THE MEASUREMENT OF OCEAN WAVELENGTHS BY SATELLITE ALTIMETERS (I)

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1. Introduction

Satellite altimeters, one of microwave active sensors, are basically a short pulse monostatic radar[1, 2]. The radar pulses are transmitted to ocean surfaces successively as a pulse repetition frequency. In existing satellite altimetry, the ocean waveheight is measured by analyzing the leading edge of the mean return waveform of backscattered pulses from ocean surfaces. To observe other parameters of ocean waves: for example, the wavelength as well as to increase the accuracy of existing measurement is the center of interest in satellite altimetry. To solve this subject, we have studied new methods for data processing. This study needs raw data of scattering, but it is difficult to obtain them by measuring ocean waves simultaneously. Our approach is to generate three-dimensional ocean waves numerically and to evaluate the pulse train backscattered from them, which pulse train needs to have the same statistical properties as the real ones: e.g., the pulse trains obtained by SKYLAB and SEASAT altimeters. We have already shown that the pulse train simulated by our method has the same statistics[3, 4].

In previous studies, we have proposed a method of measurement of ocean wavelengths[4, 5]. In this paper, we investigate the validity of measurement of ocean wavelengths by considering the off-nadir angle of antenna.

2. Models of ocean waves

Let us assume that ocean waves are characterized by the Pierson-Moskowitz spectrum[6] of deep sea. Then we approximate the spectrum by using several line spectra ($f/f_m = 0.9, 1.0, 1.3, 1.5, 1.7, 2.0, 3.0$), and add to them extra four higher line spectra ($f/f_m = 5.0, 7.0, 8.0, 10$) which show small undulation on ocean waves. Once defining the spectra and giving the significant waveheight H and the significant wavelength L for an ocean wave, we can determine the amplitude a_i and the wavelength l_i of each component wave. On the above assumption, the ocean surface may be expressed as follows:

$$h(x,y) = \sum_{i=1}^{11} a_i \sin\left(\frac{2\pi}{l_i} x\cos\theta_i + \frac{2\pi}{l_i} y \sin\theta_i + \varepsilon_i\right) \tag{1}$$

where, θ_i, decided in the manner that component waves do not harmonic for each other, indicates the direction of propagation and ε_i, selected from uniform random numbers between 0 and 2π, is the initial phase angle of each component wave.

3. Formulation of backscattered pulses

First we consider backscattered pulses from the models of ocean waves, of which geometry is shown in Figure 1. It may be assumed that an incident pulse wave is radiated from a small electric dipole oriented in the x direction and that only the x component of electric fields is received on satellite. The transmitted pulse width is short enough that the entire ocean target may be regarded as stationary one. The ocean surface is assumed to be a perfect conductor for simplicity. By using the physical-optics approximation, the backscattered waves at the satellite can be given by

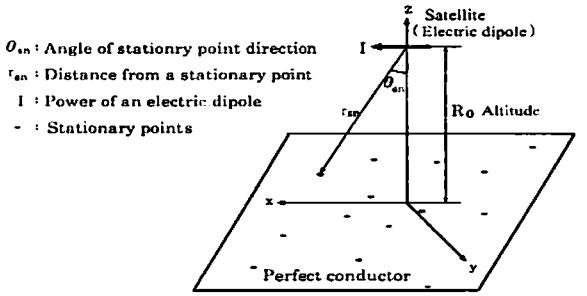

Figure 1. Geometry of the problem

$$\mathbf{E}^S(\mathbf{R}_0) = \frac{\exp[-jkR_0]}{kR_0}(\mathbf{i}_R \times \mathbf{F}) \times \mathbf{i}_R, \quad \mathbf{i}_R = \frac{\mathbf{R}_0}{|\mathbf{R}_0|} \tag{2}$$

$$\mathbf{F} = \frac{k^3 Z_0 I}{8\pi^2} \int dx \int dy \mathbf{K}_0(\mathbf{R}') \exp[jk\{h(x,y) - r\}] \tag{3}$$

$$\mathbf{K}_0(\mathbf{R}') = \frac{1}{r^2}\left[\mathbf{i}_x \left\{h(x,y) - R_0 - y\frac{\partial h}{\partial y}\right\} + \mathbf{i}_y y \frac{\partial h}{\partial x} + \mathbf{i}_z \{h(x,y) - R_0\} \frac{\partial h}{\partial x}\right] \tag{4}$$

