

Sea-surface acoustic backscattering measurement at 6–25 kHz in the Yellow Sea

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Abstract

Sea-surface acoustic backscattering measurements at moderate to high frequencies were performed in the shallow water of the south Yellow Sea, using omnidirectional spherical sources and omnidirectional hydrophones. Sea-surface backscattering data for frequencies in the 6–25 kHz range and wind speeds of (3.0 ± 0.5) and (4.5 ± 1.0) m/s were obtained from two adjacent experimental sites, respectively. Computation of sea-surface backscattering strength using bistatic transducer is described. Finally, we calculated sea-surface backscattering strengths at grazing angles in the range of 16° – 85° . We find that the measured backscattering strengths agree reasonably well with those predicted by using second order small-roughness perturbation approximation method with “PM” roughness spectrum for all frequencies at grazing angles ranged from 40° to 80° . The backscattering strengths varied slightly at grazing angles of 16° – 40° , and were much stronger than roughness scattering. It is speculated that scattering from bubbles dominates the backscattering strengths at high wind speeds and small grazing angles. At the same frequencies and moderate to high grazing angles, the results show that the backscattering strengths at a wind speed of (4.5 ± 1.0) m/s were approximately 5 dB higher than those at a wind speed of (3.0 ± 0.5) m/s. However, the discrepancies of backscattering strength at low grazing angles were more than 10 dB. Furthermore the backscattering strengths exhibited no significant frequency dependence at 3 m/s wind speed. At a wind speed of 4.5 m/s, the scattering strengths increased at low grazing angles but decreased at high grazing angles with increasing grazing angle.

Key words: sea-surface acoustic scattering, moderate frequency, scattering model, bistatic backscattering, frequency dependence

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1 Introduction

Ocean reverberation has adverse effects on the transmission of underwater acoustic signals and the detection of underwater targets (McDaniel, 1993a, b; Norton and Novarini, 2001; Van Vossen and Ainslie, 2011). Consequently, it is of great significance to study the backscattering characteristics of the sea surface, which is one of the two major interfaces that affect ocean reverberation. Since the 1950s, a great number of experimental measurements and theoretical research projects have been conducted and many conclusions, empirical formulas, and theoretical equations have been obtained on sea-surface backscattering. Besides sea-surface wind speed, sound frequency, and grazing angle, many other environmental conditions have some effect on sea-surface scattering, including wind direction, water temperature, sound speed profile, wave spectrum, air saturation of seawater, bubble size and density, depth of the bubble layer, microorganisms in the water body, seasonal changes, and offshore and

open seas. Based on experiment measurements, in this paper we investigate the effect of wind speed, grazing angle, and acoustic frequency on sea-surface acoustic backscattering under specific environmental conditions.

Sea-surface backscattering at high frequencies is usually measured using directional sources and hydrophones to avoid contamination from volume and seafloor reverberation. Wildt (1946) measured the sea-surface backscattering strength at a frequency of 25 kHz and small grazing angles using directional sources in water depths of 5–20 m and found that wind-generated micro-bubbles existing below the sea surface had an important influence on the reverberation process. Urlick and Hoover (1956) performed reverberation experiments in an open sea at 60 kHz and over a wide grazing angle range. They found a dependence of sea-surface backscattering strengths on wind speed and grazing angle and attributed the three grazing angle ranges to three different scattering mechanisms. Garrison et al. (1960) also conducted

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ted reverberation experiments at a frequency of 60 kHz in coastal waters and concluded that resonant micro-bubbles have important influences on sea-surface backscattering strengths at small grazing angles and higher wind speeds. In 1995, Dahl (2003) used directional sources to continually measure the sea-surface backscattering strengths at a frequency of 30 kHz and grazing angle of 20° over a 24-h period in a Florida offshore area. He found that wind speeds exhibit a hysteresis effect on sea-surface backscattering. Limited by sources and the influence of the seafloor interface, measurements of sea-surface backscattering at low frequency have been generally made in deep open sea using explosive charges as sources. In 1961, Chapman and Harris (1962) measured sea-surface backscattering strengths at intermediate and low frequencies (400–6 400 Hz) in the North Atlantic Ocean using explosive charges as sources, deriving the famous Chapman–Harris (CH) empirical formula through summarization based on their experiment data. In December of the same year, Chapman and Scott (1964) performed a second sea-surface scattering experiment in the North Atlantic Ocean and extended the frequency range for the CH formula down to a minimum of 100 Hz. Ogden and Erskine (1994a, b) using explosive charges measured the low frequency sea surface backscattering strengths, found that CH formula are valid predictors for rougher seas and higher frequencies. Bachmann (1973) and Crowther (1980) measured sea-surface backscattering strengths at 3–35 kHz in the North Atlantic Ocean and in the Mediterranean Sea using directional sources, respectively. Similarly, Nutzel et al. (1987) measured sea-surface backscattering strengths at 3–35 kHz in an offshore sea. The experimental results at grazing angles $>30^\circ$ showed a substantial consistency with the prediction results of roughness scattering theory. At low grazing angles, the sea-surface backscattering strengths obtained from all experiments exceeded those predicted by roughness scattering theory, showing that other environmental factors including bubbles influenced the sea-surface backscattering strengths at low grazing angles. However, at equivalent wind speed values, their experimental results differed considerably at low grazing angles. This disparity might be caused by the different concentrations of bubbles in seawater and other environmental factors (McDaniel, 1993a).

Historically, sea-surface backscattering experiments have mostly been conducted at low frequencies below 3.5 kHz and high frequencies above 20 kHz, with fewer being conducted at intermediate frequencies in the range from 6 to 20 kHz. Though it was generally considered that frequency might have some influence on sea-surface backscattering strengths, the results of experiments performed at frequencies from 15 to 60 kHz by Lilly and McConnell (1978) in coastal and open waters showed that there was no dependence of backscattering strength on frequency. Reeves et al. (1969) found a weak directional dependence for wind speed below 5 m/s. In June 2017, we made a sea-surface backscattering experiment employing omnidirectional sources at intermediate frequencies from 6 to 25 kHz in Qingdao coastal waters and obtained sea-surface backscattering strengths at a wide range of grazing angles and different wind speeds. In this paper the sea-surface backscattering experiment and computation of backscattering strengths are described. Then we analyze the influences of wind speed, grazing angle, and frequency on sea-surface backscattering strength under specific environmental conditions. In addition, the experimental results are compared with rough surface scattering and bubbles scattering, and the sea-surface backscattering mechanisms are discussed. Finally, defects in this experiment are summarized and experiment improvements are proposed for future research.

