Time Domain Numerical Simulation of Microwave Backscattering from Sea Surface for Radar Remote Sensing

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***Abstract*- Time domain numerical simulation technique has been developed to understand microwave backscattering mechanisms and evaluate sea surface observation methods. Backscattering coefficients and Doppler spectra can be obtained by this simulation technique. Physical optics approximation is applied to calculate scattering electric fields. The validity of the simulation has been verified by comparing with the results of the experimental basin. The results indicate that the simulation technique is effective to calculate microwave backscattering from the water surface changing in time. As an application of the simulation, we have simulated microwave backscattering with a pulse Doppler radar to evaluate sea surface observation methods. Radar images of backscattering coefficient and Doppler velocity have been generated. The results of the simulation show that radar images of Doppler velocity are more effective than images of backscattering coefficient for sea surface observation.**

I. INTRODUCTION

Sea surface observation is important as the base of ocean researches and developments. In order to ensure safe and reliable observation technique, radar remote sensing is used to observe the broad sea surface. The principle of sea surface observation by active microwave remote sensing is radiating microwaves to the sea surface and estimating sea surface profiles by analyzing backscattering microwave. When the microwave is radiated to the sea surface, backscattering microwave shows the scattering property corresponding to the condition of the sea surface.

In order to improve measurements of the sea surface by active microwave remote sensing, it is necessary to understand mechanisms of microwave backscattering from the sea surface. A microwave scattering phenomenon at the sea surface is complicated and not clarified enough. In general, microwave backscattering has been explained by scattering theories [1][2]. Most scattering theories have mentioned about the amplitude modulation of microwave backscattering, but they have hardly mentioned about the frequency modulation. The frequency of backscattering microwave is modulated by Doppler shift due to motions of water particles. A Doppler radar can measure the sea surface condition by using the frequency modulation of backscattering microwave [3][4].

Sea surface observing algorithms of remote sensing with a Doppler radar have been verified by the results of experimental basin. However, experiments can be conducted under the simple condition, because there are a lot of limitations such as equipment, water condition, etc. Therefore, numerical simulation technique has been expected to be a substitute for an experiment and it will be a useful tool to evaluate sea surface observation method for radar remote sensing. So far, numerical simulation technique to obtain microwave backscattering from sea surface at one time has been developed by Rheem and Kobayashi [5] and Ano[6].

The purpose of the present research is developing the time domain numerical simulation technique. This simulation technique can calculate microwave backscattering from the numerical sea surface changing in time. Doppler spectrum is obtained by analyzing time series data of scattering electric fields. The validity of the simulation is shown by comparing with the result of experimental basin. Furthermore, as an application of the simulation technique, we have simulated microwave backscattering with a pulse Doppler radar and evaluate sea surface observation methods by radar images.

II. SIMULATION METHOD

Backscattering coefficients and Doppler spectra can be obtained by the simulation. The flowchart of the numerical simulation is shown in Figure 1 and is described as follows.

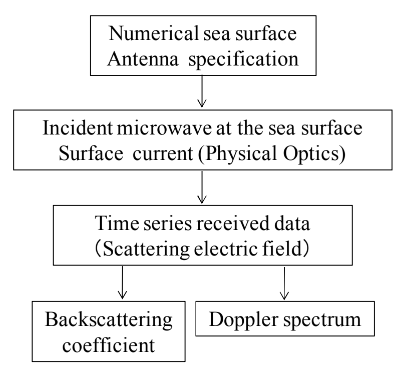

Fig.1 Flowchart of numerical simulation.

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A. Numerical Simulation of Sea Surface Profile

Microwave backscattering is influenced wind wave whose wavelength is the same level as the microwave. In the simulation, the wavelength λ of microwave is 0.03125 m(X-band). Local sea surface profiles are numerically generated by wind wave spectra. Mitsuyasu&Honda spectrum [7] is used in this study. Mitsuyasu and Honda proposed a high frequency wave spectrum which gives frequency and wind speed dependences as following equation

$$S(\omega) = \alpha_S g_* u_* \omega^{-4} \tag{1}$$

where ω is the angular frequency of the spectral component and u_* is the friction velocity of the wind. α_s is the value relating to u_*. g_* is gravitational acceleration with regard to surface tension. Some examples of Mitsuyasu&Honda spectra to generate numerical sea surface profiles in the simulation are shown in Figure 2, where U is the wind speed at 0.3 m height.

