# Exploration and Validation of Wave-Height Measurement Using Multifrequency HF Radar

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## ABSTRACT

For operations across a wide range of oceanographic conditions, a radar system able to operate at more than one frequency is theoretically and experimentally recommended for robust wave measurement in recent years. To obtain more sea-state information by HF radar, a multifrequency HF (MHF) radar system, which can simultaneously operate at four frequencies at most in the band of 7.5–25 MHz, was developed by the Radio Wave Propagation Laboratory of Wuhan University in 2007. This paper mostly focuses on detailing the data process method of MHF radar wave-height estimation. According to different bands of operating frequencies, a least-mean-square (LMS) linear fitting method is adopted to calibrate wave-height estimation formulation, which is introduced by Barrick to extract significant wave height from backscatter Doppler spectra. Both the wave-height measurements of the initial and modified methods are compared with wave buoy measurements. Afterward, a data fusion algorithm of multifrequency estimates based on relevant factors quantification is discussed step by step. Three comparisons between radar-derived and buoy-measured estimates are presented to illustrate the performance of the MHF radar wave-height measurement. The statistics of the MHF radar wave-height measurements are listed and analyzed. The results show that the wave-height measurements of the MHF radar are in reasonable agreement with the measurements of the wave buoy.

# 1. Introduction

Barrick set up the theory of first- and second-order electromagnetic backscatter from the ocean surface (Barrick 1972), and since then HF radar systems located on the coast have become more efficient and effective in extracting currents, winds, and waves from close to the coast to more than 100 km offshore (Heron and Prytz 2002; Wyatt et al. 2006; Chavanne et al. 2007; Cochin et al. 2008; Wyatt 2012). Nowadays, current measurement using HF radar is a well-accepted technology and there are many systems of different types in operation around the world, such as SeaSonde and Wellen Radar (WERA; Shay et al. 2007; Liu et al. 2010). However, HF radar wave measurement has not been applied as extensive as current measurement, on account of complicated inversion algorithm and low signal-to-noise ratio (SNR) of second-order spectrum in the Doppler spectrum (Wyatt 2002; Wyatt et al. 2005; Hisaki 2007). Up to the present, the HF radar wave estimation algorithm has not been robust enough for accurate observations. How to improve the accuracy and increase the stability of wave measurement is still a hot topic in the HF radar remote sensing field (Lipa et al. 2008; Hisaki 2009; Wyatt et al. 2009; Haus et al. 2010).

Significant wave height, which is one of the most important wave parameters, can be derived from first- and second-order backscatter Doppler spectrum of HF radar. A number of scientists have developed several different

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inversion methods to provide wave-height measurements using HF radar. The frequently used approach to get significant wave height is using the standard method to derive wave parameters from wave directional spectrum. Unfortunately, it is still a hard problem for researchers to obtain wave directional spectrum from HF radar. Though methods to invert the Barrick's integral equation and retrieve the wave directional spectrum have been developed by Lipa (1977), Wyatt (1986), Howell and Walsh (1993), Hisaki (1996), and Green and Wyatt (2006), these methods require that the secondorder spectra are sufficiently above the noise floor (at least 15 dB) to be measured by a pair of overlapping radar stations. It is necessary to make use of at least two radar sites to avoid the directional ambiguities of the integral inversion method. Alternatively, methods to obtain significant wave height without a full integral inversion have also been developed by Barrick (1977), Maresca and Georges (1980), Heron and Heron (1998), Wyatt (1988), Lipa and Nyden (2005), Gurgel et al. (2006), Wyatt et al. (2009), Ramos et al. (2009), and Long et al. (2011). These methods, which have always been known as the empirical approach, are often applied to single-site HF radar systems to quickly estimate significant wave height from Doppler spectra.

