

WAVE AND CURRENT FIELDS EXTRACTED FROM MARINE RADAR IMAGES

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Abstract: Commercial X-band marine radar which original used for ship navigation purpose is now developed as a remote sensing technique for ocean wave and current measurements. This paper presents the coastal wave and current distribution extracted from marine radar image sequences. The spatial current results from radar are verified by in-situ current data measured by GPS drifting buoy. The result shows that the average error of current measurement by radar is around 0.09 m/s. In addition, it is found that the properties of coastal wave and current are non-homogeneity. By this study, the idea of applying a non-homogeneous image spectrum analysis method to derive the spatial wave and current fields is essential.

INTRODUCTION

The measurement and quantification of ocean waves and current for verifying wave theory, understanding wave characteristics, and producing economically and environmentally sensitive design are important needs in modern coastal technology. Wave and current measurements instrumentations are largely classified into two categories as in-situ and remote sensing. While ordinary measurements of waves and currents by an in-situ instrument are used for a time variation of wave height/current at a point, remote sensing techniques gives information over a broader area. There are two methods of wave/current measurement used in remote sensing. They are the space borne sensors such as SAR and microwave altimeter, and the ground base

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radar such as X-band radar and HF Doppler radar. As the space borne sensors have properties of global measurements, large size footprint, and lower resolution of the order of a few ten meters to a few kilometers. On the other hand, ground based radar is suitable for monitoring the waves in near offshore or shallow zones, with the wave field of a few ten centimeters to a few hundred meters. For the data requirements of coastal engineering, coastal area protection and management and oceanic recreation, the interesting area is always within several kilometers to the land and high measurement resolution requirement. The ground based X-band radar is therefore the adapted wave and current measurement tool. The ground based X-band radar is used for measurement of reflectivity from the sea clutter at similar wavelengths to the sensors based on Bragg scattering. X-band radar using microwave frequency band (0.01-1 m), which can measure the Bragg scattering from the sea clutter with wavelengths of 0.5-50 cm. An X-band radar wave measurement system includes data acquisition and image process units. Nowadays, using X-band radar to measure wave and current has been commercialized, such as the WAve MOnitoring System (WaMoS), developed by GKSS research center in Germany (Ziemer and Dittmer, 1994) and the Marine Radar Wave Extractor (WAVEX), developed by the MIROS AS Company in Norway (Grønlie, 1995). In Taiwan, the Coastal Ocean Monitoring Center also self-constructed an X-band wave/current measurement system for research.

The wave and current analysis of a X-band radar system is on the point view of that ocean waves should follow the wave dispersion relationship. The X-band radar image data set which use for wave and current measurement purpose are always 32 or 64 image sequences and has 3~5 km radius for each image. Normally, a sub-image which has size of 1 x 2 km is cut for wave and current analysis (Borge et al., 1999). This is the spatial representation of wave and current of such a certain sub-image area. Since remote sensing has capability of measurement in large domain, the spatial distribution of wave and current needs to be presented, especially at the coastal non-homogeneous area. Therefore, the purpose of this paper is to estimate the spatial distribution of wave and current fields from coastal marine radar image sequences. The extracted currents from radar images are compared with the in-situ current data obtained from GPS drifting buoy measurement.

METHODOLOGY

The measurement of ocean waves and surface currents from marine radar is based on the spatial and temporal structure analysis. Radar images are generated by the interaction of electromagnetic waves with the sea surface ripples at grazing incidence. Radar backscatter is presented as gray value. For wave and current analysis, a sub-image has to be extracted from the full radar image. This sub-image is then transformed into image wavenumber spectrum by transformation theory, such as 3D Fourier transform. Young et al. (1985) proposed that energy associated with ocean waves can be separated from the background noise energy by applying the wave dispersion relation as a filter. Ocean waves are dispersive under the certain relationship between wavenumber and frequency. For linear wave theory, the dispersion relation is given by