Irregular sea surface elevation η is expressed as the summation of linear waves with random phase ε, and is the following equation

$$\eta(x, y, t) = \lim_{N,M\to\infty} \sum_{j=1}^{M} \sum_{i=1}^{N} \cos\left(k_i x \cos\theta_j + k_i y \sin\theta_j - \omega_i t + \varepsilon_{ij}\right) \cdot \sqrt{2S(\omega_i) D(\theta_j) \Delta\omega_i \Delta\theta_j} \tag{2}$$

where k is the wave number, θ is the angle of wave direction, $D(\theta)$ is the dimensional distribution function. Irregular sea surface velocity is also expressed as the summation of linear waves with random phase.

In order to generate numerical sea surface profiles with capillary waves, we use following dispersion relation. (Rheem et al. [8])

$$\omega = \sqrt{g_* k} + k\left[u_0 + u_r e^{2kz_0}\left(Chi 2kz_0 - Shi 2kz_0\right) + u_c\right] \tag{3}$$

where *Chi* is hyperbolic cosine integral and *Shi* is hyperbolic sine integral. z_0 is roughness parameter and u_c is uniform current. u_0 and u_r are surface current and current gradient due to wind, respectively. Numerically-simulated sea surface conditions (surface elevation at one point, surface profile at one time and two-dimensional surface velocity) are shown in Figure 3.

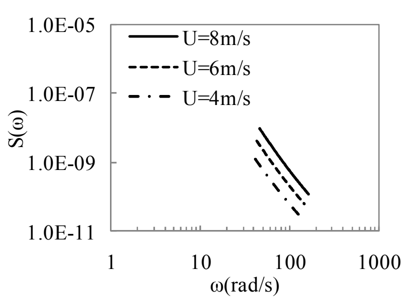
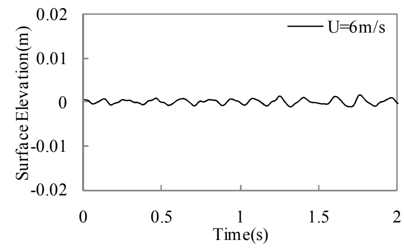
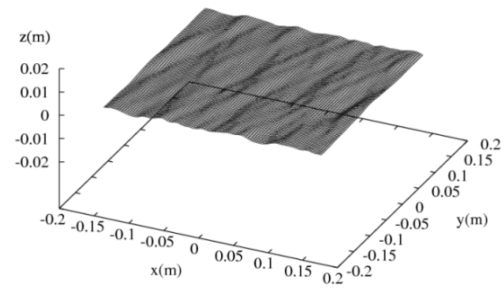


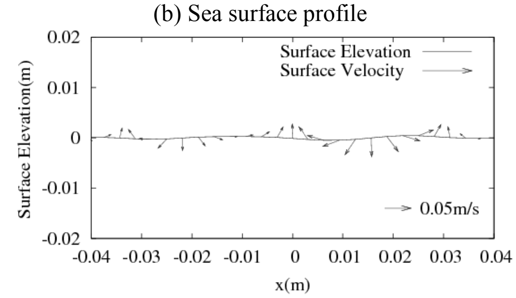
Fig.2 Mitsuyasu&Honda spectra of wind waves.



(a) Sea surface fluctuation



(b) Sea surface profile



(c) Sea surface velocity

Fig.3 Numerically-simulated sea surface condition of wind waves.

B. Antenna specification

The formula relating the power density S_i of an antenna to the input power P is as follows.

$$S_i = \frac{PG}{4\pi R^2} \tag{4}$$

where R is the distance from the observation point to the scattering point. The gain G of an antenna is defined as the ratio of the power density radiated by the subject antenna to a lossless isotropic antenna.

The main-beam antenna gain is expressed approximately as the following equation

$$G(\beta) = G_0 \exp\left[-\left(\frac{\beta}{\beta_{1/2}}\right)^2 \ln 2\right] \tag{5}$$

where G_0 is the maximum gain. β is the angle defined as the directional properties of the radiation pattern. $\beta_{1/2}$ is the half-power beam width defined as the angular width of the main lobe between the two angles at which the magnitude is equal to half of its peak value.

