Estimation of the sea surface wind from surface reverberation signals

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Abstract

From the reverberation signals received in the shallower water, the surface scattered signals are identified by using the multipath eigenray model that provides launch angles, grazing angles and transmission loss from the high frequency directional source to and from the rough surface. For small scale surface waves, the perturbation method is used to compute the backscattering strength for various grazing angles and wind speeds. A scheme to inversely estimate the wind speed, by which the observed surface reverberation levels are produced, has been tested. In result, for low grazing angles the perturbation method can be used to predict the backscattering strength, thereby the surface wind can be indirectly estimated.

I. Introduction

An acoustic signal projected into the sea will be reflected and scattered by the inhomogeneous medium, rough sea surface and sea floor. The sum of these echoes in the receiver is known as reverberation and is divided into three classes; volume, surface and bottom reverberation. The received reverberation level RL can be calculated by using the sonar equation

$$RL = SL - 2TL + S_s + 10 \log A$$

where, RL is reverberation level, SL is source level, TL is transmission loss from the source to scattering area, A is ensonified area and S_s is backscattering strength.

It is well known that the sea surface reverberation is caused by the rough sea surface and by microbubbles within a meter or so of the surface.

At present, it is generally agreed that the rough sea surface has relatively weaker wind speed and frequency dependence in scattering while the bubbles and plumes of bubbles play more important role in scattering for various frequencies and wind speeds[1, 2]. Several experiments by using high frequency directional sources also reveal that the measured reverberation levels are dependent on acoustic frequency, grazing angle, and wind speed[3, 4].

Since the surface acoustic scattering can be used to monitor the environmental condition at the sea surface, i.e. the wind speed, an inversive method to estimate the sea surface wind from the surface scattering signal is proposed. The wind above the sea surface generates the sea surface waves of different amplitudes of frequencies, that is, the rough sea surface, whereas the wind-wave action produces breaking waves and whitecaps such that the microbubbles are driven to a depth of few meters below the surface. However the exact estimation of the size and void fraction of subsurface bubble structures has not been successful yet. In particular, acoustic estimation of the bubble structures based on resonant behaviors of individual as well as plumes of bubbles have been tried and it shows some improvement in estimation.

From a series of field measurements of backscattering strength for different frequencies, wind speed and grazing angle, the data gathered by Chapman and Harris (1962) has been widely used. For example their empirical formula for the sea surface backscattering strength(S_s) is given by

$$S_s = 3.3\beta \log \frac{\theta}{30} - 42.4 \log \beta + 2.6,$$

where, $\beta = 158(vf^{1/3})^{-0.58}$, θ is grazing angle, v is wind speed in knots and f is acoustic source frequency in Hz For surfaces such as the sea surface, theory of the scattering of acoustical waves from rough surface consist of two separate approaches. One is the so-called perturbation theory [5] and is applicable for scattering from the small scale surface denoted by small Rayleigh parameter $P \equiv 2k\sigma \cos\theta_0$, where k is acoustic wavenumber, θ_0 = grazing angle and σ = rms roughness. The other is called the Kirchhoff approximation [6] and is valid on the large-scale surface or for the case of $P \gg 1$. Sometimes a composite-

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roughness theory is used to treat the case of two regimes-large-scale waves and small -scale waves [7].

Since the measured reverberation level from the field experiment includes all three effects of scattering, i.e, surface, bottom and volume, by partitioning the surface reverberation or surface scattering from other effects by using the eigenray informations, data set of backscattering strength for different grazing angles can be obtained. Based on this processed data set as well as other environmental conditions such as wind speed, sound velocity profile and source depth, etc, an inverse method will be employed to estimate the sea surface wind speed.

In this paper, procedure to establish the data set that includes the backscattering strength for various grazing angles will be introduced and it will be followed by an inversion method that will indirectly estimate the wind speed by data assimilation scheme.