2 Sea-surface acoustic backscattering experiment

The sea-surface backscattering experiment was performed in the Qingdao offshore area, approximately 150 km from the coast, and the locations for two experiment sites at different wind speeds were 4.4 km apart, with water depths of 52 and 54 m, respectively. The scattering experiments were expected to yield sea-surface acoustic backscattering data at different wind speeds and frequencies (6–25 kHz) and over a large grazing angle range. In the experiments, three omnidirectional spherical sources and one omnidirectional hydrophone were employed for transmitting and receiving signals. A self-contained acoustic wave acquisition station was used to acquire scattering signals with a sampling frequency of 96 kHz. The center frequencies of the three sources were 8, 15, and 22 kHz, which corresponded to transmitting frequency ranges of 6–12, 10–19, and 17–25 kHz, respectively, and the experimentally covered frequency range was between 6 and 25 kHz. The calibrated source levels at the center frequencies of the three sources were 193, 197, and 198 dB re $1 \mu\text{Pa}$, respectively, with both horizontal and vertical directional deviations not exceeding 1 dB re $1 \mu\text{Pa}$. The hydrophone used in the experiment had a sensitivity of $-196 \text{ dB re } 1 \text{ V}/\mu\text{Pa}$. In the experiments, the sound velocity profile was measured with a sound velocity profiler (SVP). Measurement data showed that the thermocline was near a water depth of 20 m, and the sound velocity in the water above a water depth of 20 m was homogeneously 1 506 m/s. The whole observation system was deployed above the thermocline, which effectively reduced the effect of sound velocity variation on sea-surface backscattering. In the experiments, an inclinometer and a conductivity-temperature-depth (CTD) system were attached near the sources and the hydrophone to monitor their postures and the environmental conditions at the water depths where they were deployed. The monitoring data showed that the depths for the sources and hydrophone varied little and that the water temperature at the depths was $(24.5 \pm 0.2)^\circ\text{C}$. An anemometer was used to measure the 1-min average wind speed in the experimental sea area every five minutes. The wind speeds for the first experiment and the second experiment were (3.0 ± 0.5) and (4.5 ± 1.0) m/s, respectively.

The observation system was deployed as shown in Fig. 1. A buoy ball was used to deploy the source 8 m below the sea surface. To reduce shadowing by and interaction with the source, the hydrophone was positioned approximately 1 m above the source. The buoy ball was connected with the vessel through a rope and kept apart from the ship by more than 40 m. Meanwhile the source was deployed more than 40 m above the seafloor. As omnidirectional sources were used in this experiment, such deployment could ensure that sea-surface backscattering signals within a radius of 40 m from the center of the buoy ball would not be interfered with by reflection signals from the ship or seafloor. During the experiment, the ship's motor was shut down, the vessel and the experimental apparatus drifted with currents

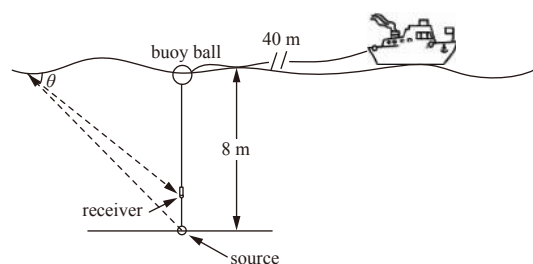


Fig. 1. Schematic diagram of the observation system.

and waves. On occasion, when the ship and observation apparatus would approach each other, the optimal distance conditions might not have been met at certain frequencies; consequently, the sea-surface scattering signals might have been contaminated by reflection signals from the ship. Based on received signal time series and experimental records, such frequencies with anomalous data were identified and contaminated signals were removed.

During the experiment, continuous wave pulse signals of 1 ms were transmitted at an interval of 2 s by omnidirectional sources and repeated 100 times at each frequency. Therefore, it took 200 s to complete the measurement at each frequency. After pulses at one frequency were transmitted, the above process was repeated by changing the frequency in steps of 1 kHz. Each source transmitted 7–10 signals of integral frequencies. Therefore, the experiment for each source lasted about half an hour. The relatively short experiment duration ensured that there was no significant fluctuation of wind speeds during the experiment, thereby contributing to obtain the frequency dependence of sea-surface backscattering at the same wind speed. After measurement in one acoustic frequency range was completed, transmission of signals was stopped, allowing the hydrophone to record underwater environmental noise for a period of time. Thereafter, the buoy observation system was recovered to replace another source and repeat the sea-surface backscattering measurement run. For each measurement run, except for replacement of the source, all other apparatuses and their relative positions remained unchanged.

Figure 2 shows the mean envelopes and strengths of 90 ping signals at 10 kHz. Different scattering and reflection signals can be clearly identified from this figure. The first received signals comprised the direct-path wave transmitted from the source. Owing to the close proximity between the source and the hydrophone (only 1 m), the received direct-path wave signals' amplitude was peak clipping. Subsequent arrivals were reflection waves and scattered waves from the sea surface. The signals at 60 ms were seafloor echoes and ship reflection waves. The strength of the signals received by the hydrophone from 40 to 60 ms remained almost unchanged, with amplitude essentially the same as ambient noise, when the backscattering signals from the sea surface at small grazing angles could not be distinguished from the background noise.

The experiment was designed for grazing angles in the range of 12°–85°. However, it was found that scattering signals at small grazing angles were received with low signal-to-noise ratio. Background noise mostly came from the following two sources: (1) wave and current noise and buoy ball collision, which interfered with the sea-surface scattering signals since the observation system was relatively close to the sea surface. Fortunately, it can be eliminated by filtering; (2) the presence of entomorphs and jellyfish in the Qingdao offshore area. It was thus speculated that strong volume scattering was caused by the great number of microorganisms. These noises finally led to rough surface backscattering signals at small grazing angles being lost amidst the background noise.