All the methods mentioned above are suitable for single-frequency HF radar systems, which are now much more widely used than multifrequency HF radar systems all over the world. However, the conventional technique of using a single-frequency HF radar system to measure wave heights needs to be improved, because the measurable wave-height range of a fixed operating frequency is limited. Generally speaking, for different operating frequencies, the measurable ranges of wave heights are much different (Wyatt and Green 2009). Figure 1 displays the relationship between operating frequencies and HF radar measurable ranges of significant wave height. This figure shows that both the maximum and minimum measurable significant wave heights decrease with the increase of operating frequency. Using a high-operating frequency can help HF radar accurately estimate the relatively low significant wave height and, on the contrary, it can be more accurate for HF radar to estimate the relatively higher significant wave height with a low-operating frequency. Moreover, the single-frequency mode also has some difficulties in the practical application. When it is in a low sea state, the SNR of the second-order Doppler spectrum of a low-operating-frequency HF radar always drops down to a poor level that is too low to obtain accurate estimation. In a high sea state, it is hard to separate the firstand second-order parts of the Doppler spectrum, which are indispensable to get the wave heights. In brief,

of significant wave-height measurement of different operating frequencies. This figure is plotted by the formula  $0.15 \le k_0 H_s \le 1$ , where  $k_0$  is radio wavenumber,  $H_s$  is significant wave height; H(f1), H(f2), H(f3), and H(f4) denote the optimum significant wave height measurable ranges of these four bands.

a single-frequency HF radar system is unfit for measuring widely changing wave heights. Wyatt et al. (2011) also indicated the same point: an HF radar system able to operate at more than one frequency is recommended for robust wave measurement.

Commercial single-frequency HF radar systems are widely used for ocean surface current and wave observations in various countries, groups, and areas. On the other hand, there is not any commercial multifrequency HF radar system in operation around the world. Teague (1986) and Teague et al. (2001) showed the current observations measured by multifrequency coastal radar (MCR). In the last several years, they have concentrated their research on current and wind observations by MCR in different environments. Up to now, there has been hardly any comprehensive study on multifrequency HF radar wave measurement.

To obtain more sea-state information and to enhance the HF radar measuring performance of widely changing significant wave heights, the Radio Wave Propagation Laboratory of Wuhan University began to research and develop the MHF radar system in 2007, and the mission was completed in 2009 (Zhao et al. 2008; Chen et al. 2011). The MHF radar system adopts the frequencymodulated interrupted continuous wave (FMICW) mode and can simultaneously operate at four frequencies at most. The four frequencies are usually set to be in four bands, which are 7.5–10, 10–15, 15–20, and 20–25 MHz. In Fig. 1, f1–f4 stand for the four bands in which the





MHF radar works, and the four rectangles—H(f1), H(f2), H(f3), and H(f4)—denote the optimum significant wave-height measurable ranges of these four bands. For instance, Fig. 1 shows that it is suitable for MHF radar to use f1 to measure the wave heights between 1.9 and 9.5 m.

This paper is concerned with the method of MHF radar significant wave-height measurement, which includes the two steps according to the order of data processing: wave-height estimation of four operating frequencies and the data fusion algorithm. To demonstrate the performance of this method, some experimental results obtained from two MHF radar systems are also presented. The paper is structured as follows: the second section describes the wave-height measurements of each operating frequency of MHF radar using the initial and modified methods. A least-mean-square (LMS) fitting approach, which is adopted to obtain modifying parameters, is also presented in this section. Section 3 presents the whole data processing procedure of MHF radar wave-height measurement, including data processing steps of the MHF radar wave-height data fusion algorithm. Section 4 starts with the basic description of a 10-day observation, and then shows three comparisons of wave-height measurements between the MHF radar system and wave buoy. The last section is a discussion and summary of the full paper.