C. Physical Optics

Physical optics approximation is applied to calculate scattering electric field $\boldsymbol{E}_s$ by surface integral of induced surface currents $\boldsymbol{J}$.

$$\boldsymbol{E}_s = -j\omega\mu \int_S \boldsymbol{J} \frac{e^{-jkR}}{4\pi R} dS \tag{6}$$

$$\boldsymbol{J} = 2\boldsymbol{n} \times \boldsymbol{H}_i \tag{7}$$

where ω and k are the angular frequency and wave number of microwave respectively. μ is the magnetic permeability. $\boldsymbol{n}$ is the surface normal vector of each computational grid and $\boldsymbol{H}_i$ is the incident magnetic field.

D. Backscattering Coefficient

Radar cross section σ represents the ability of scattering microwave energy to an antenna and is defined as following equation

$$\sigma = 4\pi R^2 \frac{|\boldsymbol{E}_s|^2}{|\boldsymbol{E}_i|^2} \tag{8}$$

where $\boldsymbol{E}_i$ is the incident electric field. Backscattering coefficient is defined as σ/A, where A is a microwave illumination area.

E. Doppler Spectrum

When a water particle is moving at a velocity (toward an antenna) v_r , Doppler frequency shift Δf is described as following equation

$$\Delta f = f_0 \frac{2v_r}{c} \tag{9}$$

where f_0 is the frequency of incident microwave, c is the light velocity. Doppler spectra are obtained by analyzing backscattering electric fields which are modulated in frequency. In the actual wave observation by using a Doppler radar, received electric fields are divided into I (In-phase) and Q (Quadrature) signals. Then, positive and negative Doppler shift are obtained by analyzing IQ signals.

In the simulation, time series backscattering electric fields are calculated. Then, real part and imaginary part of them are defined as I and Q signals.

F. Simulation mesh size

Coordinate system of the simulation is shown in Figure 4. Numerical sea surface is divided into triangle meshes. Microwave backscattering from a flat surface is calculated to evaluate mesh size effects. Simulation results are compared to analytical solution in eq.(6). Microwave backscattering at φ = 0° obtained by analytical solution and numerical simulation are shown in Figure 5. The results of the simulation correspond to the analytical solution. This result shows that mesh size of λ/10 is enough to simulate microwave backscattering from the sea surface.

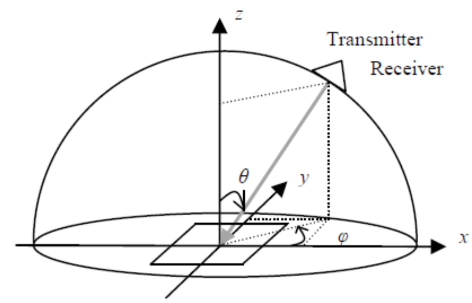


Fig.4 Coordinate system of numerical simulation.

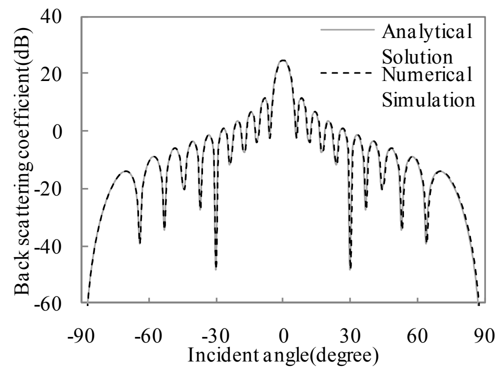


Fig.5 Comparison of backscattering coefficients between numerical simulation and analytical solution.

III. COMPARISON WITH EXPERIMENT

To verify the validity of the simulation technique, microwave backscattering was simulated under the same condition as the experiment and compared to the results of the experimental basin at the Chiba experiment station of the Institute of Industrial Science, the University of Tokyo. In the simulation, Mitsuyasu&Honda spectra shown in Figure 2 are used to generate numerical sea surface of wind waves.