$$\omega = \sqrt{gk \tanh(kd)} + \vec{k} \cdot \vec{U} \quad (1)$$

where d is the water depth, $\vec{k}$ is the wavenumber vector and $\vec{U}$ is the surface current speed. The distribution of wave energy in the wavenumber-frequency space is formed as a trumpet shape. In the presence of the sea surface current $\vec{U}$, the trumpet shape is distorted (Senet et al, 2001) as shown in Fig. 1. The energy of ocean waves should be located in the vicinity of the dispersion shell and thus can be separated from the other spectral contributions. The wave energy of the radar image spectrum is the summation of energy located at the frequency (period) band where ocean wave belongs. The noise energy is thus the difference between total energy and wave energy. The significant wave height from marine radar image is thus estimated based on a linear correlation with the ratio of signal energy to noise energy. (Nieto et al., 1998).

During this approach, the surface current speed can be estimated by an iterative method. Gangeskar (2002) used the same idea and derived a cost function as Eq. (2) to estimate the current speed and direction.

$$J = \sum \sum \sum (\Delta\omega)^2 E(\omega, k_x, k_y) \quad (2)$$

where

$$\Delta\omega = \omega - \sqrt{g|\vec{k}|} - k_x U_x - k_y U_y \quad (3)$$

$E(\omega, k_x, k_y)$ is the radar image spectrum, U_x and U_y are the x and y components of $\vec{U}$ respectively. By minimize the cost function, the current can be estimated by followed equation.

$$\begin{bmatrix} U_x \\ U_y \end{bmatrix} = \begin{bmatrix} \sum E k_x^2 & \sum E k_x k_y \\ \sum E k_x k_y & \sum E k_y^2 \end{bmatrix}^{-1} \begin{bmatrix} \sum E (\omega - \sqrt{g|\vec{k}|}) k_x \\ \sum E (\omega - \sqrt{g|\vec{k}|}) k_y \end{bmatrix} \quad (4)$$

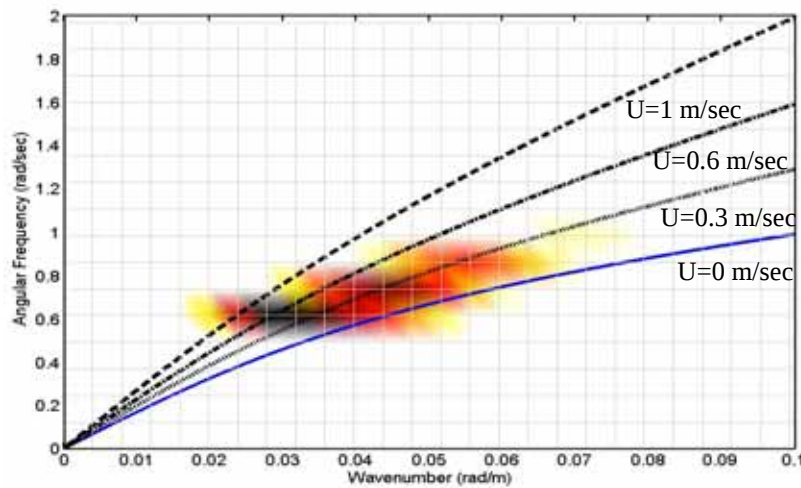


Fig. 1. Correlation of wavenumber and angular frequency defined by wave dispersion relationship

FIELD RADAR IMAGES ANALYSIS

Data Source

In order to test the accuracy of wave and current measured by marine radar system, the field test is necessary. The layout of the field experiment is shown in Fig. 2. A marine radar system which developed by Coastal Ocean Monitoring Center (COMC) of National Cheng Kung University in Taiwan was setup at southern Taiwan Island since 2004. Fig. 3 is the photo of another mobile type of marine radar wave/current measurement system. Near the Kenting coast, a moored data buoy, as shown in Fig. 4, which also developed by COMC is located at the point of water depth 45m and 3 km distance to the coastline. The data buoy collects the data of wind, wave, current and meteorological elements. In addition, a GPS drifting buoy, as shown in Fig. 5, is deployed to measure the spatial current field in order to verify the current extracted from marine radar image.

