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# NOTA TÉCNICA
# ERS-1 MODEL FOR SIGNIFICANT WAVE DETECTION

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## ABSTRACT

A quasi-linear transfer function has been applied to radar data (ERS-1) to model the significant wave height in two seasons. These seasons are the end of the southwest monsoon and the inter-monsoon period. The quasi-linear transfer model has been based on the azimuth cut-off. The results show that the significant wave height varied with the different period of the ERS-1 images. The modeled significant wave height are in good agreement with sea truth data. In conclusion, the quasi-linear transfer model can be used as monitoring model in detecting the significant wave height variation with different monsoon periods.
**Keywords:** azimuth cut-off, ERS-1, wave spectra, South China Sea.

## RESUMEN

Se aplicó una función cuasi-lineal a datos de radar (ERS-1) para modelar las alturas de las olas significativas en dos estaciones del año. Estas corresponden al final de la estación del Monzón del SW y el período entre monzones. El modelo cuasilineal se basó en el corte por azimut. Los resultados muestran que la altura significativa de las olas varían en los diferentes períodos de las imágenes ERS-1. Loa alturas de las olas significativas modeladas están en buena correlación con los datos observados. Por lo tanto, el modelo puede ser utilizado para detectar la altura de las olas significativas en diferentes períodos del Monzón.
**Palabras claves:** espectro de olas, ERS-1, Mar del Sur de China.

## 1. INTRODUCTION

The wave studies from space along the coastal waters of Peninsular Malaysia are still in an early stage. They play a vital role in a number of natural processes (Populus *et al.*, 1991). The coastal wave dynamics induce a littoral transport of sediments. The redistribution of the sediment from period to period could induce erosion or sedimentation along the coasts (Komar, 1976). The coastal wave dynamics also play a major role in coastal engineering structures output. They are based on the available climate wave information. For instance, the degree of wave dynamic changes could affect the harbor localization and coastal engineering structure defenses such as jetties and wave breakers.

The coastal wave studies from space have been based on the microwave observation sensors. Microwave instruments such as the Synthetic Aperture Radar (SAR) have ability to work under heavy cloud cover and can cover a large spatial area of 100 km x 100 km as found with ERS-1 (Hasselmann and Hasselmann, 1991). However, the ocean wave studies by SAR are difficult because SAR wave imaging is

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usually dominated by motion induced effects. This means the effects of the velocity bunching and degradation in azimuthally resolution (Vachon *et al.*, 1994). The physical theory that could be used to determine the climate wave from SAR image is well understood. This theory assumed that there is linear relationship between the SAR image backscatter and sea truth conditions. In this case, a quasi linear model could be applied (Hasselmann and Hasselmann, 1991; Vachon *et al.*, 1994). The most important theme of the quasi-linear model is the azimuth cut-off. According to Vachon *et al.* (1997) the azimuth cut-off is the degree to which the SAR image spectrum is constrained in the azimuth direction. The azimuth cut-off is affected by the wind and wave conditions. The quasi-linear model should use the information of wind speed and significant wave height for modeling ERS-1 wave spectra with the real ocean waves. There are several studies that have been carried out (Hasselmann *et al.*, 1985, Hasselemann and Hasselmann, 1991; Vachon and Dobson, 1996; Vachon *et al.*, 1997) to develop wave spectra simulation model based on the azimuth cut-off information. This is because in SAR images, waves propagating are in the azimuth direction. Hasselmann *et al.* (1985); Vachon *et al.* (1994) Vachon *et al.* (1995) and Vachon *et al.* (1997) concluded that azimuthally-traveling wave components contribute an order of magnitude less to the tilt modulation than range-traveling waves.