Microwave frequency is 9.6 GHz, wave length λ is 0.03125 m(X-band, VV polarization). Antenna gain is 20 dBi, and half-power width is 13.7°.

The relation between incident angle and backscattering coefficient obtained by simulation is compared to the experimental result. In the experiment [9], the distance from the water surface to the antenna is 3.5 m. Wind speed is 8.6 m/s. In the simulation, the distance from the water surface to the antenna is 4.25 m. Wind speed is 8 m/s. Calculation area is 40λ × 40λ (1.25 m × 1.25 m). Sampling frequency is 100 Hz. The result of backscattering coefficients is shown as an accumulated for 5 s sampling. Incident angle dependence in the case of existing only capillary waves is shown in Figure 6. In the simulation result, the area of received antenna is not considered and illumination area is different from the experimental result. Thus, absolute values are different from each other. However, tendency of simulation results shown in Figure 6 is quite similar to the experimental result.

The relation between wind speed and backscattering coefficient obtained by simulation is compared to experiment and is shown in Figure 7. In the experiment in 2008 and the simulation, the distance from the water surface to the antenna is 4.25 m. Incident angle is 30°. Calculation area is $40\lambda \times 40\lambda$ (1.25 m × 1.25 m). The result of backscattering coefficients is shown as an accumulated mean value for 5 s sampling. Backscattering coefficients of both simulation and experiment are increasing with wind speeds.

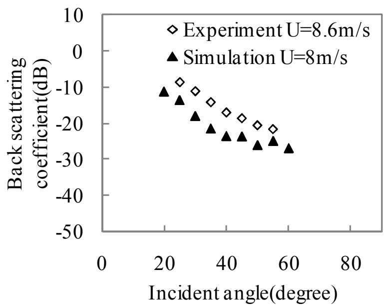


Fig.6 Comparison of relation between incident angle and backscattering coefficient (Incident angle dependence).

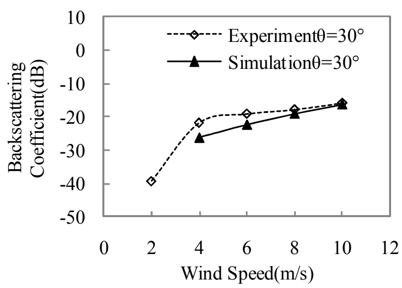


Fig.7 Comparison of relation between wind speed and backscattering coefficient (Wind speed dependence).

In addition, backscattering coefficients and Doppler velocity are simulated and compared with the experiment in the case of existing both capillary waves and regular gravity waves. The regular wave period is 2 s and the wave height is 0.12 m. Wind speed is 6 m/s.

The distance from the water surface to the antenna is 4.25 m. Incident angle is 30°. Calculation area is $60\lambda \times 60\lambda$ (1.875 m × 1.875 m). Sampling frequency is 1000 Hz. The result of backscattering coefficients is shown as moving average for 0.1 s. Doppler spectra are analyzed data for 0.128 s. The result is the Doppler velocity which shows the mean value of Doppler spectrum.

Figure 8 shows the fluctuation of backscattering coefficients which is influenced by the regular wave. Tilt modulation of backscattering coefficients is shown in Figure 8.

Fluctuation of Doppler velocity is shown in Figure 9. Numerical sea surface is generated simply as the summation of linear waves, but actual sea surface is nonlinear phenomenon. Therefore, simulated Doppler velocity variation is different from experiment. However it is almost the same value as the regular wave orbital velocity. Furthermore, the fluctuation period of Doppler velocity is consistent with the period of the regular wave. These results show that this simulation technique is effective to demonstrate microwave backscattering from the water surface changing in time. This simulation technique is verified to be a substitute for an experiment.

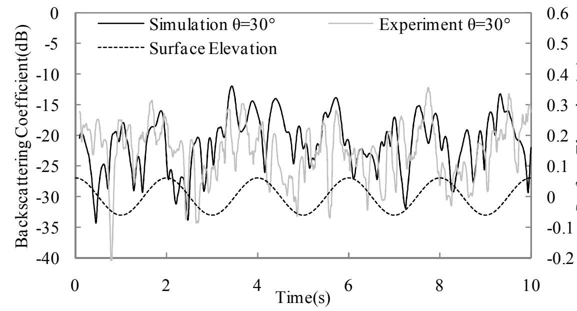


Fig.8 Comparison of backscattering coefficients in the case of regular wave and capillary waves.