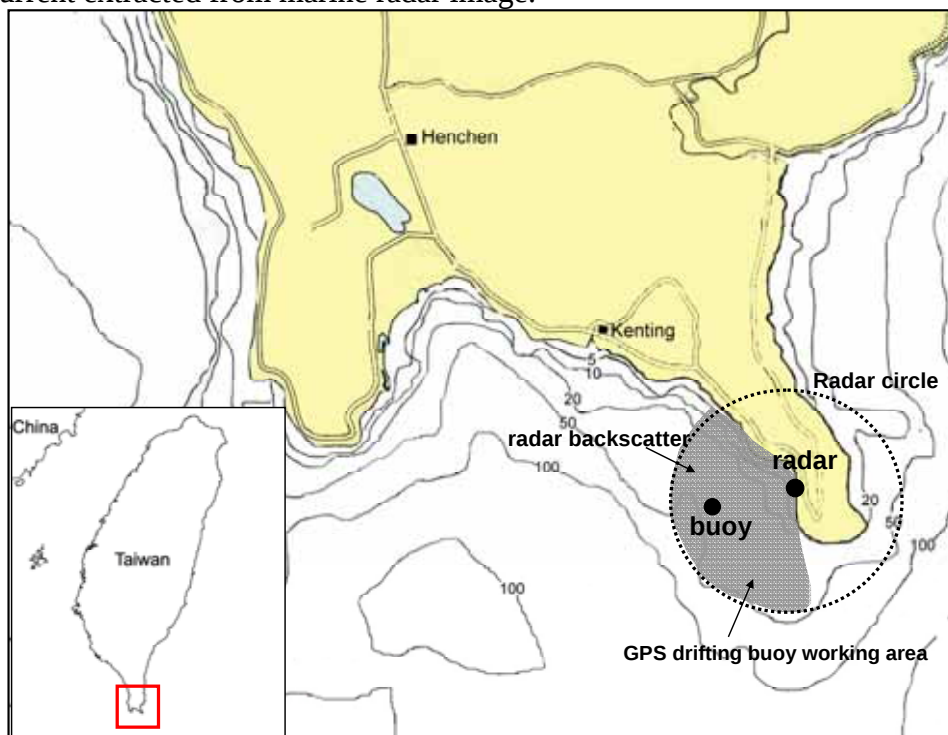


Fig. 2. Study Area – Southern Taiwan Island



Fig. 3. Mobile marine radar wave and current measurement system



Fig. 4. Data Buoy



Fig. 5. Drifting GPS buoy

Representative Wave and Current

According to the wave and current analysis method introduced in previous chapter, a large enough sub-image which has 1 x 2 km size and covers data buoy is cut for analysis as shown in Fig. 6. Traditionally, the results are always compared with in-situ data buoy measurements to assess the accuracy. As shown in Table 1, the average error of wave data is around 9% as well as error of current data is around 12%. For some certain purpose, this error range is still acceptable. However, this result can be improved. The improvement is not in accuracy, but in presentation. The wave and current elements presented in Table 1 are the representative value since they are derived from a large size sub-image. By this process, the remote sensing technology which original mentioned the wide range observation is now one representation, like the average value. This process is acceptable in deep water area; however may disagreement in shallow water area because of the non-homogeneous characteristics. For the coastal radar images, the spatial wave and current have to be presented.