The quasi-linear transform increase with an azimuth-oriented low-pass filter (Beal *et al.*, 1986; Vachon *et al.*, 1994). In this case, the cut-off wave-number depends upon the scene coherence time. Furthermore, this quasi-linear transform also includes a Gaussian low-pass filter (Vachon *et al.*, 1994; Hasselmann *et al.*, 1996; Zurk and Plant, 1996). In addition, the effective cut-off wavelength should have at least two contributions. First, owing to velocity bunching, sub-resolution scale scene motion contributes to a cut-off wavelength that is proportional to the standard deviation of the azimuth shift field. Second, the actual scatters within the scene have a finite life time (i.e., coherence time). Vachon and Raney (1991); Monaldo and David (1986) and Vachon *et al.* (1993) found that this coherence time leads to an intrinsic cut-off wavelength. Furthermore, Vachon and Dobson, (1996) stated that the coherence time might be considerably shorter than the lifetime of an individual Bragg-scale wave crest. The intrinsic coherence scene time decreases with increasing wind speed (Vachon and Raney, 1989, Vachon *et al.*, 1992).

Vachon *et al.* (1994) developed quasi-linear techniques to estimate the azimuth spectral width. This quasi-linear transform is forward-mapping directional wave buoy spectra onto ERS-1 SAR image. The width measurements are correlated with observed values for significant wave height or the azimuth shift and the local wind speed. This allowed definition of a quasi-linear transform that includes the velocity bunching deceleration effects and wind speed dependent coherence time effects. In addition, Vachon *et al.* (1994, 1997) used a cut-off wavelength to estimate SAR wave spectra. The cut-off azimuth wavelength is scaled as function of ocean wave conditions and could scale with the wind speed and significant wave height, which is related to the scene range-to-platform velocity ratio (Beal *et al.*, 1986; Hasselmann *et al.*, 1985; Vachon *et al.*, 1993). The larger this ratio, the more susceptible the SAR image spectrum becomes to imaging non-linearity and azimuth spectral cut-off.

The study area is located in the coast of Kuala Terengganu, on the eastern part of Peninsula Malaysia. This area is located in South China Sea between 5°15' N to 5°33' N and 103°10' E to 104°00' E. According to Maged (1994), the coastal water less than 50 nautical miles from shore are quite shallow with the deepest area being approximately 50 m. The bottom has gentle slopes, gradually deepening towards the open sea. According to Wong (1981); Chu (1984) and Lokman *et al.* (1995), Terengganu coastline is exposed to the highest waves during the northeast monsoon compared to the southwest monsoon and the transitional period. The maximum wave height is 4 m during the northeast monsoon period (Wong, 1981) and less than 1 m during southwest monsoon season.

The main objective of this work is to apply the quasi-linear model in order to determine the significant wave height variation between different periods along the coastal waters of Kuala Terengganu, Malaysia. This study will focus on the following hypothesis: (i) The azimuth cut-off wavelength varied from one season to another (ii) the azimuth cut-off model could be used to detect significant wave height and (iii) quasi-linear model could be suitable tool for modeling significant wave height along the coastal water of Kuala Terengganu Malaysia.

## 2. METHODOLOGY

### 2.1. Data Acquisition

The truth sea wave have been measured during the flight time of the ERS-1 pass over the by wave rider buoy from Malaysian Petronas Platform in the months of August, September and October 1993. The platform observations were obtained through the Malaysian Meteorological Service. These data included wave height and wave direction. These data were observed at Petronas oil platform at 5°02 ' N and 105° 3' E in the months of August, September and October 1993. These data were used for wave spectra modulation with ERS-1 data.

The wind data were collected by the Meteorological Station at Sultan Mahmud Airport, Kuala Terengganu and obtained from the Malaysia Meteorological Service in Kuala Terengganu. Wind speed data were used to determine the azimuth cut-off modeled from satellite data. The azimuth cut-off was used to model significant wave height from radar imageries.

### 2.2. SAR Data Analysis

The ERS-1 data were acquired over the coastline of Chendering, Kuala Terengganu between 103°5' E to 103°50' E and 5°5' N to 5°20' N. These data were obtained on 8 August 1993, 10 September 1993 and 12 October 1993. August represents the end of southwest monsoon while September and October represent the transitional periods (Wong, 1981). In this study, a single SAR image frame comprising of 512 x 512 image pixels was extracted from ERS-1 imageries. The band used in this processing was Cvv-band. Each pixel represents a 12.5 m x 12.5 m area for ERS-1.

