Research on wave height cross-sections of UHF radio wave scattering from periodic water surface waves

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Abstract The relationship between wave field information (wave height, wavelength, etc.) and radar echo is hard to analyze with conventional measurement and extraction methods due to the randomness and complexity of the ocean. To improve wave field information estimates, we used an ultrahigh-frequency (340 MHz) radar to probe subscale water waves in the laboratory. First-order radar cross-section Doppler spectra were measured and analyzed. The results indicate a significant linear correlation between RCS (dB) and wave height (dB) (all correlation coefficients $R > 0.9$) but no linear correlation exists between RCS (dB) and wavelength (dB).

Keywords: ultrahigh-frequency radar, Bragg scattering, flume experiment, radar cross section

Classification: Electromagnetic theory

1. Introduction

Information about ocean dynamics such as wind speed, wave height and flow rate have great significance for national defense, production and research since Crombie first interpreted the dominant components of backscattered sea echoes with Bragg resonance theory [1]. In most research, ocean dynamics information is gathered by high-frequency (HF) radar. In 1977, Barrick [2, 3, 4] proposed an approximate method for inverting the ocean wave height nondirection spectrum using first-order and second-order radar cross-sections (RCS). Wyatt et al. [5, 6, 7, 8] studied wave measurements in different sea-states. Roarty et al. [9, 10] examined several wave-inducing factors to improve wave measurements. Zhou et al. [11, 12, 13, 14] proposed an inverse method by using the unsaturated property of the first-order Bragg spectral power in 2015. Tian [15, 16, 17] estimated wave height from dual-frequency radar data in 2017. However, it is hard to describe the ocean status with an accurate expression because of random wavelengths, wave heights and wave directions. In order to analyze complex ocean waves thoroughly, the random ocean model should be idealized with a single wavelength, wave height and wave direction; however, it is unrealistic to generate such a water wave in the ocean. In this project, a subscale water wave is generated to simulate the actual ocean in a multifunctional flume by controlling a single variable, such as the single frequency of a water wave. Similar methodology is widely used in research. Dennis C Cooper [18, 19, 20] conducted a series of laboratory experiments to analyze the first- and second-order backscatter Doppler spectra of water surface waves in a flume based on microwave frequencies (2.5 GHz). Lee PHY [21, 22, 23] conducted a series of laboratory experiments to analyze Bragg and non-Bragg scattering between different polarizations. Research on wave water electromagnetic scattering in a flume focuses on microwave and capillary waves, which have different mechanisms from deep water gravity waves.

Minimal research regarding ocean dynamics has been based on ultrahigh-frequency radar (UHF radar) and a multifunctional flume. UHF radar has many advantages on subscale experiments in a flume. First, the UHF electromagnetic wave scattering mechanism on a water wave satisfies the dispersion relation of gravity waves. Second, UHF electromagnetic waves have wavelengths on the magnitude of decimeters, which are between microwave and high-frequency waves [24, 25, 26, 27]. This wave is sensitive to decimeter water waves, which are easy to generate in a multifunctional flume. Third, the UHF radar studied in this paper has a range resolution of only 10 m, with a maximum detection length of 300 m, which can cover the entire flume and accurately detect water waves in the flume. In summary, this paper utilized UHF radar to conduct the subscale experiment, and used a multifunctional flume to generate certain wavelengths and certain wave heights of a sine water wave.

2. Wave flume experiment

The multifunction wave flume was provided by the State Key Laboratory of Coastal and Offshore Engineering of Dalian University of Technology. The overall structure of the experimental flume is shown in Fig. 1 [28]. The working depth of the wave flume is 0.8 m. The distance between two sensors is 34.7 cm. This radar system was designed and made by Radar and Signal Processing Laboratory of Wuhan University. It adopts a linear frequency modulated interrupted continuous waveform (LFMICW) mechanism and operates at 340 MHz, which depends on the presence of 44-cm-wavelength waves (one-half of the radar wavelength $\lambda = 0.88$ m). Both the transmitting and receiving antennas are TDJ-350A Yagi antenna, and their gain is 11 dB. The specific waveform parameters are as shown in Table I [29, 30, 31].

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According to the waveform parameters of the UHF radar above, its Bragg frequency is caused by a gravity wave $f_B = 1.88$ Hz; the wavelength of the water caused Bragg scattering $L_B = \lambda/2 = 0.44$ m, and its wave period $T = 0.54$ s.

