Ocean gravity wave phase velocity detection by HFSWR

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Abstract: The formula of inversion ocean gravity wave phase velocity from high frequency surface wave radar (HFSWR) sea echo is derived. By field data analysis at deep water condition, the ocean gravity wave phase velocity is verified by comparison with theoretical velocity based on deep water dispersion relationship.

Keywords: ocean gravity wave phase velocity, high frequency surface wave radar, inversion

Classification: Electron devices, circuits, and systems

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1 Introduction

High frequency surface wave radar (HFSWR) takes advantage of the low attenuation characteristic of high frequency electromagnetic waves (3 MHz to 30 MHz) propagating across the ocean surface to measure the ocean surface current, wind and wave [1]. Current is measured by Doppler principle based on the Bragg resonance between radio wave and ocean gravity waves with half wavelength of radio wave moving directly towards and away from radar [2, 3, 4, 5].

Till now ocean surface current inversion from the HFSWR all assume deep water condition and the Bragg ocean gravity wave phase velocity is independent of water depth. But in fact, there is shallow water which may cause uncertain about the ocean gravity wave phase velocity, especially at the near shore area closely related with people’s lives. This will influence the accuracy of ocean surface dynamic parameters inversion from HFSWR [6, 7].

In this paper, ocean surface gravity wave phase velocity inversion method from HFSWR sea echo is provided. The phase velocity calculation formula is derived with the positive and negative peak of the first order Doppler spectra. The algorithm diagram of gravity wave phase velocity is also introduced. In order to test the advanced method, field experiment data is analyzed.

2 Principle

Barrick derived the first-order sea echo radar cross section by perturbation method which lay the foundation for HF radio wave ocean surface current detection [8]. The formula can be expressed as

$$\sigma^{(1)}(\omega) = 2^6 \pi k_0^4 \sum_{m=\pm 1} S(-2m\vec{k}_0) \delta(\omega - m\omega_B) \quad (1)$$

where ω is the Doppler frequency, ω_B is the resonant Bragg circular frequency, $S(-2m\vec{k}_0)$ is the directional wave spectrum of ocean wave $-2m\vec{k}_0$, $\vec{k}_0$ is the wave vector of incident radio wave, $m = \pm 1$ denotes the two wave vector moving towards and away from the radar. The δ function describes a pair of distinct peaks located on either side of the 0 Hz line.

In the formula (1) ω_B is caused by ocean gravity wave phase velocity, and the current velocity can also cause Doppler shift, so the Doppler frequency can be denoted as

$$\begin{cases} f_+ = f_B + f_r \\ f_- = -f_B + f_r \end{cases} \quad (2)$$

where f_+ and f_- are the Doppler frequency of positive and negative first-order spectra respectively, f_B is Bragg Doppler frequency and $f_B = \frac{\omega_B}{2\pi}$, f_r

is the Doppler shift caused by current. And we have

$$\begin{cases} f_B = \frac{2V_P}{\lambda_0} \\ f_r = \frac{2V_r}{\lambda_0} \end{cases} \quad (3)$$

where V_P is ocean gravity wave velocity, V_r is ocean radial current and λ_0 is radio wavelength.

In deep water, the dispersion relationship for gravity wave is $\omega^2 = gk$, and phase velocity $V_P = \frac{\omega}{k} = \sqrt{\frac{g}{k}}$, where g is gravity acceleration, k is gravity wave number, so we know that when ocean gravity wave number is constant, the phase velocity is invariable, and the Doppler frequency caused by gravity wave is invariable. But in shallow water, the phase velocity is a function of water depth, which is not suitable for current inversion with the popular algorithm. In this paper we process (2) by subtraction and obtain the f_B

$$f_B = \frac{f_+ - f_-}{2} \quad (4)$$

Simultaneous equation (3) and (4), we can obtain the ocean gravity wave phase velocity

$$V_P = \frac{(f_+ - f_-)\lambda_0}{4} \quad (5)$$

3 Phase velocity inversion from broad beam HFSWR

3.1 Inversion method

The currently HFSWR in the world such as SeaSonde, Wera (Wellen Radar) and OSMAR (Ocean State Monitoring and Analysis Radar) are all broad beam HF radars. This kind of HF radars have one transmitting antenna with a broad wave beam up to 120° and with 3 to 16 antennas consisting as a receiving array the signal direction of arrival can be estimated, so the first-order spectra of sea echo is composed of sea echo from broad directions. To the broaden first-order spectra we cannot use (6) to calculate ocean gravity wave velocity directly, and we should get the Doppler spectra points at the same direction first. Here we can use spectral space estimation method to estimate signal direction and Fig. 1 shows the basic flow chart of phase velocity inversion from broad beam HFSWR.

3.2 Direction estimation

To the broad beam HFSWR, MUSIC (Multiple Signal Characteristic) algorithm is widely used for signal direction of arrival estimation. The algorithm is super-resolution, small amount of calculation and fast speed [9]. Assuming that the receiving antenna array has N elements and the coordinate denotes as (x_i, y_i) , $i = 1, 2, \dots, N$, the directions of narrow band signal are $\theta_1, \theta_2, \dots, \theta_k$, then the signal model of receiving array is

$$\mathbf{X}(t) = \mathbf{A}(\theta)\mathbf{S}(t) + \mathbf{N}(t) \quad (6)$$

Fig. 1. The flow chart of phase velocity inversion from broad beam HFSWR

where $\mathbf{A} = [\mathbf{a}(\theta_1) \ \mathbf{a}(\theta_2) \ \cdots \ \mathbf{a}(\theta_k)]$, $\tau_i = [x_i, y_i][\sin(\theta), \cos(\theta)]^T$ and $\mathbf{a}(\theta_i) = [1, \exp(-j\frac{2\pi}{\lambda}\tau_2), \dots, \exp(-j\frac{2\pi}{\lambda}\tau_N)]^T$, λ denotes the wavelength of radio wave, $\mathbf{N}(t)$ and $\mathbf{S}(t)$ are the observation noise and signal. And the estimation of covariance matrix $\mathbf{R}_{xx}$ is

$$\mathbf{R}_{xx} = E[\mathbf{X}(t)\mathbf{X}^H(t)] = \mathbf{A}\mathbf{R}_{ss}\mathbf{A}^H + \sigma^2\mathbf{I} \quad (7)$$