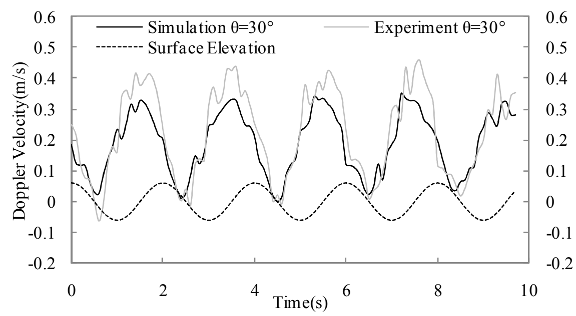


Fig.9 Comparison of Doppler velocities in the case of regular wave and capillary waves.

IV. Application of Simulation to Pulse Doppler Radar

As an application of the simulation technique, we have simulated microwave backscattering with a pulse Doppler radar. Backscattering microwave in space and time can be obtained by using a pulse Doppler radar.

In the simulation, spatial resolution is 0.15 m, calculation area is $4.8\lambda \times 6.4\lambda$ (0.15 m × 0.2 m). Incident angle is 45 degree. The position of radar is 10 m height at the origin. Microwave frequency is 9.6 GHz, wave length λ is 0.03125 m(X-band, VV polarization). Antenna gain is 20 dBi, and half-power width is 20° in the E-plane and 1° in the H-plane. The regular wave period is 2 s and the wave height is 0.3 m. Wind speed is 4 m/s. The regular wave propagates toward the direction that goes away from the radar. Sampling frequency is 1000 Hz. The results of backscattering coefficients are shown as accumulated mean values for 0.1 s sampling. Doppler spectra are analyzed IQ signals for 0.128 s.

The results are shown in Figure 10 at time 0, 0.5, 1.0, 1.5 s. Wave conditions in space and time can be estimated by analyzing the results. Wave conditions are shown more clearly in the results of Doppler velocity than backscattering coefficient. Thus, Doppler radar is effective for sea surface wave observation.

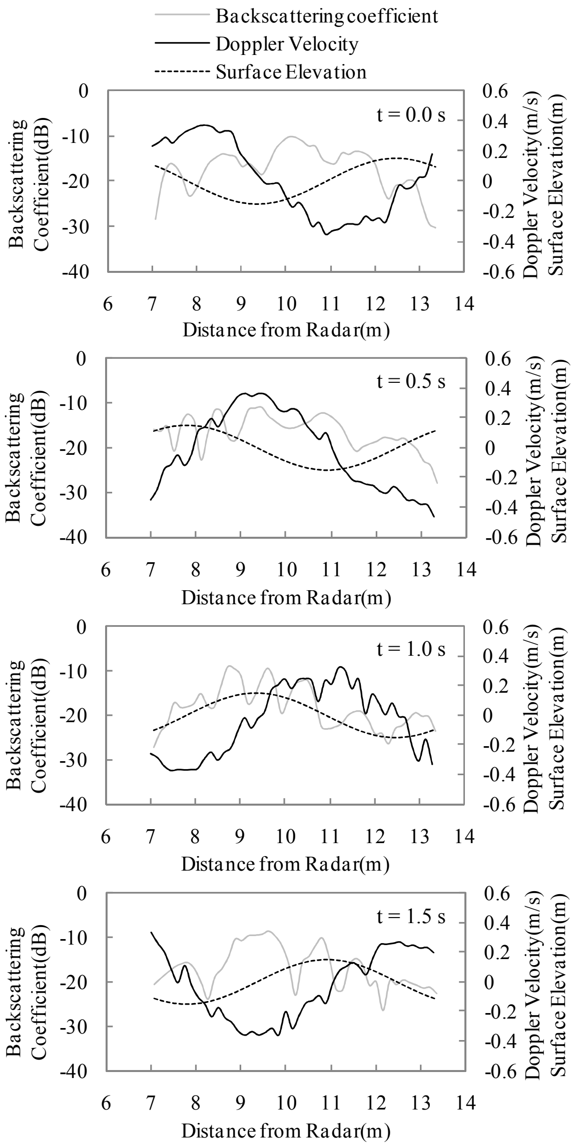


Fig.10 Space and time fluctuation of backscattering coefficient and Doppler velocity with pulse Doppler radar.