Ⅱ. Reverberation signal analysis and inversion method

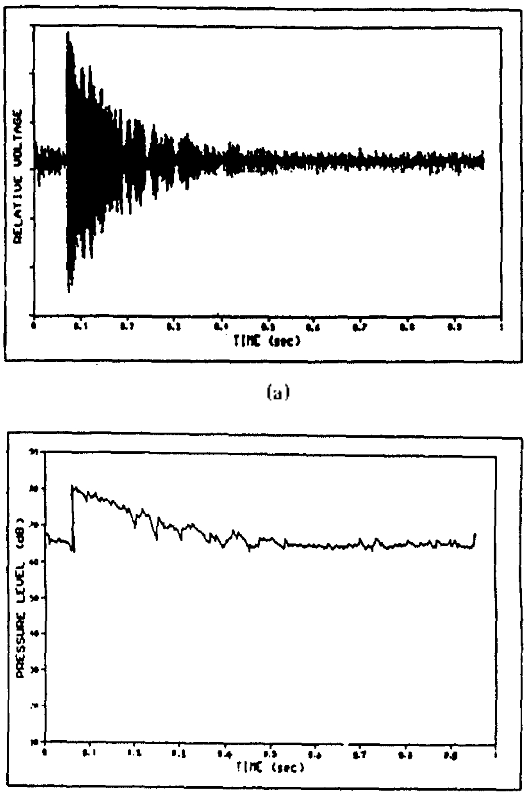
A high frequency, directional, monostatic transducer is located at 10m depth over the shallow water depth of 21m in the south sea during October, 1994. The vertical distribution of water temperature shows almost isothermal condition to make sound wave refracting upwards, which is a very good situation for surface scattering measurement (Table 1).

Table 1. Environmental conditions during the field experiment to obtain the reverberation signals.

Environmental parameters			
depth(m)	temp.(℃)		
0	20.82	windspeed	~5 knots
5	20.83	wave height	~0.5m
10	20.83	bottom depth	21m
15	20.83		
21	20.83	sediment type	mud

The time series data of the reverberation signals in analog form has been converted into digital format in dB scale by considering TVG(Time Varying Gain), pre-amplifier gain and receiving sensitivity (Fig.1).

In order to identify the arrival order of received signals that correspond to surface scattering and to determine the grazing angles, the multipath eigenray model[8] is used. The eigenray information as shown in Table. 2 provide horizontal range, travel time, launch angle, grazing angle and transmission loss, etc. The travel time and transmission loss level are obtained in the situation of one-way path whereas, the observed signal is calculated for two-way condition, i.e. from the source to and from the scatterer to the source. The travel times for each eigenray have been compared with significant peaks appearing on the received signals, and the data set of backscattering strengths for different grazing angles are established and some of them are shown in the Table 3. In fact, during



(a)

(b)

Fig. 1. Time series of observed reverberation signal in relative voltage(a) and decibel(b) scale. The surface reverberation is dominant right after the pulse, i.e. less than 0.1 second

Table 2. Eigenray informations computed by the multipath eigenray model showing horizontal range from the source to the sea surface, travel time, launch and grazing angles and the one-way pressure level for the surface reverberation signals.

range (m)	time (sec)	launch angle(deg)	grazing angle(deg)	level (dB)
60.0	0.039	10.32	9.20	−37.23
80.0	0.052	8.24	6.78	−39.98
100.0	0.065	7.08	5.29	−42.34
120.0	0.078	6.35	4.27	−43.81
140.0	0.091	5.89	3.55	−45.55

Table 3. The backscattering strengths from the observed signals for different grazing angles based on the multipath eigenray model(the angles have ±1° error with 90% confidence interval).

data set grazing angle	1	2	3	4
4°	−70.4 dB	−69.9 dB	−70.3 dB	−68.9 dB
6°	−67.3 dB	−68.3 dB	−70.0 dB	−67.8 dB
7°	−66.0 dB	−65.7 dB	−65.4 dB	−66.5 dB
9°	−63.6 dB	−62.3 dB	−64.2 dB	−65.0 dB

the period of field measurements, the ocean surface was rather smooth with the observed wave height of 0.5m and wind speed about 4 knots. Therefore the data set must reflect the conditions of small-scale surface without any significant effects of bubble-induced backscattering.