# 2. Single-frequency wave-height estimation method

# *a. Initial wave-height estimation of four operating frequencies*

Full mathematical details for the analysis of the relationship between the power spectrum of backscattered signal and the ocean directional wavenumber spectrum can be found in Weber and Barrick (1977), Barrick and Weber (1977), and Lipa and Barrick (1986). Equations (1) and (2) show the first- and second-order forms in deep water:

$$\sigma^{(1)}(\omega,\phi) = 2^{6}\pi k_{0}^{4} \sum_{m'=\pm 1} S(-2m'\mathbf{k}_{0})\delta(\omega - m'\omega_{B}), \quad (1)$$

where m' denotes the sign of the Doppler shift,  $\mathbf{k}_0$  is the radar wavenumber vector,  $k_0$  is the magnitude of  $\mathbf{k}_0$ , and  $S(-2m'\mathbf{k}_0)$  is the ocean directional wavenumber spectrum,  $\omega_B = \sqrt{2gk_0}$ ; and

$$\sigma^{(2)}(\omega,\phi) = 2^6 \pi k_0^4 \sum_{m,m'=\pm 1} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} |\Gamma|^2 S(m\mathbf{k}) S(m'\mathbf{k}') \delta\left(\omega - m\sqrt{gk} - m'\sqrt{gk'}\right) dp \, dq, \tag{2}$$

where **k** and **k**' are two wave vectors,  $\mathbf{k} = (p - k_0, q)$ ,  $\mathbf{k}' = (-p - k_0, -q)$  and  $-2\mathbf{k}_0 = \mathbf{k} + \mathbf{k}'$ ; and *m* and *m*' locate the second-order contribution either to the left or the right of the first-order peaks. The coupling coefficient  $\Gamma$ , including the electromagnetic part  $\Gamma_{\text{EM}}$  and the hydrodynamic part  $\Gamma_H$ , is given by

$$\Gamma = \Gamma_H + \Gamma_{\rm EM} \tag{3}$$

$$\Gamma_H = \frac{-i}{2} \left[ k + k' - \frac{(kk' - \mathbf{k} \cdot \mathbf{k}')(\omega^2 + \omega_B^2)}{mm'\sqrt{kk'}(\omega^2 - \omega_B^2)} \right] \quad (4)$$

$$\Gamma_{\rm EM} = \frac{1}{2} \left[ \frac{(\mathbf{k} \cdot \mathbf{k}_0)(\mathbf{k}' \cdot \mathbf{k}_0)/k_0^2 - 2\mathbf{k} \cdot \mathbf{k}'}{\sqrt{\mathbf{k} \cdot \mathbf{k}'} - k_0 \Delta} \right].$$
 (5)

More details can be found in Lipa and Barrick (1986).

A pair of MHF radar systems were deployed at Sheng Shan and Zhu Jiajian on the coast of the East China Sea for current, wave, and wind observations in the summer of 2009. The two radar systems were deployed too far away from each other (about 100 km) that they did not have common coverage for wave observation. The MHF radar worked at more than one operating frequency, and significant wave heights were simultaneously estimated from the echoes of each operating frequency.

Initially, we adopted Barrick's empirical approach to obtain significant wave-height measurements from the Doppler spectrum. Barrick first showed the empirical approach, that there is a direct relationship between root-mean-square (RMS) wave height and the ratio of the total second-order energy to the total first-order energy (Barrick 1977):

$$H_{s} = 4 \left\{ \frac{2 \int_{-\infty}^{+\infty} \left[ \sigma^{(2)}(\omega) / W(\omega/\omega_{B}) \right] d\omega}{k_{0}^{2} \int_{-\infty}^{+\infty} \sigma^{(1)}(\omega) d\omega} \right\}^{1/2}, \qquad (6)$$

where  $H_s$  is significant wave height and the term  $W(\omega/\omega_B)$  is a weighting function of Doppler shift scaled by the Bragg frequency. In our practical application, noise floor, which is evaluated by the rank ordering technique (Heron and Heron 2001), is subtracted from first- and second-order Doppler spectra.