Table. 1. Comparison of wave and current measurements from radar and buoy

	Marine radar	Data Buoy	Error
wavelength (m)	171	185	14 (8.2%)
wave direction (°)	146	158	12 (8.2%)
wave height (m)	2.91	3.24	0.33 (11.3%)
wave period (sec)	10.3	11.2	0.9 (8.7%)
current speed (m/s)	0.32	0.18	0.14 (44.0%)
current direction (°)	321	340	19(5.9%)

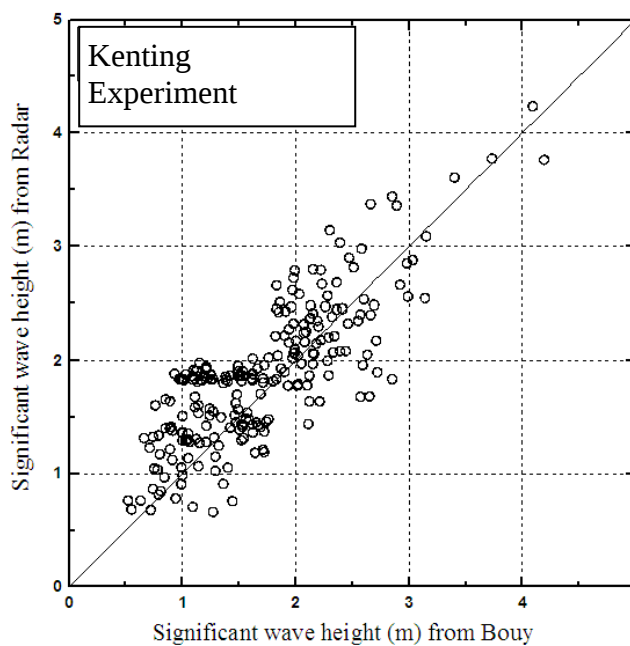


Fig.6. Long-term comparative result of significant wave height between marine radar and in-situ data buoy

SPATIAL WAVE AND CURRENT FIELDS

Spatial wave and current fields from marine radar image sequences are estimated in this paper. The same process is used to simultaneously apply on different sub-images in one full image. The image sequence contains 64 radar images. One radar image sequence with obvious refraction and diffraction phenomena is used for analysis, as shown in Fig. 7. This image is acquired at Kenting of Taiwan during typhoon period. The results are shown in Fig. 7 and Fig. 8. From the spatial wave field in Fig. 7, the wave heights distribute from 2.7 to 3.1 m, however the wave direction changes from 127° to 192° . The extracted current speeds are from 0.15 to 0.3 m/s as well as current directions from 302° to 351° . This is a non-homogeneous radar image. From the measurement of moored data buoy, the significant waves are 3.2m height and 11.2sec period. The current speed is 0.21 m/s. The error will be large and unreasonable if use the homogeneous method to only analyze a large sub-image for this case. From this case, it is shown the necessary of derivation of wave and current representations on spatial domain.