From the sonar equation given earlier we have RL, TL, SL and ensonified area A and thus the backscattering strength S_s can be calculated for different grazing angles which turned out to be low-grazing angle conditions. For small-scale sea surface the Rayleigh parameter P is much less than 1 and it is natural to apply the perturbation method to calculate the backscattering strength coefficient as given by Brekhovskikh and Lysanov [9]

$$m_s = (2^{1/2}\, C/g^3)(k/x)^4\, v \cos^2\theta_0 \cos^2\theta\, a^{-1/2} \exp(-1/a) K(v, \alpha),$$

where, $a \equiv (2g)^{-1}\, xv^2$, v is wind speed in m/sec, C is 2.4 m^2/sec^5, k is acoustic wavenumber, x is sea surface wave number, g is gravitational acceleration and $K(v, \alpha)$ is function of the angular distribution of sea wave energy. At high frequencies $K(v, \alpha) = b\cos^2\alpha$, but with $b = (\pi)^{-1}$ for $\alpha = 0$ from normalization condition of $\int_{-\infty}^{\infty} K(x, \alpha) d\alpha = 1$, K becomes $(\pi)^{-1}$. The wavenumber of the surface waves x can be determined from the relation $x = 4\pi^2/gT^2$, where T is the period of surface waves and it is taken as 1.5 seconds based on the observations. Furthermore, in order to have $P \ll 1$, we have used observed wind speed of 5 knots to determine the average wave height $\overline{H}$ from the Pierson-Moscowitz spectra(1964), that is, $\overline{H} = 1.34 \times 10^{-2} \times v^2$, where v is the wind speed in m/sec, and $\overline{H} \simeq$ 8.8cm gives $P \ll 1$. The expression from the backscattering strength given above shows the dependence on the wind speed, grazing angle and acoustic frequency. Eventually we are going to use this expression to estimate the wind speed by comparing various values of backscattering strength for different grazing angles.

The procedure of indirect estimation or an inversive method shown in Fig. 2 can be summarized as follows; from the processed data set, select grazing angles and corresponding scattering strength(S_s). Then using the S_s as input, repeat the computation by changing the wind speed until the computed S_s converges to the input value of S_s for the selected given grazing angle. When the convergence is satisfied by a given criteria, for example, the difference of two S_ss in dB scale falls below 2~3 dB, that wind speed is selected as an estimate.

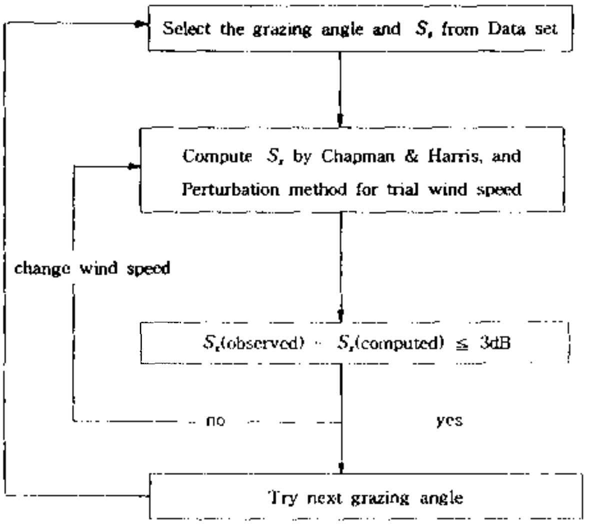


Fig. 2. Block diagram showing the procedure of indirect estimation of wind speed by comparison of observed S_s with computed S_s for different grazing angles.

Because of the field measurements under the condition of small scale roughness (wind speed of 5 knots), S_s computations were carried out by two methods;Chapman and Harris empirical formula and the formula derived by the perturbation method. Fig. 3 and 4 show the backscattering strength VS. grazing angles for different wind speeds computed by the formula given by Chapman and Harris and by the perturbation method, respectively. Also shown in these figures are curves drawn for different wind speeds. In Fig. 3, a curve that includes four values of grazing angle selected from reverberation signal is closely following the one that is corresponding to the wind speed of 5 knots for lower grazing angles but disparities of about 8 dB exist for higher grazing angles.

However, when measured backscattering strength is compared with those computed by the perturbation method(Fig. 4), the disparities are very much reduced even for higher grazing angles. Considering the error bars, which may be a consequence of variations in transmission loss, the observed curve is more closely following 5 knots-wind speed curve. Therefore, when the sea surface has a small-scale roughness, the perturbation method can be used to estimate the sea surface wind speed despite the lack of observed data for different grazing angles.