FIG. 2. Significant wave-height measurements of MHF radar and wave buoy. Measurements of (a) f1, (b) f2, (c) f3, and (d) f4.

| Frequency | Mean<br>error (m) | RMS<br>error (m) | Corr<br>coef | No. of comparisons | Mean<br>H <sub>s</sub> (m) |
|-----------|-------------------|------------------|--------------|--------------------|----------------------------|
| f1        | 1.75              | 1.83             | 0.46         | 125                | 0.89                       |
| f2        | 0.50              | 0.58             | 0.67         | 128                | 1.31                       |
| f3        | 0.23              | 0.35             | 0.84         | 125                | 1.30                       |
| f4        | 0.15              | 0.35             | 0.82         | 144                | 1.28                       |

TABLE 1. Statistics of the comparison between significant waveheight measurements of MHF radar and wave buoy.

Figure 2 presents the comparison between radarderived and buoy-measured estimates during a 10-day experiment. The significant wave-height measurements of four operating frequencies obtained from MHF radar are displayed in Figs. 2a–d, respectively. The details of this experiment will be showed in section 4. The total observation of each operating frequency lasts longer than 120 h. When the significant wave height is above 1 m, the measurements of f2–f4 match well with the measurements of wave buoy. However, when the significant wave height is below 1 m (actually, the significant wave heights are about 0.5 m from 26 August 2009 to 28 August 2009), the measurements of f1–f4 are overestimated. The error parameters are shown in Table 1. The measurements of f3 and f4 are better than the measurements of f1 and f2. For both f3 and f4, the correlation coefficients between MHF radar measurements and wave buoy measurements are more than 0.8.

#### b. Modifying parameter of wave-height measurement

As seen from the previous results, the initial method adopted in the MHF radar system results in some overestimation, especially in low sea state. To improve the performance of the initial method, an LMS linear fitting method is adopted to adjust the parameters of Barrick's empirical approach. This linear method will not change the tendencies of the MHF radar measurements in most situations, but it can decrease the mean error and RMS error of MHF radar wave-height measurements. The LMS fitting method is applied to the wave-height measurements of four operating frequencies. The fitting function is set as  $y = a_i x + b_i$ , where  $a_i$ and  $b_i$  are the first-order coefficients of the fitting function, i denotes the *i*th operating frequency, x is the measurements of wave buoy, and y is the measurements of the MHF radar. The first-order coefficients  $a_i$  and  $b_i$ can be obtained by fitting the measurements of the wave buoy and MHF radar by the LMS linear method.



FIG. 3. Scatterplots of MHF radar significant wave-height measurements. Results of LMS linear fitting are shown (solid lines). Scatterplots of (a) f1, (b) f2, (c) f3, and (d) f4.

| Frequency    | $a_i$ | $b_i$ |  |
|--------------|-------|-------|--|
| f1 $(i = 1)$ | 1.15  | 1.43  |  |
| f2 $(i = 2)$ | 0.64  | 0.95  |  |
| f3 $(i = 3)$ | 0.61  | 0.72  |  |
| f4 $(i = 4)$ | 0.63  | 0.57  |  |

TABLE 2. Modifying parameters of four operating frequencies.

In Figs. 3a–d, the solid lines are the results of fitting function  $y = a_i x + b_i$ , the dotted lines are y = x, and  $a_i$  and  $b_i$  of different operating frequencies are listed in Table 2.

#### c. Modifying parameter of wave-height measurement

After obtaining  $a_i$  and  $b_i$ , the MHF radar significant wave-height measurements of four operating frequencies can be modified by the following equation:

$$(H_s)'_i = \frac{(H_s)_i - b_i}{a_i},$$
 (7)

where  $(H_s)_i$  and  $(H_s)'_i$  are the initial and modified measurements of the *i*th operating frequency, respectively.

The following modified wave-height measurement method can be deduced from Eqs. (6) and (7):

$$H_{s} = \frac{4}{a_{i}} \left\{ \frac{2 \int_{-\infty}^{+\infty} [\sigma^{(2)}(\omega) / W(\omega / \omega_{B})] d\omega}{k_{0}^{2} \int_{-\infty}^{+\infty} \sigma^{(1)}(\omega) d\omega} \right\}^{1/2} - \frac{b_{i}}{a_{i}}, \qquad (8)$$

where  $a_i$  and  $b_i$  are the modifying parameters that are listed in Table 2.

