fitting with the Smith function for the real radar image: Ieodo dataset at time 03:40 on 15 June 2008.

Finally, H_S is calculated using the estimated total mean surface slope, and T_4 is obtained based on the 3D-FFT-based analysis. A larger MTF exponent ($\beta_{MTF} = 1.0$) has been used than that in the synthetic radar image cases because high-frequency components were more overestimated owing to additional nonphysical effects encountered for measuring the realistic ocean environment. Figure 15 depicts a comparison of the H_S estimated by the present shadowing-based method with the reference measurement obtained from the tide gauge installed on the Ieodo ocean research station. The comparison indicates that the proposed shadowing-based method, with a rigorous consideration of the physical characteristics of ocean waves (i.e., w/SACF and w/orthogonality), can accurately estimate H_S for real radar images under realistic sea conditions.

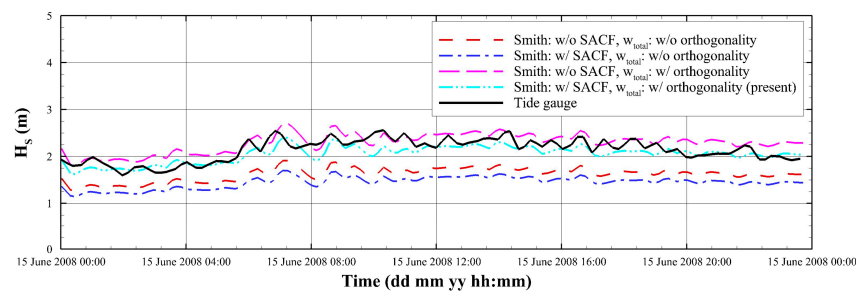


Figure 15. Comparison of significant wave height from shadowing-based estimations with the independent reference measurement: Ieodo dataset on 15 June 2008.

3.2.3. Results of Significant Wave Height Estimation: NIMS Dataset

The same H_S estimation procedure, including the shadowing distinction [14], has been performed for the NIMS dataset. Figure 16 illustrates a sample radar image of the NIMS dataset and the corresponding shadowing masks. Compared to the Ieodo dataset, the radar installation height of the NIMS dataset is lower, and the maximum reliable sensing range is smaller. From the viewpoint of the radar ray slope, more measurement data with low grazing incidences, where the shadowing occurs significantly, have been obtained. Overall, the trends of the shadowing occurrence are similar in the two datasets; therefore, the same fitting range for the mean surface slope estimation ($\mu < 0.03$) is used to exclude the overmeasured intensities near the radar due to the range dependency. Figure 17 presents the curve fitting between the illumination ratio and the Smith function for the NIMS dataset.

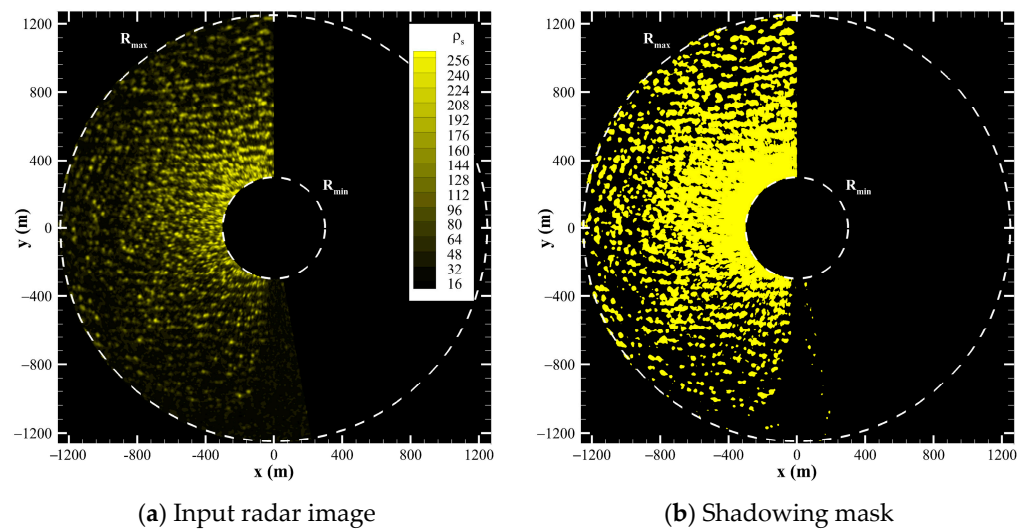


Figure 16. Real radar image and the corresponding shadowing mask: NIMS dataset at 02:50 on 17 October 2022.

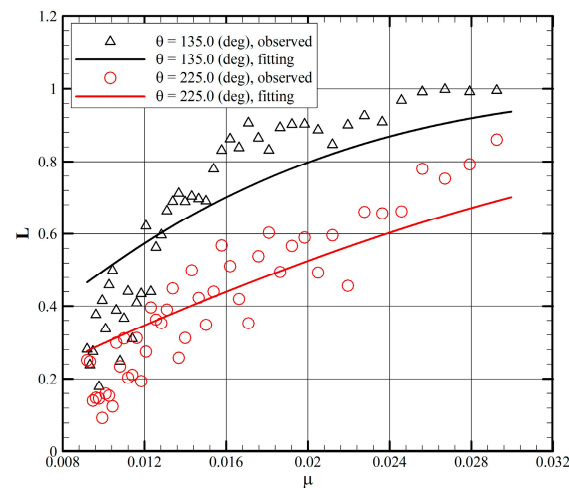


Figure 17. Fitting with the Smith function for the real radar image: NIMS dataset at 02:50 on 17 October 2022.