3 Computation of sea-surface backscattering strength

As the seafloor backscattering strengths, the sea-surface backscattering strengths can be computed with the sonar equation too:

$$BS(\theta) = RL - SL + TL_{in} + TL_{out} - 10 \log_{10}(A), \quad (1)$$

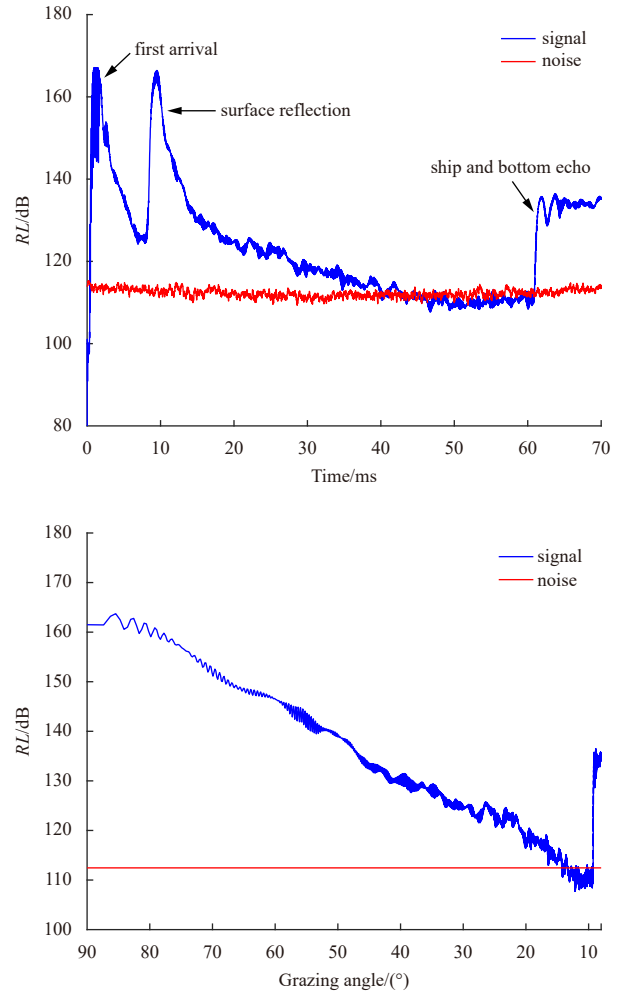


Fig. 2. Mean signal and noise levels of 90 samples at 10 kHz.

where $BS(\theta)$ denotes the backscattering strength at grazing angle θ , RL is the strength of received signals, SL is the source level, TL_{out} is one-way transmission loss from the source to the sea surface, TL_{in} is the corresponding transmission loss from the sea surface to the hydrophone, and A is the insonified area of acoustic pulses at grazing angle θ , which is a ring (circular plane near vertical incidence) at the sea surface as an omnidirectional source was employed. For a monostatic transducer, TL_{out} and TL_{in} are equal. However, they have to be computed separately as their propagation paths are different because of the 1 m distance from the source to the hydrophone. The transmission losses are computed based on spherical wave expansion, with loss from water absorption ignored. Hence, they are written as

$$TL_{out} = 20 \log_{10}(r_1), \quad (2)$$

$$TL_{in} = 20 \log_{10}(r'_1). \quad (3)$$

From the geometry shown in Fig. 3, we may obtain

$$R_1^2 = r_1^2 - H_2^2 = r'_1{}^2 - H_1^2, \quad (4)$$

$$R_2^2 = r_2^2 - H_2^2 = r'_2{}^2 - H_1^2, \quad (5)$$

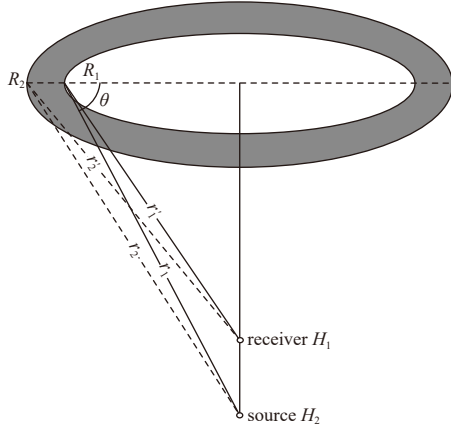


Fig. 3. Diagram of relative positions of the observation system.

and the relation between the sound propagation path and time is given by

$$r_1 + r'_1 = c_w T, \quad (6)$$

$$(r_2 + r'_2) - (r_1 + r'_1) = c_w \tau, \quad (7)$$

where T is the time it takes an acoustic wave at grazing angle θ to propagate from the source to the sea surface and then be backscattered to the hydrophone, τ is the pulse duration, which was fixed at 1 ms in the experiment, and c_w is the sound velocity in water. From the above Eqs (4)–(7), r_1 , r'_1 , r_2 , and r'_2 may be calculated, respectively, as

$$r_1 = \frac{c_w T}{2} + \frac{H_2^2 - H_1^2}{2c_w T}, \quad (8)$$

$$r'_1 = \frac{c_w T}{2} - \frac{H_2^2 - H_1^2}{2c_w T}, \quad (9)$$

$$r_2 = \frac{c_w (T + \tau)}{2} + \frac{H_2^2 - H_1^2}{2c_w (T + \tau)}, \quad (10)$$

$$r'_2 = \frac{c_w (T + \tau)}{2} - \frac{H_2^2 - H_1^2}{2c_w (T + \tau)}. \quad (11)$$

So the area of the ring insonified by the acoustic pulses may be obtained as

$$A = \frac{\pi}{4} \left\{ (r_2 + r'_2)^2 - (r_1 + r'_1)^2 + (H_2^2 - H_1^2)^2 \times \left[\frac{1}{(r_2 + r'_2)^2} - \frac{1}{(r_1 + r'_1)^2} \right] \right\}. \quad (12)$$