By eigenvalue decomposition (EVD) the observation space can be partitioned into a signal subspace $\mathbf{E}_S$ and a noise subspace $\mathbf{E}_N$. And the two subspace is orthogonal, so we can obtain the MUSIC spectra [9]

$$P_{MUSIC} = \frac{1}{\mathbf{A}^H\mathbf{E}_N\mathbf{E}_N^H\mathbf{A}} \quad (8)$$

In formula (8), the determination of signal subspace and noise subspace needs estimate the signal number and the general methods are gerschgorin disk criterion method, eigenvalue gradient method and so on. In this paper, the eigenvalue gradient method is used, which can refer to reference [10].

4 Data analysis

4.1 Radar system

The HFSWR system OSMAR071 is located at Longhai, Fujian Province of China Sea. The system is consists of transmitter, receiver, antenna system, display and storage system. Fig. 2(a) shows the hardware structure. OSMAR071 applies the Frequency Modulated Interrupted Continuous Wave (FMICW) waveform with 30 kHz bandwidth and 5 km distance resolution. A three-element Yagi-Uda antenna serves as transmitting antenna and an 8-element non-linear receiving array as the radar antenna filed. Array amplitude and phase correction is obtained by real-time software calibration [11].

Fig. 2. Radar system OSMAR071 and data processing result: (a) The hardware structure; (b) Sea echo of range frequency Doppler spectra (c) First-order Doppler spectra determination; (d) Direction estimation at Doppler frequency 0.2815 Hz; (e) Direction estimation at Doppler frequency -0.2755 Hz; (f) The ocean gravity wave phase velocity extracted from HFSWR; (g) Absolute error statistic diagram.

Table I. Inversion result

Item	Negative frequency (Hz)	Positive frequency (Hz)	Phase velocity (m/s)
1	-0.2725	0.2935	5.4321
2	-0.2635	0.2995	5.4034
3	-0.2755	0.2905	5.4321
4	-0.2606	0.3055	5.4321

Fast Fourier Transform (FFT) process is used by every pulse-repetition-interval (PRI) which called as a snapshot to produce a Range spectrum. After coherent accumulation at the same range, a second FFT is used to produce range frequency Doppler Spectrum. Fig. 2 (b) shows the measured range frequency Doppler Spectrum of 1024 PRI coherent accumulation, which is from Longhai NO.3 receiving antenna. From Fig. 2 (b), we can see that a typical HFSWR sea echoes' range frequency Doppler Spectrum contains two nearly symmetrically located first-order peaks (within 200 km), second-order continuum spectral points (within 100 km), the obvious distance belt distributed ionosphere reflection echo (near 150 km and 220 km) and the noise floor.

4.2 Result

The analysis data is collected from July 28 to July 29, 2008. In Fig. 2 (c), the area between red lines is first-order spectra and the green line is the Bragg frequency at deep water condition. The data is at 10 range cell which is 50 km away from the radar site and the time is 4:30, July 28, 2008. The negative first-order spectra frequency is from -0.3025 Hz to -0.2546 Hz and the positive is from 0.2725 Hz to 0.3055 Hz respectively, the frequency resolution is 0.0030 Hz. The signal number and direction of every first-order spectra is estimated by MUSIC algorithm. In Fig. 2 (d) the analyzed spectra Doppler frequency is 0.2815 Hz, the estimated signal number is 2 and the signal directions are -50° and 34° . In Fig. 2 (e) the analyzed spectra Doppler frequency is -0.2755 Hz, the estimated signal number is 1 and the signal directions is 47° .

The ocean gravity wave phase velocity extracted by the method involved in this paper are listed in the Table I. The data is at 8 range cell which is 40 km away from the Longhai radar site and the time is 12:00, July 28, 2008.

4.3 Analysis

The radio frequency of HFSWR data collected above is 7.81 MHz, the radio wavelength is 38 m and the Bragg ocean gravity wave length is 19 m. The 40 km away from Longhai Radar Site is deep water, so the Bragg frequency is 0.2851 Hz, and the theory ocean gravity wave phase velocity is 5.4715 m/s. Compare with the inversion phase velocity, the error is within 0.1 m/s.

In order to confirm the accuracy of gravity wave phase velocity, the 271 range frequency Doppler spectrum from July 28 to July 29, 2008 is analyzed. The analyzed data is from range cell 6 to 10, and the distance is 30 km

to 50 km. 1726 pairs of positive and negative first-order Doppler spectra are obtained. The Fig. 2 (f) shows the inversion ocean gravity wave phase velocity. The Fig. 2 (g) shows the statistic absolute error. The confidence interval of different absolute error is that 90% inversion phase velocity's error is with threshold 0.3342 m/s, and at 85%, 80%, 75%, 70% the threshold are 0.2693 m/s, 0.2193 m/s, 0.1905 m/s, 0.1618 m/s, respectively.

5 Conclusion

The ocean gravity wave phase velocity can be extracted from HFSWR sea echo. We propound an algorithm for the ocean gravity wave phase velocity from broad beam HFSWR. The inversion phase velocity is agree well with theory calculation value by deep water sea echo analysis. The method involved in this paper is suitable for any sea water depth, moreover for the bistatic HFSWR.

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