The MHF radar data are recalculated using the modified method and the results are reanalyzed. Figure 4 displays the scatterplots of modified significant waveheight measurements, and Table 3 lists the error parameters of the comparison between significant wave-height measurements of MHF radar and wave buoy. Comparing the initial method, the modified method has a better performance: it decreases both the mean error and RMS error of MHF radar wave-height measurements. The correlation coefficients of the two methods are mostly the same except f1. The correlation coefficient of f1 changes because some unpractical results (<0 m) are deleted during the linear modifying process. In this low sea-state condition (mean  $H_s < 1.5 \,\mathrm{m}$ ), the modified wave-height measurements of f3 and f4 are better than the measurements of other two operating frequencies. These results have also proved that high-operating



FIG. 4. Scatterplots of modified MHF radar significant wave-height measurements. Scatterplots of (a) f1, (b) f2, (c) f3, and (d) f4.

TABLE 3. Statistics of the comparison between significant waveheight measurements of MHF radar (modified method) and wave buoy.

| Frequency | Mean<br>error (m) | RMS<br>error (m) | Corr coef | No. of comparisons |
|-----------|-------------------|------------------|-----------|--------------------|
| f1        | 0.17              | 0.53             | 0.45      | 123                |
| f2        | 0.04              | 0.33             | 0.67      | 128                |
| f3        | 0.03              | 0.24             | 0.84      | 125                |
| f4        | 0.08              | 0.28             | 0.82      | 144                |

frequency is more appropriate than low-operating frequency for relatively low significant wave-height estimation.

# **3.** Data fusion algorithm of multifrequency estimates

According to the theoretical limitation of significant wave-height estimation algorithm (as showed in Fig. 1), it is not always appropriate for a fixed operating frequency to measure wave height in different sea states. The previous results in section 2 have also proved this standpoint. This problem can be solved by the MHF radar system, which has the capability of simultaneously obtaining more than one measurement from different operating frequencies. Two or up to four wave-height measurements should be synthesized to a final measurement. Because of the advantage of the multiscale wave-height measurement, how to make full use of the wave-height measurements of different operating frequencies to get an optimal result plays a crucial role in the process of MHF radar wave-height measurement. The data fusion algorithm quantifies the factors such as echo quality, sea state, and operating frequency, which are closely relevant to wave-height measurement, and then synthesizes the measurements of different operating frequencies to a final result. The steps of the MHF radar significant wave-height estimation algorithm are presented as follows:

- Estimate significant wave-height measurements of different operating frequencies using the modified method [Eq. (8)]. The minimum SNR requirement is 20 dB, and the minimum SNR requirement for the second-order spectrum is 10 dB. (The SNR from the strong first-order peak to the noise floor is defined as SNR, and the SNR from the second-order peak in the strong first-order side to the noise floor is the SNR of the second-order spectrum.) The time series of MHF radar wave-height measurements using the modified method during this experimental period is displayed in Fig. 5.
- 2) Average all the wave-height measurements that are simultaneously estimated from different operating



FIG. 5. Modified significant wave-height measurements of MHF radar of four operating frequencies.

frequencies at the same measuring grid point. The averaged value  $\overline{H}$  will help the procedure estimate the present sea state. For example, there are four measurements—1.2, 1, 0.8, 0.6 m—estimated from four operating frequencies at the same grid point at the same time;  $\overline{H}$  (present sea state) is computed as 0.9 m by the procedure.

3) Use  $\overline{H}$  (present sea state) to choose one or more appropriate operating frequencies according to the theoretical limitation of the significant wave-height estimation algorithm displayed in Fig. 1. For instance, if  $\overline{H}$  is 0.9 m, then f4 (20–25 MHz) is chosen as the appropriate operating frequency, and the measurement of f4 is considered to be optimal. If there are more than one operating frequency appropriate for the wave-height estimation, then average the measurements weighted by the second-order SNR.