Substituting Eqs (6) and (7) into Eq. (12), we may convert the insonified ring area to

$$A = \frac{\pi}{4} \left\{ c_w^2 \left[(T + \tau)^2 - (T)^2 \right] + \frac{(H_2^2 - H_1^2)^2}{c_w^2} \times \left[\frac{1}{(T + \tau)^2} - \frac{1}{(T)^2} \right] \right\}, \quad (13)$$

where H_1 is the distance from the hydrophone to the sea surface and H_2 is the depth of the source. The corresponding grazing angle is

$$\sin \theta = \frac{H_2}{r_1} = \frac{2c_w T H_2}{(c_w T)^2 + H_2^2 - H_1^2}. \quad (14)$$

Therefore, we may obtain

$$T = \frac{H_2 + \sqrt{H_2^2 \cos^2 \theta + H_1^2 \sin^2 \theta}}{c_w \sin \theta}. \quad (15)$$

For a monostatic transducer, $H_1 = H_2$, so insonified area may be simplified as

$$A = \pi \left(r + \frac{1}{4} c_w \tau \right) c_w \tau. \quad (16)$$

where $r = c_w T/2$ is the slant distance from the transducer to the sea surface. The difference in the locations of the source and the hydrophone had a major influence only on the scattering areas at high grazing angles and had little influence on those at intermediate to low grazing angles. Hence, Eq. (16) can be used for the calculation of bistatic scattering strength at low grazing angles.

Further, the insonified area near vertical incidence is a circle. In our case, we regard the bistatic scattering geometry as monostatic, and the equivalent depth of transducer is

$$H = \frac{H_1 + H_2}{2} \quad (17)$$

The insonified area near vertical incidence is

$$A_{\text{ver}} = \pi (H_1 + H_2)^2 \frac{1 - \sin \theta}{\sin^2 \theta}. \quad (18)$$

The relationship between mean grazing angles and received signal time series is

$$\sin \theta = \frac{H_1 + H_2}{c_w T}. \quad (19)$$

The sound pressure level of scattering signals may be computed from the voltage of received signals and the sensitivity of the hydrophone:

$$RL = 20 \log_{10} (V_e) - RS, \quad (20)$$

where V_e is the effective voltage value of scattering signals and RS denotes the sensitivity of the hydrophone used in the experiment, which was approximately (-196 ± 1) dB re 1 V/ μ Pa in the experiment frequency ranges.

4 Experimental results and analysis

In general, sea surface scattering is comprised of rough surface scattering and bubbles scattering. Consequently, the total scattering cross section σ_{tot} is given by:

$$\sigma_{\text{tot}} = \sigma_r + \sigma_b \quad (21)$$

Where σ_r and σ_b denotes rough surface and bubbles components respectively. The complete model for scattering strength is $10\log_{10}\sigma_{\text{tot}}$.

In this paper, the experimental results are compared with second order perturbation theory with “Pierson-Moskowitz” (PM) roughness spectrum and near-surface bubbles model follows [Dahl et al. \(1997\)](#). The results shows that the measured sea-surface backscattering strengths at grazing angles of 40°–80° are consistent with the prediction results of the small roughness perturbation theory, and the backscattering strengths at lower grazing angles are dominated by bubbles scattering.

For 1-D rough surface backscattering, $k_{ix} = -k_{sx}$ and $k_{iz} = k_{sz}$, where k_i and k_s are the incident and scattered wave numbers, respectively. The components are indicated by subscript. Then the second order perturbation backscattering cross section is given by:

$$\sigma_{1D}^{(2)} = \frac{4k_{iz}^4}{k} W(2k_{ix}). \quad (22)$$

With the PM roughness spectrum

$$W(k_{ix}) = \frac{\alpha}{4|k_{ix}|^3} \exp\left(-\frac{\beta g_c^2}{k_{ix}^2 U_{19.5}^4}\right), \quad (23)$$

where $U_{19.5}$ is wind speed at a height of 19.5 m, and $\alpha = 8.1 \times 10^{-3}$, $\beta = 0.74$, g_c is gravitational acceleration. Note that the measured backscattering strengths are from 2-D surfaces in our experiment. In general, there are intrinsic differences between scattering from 1-D and 2-D surfaces. However, [Thorsos \(1990\)](#) found the accurate relationship between scattering from 1-D and 2-D surfaces for second order perturbation theory expressions

$$\sigma_{2D}^{(2)} = \sigma_{1D}^{(2)} \frac{\Phi(2k \cos \theta_i, \phi)}{\cos \theta_i}, \quad (24)$$

where $\Phi(K, \phi)$ describes the azimuthal dependence of roughness spectrum, ϕ is azimuthal angle. In our case, scattering is from all the azimuthal angles. So, the averaged $\Phi(K, \phi)$ is

$$\Phi(K, \phi) = \frac{1}{2\pi}. \quad (25)$$

It then follows from Eqs (22)–(25) that the 2-D surface second order perturbation backscattering cross section

$$\sigma_{2D}^{(2)} \approx \mu_p \tan^4 \theta \exp\left[-\frac{\sigma}{f^2 U_{19.5}^4 \cos^2 \theta}\right], \quad (26)$$

where $\mu_p = 1.61 \times 10^{-4}$, $\sigma = 1.01 \times 10^6 \text{ m}^4 \cdot \text{s}^{-6}$, f is the acoustic frequency in hertz, and θ is the grazing angle. The scattering cross section $\sigma_{2D}^{(2)}$ in Eq. (26) was affected very little by variation in wind speed and frequency but was strongly dependent on the grazing angle; in particular, at small grazing angles, it sharply declined as the grazing angle decreased.

The bubbles scattering model used here is based on Dahl’s research, which summarized researchers’ works ([Clay and Medwin, 1977](#); [Crowther, 1980](#); [Sakar and Prosperetti, 1994](#)) with some simplifications. The bubbles scattering cross section is:

$$\sigma_b = \frac{\sin \theta}{8\pi} \frac{\delta_r}{\delta} (1 + 8\gamma e^{-2\gamma} - e^{-4\gamma}), \quad (27)$$

where $\gamma = \gamma_g / \sin \theta$, $\delta_r = 0.0136$ is the radiation damping constant at resonance, δ is the total damping coefficient at resonance, which is related to frequency by $\delta = 2.55 \times 10^{-3} f^{1/3}$, and γ_g describes the concentration of bubbles in seawater and is defined as the depth-integrated extinction cross section per unit volume. Generally, γ_g varies with seawater environment. Based on a large amount of experimental data, Dahl developed the following empirical formula for γ_g as a function of wind speed and frequency:

$$\log_{10} \gamma_g = -6.45 + 0.47 U_{10} + 0.85 \log_{10} f, \quad (28)$$

where U_{10} is the wind speed at 10 m height above sea surface, and f is the resonance frequency.