The above integral can be calculated by the stationary phase method. As only the x component of electric fields is received on satellite, Eq. (2) can be written as

$$\begin{aligned}\mathbf{E}^S(\mathbf{R}_0) &= \frac{kZ_0 I}{4\pi R_0} \sum_{n=1}^{N} \frac{\sigma}{|d|^{\frac{1}{2}}} D_0^2 \exp\left[-\frac{4\ln 2}{\theta_h^2}(\theta_{sn} - \theta)^2\right] \mathbf{i}_x \{h(x_{sn}, y_{sn}) - R_0 - y_{sn}\frac{\partial h}{\partial y}\} \\ &\quad \cdot \frac{1}{r_{sn}^2} \exp[jk\{h(x_{sn}, y_{sn}) - R_0 - r_{sn}\}]\end{aligned} \tag{5}$$

where (x_{sn}, y_{sn}) is a stationary point, N is the number of stationary points in a searching ocean region, θ_h is the half-power beamwidth, θ is the off-nadir angle, and d and σ, respectively, are given as follows:

$$d = f_{xx}f_{yy} - f_{xy}^2, \quad \sigma = \begin{cases} 1; & d < 0 \\ j; & d > 0,\ f_{xx} > 0 \\ -j; & d > 0,\ f_{xx} < 0 \end{cases} \tag{6}$$

The backscattered wave pulse $\mathbf{P}_s(\mathbf{r}, t)$ against a continuous wave pulse is given by multiplying $\mathbf{E}^S(\mathbf{R}_0)$ by the spectral function of the incident rectangular pulse and then by taking the inverse Fourier transform. Assuming that the backscattered wave pulse is square-law detected at satellite, the pulse response against an incident pulse wave, that is, the single pulse response can be given by

$$P_{SPR}(t) = \frac{1}{2Z_0}(\{\mathrm{Re}[\mathbf{P}_{s0}(\mathbf{r}, t)]\}^2 + \{\mathrm{Im}[\mathbf{P}_{s0}(\mathbf{r}, t)]\}^2) \tag{7}$$

where $\mathbf{P}_{s0}(\mathbf{r}, t)$ is the complex envelope of $\mathbf{P}_s(\mathbf{r}, t)$. Then the mean pulse response can be given as the sum of many pulse responses:

$$P_{MPR}(t) = \frac{1}{M} \sum_{m=1}^{M} P_{SPR}[t + (m-1)\Delta t] \tag{8}$$

where Δt is the pulse repeated interval and M is the number of single pulses.

4. Method of computer simulation

Let us calculate the mean return waveform from Eq. (8). As mentioned above, return pulses are determined from stationary points of the ocean surface illuminated by each pulse. However, it takes extremely much time to find all the stationary points in an illuminated ocean region. Hence, we select randomly some points out of the stationary points in the region, keeping the statistical property of return pulses. The random sampling method is as follows: The region is first divided into small squares of which side length is the one-sixth wavelength of the component wave with the maximum energy. Next we search a stationary point in the

neighborhood of the center in each square. By using this method, the computation time can be reduced remarkably.

We use SKYLAB and SEASAT altimeters, of which parameters are given at Table 1 where the time slot is used to measure the pulse response within a given period as an instantaneous value for computation. For simplicity, the foot prints of SKYLAB and SEASAT are assumed to be 6[km]×6[km] square and 1.3[km]×1.3[km] square in our simulation, respectively.

Table 1. The parameters of satellite altimeters

	SKYLAB	SEASAT
Altitude R_0	435[km]	800[km]
Velocity	7650[m/s]	7450[m/s]
Pulse repeated interval	4.0[ms]	5.0[ms]
Antenna beam width	1.5°	1.5°
Frequency	13.9[GHz]	13.5[GHz]
Pulse width	1.0e-7[s]	3.125e-9[s]
Time slot for measurement	1.25e-9[s]	1.25e-9[s]
Foot print size	7.2[km]	1.7[km]

5. Results of data analysis

We try to obtain the pulse train by computer simulation and to calculate the mean return waveforms for some ocean wave models. Figures 2 and 3 show the mean return waveforms for ocean wave models of H = 3[m] and four different significant wavelengths, where the off-nadir angle $\theta = 0$ and 0.2° are assumed, respectively. The ripple of waveforms in Fig. 3(b) are caused by the reduction of the number of stationary points in our simulation scheme used here. Figures 2 and 3 also show that the maximum received power becomes large as increasing L, which result is independent of the off-nadir angle. It may be possible to determine ocean wavelengths by using this difference.