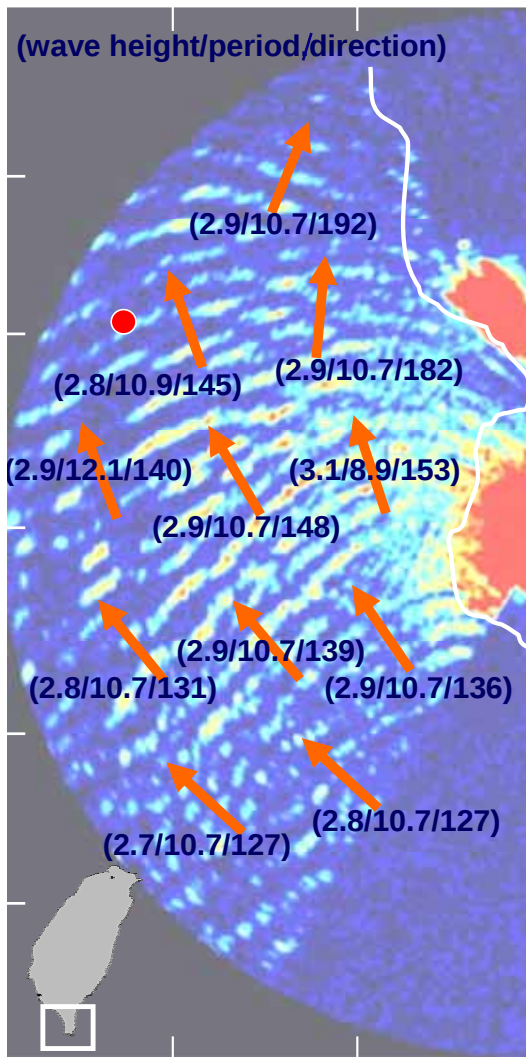


Fig. 7. Spatial wave field

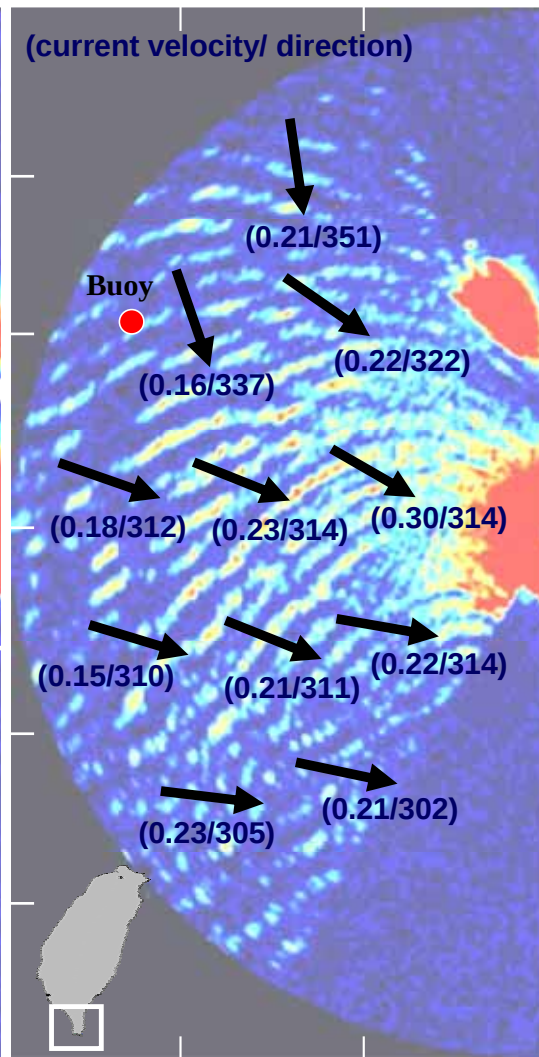


Fig. 8. Spatial current field

To verify the current results from radar, three experiments of drifting GPS buoy were done in Apr, 2005. The GPS buoy is free drifting at the sea surface. By the received GPS position and time, the Lagrange sea surface current is known. In Fig. 9, each circle means the GPS buoy position for every 10 minutes. The non-homogeneous property at the coastal ocean can also be identified from the results because of the unsteady current speed and direction. Simultaneous radar measurements are also done. The current result of close sub-image from radar measurement is used to compare with in-situ current from drifting GPS buoy, as shown in Table 2. It is found the average errors are 0.09 m/s on current speed and 5.9° on current direction.

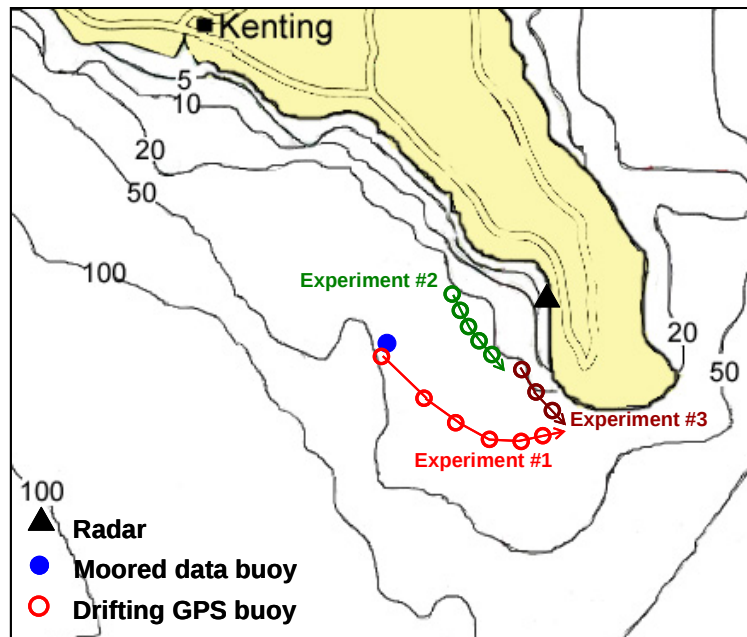


Fig. 9. Validation of spatial current measurement from radar by GPS drifting buoy experiments