The comparisons of the measured backscattering strengths with second order perturbation theory and bubbles model are presented in [Fig. 4](#) and [Fig. 5](#). The red circle with error bar represents the measured backscattering strength, and the solid black line and dotted line indicate second order perturbation theory and bubbles model respectively. The total backscattering strengths are represented by dashed line. As shown in [Fig. 4](#) and [Fig. 5](#), the measured backscattering strengths agree well with the predictions of perturbation theory at mid to high grazing angles

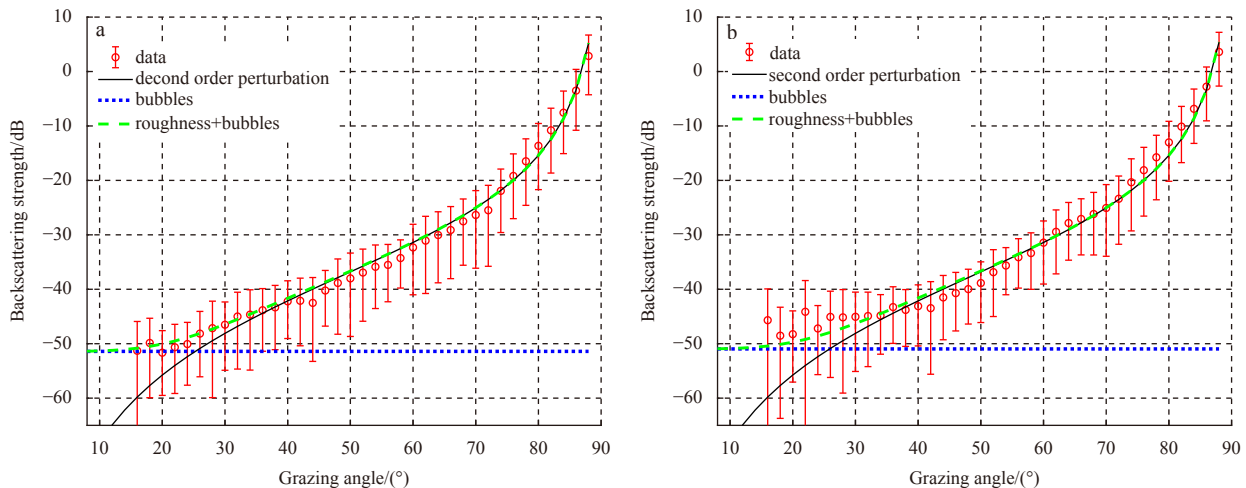


Fig. 4.

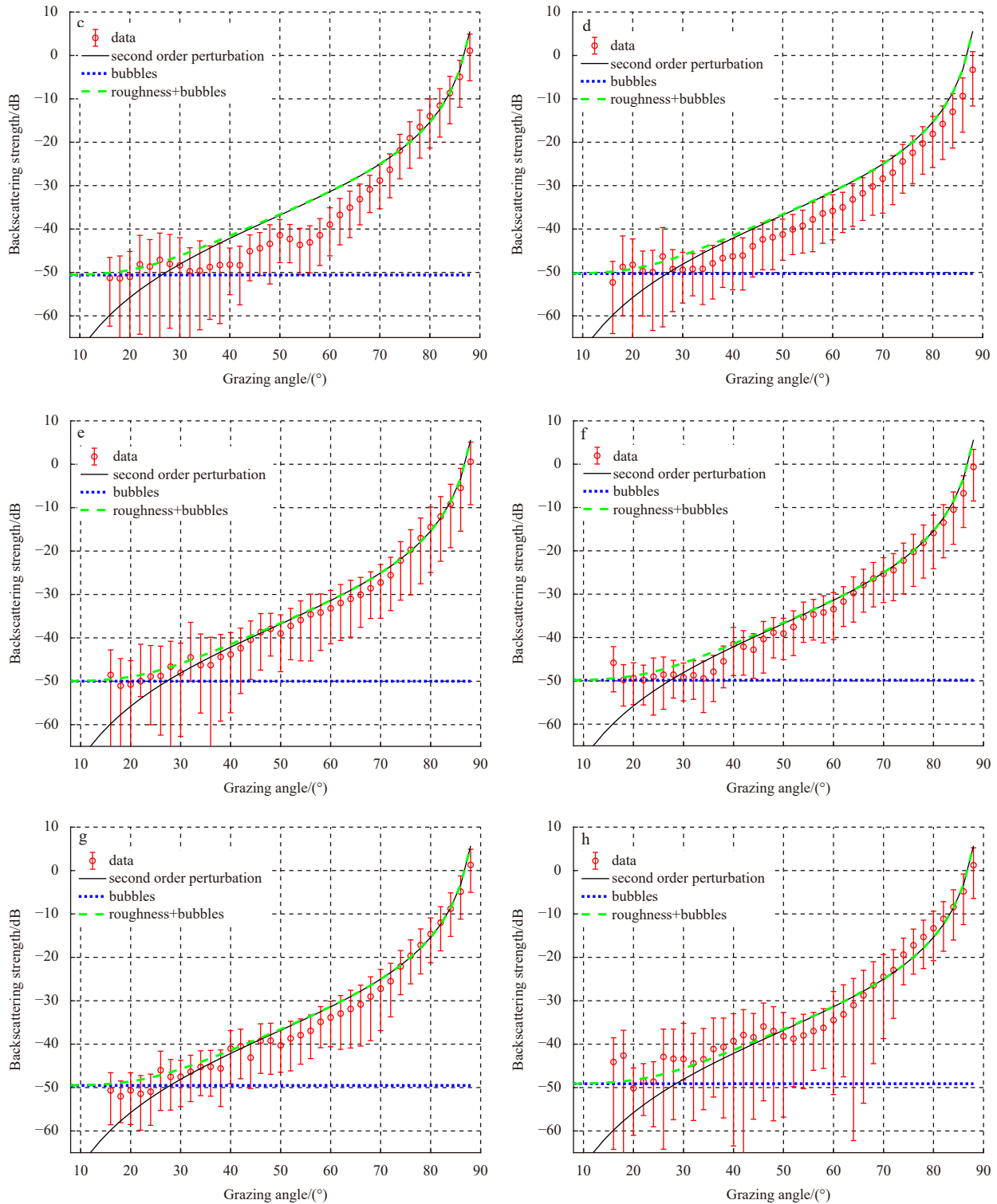


Fig. 4. Comparisons of the measured backscattering strengths with second order perturbation theory and bubbles model at wind speeds of 3 m/s. The frequencies are 9 kHz (a), 11 kHz (b), 13 kHz (c), 15 kHz (d), 17 kHz (e), 18 kHz (f), 21 kHz (g), 25 kHz (h), respectively.

