A new method for measuring ocean wave from SEASAT SAR remote sensing image

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Abstract: A new method for measuring the ocean wave length and direction from SEASAT Synthetic Aperture Radar(SAR) remote sensing images is presented in the paper. In the new method, an ocean wave image is sampled in certain directions, the samples are then analyzed by using one dimensional Fourier Transformation to calculate the ocean wave correlation function. At last the ocean wave length and direction are measured from the ocean wave correlation function. The new method is better than the traditional two dimensional Fourier Transformation method in both consuming time and precision.

1. Ocean wave model

As we know the ocean is about 70% of the earth surface. The researches on the ocean have great scientific and economic values. American satellite SEASAT was lunched in 1978, and Japan satellite MOS-1 was lunched in 1987 for ocean researches. The remote sensing data from the satellites are very useful for researches of the ocean surface. In this paper we shall deal with the wave length and direction by using SEASAT SAR remote sensing image.

Ocean waves could be divided into three types: storm waves, swell waves and breakers. In this paper we shall deal with swell waves only, which are called ocean waves or waves for short.

The simplest dynamic model of waves is sinusoidal model which can be expressed as follow[1].

$$H(x, t) = \sum_m A_m e^{i(k_m x - w_m t)} \qquad (1)$$

and the corrsponding static model as

$$h(x, y) = \sum_m |A_m| \cos(k_{xm} x + k_{ym} y + \varphi_m) \qquad (2)$$

where w_m is the frequency, A_m is the amplitude, and k_m , k_{xm} , k_{ym} are constants. This type of sinusoidal models plays an essential role in studying physical oceanography. They assume the waves are the coherent waves with long crest. Even though in practice, the waves change with time and space complicatedly but they are of good statistical characteristics. In 1952, the first wave spectrum formula (3) was proposed by Neaumann, and another formula (4) was proposed by Pierson in 1964. Those formulas are in keeping with practice very well.

$$F_n(w) = \frac{\alpha_n}{W^6} \exp[- \frac{\beta_n^2}{W^2}] \quad (3)$$

$$F_p(w) = \frac{\alpha_p}{W^5} \exp[- \frac{\beta_p^4}{W^4}] \quad (4)$$

Where $F_n(w)$ and $F_p(w)$ are the related spectra of the sea level changing with time at a specific spot. α_n, β_n, α_p, and β_p are constants, and β_n and β_p are inversely proportional to wind speed.

2. 2D-FFT method

The wave length and direction are calculated commonly using Two-dimensional Fourier Transform[2.3]. The wave length L and direction θ can be obtained from the main frequency (u_0, v_0). The formulation is

$$L = N \cdot \Delta x \ / \ (u_0^2 + v_0^2)^{1/2} \quad (5)$$

$$\theta = \arctan (v_0 \ / \ u_0) \quad (6)$$

Where N and Δx are the pixel number and the pixel resolution of the SAR image respectly. Then $N \cdot \Delta x$ is the total length of the image.

This method we simply call as 2D-FFT method. Fig. 1 is the SEASAT SAR image of the Atlantic Ocean recorded on 19th of August, 1978. The pixel resolution is 24m, and the image size is 1024X1024 pixels. Fig. 2 is the frequency spectrum where the lightest point represents the main frequency (u_0, v_0).

There may be some disadvantages in 2D-FFT mrthod. On one hand it is the consuming time. As we know that 2D-FFT method has to take two dimensional FFT transform while only the frequences in the vicinity of the main frequency point(u_0, v_0) take part in the wave length and direction evaluation. On the other hand, it is not easy to find the main frequency point (u_0, v_0). The contour distribution of the spectrum at the vicinity of the main frequency point is shown in Fig. 3. We can see that the distribution is asymmetrical. In general, the smoothing is needed to filter the random noise. For the symmetrical distribution the smoothing doesn't cause the moving of the main frequency point (u_0, v_0), but for asymmetrical distribution it does. Therefore 2D-FFT method could cause higher error.

3. 1D-FFT method

In face of the disadvantages in 2D-FFT method, we propose a one dimensional Fourier Transform method (1D-FFT). The main point of this method is to calculate the correlation function of the waves using inverse FFT of the power spectrum which is the square of the frequency spectrum. The wavelength can be obtained from the distance between the origin and the first maximum point of the correlation function. For reducing computer time, we can just take samples in four special directions to take FFT. This method can be realized as follows.

(1) take four special directions -45, 0, 45, 90 degree as show in Fig. 4.

(2) take 25 parallel sample lines in each direction as show in Fig. 5.

(3) perform FFT on each sample line to obtain the spectrum.

(4) calculate the average spectrum of the 25 spectra in each direction.

(5) perform inverse FFT on the square of the average spectra then obtain the correlation function in each direction.

(6) on the correlation function curve, find the nearest maximum point, and then record the distance between the origin and the nearest maximum point of the correlation function λ_{-45}, λ_{0}, λ_{45}, and λ_{90}.