Table. 2. Comparison of spatial current from radar with GPS drifting buoy

Experiment No.	Radar sub-image	Current speed (radar/GPS buoy) unit: m/s	Current direction (radar/GPS buoy) unit: degree
Experiment #1	sub-image 1	0.46 / 0.54	320 / 324
	sub-image 2	0.42 / 0.48	315 / 311
	sub-image 3	0.40 / 0.42	295 / 292
	sub-image 4	0.36 / 0.34	280 / 278
Experiment #2	sub-image 1	0.35 / 0.60	310 / 323
	sub-image 2	0.35 / 0.63	312 / 314
Experiment #3	sub-image 1	0.29 / 0.30	310 / 322
	sub-image 2	0.35 / 0.35	310 / 317
average		0.09 m/s	5.9°

NON-HOMOGENEOUS RADAR IMAGE ANALYSIS METHOD

The spectrum shows energy distribution in the frequency domain. Traditionally, the homogeneous 3D Fourier transform is used to estimate the image spectrum. However, this sometimes presents unreasonable results such as shown in previous chapter. Owing to possible non-homogeneous property at the coastal radar images, the non-homogeneous image spectrum analysis method has to be developed. For non-stationary or non-homogeneous data, several methods have been developed in the past few decades, such as the Short-time Fourier transform and more recently, the Wavelet transform (Daubechies 1990). The Wavelet transform allows exceptional localization in the space domain via translations of the so-called mother wavelet, and in the frequency domain via dilations. It is recognized as a powerful tool for non-homogeneous signal and image processes.

Wavelet transform divide the signal into its wavelet functions which are scaled, rotated and shifted of the mother wavelet function. For radar image sequence analysis, 3D wavelet transform is applied. The mathematical form is shown as followed:

$$S(a, \theta, \bar{b}) = \iiint f(\bar{z}) \cdot \psi_{a, \theta, \bar{b}}^*(\bar{z}) d\bar{z} \quad (5)$$

where $f(\bar{z}) = f(t, x, y)$ is the gray value matrix of radar backscatter, $\psi_{a, \theta, \bar{b}}(\bar{z})$ is wavelet function which is considered as a function of scale a , rotation $\bar{b}$ and shift θ of mother wavelet function $\psi(\bar{z})$ and $\psi_{a, \theta, \bar{b}}^*$ denotes the complex conjugate quantity. The wavelet coefficients are related to wave characteristics. They are shown in Eq. (3), where (ω, k_x, k_y) is the domain of image spectrum and (ω^*, k_x^*, k_y^*) is the center of the mother wavelet function.

$$\begin{bmatrix} \omega \\ k_x \\ k_y \end{bmatrix} = \begin{bmatrix} \omega^* / a_\omega \\ (k_x^* \cos \theta - k_y^* \sin \theta) / a_k \\ (k_x^* \sin \theta + k_y^* \cos \theta) / a_k \end{bmatrix} \quad (6)$$

In this paper, one simulation image is used to show the difference of image spectra by Fourier and Wavelet transform respectively. Fig. 10a is an wave pattern image that induced by a source, such as the tsunami waves. Fig. 10b is the image spectrum by Fourier transform at sub-image B. It is shown that unreasonable spectrum is presented. On the other hand, Fig. 10c and 10d are image spectra at sub-image C and D. It presents acceptable wave propagation directions. This simple case shows the image transformation method plays an important role. At the costal non-homogeneous, wave direction or current direction may change rapidly. A non-homogeneous image analysis method is necessary to develop the marine radar measurement system.