Then, we have simulated radar images with a pulse Doppler radar. Specifications of the radar are the same as above. Radar images of backscattering coefficients and Doppler velocity are obtained by the simulation. We evaluate the sea surface observation method with radar images.

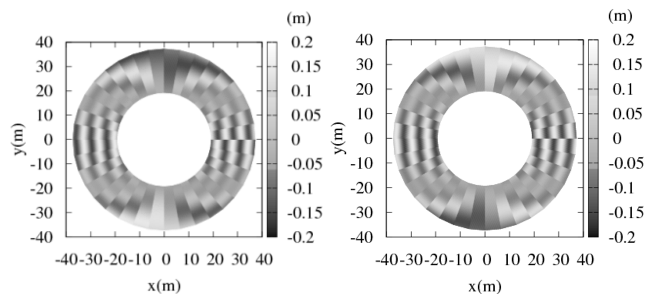
In the simulation, a pulse Doppler radar is rotated at 20 rpm. Microwave backscattering is measured every 10°. Radar images of backscattering coefficients and Doppler velocity are obtained in the case of regular gravity wave and irregular gravity wave. The regular wave period is 2 s and the wave height is 0.3 m. The wave direction is along the x-axis. Sampling frequency is 1000 Hz. The results of backscattering coefficients are shown as accumulated mean values for 0.064 s sampling. Doppler spectra are analyzed IQ signals for 0.064 s.

Sea surface elevation is shown in Figure 11, radar image of backscattering coefficient is shown in Figure 12 and radar image of Doppler velocity is shown in Figure 13. These are the radar images of two rotations of the radar.

Instead of Mitsuyasu&Honda spectrum in eq.(2), Bretschneider - Mitsuyasu spectrum [10] is used to generate numerical irregular gravity wave surface. The significant wave period is 2.6 s and the significant wave height is 0.28 m.

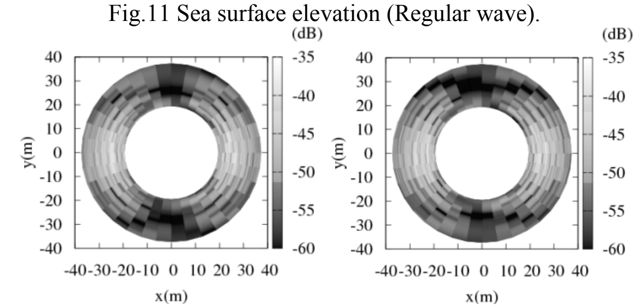
In the case of irregular wave, sea surface elevation is shown in Figure 14, radar image of backscattering coefficient is shown in Figure 15 and radar image of Doppler velocity is shown in Figure 16.

Sea surface conditions are shown more clearly in the images of Doppler velocity. Positive Doppler velocity means a wave that approaches the radar and negative Doppler velocity means a wave that goes away from the radar. Wave conditions such as wave length, wave height and wave direction can be estimated by radar images of Doppler velocity. The results indicate that radar image of Doppler velocity is more effective than the image of backscattering coefficient for sea surface observation. Therefore, it is possible to observe sea surface precisely by using radar images of Doppler velocity.



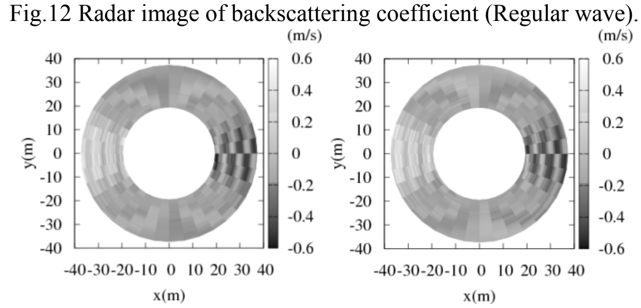
(a) t = 0.0 – 3.0 s (b) t = 3.0 – 6.0 s

Fig.11 Sea surface elevation (Regular wave).