The multifunction wave flume could generate a specific single-frequency sinusoidal water wave with different wavelength and wave height. Two pressure sensors record the water surface profile, which is shown in Fig. 2. The distance between the two sensors is 34.7 cm.

3. Analysis

3.1 Experimental data and analysis

The power density spectra of the backscatter from the water surface pro
duced by the UHF radar are shown in Fig. 3. In this system, there are $N = 256$ sweep periods in each coherent integration period; thus, one coherent integration period is $T = N \times T_s = 11.08$ s. Fig. 4 shows the relationship between RCS and wave height from different wavelengths $L$. ‘*’ represents the average power value $P$ (dB) of first peak at every data point (every coherent integration period). ‘0’ represents the average power value $P$ (dB) = $E(P)$ of the first peak in each coherent integration period and the same parameter (same wave height $h$ and same wavelength $L$). The slash is the curve fitting of $P$ (dB) and $h$ (dB). The correlation coefficients in the two sets of parameters are $0.9957$ and $0.9945$. The results indicate that the linear correlation between $P$ (dB) and $h$ (dB) is very prominent.

3.2 The relationship between RCS and wavelength

When the echo signal from the water wave is steady, the longer the coherent integration period is, the stronger the echo signal power, the greater the signal-to-noise ratio, and the more conducive to extraction are the ocean state parameters. In this system, there are $N = 256$ sweep periods in each coherent integration period; thus, one coherent integration period is $t = N \times T_s = 11.08$ s. Fig. 4 shows the relationship between RCS and wave height from different wavelengths $L$. '0' represents the average power value $P$ (dB) = $E(P)$ of the first peak in each coherent integration period and the same parameter (same wave height $h$ and same wavelength $L$). The slash is the curve fitting of $P$ (dB) and $h$ (dB). The correlation coefficients in the two sets of parameters are $0.9957$ and $0.9945$. The results indicate that the linear correlation between $P$ (dB) and $h$ (dB) is very prominent.

3.3 The relationship between RCS and wavelength

The overall structure of the experimental flume. Two antennas are 1 m above the water surface.
3.4 Slope k and correlation coefficient of the fitted curve

Table II shows slope k and correlation coefficient R of the fitted curve of different wavelengths L. Regardless of wavelength change, slope k is stable near 1, and all correlation coefficients R are greater than 0.9. Thus,

\[ P = Ah^k \]  \hspace{1cm} (4)

Fig. 2. Wave profile recorded by two sensors.

(a) Wavelength \( L = 6 \times \lambda/2 \), wave height \( h = 3\) cm, 6cm, 10cm, 16cm

(b) Wavelength \( L = 8 \times \lambda/2 \), wave height \( h = 3\) cm, 6cm, 10cm, 16cm

Fig. 3. Power spectra of the backscatter from different wavelengths. The horizontal axis is Normalized Doppler Frequency (NDF)

Fig. 4. Relationship between RCS and wave height \( h \) from different wavelengths L

(a) Wavelength \( L = 6 \times \lambda/2 \)

(b) Wavelength \( L = 8 \times \lambda/2 \)
Fig. 5. The relationship between RCS and wavelengths $L$ from different wave heights $h$

| $L$ | $k$ | $R$ |
|-----|-----|-----|
| $2 \times \lambda/2$ | 1.0657 | 0.9894 |
| $3 \times \lambda/2$ | 1.0282 | 0.9929 |
| $4 \times \lambda/2$ | 0.8825 | 0.9622 |
| $5 \times \lambda/2$ | 0.8288 | 0.9790 |
| $6 \times \lambda/2$ | 0.9646 | 0.9957 |
| $7 \times \lambda/2$ | 1.2283 | 0.9689 |
| $8 \times \lambda/2$ | 1.0139 | 0.9494 |
| $9 \times \lambda/2$ | 0.9519 | 0.9757 |
| $10 \times \lambda/2$ | 0.7852 | 0.9960 |

4. Conclusion

This result obtained from the scaled experiment in the flume verified that the linear correlativity between RCS and wave height is very prominent, and no correlativity exists between RCS and wavelength. Wave height is one of the most important dynamic parameters of the ocean. This research prepares dynamic parameters of the ocean for quantitative analysis via radar, and the relationship between the power of other peaks and hydrodynamic parameters will be studied in future work.

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