The algorithm can also be expressed as follows:

$$H_{s} = \frac{\sum_{i=1}^{4} F_{i} \times \text{SSNR}_{i} \times H_{i}}{\sum_{i=1}^{4} F_{i} \times \text{SSNR}_{i}},$$

$$F_{i} = \begin{cases} 1, \quad H(f_{i})_{\min} \leq \overline{H} \leq H(f_{i})_{\max} \\ 0, \quad H(f_{i})_{\min} \geq \overline{H} \quad or \quad \overline{H} \geq H(f_{i})_{\max} \end{cases}, \quad (9)$$

where subscript *i* denotes the *i*th operating frequency,  $F_i$  is the validity flag of wave-height measurement,  $H_i$  is the wave-height measurement, SSNR<sub>i</sub> is the SNR from the second-order peak on the strong first-order side to the noise floor,  $H(f_i)$  denotes the optimum significant



FIG. 6. Array beam patterns of MHF radar system at five typic frequencies. (a) Array beam pattern at 7.5 MHz, with a beamwidth of 25.3°. (b) Array beam pattern at 10 MHz, with a beamwidth of 23.4°. (c) Array beam pattern at 15 MHz, with a beamwidth of 15.5°. (d) Array beam pattern at 20 MHz, with a beamwidth of 12.9°. (e) Array beam pattern at 25 MHz, with a beamwidth of 10.3°.

wave-height measurable range of operating frequency  $f_i$ , and  $\overline{H}$  is the averaged wave-height measurement.

### 4. Observation

#### a. Experiment

Two MHF radar systems have been installed offshore at Sheng Shan and Zhu Jiajian with the purpose of oceanographic measurement in the East China Sea since 2009. MHF radar system can simultaneously operate at four frequencies at most in the band of 7.5-25 MHz. The system consisted of separate transmit-and-receive antennas. The receive array comprising eight antennas needs a location of  $54 \text{ m} \times 18 \text{ m}$  and can provide a beamwidth of about 10°-25° (approximately 25° at 7.5 MHz), which seems to achieve the basic requirement for wave observation. The array beam patterns at five boundary frequencies are shown in Fig. 6. Antenna beam patterns calibrated by ship signals appear in radar echoes before the extraction of sea-state information. The Automatic Identification System (AIS), which is an automatic tracking system used on ships and by vessel traffic services (VTS) for identifying and locating vessels by electronically

exchanging data with other nearby ships and AIS base stations, provides the location information of the ship.

A 10-day observation was made in the East China Sea from 26 August 2009 to 4 September 2009. This section



FIG. 7. Map of MHF radar systems deployed at Sheng Shan and Zhu Jiajian on the coast of the East China Sea. Three wave buoys were deployed at C1, B1, and B31 in this experiment. Two pie slices denote the wave measurements coverage areas of the two MHF radar systems.



FIG. 8. In situ observations of winds, waves, and currents at C1 point during the experiment. (a) Wave direction measurements. (b) Current speed measurements. (c) Current direction measurements. (d) Wind speed measurements. (e) Wind direction measurements.



FIG. 9. Significant wave-height measurements of C1 point using Shan MHF radar and wave buoy; mean significant wave-height measured by wave buoy is 1.13 m. (a) Time series plot of final measurements of MHF radar and wave buoy, 191 points. (b) Scatterplot of MHF radar final measurements.

presents the results obtained from the MHF radar systems deployed at Sheng Shan and Zhu Jiajian during this observation period. As shown in Fig. 7, three wave buoys, which are considered as the most accurate instrument for wave measurement over the world, were installed within the coverage area of MHF radar wave observation, and sampled the ocean surface every hour. Two wave buoys were located at C1 and B1, which are 10 km away from the Sheng Shan site and the Zhu Jiajian site, respectively. The wave buoy located at B31 is 20 km away from the Zhu Jiajian site. The depth of water at C1, B1, and B31 is 40, 30, and 30 m, respectively. In situ measurements of winds and currents are also obtained at C1 and B1. MHF radar systems and wave buoys worked uninterruptedly during the period of this experiment. The MHF radar system samples the ocean surface in accordance with the Doppler sampling frequency. The application program of the MHF radar system, which makes use of the newest 30-min sampling data, runs every 10 min to estimate wave-height parameters. Twenty-minute sampling data have been reused for the wave-height estimation every time. The data processing of MHF radar wave-height measurements is presented in detail in section 3.