Figure 18 depicts the H_S estimated by the shadowing-based technique for the NIMS dataset. In addition, the measurement results by a wave buoy around the radar (~1.5 km from the radar) and the computed value by the commercial radar system installed on the research vessel are also presented for validation. In light of the comparably overestimated results compared to the buoy records, it seems that further calibrations for empirical parameters or computation procedures are required for the commercial radar system. On the other hand, the estimated H_S by the presented shadowing-based technique agrees well with the buoy measurements. It should be noted that the same procedures and parameters have been used for the two real radar image datasets, with different sensing settings for various sea states. In conclusion, the robustness of the proposed H_S estimation technique without any empirical or additional measurement database is confirmed.

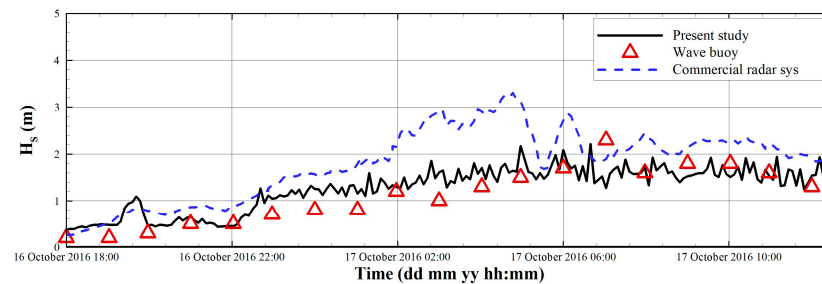


Figure 18. Comparison of significant wave height from shadowing-based estimations with the independent reference measurement: Ieodo dataset on 16~17 October 2016.

4. Conclusions

An enhanced significant wave height estimation procedure has been proposed based on the shadowing characteristics of the X-band marine radar images. This method consists of H_S estimation and FFT-based spectral analysis, which do not require additional independent measurements for scaling. Numerical tests are conducted on synthetic and real radar images to validate the accuracy and robustness of the proposed technique. The following conclusions can be drawn from this study:

- Rigorous consideration of the physical characteristics of the ocean wave field, including the SACF effect, orthogonality of the mean surface slope, and the relationship between sea state parameters, enables accurate shadowing-based significant wave height estimation without any independent measurement database.
- To validate the proposed methodology, simulation-based synthetic radar images are generated and employed for the estimation of significant wave heights. Across various sea state conditions, the enhanced method consistently improves prediction accuracy, showcasing its capability for accurate and significant wave height prediction.
- For the H_S estimation, the same procedures and parameters, such as the SACF form, fitting range for mean surface slope, and spectrum modification parameters, are used for two independent real radar image datasets. The estimation results are both in good agreement with the reference measurements, indicating the robustness of the proposed shadowing-based H_S estimation technique for various ocean environments and marine radar systems.
- Although the real radar images used in this study are not complete in terms of the amount of dataset and range of sea state severity, it is encouraging that, considering that the proposed technique is in its early development stage, its effectiveness and physical validity have been demonstrated through the present study. For a more systematic validation of the present method, comparisons with much longer measurement data should be made in the future study.

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Nomenclature

$A(k_x, k_y, \omega)$	Complex wave amplitude
dx	Spatial resolution of radar image (x -axis)
dy	Spatial resolution of radar image (y -axis)
g	Gravitational acceleration
H_S	Significant wave height
h	Water depth
h_r	Radar height
k_x	Wave numbers along the x -axis
k_y	Wave numbers along the y -axis
L	Illumination ratio
l_0	Empirical fitting parameters for SACF
MTF	Modulation transfer function
m_0	Zeroth-order spectral moment
m_4	Fourth-order spectral moment
p_0	Empirical fitting parameters for SACF
q	Wave slope
R_{min}	Minimum sensing radius
R_{max}	Maximum sensing radius
r	Range from radar
SACF	Spatial autocorrelation function
$S(\mu(r); w(\theta))$	Smith function
S_{3D}	3D power spectrum
S_f	Filtered 3D power spectrum
$S_f^{(MTF)}$	MTF applied a 3D power spectrum
$S_u(\mu(r); w(\theta))$	Uncorrelated Smith function
$S_c(\mu(r); w(\theta))$	Correlated Smith function
$\hat{S}(\zeta_0, q_0, \mu(r); \sigma, w(\theta))$	Shadowing probability density function
T	Duration of the time window
T_{mean}	Mean period
u_c	x -directional surface current
$V(\mu(r); w(\theta))$	Smith variance
v_c	y -directional surface current
w	Standard deviation of the wave slope
w_{est}	Azimuthal surface slope
w_{total}	Total mean surface slope
α_{MTF}	Scaling coefficient of MTF
β_{MTF}	Exponent of MTF
β_{mean}	Mean-shift parameter
Ω	Visibility function
ζ	Wave elevation
ζ_{exact}	Exact wave elevation for synthesized wave fields

θ	Azimuthal direction
θ_{min}	Minimum azimuthal range of radar measurement
θ_{max}	Maximum azimuthal range of radar measurement
κ_1	Filtering range of a high-pass filter
κ_2	Filtering range of dispersion filter
μ	Slope of the radar ray
ρ_C	Calibrated radar image intensity
ρ_m	Mean-shifted radar image intensity
ρ_{mean}	Mean value of image intensity for non-shadowed regions
ρ_S	Measured radar image intensity
σ	Standard deviation of wave elevation
χ_M	Main wave direction
χ_s	Wave spreading angle
ω	Wave frequency
Δt	Time interval of images

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