(30°–85°). While at low grazing angles, the measurement scattering strengths exceeded the prediction of the small roughness perturbation approximation. The contribution of bubble scattering at frequencies of 6–25 kHz ranged from –52 to –49 dB at a wind speed of 3 m/s and from –45 to –42 dB at a wind speed of 4.5 m/s; these values are slightly smaller than the total backscattering

strength computed at grazing angles of <30°. Dahl et al. believed that near-surface bubbles have a crucial effect on sea-surface scattering mainly at low grazing angles (<30°) and high wind speeds (wind speeds > 3 m/s as generally considered). This assumption is supported by the results of our experiment. In summary, the sea-surface backscattering strengths at intermediate to

high grazing angles were primarily affected by the rough sea surface, and the contribution of near-surface bubbles generated by breaking waves to the total backscattering strengths was inconsiderable. Whereas the bubbles scattering is dominated at low grazing angles.

Figure 6 shows the comparisons of measured backscattering strengths at different wind speeds and at the same frequencies. It is evident that, within the frequency range from 6 to 21 kHz, the

backscattering strengths increased as the grazing angle increased. Moreover, At grazing angles in the range of 40° – 80° , the backscattering strengths are on average 5–10 dB higher at a wind speed of 4.5 m/s than at a wind speed of 3 m/s, in which the roughness scattering is dominated. Noted that the scattering strengths near the grazing angle of 50 at a wind speed of 3 m/s and frequencies of 12–14 kHz is abnormally stronger than that of adjacent grazing angles. Some kind of fixed interference of obser-

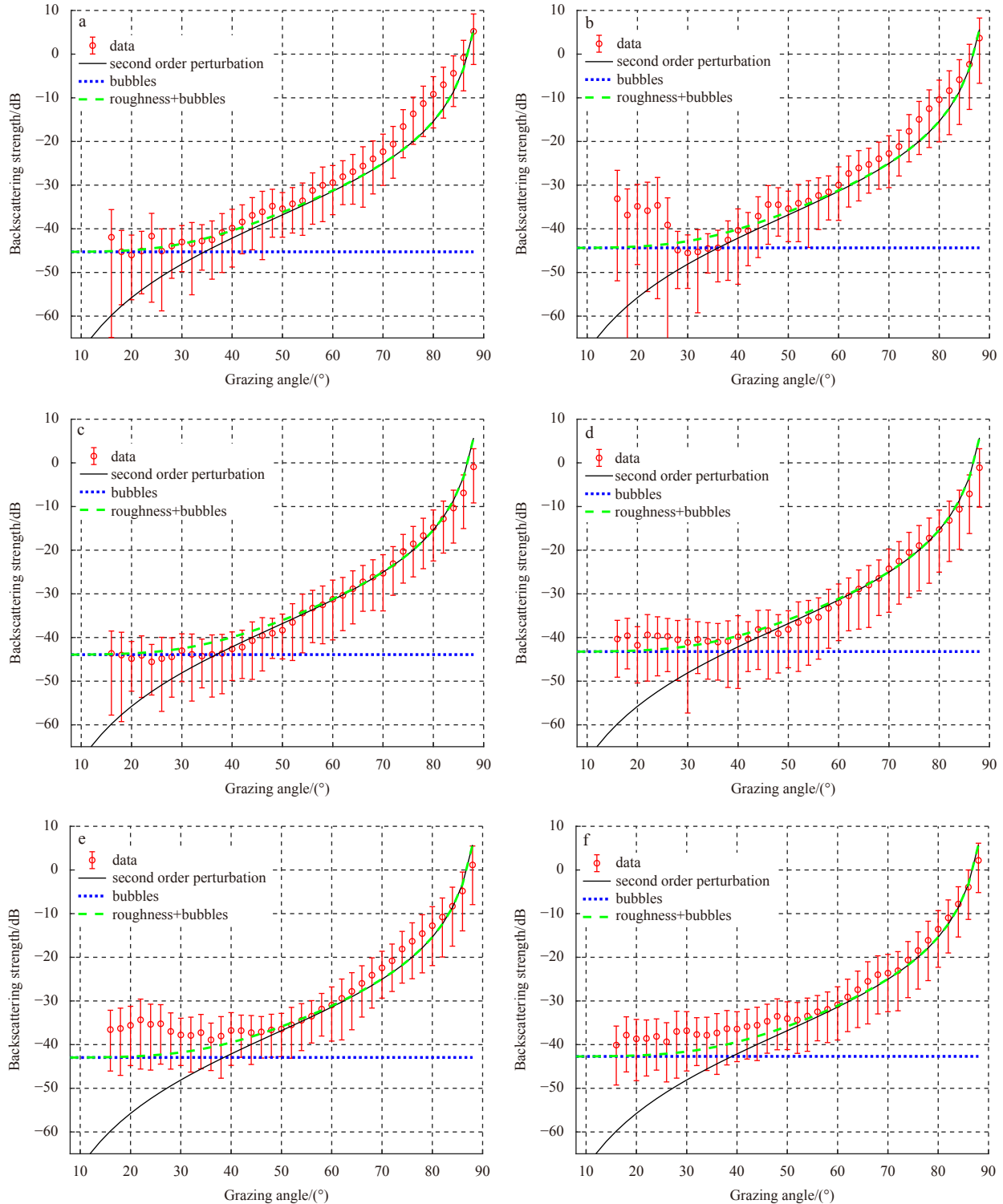


Fig. 5.