Next let us investigate the accuracy of measurement of ocean wavelengths. Table 2 shows the mean and the standard deviation of the maximum received power for ocean waves of four significant wavelengths, where $\theta = 0.2°$. We can see from Table 2 that even if $\theta \neq 0$, then L may be determined with about 5m accuracy which depends on the fluctuation of received pulse power from the mean. We note that the pulse width and the off-nadir angle have no effect on the measurement of ocean wavelengths. The rise times of pulses shown in Figs. 2 and 3 are almost equal to each other, independent of L, which result shows the validity of the computer simulation.

6. Conclusion

The computer simulation permits one to calculate some return-pulse waveforms by changing the significant wavelengths of ocean waves. We have shown the validity of measurement of ocean wavelengths by using the first statistics of the return pulses. We are developing a method to determine ocean wavelengths by using the second statistics as well as the first.

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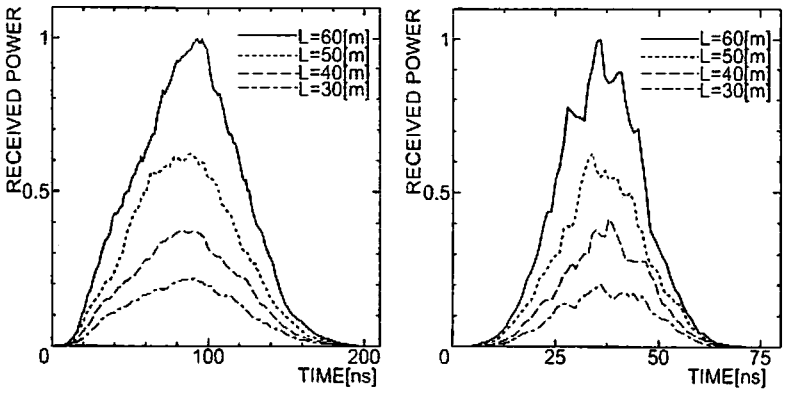
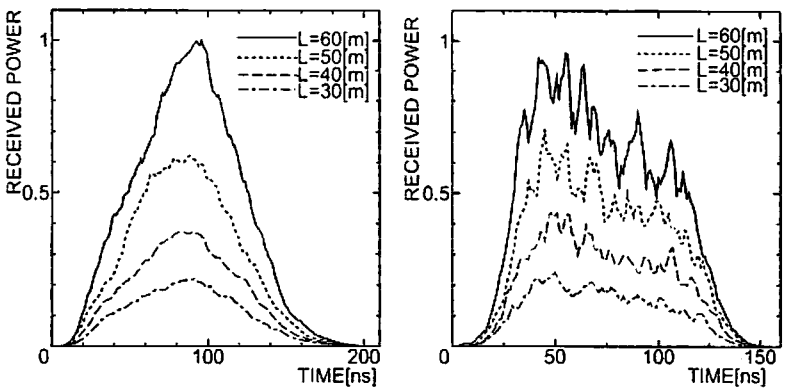


(a) (b)

Figure 2. The normalized powers as a function of time for ocean wave models of four significant wavelength L = 60, 50, 40, and 30[m], received by (a) SKYLAB and (b) SEASAT altimeters. The significant waveheight H is fixed at 3[m]. The off-nadir angle $\theta = 0$



(a) (b)

Figure 3. The normalized powers as a function of time for ocean wave models of four significant wavelength L = 60, 50, 40, and 30[m], received by (a) SKYLAB and (b) SEASAT altimeters. The significant waveheight H is fixed at 3[m]. The off-nadir angle $\theta = 0.2°$

Table 2. The mean and the standard deviation of the maximum received power for ocean waves of several significant wavelengths , where the off-nadir angle $\theta = 0.2°$ is assumed and 100 pulses received by SKYLAB and SEASAT altimeters are used for obtaining each mean.

significant wavelength L[m]	normalized maximum received power			
	SKYLAB		SEASAT	
	mean	standard deviation	mean	standard deviation
60	1.00	0.096	1.00	0.062
50	0.61	0.041	0.66	0.046
40	0.41	0.046	0.45	0.023
30	0.23	0.029	0.25	0.015