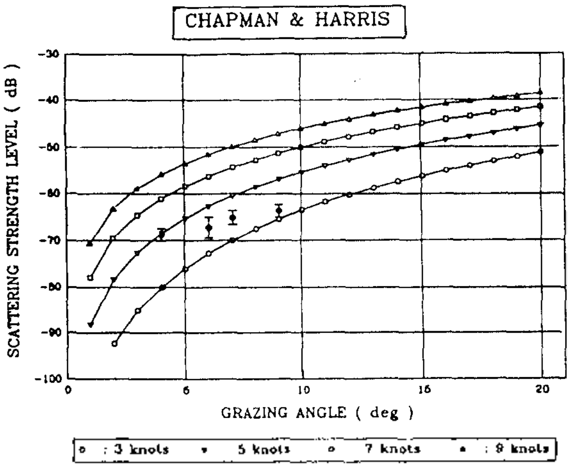


Fig. 3 Backscattering VS. grazing angles for several wind speeds computed by the formula of Chapman and Harris. Observed values are plotted with variability showing except for very low grazing angles, the disparities are significant compared to Fig. 4.

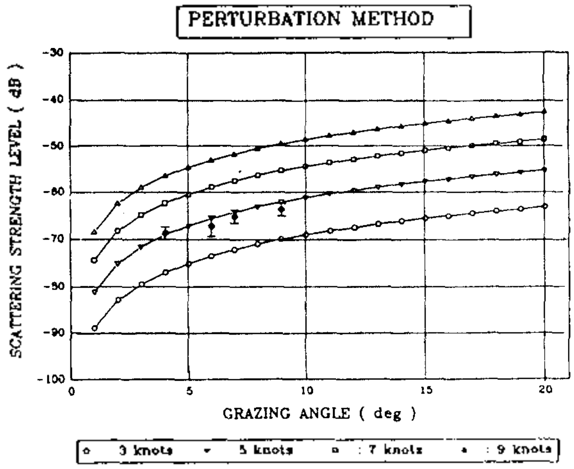


Fig. 4. Backscattering VS. grazing angles for several wind speeds computed by the perturbation method. The observed values are plotted with variability and they closely follow the curve for the 5 knots wind

Ⅲ. Discussion and Conclusions

When a sonar system, that is installed on a moving platform, is used for detection of underwater target, in order to avoid boundary scattering, especially, surface reverberation, the transmitting beam is usually steered to horizontal direction. This type of sonar operation results in low grazing angle backscattering from the rough surface and the reverberation signals caused by rough surface contain information on the sea state in terms of wind speed.

The reverberation signals obtained from field experiment in shallow coastal water have been analysed to establish the data set. The data set consists of travel time, launch angle, grazing angle and backscattering strengths for each eigenray. Eigenray informations have been computed by using the multipath eigenray model. For small-scale roughness, without considering any effects of bubbles or bubble plumes in resonant backscattering, the perturbation method has been used to iterate the wind speed until the measured value of scattering strength approaches the value computed by the theory. Since the data set reflects low grazing angle scattering and also the sea surface was rather calm, estimation of the wind speed based on the perturbation theory turns out to be acceptable within the error range of 2~3dB.

In fact, the state of sea surface in terms of wave height, period and direction of propagation is dependent upon the wind speed, duration of wind, and the distance over which the wind has blown. However, during the period of observation wind speed of 5knots, according to the Pierson and Moscowitz spectrum[10], gives the average wave height of less than 0.1m. Therefore for such a small scale roughness, wind speed prediction or estimation may be possible by using the perturbation method to calculate the backscattering strength. But in case of large scale roughness, a formula based on the Kirchhoff approximation is known to be valid. For example, Brekhovskikh and Lysanov(1982) presents the scattering coefficient m_s as

$$m_s = V^2 (8\pi\delta^2 \cos^4 \theta_0)^{-1} \exp(-\frac{\tan^2 \theta_0}{2\delta^2})$$

where δ is rms roughness and is given by $\delta^2 = (3 + 5.12\ v) \times 10^{-3}$ where v is wind speed in m/sec. V is the reflection coefficient and $V^2 = 1$ for the free surface. If we apply the observed wind speed and the grazing angle, the ms becomes near zero and this means that the formula given above is valid only for forward scatter[11].

From the reverberation signals, one can determine the surface grazing angles and the corresponding backscattering strength by using the multipath eigenray model. Then using the iteration scheme to make the difference between the observed backscattering strength and the computed one based on the perturbation theory, wind speed over the rough sea surface can be estimated inversely. This method, however, is limited to lower grazing angles since actual reverberation signals received right after the pulse transmission reflects a short period of duration for the surface scattered rays.

More data with high frequency directional transducer is required to produce various grazing angles as well as signals under the higher wind speed to have large scale roughness.

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