# b. Results

Three comparisons between radar-derived and buoymeasured estimates from two radar sites at C1, B1, and B31 points are shown in this section. Figure 8 displays the time series of winds, waves, and current observations by in situ equipment at C1 point. During this experiment, the wind speed varied between 4 and  $15 \text{ m s}^{-1}$  and the wind direction was relatively stable except changing quickly from south to northeast on 28 August 2009. There was a big and rapid variation of wave direction in 28 August 2009. The current at C1 point fluctuated frequently between 0 and  $60 \text{ cm s}^{-1}$ , and the shift of firstorder peak caused by radial current did not have an influence on wave measurement. Figures 9a and 9b show significant wave-height measurements of C1 point. In this experiment, MHF radar measurements match well with the buoy measurements for a low sea state (significant wave heights are mostly below 2 m), with a correlation coefficient of 0.83. The mean and RMS error of significant wave heights, which are calculated from a comparison of a 191-point time series, are 0.13 and 0.31 m, respectively. In addition, the error statistics of significant wave-height measurements from 1800 UTC 29 August to 0000 UTC 3 September are specially listed in Table 4 to illustrate the performance of the data fusion algorithm, because the raw data of f2-f4 and the data fusion algorithm are the same during this period. As seen in Table 4 errors become smaller by applying the data fusion algorithm.

TABLE 4. Statistics of the comparison between significant waveheight measurements with MHF radar (modified method) and wave buoy from 1800 UTC 29 Aug 2009 to 0000 UTC 3 Sep 2009; mean significant wave height measured by wave buoy is 1.49 m during this period.

| Frequency                             | Mean<br>error (m) | RMS<br>error (m) | Corr coef | No. of comparisons |
|---------------------------------------|-------------------|------------------|-----------|--------------------|
| f2                                    | 0.01              | 0.31             | 0.70      | 103                |
| f3                                    | 0.01              | 0.23             | 0.81      | 103                |
| f4                                    | 0.04              | 0.22             | 0.83      | 103                |
| Final results (data fusion algorithm) | 0.02              | 0.19             | 0.85      | 103                |



FIG. 10. As in Fig. 8, but at B1 point.



FIG. 11. Significant wave-height measurements of B1 point using Zhu Jiajian MHF radar and wave buoy; mean significant wave-height measured by wave buoy is 0.88 m. (a) Time series plot of final measurements of MHF radar and wave buoy, 211 points. (b) Scatterplot of MHF radar final measurements.

The data processing algorithm is also applied to the datasets obtained by MHF radar located at Zhu Jiajian. Two comparisons of B1 and B31 points are presented in this section. Figure 10 shows some basic oceanographic information, such as winds, waves, and currents, obtained by in situ method at B1 point. During this experiment, wind speed varied between 3 and  $13 \text{ m s}^{-1}$ . As the same as C1 point, the wind direction at B1 was also stable except changing quickly from south to northeast on 28 August 2009. The wave direction also changed on that day. Stronger than C1 point, the biggest current at B1 reached nearly 80 cm s<sup>-1</sup>. Fortunately, the wave estimating algorithm would not be disturbed by the radial current less than 1.5 m s<sup>-1</sup>.