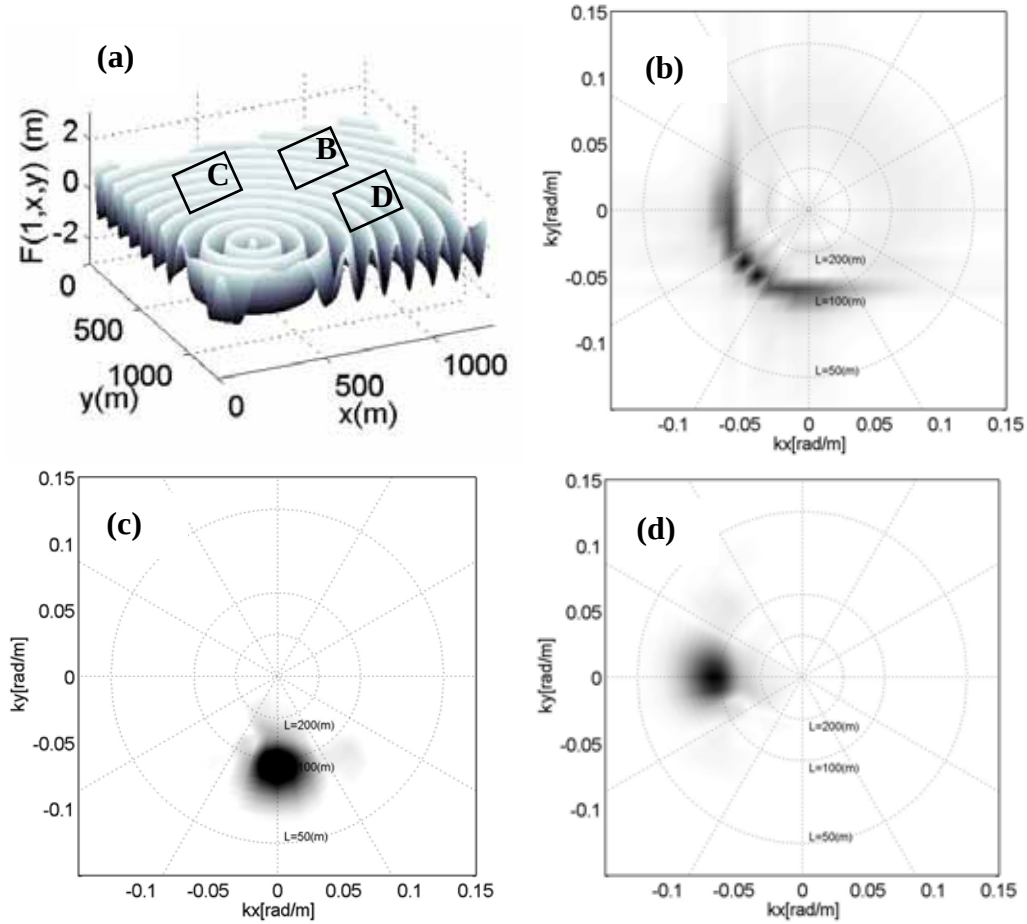


Fig. 10. Comparative results of Fourier spectrum and Wavelet spectrum.
(a)Simulation image (b)Fourier spectrum at sub-image B (c)Wavelet transform
at sub-image C (d)Wavelet transform at sub-image D

CONCLUSIONS

Land based marine radar is starting to wide use on measuring coastal ocean waves and currents. Traditionally, homogeneous analysis on a large sub-image gives only the representative parameters. This paper estimates the spatial wave and current fields. It is found that the homogeneous approach loses the information of spatial variation. The extracted spatial current data is verified by drifting GPS buoy experiments. The average error is found less than homogeneous approach. It is concluded that use a non-homogeneous approach, such as Wavelet image transformation to analyze spatial distribution of wave and current parameters on coastal marine radar image is essential.

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