DEVELOPMENT OF ACCURATE, RELIABLE AND ROBUST ESTIMATION METHOD OF DIRECTIONAL SPECTRUM FROM FIELD DATA OBSERVED WITH ULTRASONIC DOPPLER-TYPE DIRECTIONAL WAVE METER

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BACKGROWND AND OBJECTIVES

There are several methods for the observation and analysis of directional spectra. Regarding observations, independent wave quantities such as $(\eta_{tt}, \eta_x, \eta_y)$ or (p, u, v) have been measured using buoys or PUV instruments, and the directional spectrum has been estimated. However, estimating an accurate directional spectrum solely from these three wave quantities is challenging. Therefore, since the 1990s, observations using ultrasonic Doppler-type directional Wave Meters (DWM, Fig.1) have been conducted in Japan (Hashimoto, et al., 1996). DWM can increase the amount of information necessary for estimating the directional spectrum by increasing the number of layers of water particle velocity observations. Unfortunately, increasing the number of observation layers in DWM does not necessarily lead to better accuracy or stability of the directional spectrum. In other words, as the amount of information increases, there can be an unexpected increase in the concentration of directional energy, suggesting the need for further improvements (Hashimoto, et al., 2019).

On the other hand, several methods have been proposed for estimating directional spectra, including the Direct Fourier Transformation (DFT) method, Parametric methods, Extended Maximum Likelihood Method (EMLM) (Isobe, et al., 1984), Bayesian Directional spectrum estimation Method (BDM) (Hashimoto, et al., 1988), and Extended Maximum Entropy Principle (EMEP) method (Hashimoto, et al., 1994). Among these methods, EMLM is widely used due to its simplicity and high accuracy in calculations. In practice, BDM and EMEP offer higher accuracy than EMLM, but they occasionally suffer from computational instability when solving nonlinear least-squares problems. To address this issue, BDM-NNLS (Fujiki, et al., 2017) was proposed using the Non-Negative Least Squares (NNLS) method, but doubts remain about its accuracy in estimating the direction function of extremely high directional energy concentration.

Therefore, in this study, we propose a highly accurate, reliable, and robust directional spectrum estimation method that addresses both of the above-mentioned issues in observation and analysis, surpassing existing methods.

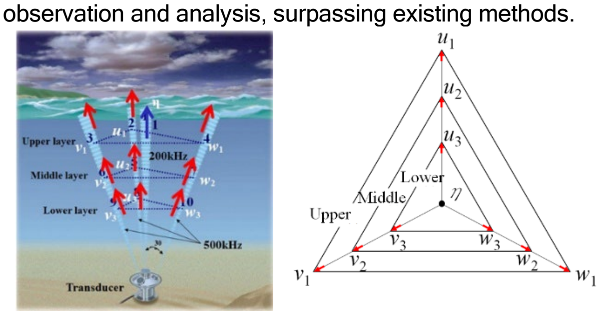

Figure 1 Ultrasonic Doppler-Type Directional Wave Meter

IMPROVEMENTS OF EQUATIONS IN DWM

The directional spectrum can be estimated by solving the following simultaneous integral equations:

$$\Phi_{mn}(f) = \int_0^{2\pi} H_m(f,\theta) H_n{}^*(f,\theta) S(f,\theta) d\theta \quad (1)$$
$$(m = 1, \ldots, K,\ n = 1, \ldots, K)$$

where, K represents the number of wave quantities, $\Phi_{mn}(f)$ is the cross-spectrum of the wave quantities $\xi_m(t)$ and $\xi_n(t)$, $S(f, \theta)$ is the directional spectrum, $H_m(f,\theta)$ is the transfer function from the wave quantity $\xi_m(t)$ to the water surface elevation $\eta(t)$, and the asterisk * denotes the complex conjugation.

First, to resolve the instability in DWM, improvements are made to the transfer function $H_m(f,\theta)$ derived from the small-amplitude wave theory. Generally, observed values may not perfectly align with theoretical values due to various sources of errors, potentially causing inconsistencies with the theoretically derived fundamental equations. By using observed data to modify the transfer function, the impact of such discrepancies is reduced, leading to enhanced accuracy and stability in directional spectrum estimation.

Next, we consider the weighting function for the weighted least-squares method. In DWM, the water particle velocity in each layer is expected to decay exponentially with depth, implying that the magnitude of errors in the cross-spectra varies with the distance from the water surface. Therefore, we propose an optimal weighting function that takes these effects into account.

Figure 2 shows the variation of the direction spreading parameter, S_{max}, estimated from field data with an increase in the number of observation layers in DWM. The two dashed lines in Fig. 2 represent estimated S_{max} using the transfer function $H_m(f,\theta)$ provided by the small-amplitude wave theory and two different weighting functions, respectively. On the other hand, the solid line represents estimated S_{max} using the modified transfer function $H_m(f,\theta)$ based on observed data and two different weighting functions. As seen in Fig. 2, the S_{max} represented by the dashed lines tend to monotonically increase as the number of observation layers of water particle velocity is increased from the uppermost layer (1st layer) to the lowermost (10th layer). In contrast, the S_{max} represented by the solid line tend to converge to an almost constant value when the number of observation layers is 3 or more. These results suggest that not only an increase in observed data but also the use of appropriate transfer functions and weighting functions can enhance the accuracy, stability, and reliability of directional spectrum estimation. It's worth noting that the change in the trend of S_{max} when adding the 10th layer is likely due to the fact that this layer is too close to the seabed, making its characteristics different from the other observation layers.