(7) plot four points (λ_{-45}, $-45°$), (λ_{0}, $0°$), (λ_{45}, $45°$) and (λ_{90}, $90°$) in the polar coordinates (λ, θ).

(8) draw a line using weighted least square fitting, the four weights are $1/\lambda^2_{-45}$, $1/\lambda^2_{0}$, $1/\lambda^2_{45}$ and $1/\lambda^2_{90}$ for point (λ_{45}, $-45°$), (λ_{0}, $0°$), (λ_{45}, $45°$) and (λ_{90}, $90°$) respectly, because the father the distance the less the weight, as show in Fig. 6.

(9) the distance between the origin and the line is the average wavelength of this image, and the normal line direction of this line is the average direction of the waves. The results using 1D-FFT and 2D-FFT are in table 1.

Table 1. The results.

	mask size	wavelength		direction	
		mean	der.	mean	der.
2D-FFT	3X3	284.6	16.9	-17.4	4.5
	5X5	272.1	13.1	-18.5	4.0
	7X7	257.5	5.7	-17.4	3.4
1D-FFT		240.4	6.9	-17.4	2.8

4. The wavelength difference between 2D-FFT and 1D-FFT methods.

From table 1 we can see that there is the difference of the wavelengthes between the two methods. In fact, this difference is caused by the different definitions for the wave length. That is, the definition of 1D-FFT method is in the space domain, but 2D-FFT method is in the frequence domain as show in Fig. 7.

In the case of sinusoidal models, the two evaluation lengths are unanimous, but in the case of the Neaumann model, the ratio of the two lengths equals a constant, which is not equal to 1. This can be demonstrated as following.

(1) In the case of sinusoidal models the recorded sea level at specific spot can be expressed as $A \cos(w_o t)$, and the correspondent spectrum can be expressed as $A/2\pi\delta(w - w_o)+ A/2\pi\delta(w + w_o)$. In both of space domain and frequence domain the wavelengths are same $2\pi/w_o$, thus $\lambda f / \lambda t = 1$.

(2) For the Neaumann model, the related spectrum of the sea level at a specific spot is the Neaumann function. From Equ.(3)

$$\frac{d}{dw} F_n(w) = \frac{d}{dw} \left[\frac{\alpha_n}{w^6} \exp(- \frac{\beta_n^2}{w^2}) \right] = 0 \qquad (7)$$

we can derive

$$w_M = \frac{\beta_n}{\sqrt{3}} \qquad (8)$$

therefore

$$\lambda_f = \frac{2\pi\sqrt{3}}{\beta_n} \qquad (9)$$

In the space domain, the correlation function is

$$f_n(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F_n(w)\, e^{-jwt}\, dw \qquad (10)$$

The wavelength in the space domain means the distance between the origin point and the first maximum point of the correlation function. Let

$$\frac{d}{dt} f_n(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} (-jw) F_n(w)\, e^{-jwt}\, dw = 0 \qquad (11)$$

and $w = q\,\beta_n$, then Equ.(11) becomes

$$\frac{d}{dt} f_n(t) = \frac{-j\alpha_n}{2\pi\beta_n^4}\int_{-\infty}^{\infty}\frac{1}{q^6}\exp(-\frac{1}{q^2})e^{-jq\beta_n t}dq \qquad (12)$$

$$= 0$$

From Equ.(9) and (12) we can calculate $\lambda f / \lambda t$ as in table 2.

Table 2. Ratio $\lambda f / \lambda t$

	1.0	1.2	1.5	1.8	2.0
f/ t	1.186	1.184	1.184	1.179	1.179

From table 2 we may have the average ratio

$$\lambda f / \lambda t = 1.184. \qquad (13)$$

this ratio is consistent with the practice result 1.183 from table 1 very well.

6. Conclusion

The 1D-FFT method presented in this paper is based on the ocean wave correlation function to calculate the wave length and direction. The advantage of this method is it is easy to find the maximum of the correlation function which relates the wave length. Therefore the accuracy of this method is higher. This is very clear in table 1. Using 2D-FFT method the wave length derivation is 16.9m and the direction derivation is 4.8 degree. Using 1D-FFT method the wave length derivation is 6.9m and direction derivation is 2.8 degree. In the sense of derivation, the 1D-FFT method has lower error and higher accuracy.

In the other hand, we can reduce the computer time by using 1D-FFT method. For example on VAX-11/750, the 1D-FFTO method took about 100s, while the 2D-FFT took about 600s, and ever less time can be achieved by using less line samples then 25.

Reference

[1] E. B. Kraus, Atmospheric-ocean interaction, Oxford: Oxford University Press, 1972.

[2] R. H. Stewart, Methods of satellite Oceanogaphy, University of California Press, 1985.