Significant wave-height measurements of B1, which are obtained by MHF radar located at Zhu Jiajian, are

shown in Figs. 11a and 11b. The wave-height measurements at B1 match well with the buoy measurements, with a correlation coefficient of 0.77. The mean and RMS error of significant wave heights are 0.12 and 0.28 m, respectively. Figure 12 displays the significant wave-height measurements of B31 point using Zhu Jiajian MHF radar and wave buoy. Similar to the results of B1, the wave-height measurements of the MHF radar match well with the wave buoy measurements, with a correlation coefficient of 0.76. The mean and RMS error of significant wave heights are 0.02 and 0.29 m, respectively. Both the results of B1 and B31 point shown above prove that the data processing algorithm can be transferred to another local location in the same conditions. The performance of MHF radar wave-height measurements seems to be better than that of the single-site



FIG. 12. Significant wave-height measurements of B31 point using Zhu Jiajian MHF radar and wave buoy; mean significant wave height measured by wave buoy is 0.86 m. (a) Time series plot of final measurements of MHF radar and wave buoy, 135 points. (b) Scatterplot of MHF radar final measurements.

single-frequency HF radar (correlation coefficient: 0.75, RMS error > 0.5 m) in Wyatt's study (Wyatt 2002), though the sea state of these two experiments is somewhat different.

#### c. Estimation method discussion

With wave buoys established as "sea truth," we compare wave-height data obtained from land-based MHF radar systems to wave buoys. However, there are some differences between radar-derived and buoy-measured estimates. Wave buoys give a point measurement, while MHF radar systems give wave height averaged over range rings; wave buoys measure waves by moving with the waves on the ocean, while MHF radar systems derive the wave information from backscattered sea echo over kilometer-scale areas.

Although four operating frequencies of MHF radar system derive wave-height estimates at the same time, there are also some minor differences among them. For the receiving antenna array of the MHF radar system, longer radio wavelengths have wider beams. Consequently, lower frequencies have a larger sampling region of the ocean than higher frequencies. This feature becomes more apparent with increasing distance. In this paper, we assume that waves of each sampling cell move in a homogeneous condition.

#### 5. Conclusions

The wave-height estimation algorithm of the MHF radar system is much more complex than that of a singlefrequency HF radar system, and it can be roughly divided into two steps. One is to estimate wave heights from Doppler spectra of different operating frequencies using the single-frequency approach. This step is the equivalent of obtaining measurements from several single-frequency HF radar systems. The other is to synthesize the estimates of different operating frequencies to obtain a final result. This paper presents our work on both steps in detail:

1) This paper adopts Barrick's algorithm to estimate wave height of a single operating frequency, and then it applies an LMS fitting approach to estimate modifying parameters of four operating frequencies from an observation over 100 points to help reduce the mean and RMS error of Barrick's algorithm. Considering that the simulated Doppler spectrum and actual sea echoes are somewhat different, and the factors such as operating frequency and beamwidth of receiving array have some influence on the waveheight estimation algorithm, we obtain modifying parameters from MHF radar datasets but not from the simulated Doppler spectrum. More important, the three comparisons at C1, B1, and B31 points indicate that the modifying parameters are relatively effective for two MHF radar systems at Sheng Shan and Zhu Jiajian.

2) The data fusion algorithm regards the averaged value derived from four operating frequencies as prior information; makes use of this value to choose the appropriate operating frequency according to the theoretical condition in Fig. 1; and finally, if there is more than one appropriate operating frequency, averages their measurements weighted by second-order SNR to get the final result. This algorithm, which quantifies the factors of echo quality, sea state, and operating frequency, and then synthesizes the measurements of different operating frequencies to a final result, is verified to be effective for the MHF radar system.

Although the application of the MHF radar system to measure wave height seems to be promising, there are many factors that are closely related to the extensive application in different situations that need to be tested and verified in the future work. The modifying parameters  $a_i$  and  $b_i$  are determined from limited observations. Meanwhile, the lack of MHF radar and wave buoy measurements in high sea state restrains the further verification of the data fusion algorithm. Accordingly, in the plan for our future research, modifying parameters and the data fusion algorithm will be further explored and developed by the support of large amounts of ocean surface observation datasets, which are obtained from both MHF radar systems and wave buoys deployed at different locations in various sea states.

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