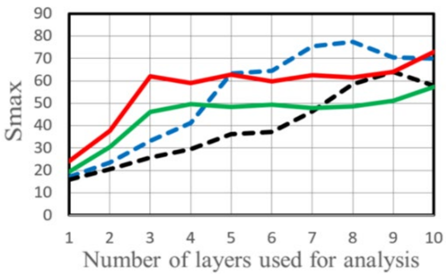

Figure 2 Comparison of estimated $S_{\max}$ using data from different numbers of observation layers (Dotted lines: $H_m(f,\theta)$ derived from small amplitude wave theory, Solid lines: modified $H_m(f,\theta)$. (Note that the two lines in each line type are due to the difference in weighting functions.)

IMPROVEMENTS IN COMPUTATIONAL METHODS

The instability observed in the original BDM and EMEP estimates is believed to be attributed to the use of a simple Newton's method for solving the nonlinear least-squares problems. Therefore, in this study, the application of Quasi-Newton methods and the Levenberg-Marquardt method to BDM and EMEP was investigated through numerical experiments. The numerical experiments encompassed both unidirectional seas with different directional spreading parameters and multidirectional seas with various spreading parameters superimposed. Generally, $S_{\max}$ for swell with a long decay distance is considered to be around 75, but there are research results indicating that $S_{\max}$ for "Yorimawari Nami" observed in Toyama Bay in Japan should be around 600. Consequently, the accuracy and stability of the improved BDM and EMEP were verified across a wide range of directional spreading parameters, from S = 1 to 1,000. Furthermore, while a symmetric directional distribution has been proposed as the standard form for directional functions, it is believed that actual coastal wave directional functions are diverse. Therefore, the study also examined the accuracy and stability of computations for various skewed directional functions.

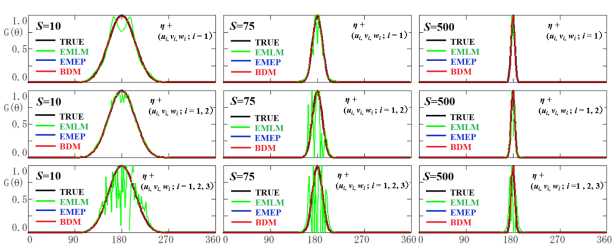

Figure 3 Estimates of directional functions with different directional spreading parameters.

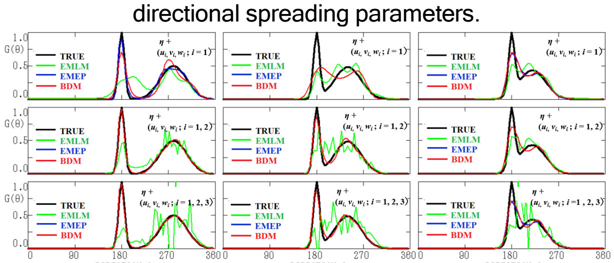

Figure 4 Estimates of directional functions having multiple directional spreading parameters.

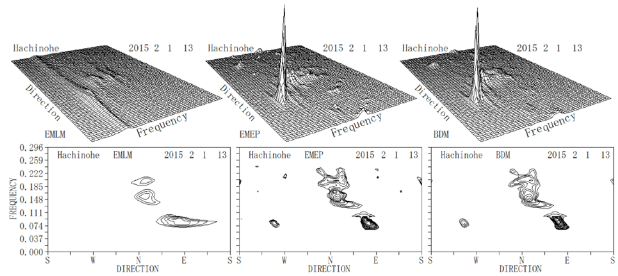

Figure 5 Directional spectra estimated from field data observed with DWM (with water surface elevation η and water particle velocities $(u_i, v_i, w_i : i=1, 2, 3)$ in three layers)

RESULTS OF INVESTIGATION

Figure 3 shows examples of directional functions for S = 10, 75, and 500. The upper panels show the estimated directional functions from one-layer observations, the middle panels from two-layer observations, and the lower panels from three-layer observations. The black lines represent the true values (TRUE), the green lines represent EMLM, the blue lines represent EMEP, and the red lines represent BDM. Despite the original BDM and EMEP being inaccurate for several hundreds of directional spreading parameters, the improved BDM and EMEP are accurate and stable for all directional spreading parameters, regardless of the number of observation layers used in the analyses.

Figure 4 shows examples of directional functions with multiple directional functions overlaid. While BDM and EMEP show improved accuracy and stability as the number of observation layers increases, EMLM becomes unstable.

Figure 5 shows the examples of estimated directional spectra from field data of water surface elevation and nine water particle velocities in three layers. The left panel represents EMLM, the middle one represents EMEP, and the right one represents BDM. The swell with a 13-second period, as estimated by BDM and EMEP, is significantly different from that estimated by EMLM. BDM and EMEP are robust against errors because they explicitly account for the errors of cross-spectra. On the other hand, EMLM, which does not explicitly consider the errors, results in broad directional spectra being contaminated by errors.

CONCLUSIONS

To estimate more accurate directional spectra using a ultrasonic Doppler-type directional Wave Meter (DWM), the characteristics of oblique water particle velocities at the multi-layers measured with DWM were investigated. As a result, improved computational methods were proposed, including new transfer functions, weighting functions, and an appropriate computational method for weighted nonlinear least-squares methods. The proposed methods have been demonstrated to contribute to accurate, reliable, and robust directional spectrum estimation.

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