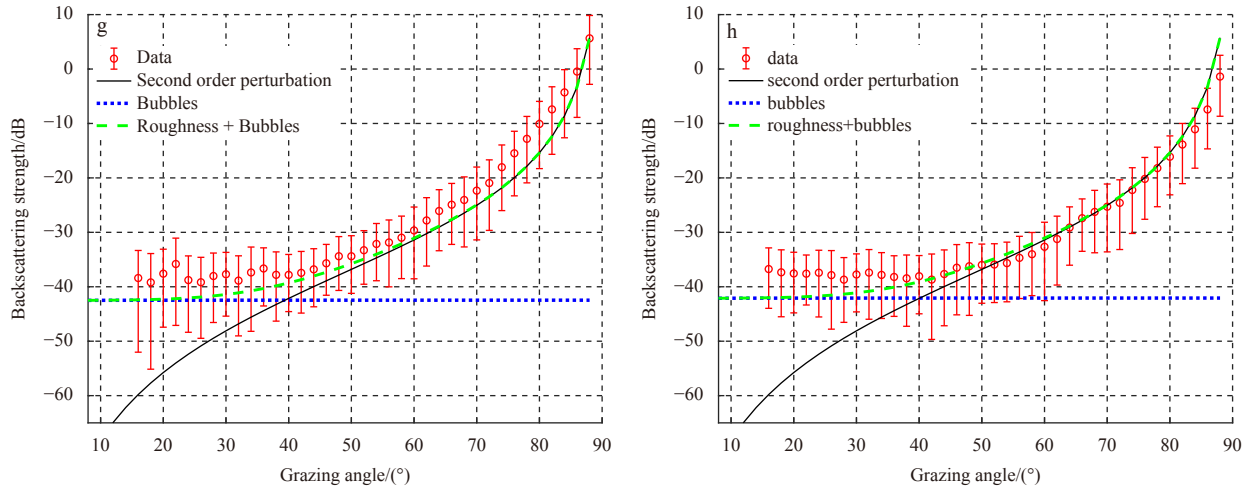


Fig. 5. Comparisons of the measured backscattering strengths with second order perturbation theory and bubbles model at wind speeds of 4.5 m/s. The frequencies are 6 kHz (a), 9 kHz (b), 11 kHz (c), 15 kHz (d), 17 kHz (e), 19 kHz (f), 21 kHz, (g), 25 kHz (h), respectively.

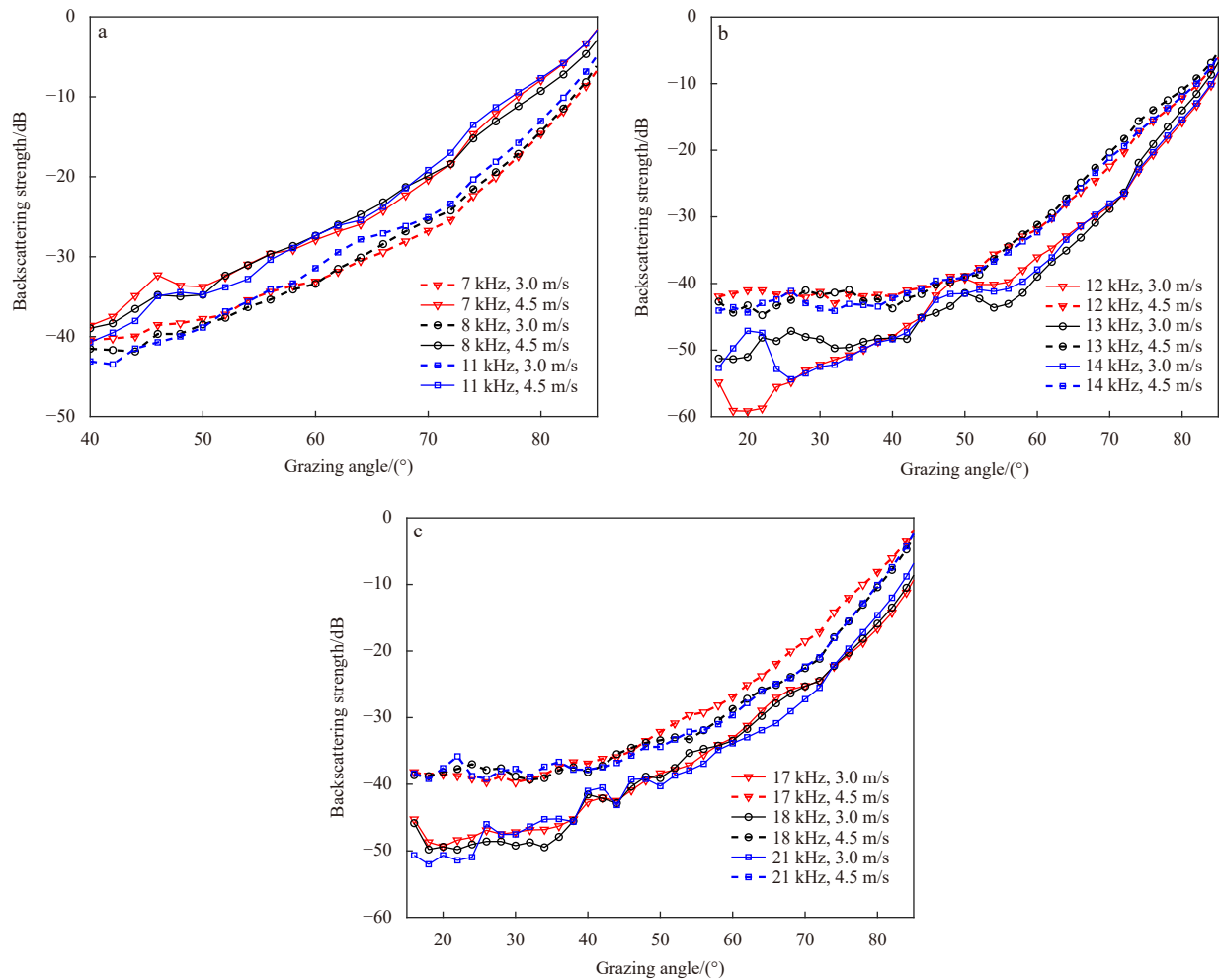


Fig. 6. Backscattering strengths at different wind speeds.

vation system may account for the phenomenon. The backscattering strengths essentially remained constant at grazing angles from 16° to 35° owing to the effect of scattering from bubbles. At a wind speed of 4.5 m/s, the bubbles scattering strengths are ap-

proximately -40 dB which are almost 10 dB higher than those at a wind speed of 3 m/s. As we can see in Fig. 4 and Fig. 5, there are some discrepancies between the data and bubbles model. The reason for these discrepancies may be related to variability in the

wind speed. Actually, γ_g in Eq. (22) is related to the depth-integrated distribution of resonant-sized bubbles, which is dependent on local environment generally. Therefore, it is very difficult to accurately predict the bubbles scattering, and this may be another reason for the discrepancies.