The entire image frame of ERS-1 corresponds to a 6.4 km x 6.4 km patch on the ocean surface. This frame size provides a sufficiently large area that at least 10 cycles of very long surface waves, up to 640 m in length, can be included in a single image frame. It is also small enough that the ocean can be reasonably assumed homogeneous within a frame (Beal *et al.*, 1986).

### 2.3. 2-D Fourier Transfer Model for Spectra Detection from ERS-1 Data

In order to extract information on wavelengths and significant wave height in radar imageries, the 2-D Fourier transformation was applied. The 2-D Fourier transformation (F ($k_0$)) is given by

$$F(n_1.k_0, n_2.k_0) = N_2^{-1} \sum_{m_2=0}^{N-1} \sum_{m_2=0}^{N-1} x(m_1, m_2) e^{(-i2\pi\ n_1 k_0 m_1 \Delta x)}\ e^{-i2\pi m_2 k_0 \Delta x} \qquad (1)$$

Where **Δx** is pixel length, **$k_0$** is **1/L**, which is a basic wave number, and n1 and n2 are integers representing different wave numbers. The wavelength estimated by applying the formula:

$$L = N.\ \Delta x \qquad (2)$$

where **L** is wavelength (m), **N** is number of pixel along one side and **Δx** is ERS-1 resolutions of 12.5 m (Populus *et al.*, 1991; Cornet *et al.*, 1993).

After 2-DFFT has been applied, a Gaussian filter was applied to remove the noise from the image and smooth the wave spectra into a normal distribution curve. Gaussian function to compute the filter weights is:

$$G(i,j) = e^{\frac{(-((i-u)^2+(j-v)^2)}{2(\sigma^2)}} \qquad (3)$$

where **(i,j)** is a pixel within the filter window **(u,v)** is the center of the filter window and **$\sigma^2$** is square of Gaussian filter parameter. The filter weights **W(i,j)** are the normalized values of G(i,j) over the entire filter window. The sum of all weights is 1. The grey-level of a filtered pixel is the sum of **W (i,j)** and **V(i,j)** over all pixels in the filter window, where **V(i,j)** is the original value at location **(i,j)**.

### 2.4. Quasi-linear Transfer Model

In order to map observed SAR spectra onto the ocean wave spectra a quasi-linear model was applied. The simplified quasi-linear theory is explained below. According to the Gaussian Linear Theory, the relation between ocean wave spectra $\psi(K)$ and SAR image spectra $S_i(K)$ could be described by tilt and hydrodynamic modulation (RAR modulation). Following Vachon *et al.* (1995) SAR image spectra can map into ocean wave spectra under the assumption of the quasi-linear modulation transfer function

$$S_Q(k) = R(K)H(K_x;K_c).\left[\frac{T_{lin}(K)^2}{2} + \frac{T_{lin}(-K)^2}{2}\psi(-K)\right] \tag{4.0}$$

where $H(K_x;K_c)$ is an azimuth cut-off function that depends upon the cut-off azimuth wave number $K_x$ and *R (K)* is the SAR point spread function. The SAR point spread function is function of azimuth and range resolutions (Vachon *et al.*, 1997). $T_{lin}$ is the linear modulation transfer function. According to Vachon *et al.*, (1994) linear modulation transfer function is composed of the real aperture radar (RAR) (the tilt modulation and hydrodynamic modulation), and the velocity bunching modulation. The SAR modulation transfer function (RAR MTF) is the coherent sum of the transfer function associated with each of these terms, i.e.,