[3] T. D. Allan and T. H. Guymer, Seasat measurements of wind and waves on selected passes over JASIN, International Journal of Remote Sensing, Vol. 5, No. 2, 1984.

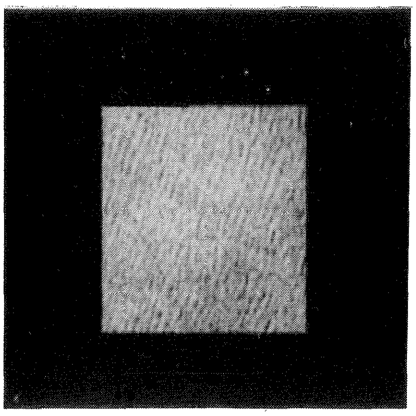


Fig. 1 Original SAR Image

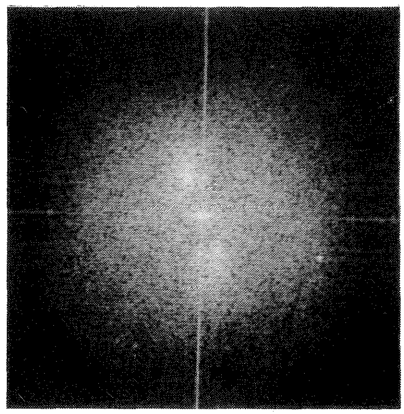


Fig. 2 Wave Spectrum

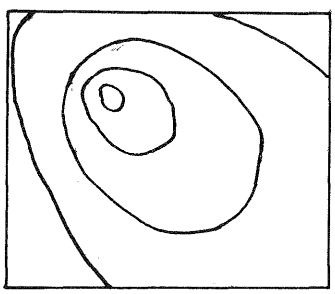


Fig.3 Contour Distribution

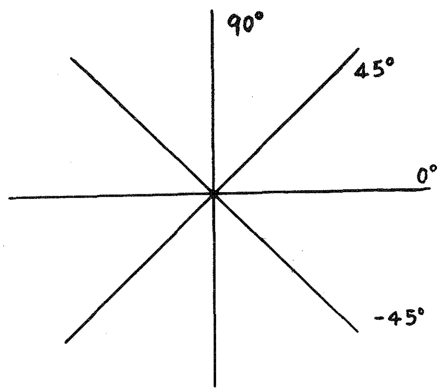


Fig. 4 Four directions

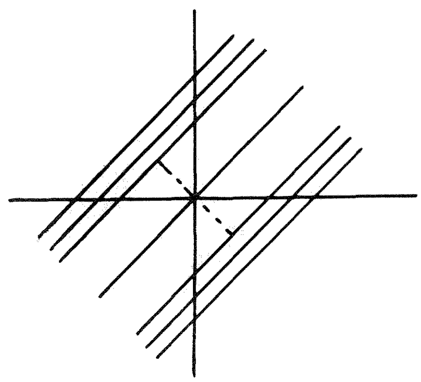


Fig. 5 Samples

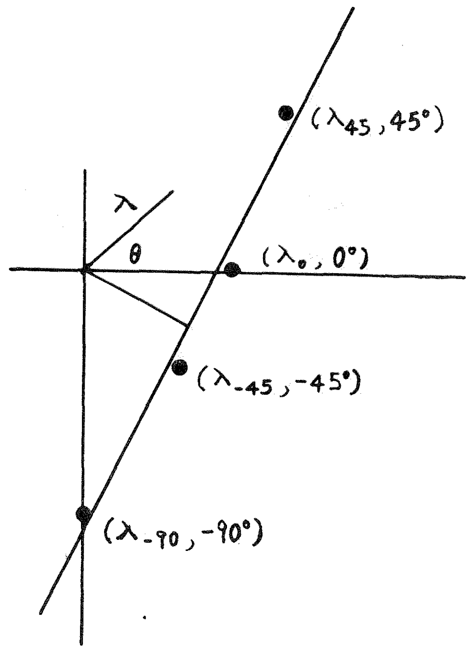
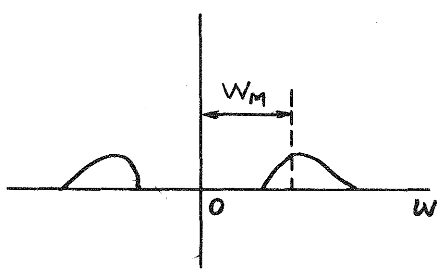


Fig. 6 Line fitting



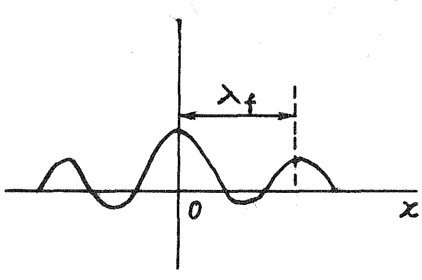


Fig. 7 Two definitions. (a) In frequency domain, (b) In space domain