As shown in Fig. 7, at a wind speed of 4.5 m/s and at all frequencies between 6 and 24 kHz, the backscattering strengths at grazing angles between 40° and 80° differ slightly, and at the same grazing angles, the maximum difference in the backscattering strengths at different frequencies does not exceed 6 dB, which means that rough surface scattering is not sensitive to the frequency. However, the maximum discrepancy of backscattering strength at low grazing angles is more than 10 dB. Furthermore, the backscattering strengths show little frequency dependence, which is consistent with the studies of reverberation at frequencies of 15–60 kHz in open ocean (Lilly and McConnell, 1978). In fact, considering the uncertainty of measured backscattering strength which incorporates the statistical error and the systematic error, it is difficult to conclude the frequency dependence. The systematic error of this experiment is about ± 2 dB, which mainly included source level error and sensitivity error. The statistical error is ± 2 dB. Hence, the total uncertainty of this experiment is approximately ± 3 dB. Meanwhile wind speeds during the experiment fluctuated between a minimum value of 3.5 m/s and a maximum value of 5.5 m/s, so the fluctuation in wind speeds might be the primary cause for the fluctuation in backscattering strengths at different frequencies. Consequently, measurement errors and variation in environmental conditions would mask the influence of frequencies on sea-surface backscattering.

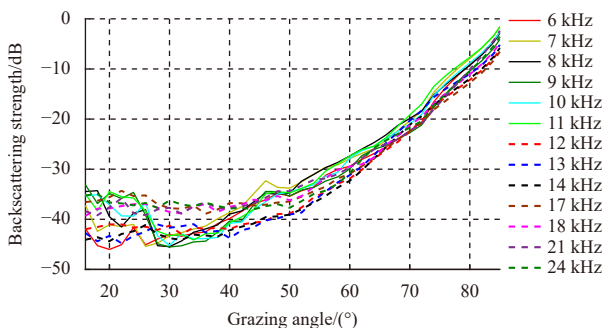


Fig. 7. Backscattering strength at a wind speed of 4.5 m/s and in the frequency range of 6–24 kHz.

Though it appears to be impossible to obtain the accurate frequency dependence, we can conclude the influence trend of frequency. As listed in Table 1, the slopes of linear regression between backscattering strength and the frequency in the range of 6–25 kHz at different grazing angles are computed. It can be seen that the slopes at low grazing angles are positive, and the slopes at high grazing angles are negative, which indicates that the scattering strengths increase at low grazing angles as the grazing angle increased but decrease at high grazing angles. The results at low grazing angles are not difficult to understand from Eq. (24). As for the results at high grazing angles, it may be the influence of bubbles. Because resonant bubbles scatter as well as absorb acoustic energy. The higher that frequency is, the stronger that the resonant bubbles scattering and attenuation is.

5 Conclusions

A sea-surface backscattering experiment was conducted in an

Table 1. Slopes of linear regression between backscattering and frequency at a wind speed of 4.5 m/s

Grazing angle/(°)	Slope/dB·kHz ⁻¹
20	0.203 0
24	0.142 6
30	0.496 5
34	0.401 9
40	0.203 7
50	−0.050 0
60	−0.170 4
70	−0.140 4
80	−0.111 2

offshore sea area employing omnidirectional sources and hydrophones. The sea-surface backscattering strengths at frequencies in the range between 6 and 25 kHz were obtained at wind speeds of (3 ± 0.5) and (4.5 ± 1) m/s, respectively. Meanwhile, environmental conditions including wind speed, water temperature, and water depth were monitored during the experiment. Backscattering strengths at grazing angles from 16° to 85° were measured, with values falling between −52 and 0 dB.

The experiment data show that the backscattering strengths at moderate to high grazing angles were dominated by sea-surface roughness and the experiment results were consistent with the prediction results of 2D second order roughness perturbation theory. Bubble scattering dominated the contribution to backscattering strengths only at low grazing angles and high wind speeds. The measured results agree well with the sum of rough scattering and bubbles scattering.

Grazing angle and wind speed made relatively important influences to the backscattering strengths. On average, the rough surface backscattering strengths at a wind speed of 4.5 m/s were 5 dB higher than those at a wind speed of 3 m/s. In contrast, At a wind speed of 4.5 m/s, the bubbles scattering strengths are approximately −40 dB which are almost 10 dB higher than those at a wind speed of 3 m/s. The backscattering strengths showed no evident frequency dependence. At a wind speed of 4.5 m/s, the backscattering strengths at high grazing angles and different frequencies had a maximum difference of 6 dB, the maximum discrepancy of backscattering strengths at low grazing angles is more than 10 dB, which is considered to be bubbles contribution. When comparing the slopes of linear regression between backscattering strength and the frequency in the range of 6–25 kHz at different grazing angles, it is clear that bubbles backscattering strengths increase as the frequency increased. In contrast, the roughness backscattering decrease as the frequency increased, which is supposed to be due to the attenuation of bubbles.

In this experiment, however, some improvement is possible. First, the environmental conditions during the experiment should be monitored in more detail. For example, measurement of wind speeds should be more accurate and be performed continually during the experiment, and measurement of the sea-surface wave spectrum should be added in the experiment. Second, scattering data require more wind speed samples to better analyze the detailed law of the effect of wind speed on sea-surface scattering.

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