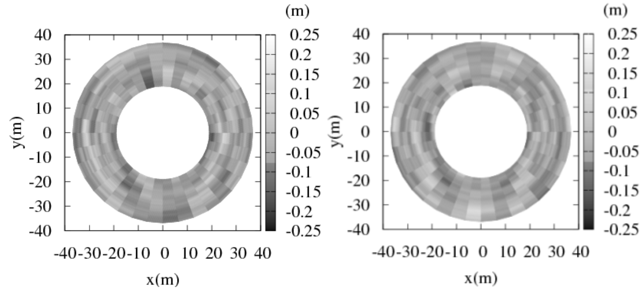
(a) t = 0.0 – 3.0 s (b) t = 3.0 – 6.0 s

Fig.12 Radar image of backscattering coefficient (Regular wave).



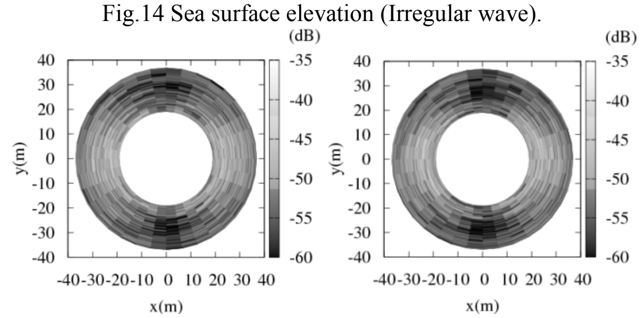
(a) t = 0.0 – 3.0 s (b) t = 3.0 – 6.0 s

Fig.13 Radar image of Doppler velocity (Regular wave).



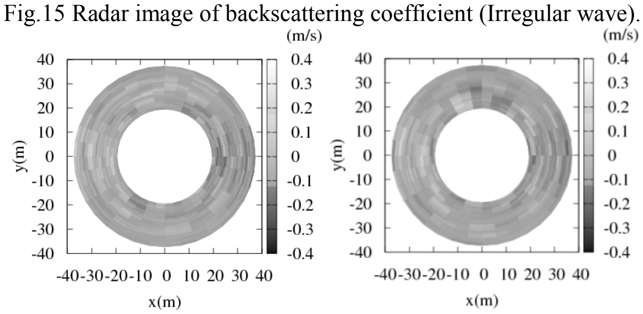
(a) t = 0.0 – 3.0 s (b) t = 3.0 – 6.0 s

Fig.14 Sea surface elevation (Irregular wave).



(a) t = 0.0 – 3.0 s (b) t = 3.0 – 6.0 s

Fig.15 Radar image of backscattering coefficient (Irregular wave).



(a) t = 0.0 – 3.0 s (b) t = 3.0 – 6.0 s

Fig.16 Radar image of Doppler velocity (Irregular wave).

V. CONCLUSION

This paper describes the development of numerical simulation technique to calculate microwave backscattering which modulated in amplitude and frequency by the sea surface profiles in time domain.

The validity of the simulation technique was verified by comparing with the results of the experimental basin. In the case of existing only capillary waves, incident angle dependence and wind speed dependence are verified by the simulation. In the case of existing both capillary waves and regular gravity waves, tilt modulation is shown in the fluctuation of backscattering coefficients. The fluctuation period of Doppler velocity is the same as the period of the regular wave. The results indicate that the simulation is effective to calculate microwave backscattering from the water surface changing in time. Therefore, this simulation technique can be a substitute for an experiment.

As an application of the simulation technique, radar images with a pulse Doppler radar are simulated to evaluate the sea surface observation. Radar images of backscattering coefficients and Doppler velocity are obtained by the simulation. Wave length and wave direction can be observed by radar images of Doppler velocity. The results show that radar images with a pulse Doppler radar are useful for sea surface observation.

One of the subjects for future research is developing the simulation technique for SAR (Synthetic Aperture Radar) images of sea surface. We attempt to clarify SAR imaging mechanisms of sea surface and suggest sea surface observing algorithm with SAR images by the simulation.

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