$$T_{lin} = M_t(k) + M_d(k) + M_v(k) \tag{4.1}$$

The tilt modulation $M_t(k)$ can be described by

$$M_t(k) = k_y \frac{4\cot\theta}{1 \pm \sin^2\theta} e^{(\frac{i\Pi}{2})} \tag{4.1.1}$$

where $k_y$ is the range wave number and $\theta$ is the local incident angle. Following Vachon *et al.*, (1994) the hydrodynamic modulation transfer function can be given by

$$M_d = 4.5\omega k \frac{\omega - i\mu}{\omega + \mu^2} \sin^2\phi \tag{4.2.1}$$

where $k$ is long wavenumber, $w$ is the radian frequency of the long waves, $\phi$ is the azimuth angle and $\mu$ is the relaxation rate of the Bragg waves which is 0.5/s.

According to Alpers *et al.* (1981); Vachon *et al.* (1994. 1997), the velocity bunching can be contribute to linear MTF by following equation

$$M_v = \frac{R}{V}\omega\left[\frac{k_x}{k}\sin\theta + i\cos\theta\right] \tag{4.3.1}$$

where R/V is the scene range to platform velocity ration, which is 115 s in the case of ERS-1 data.

## 2.5. Significant Wave Height Model

In order to estimate the significant wave height from the quasi-linear transform, we are developed the algorithm that was given by Vachon *et al.* (1994) to be fit with the boundary conditions of tropical coastal waters:

$$\lambda_c = \frac{R}{V} \int_{H_{s0}}^{H_{sn}} \int_{U_0}^{U_n} C_1 (H_s)^{0.5} + C_2 (U)^{0.1} dH_s dU \tag{5.0}$$

*Hs* and $U^2$ are the sea truth data of significant wave height and wind speed along the coastal waters of Kuala Terengganu, Malaysia. The measured wind speed was estimated for 10m height above the sea surface, $(dH_s) and (dU)$ are the changes of significant wave height and wind speed along the azimuth direction. The subscripts of zero and n are indicated the interval period of sea truth data. The subscript zero means the average sea truth data collected before flight pass over by two hours while the subscript n is the average of sea truth data during flight pass over the study area, $C_1 and C_2$ are constants that function on the relation between azimuth wavelength cut-off and significant wave height and wind speed respectively. A least squares fit was used to find degree of correlation between cut-off wavelength, from equation (5.0), and the one calculated directly from the ERS-1 image. Then, the following equation was developed from Vachon *et al.* (1994) to estimate $H_s$ from the ERS-1 image

$$H_s = \left[ \frac{V}{C_3 R} \right]^2 \int_{\lambda c_0}^{\lambda_{c0}} (\lambda_c)^2 d\lambda_c \tag{6.0}$$

where *V/R* is platform velocity-to-the scene range ratio and $C_3$ is constant value that obtained from autocorrelation between azimuth cut-off and significant wave height. For the ERS-1, *R/V* is approximately 115 s.

## 3. RESULTS AND DISCUSSION

The 2-D Fourier spectra of SAR image during southwest monsoon (August 1993), and inter-monsoon periods (September and October, 1993) are presented in figures 1, 2 and 3. These ERS-1 spectra derived by 2-D Fourier transform are presented in polar plots by three circles. These circular areas indicate individual peak spectra propagation. The scale of swell peak spectra wavelengths is attached at the top of each polar plot. These scales indicate the change of wavelength spectra in the circular areas. The wavelength values decrease from the outer to inner circle. The distance of the peaks from the center is inversely proportional to its wavelength and the angular position of the peaks indicates the wave propagation direction. The Fourier spectra of single image inherently contain 180° ambiguities in the propagation direction. The wavelength spectra vary with distance and time. The offshore swell wavelengths were larger than onshore swell wavelengths during August, September, and October 1993 (figures 1, 2, 3). In August 1993, the offshore wavelengths ranged between 300 m to 75 m. In September and October 1993, the offshore wavelength ranged from 400 m to 100 m. Comparison between onshore swell wavelength spectra among the months indicated that the shortest wavelength was found in the month of August 1993.

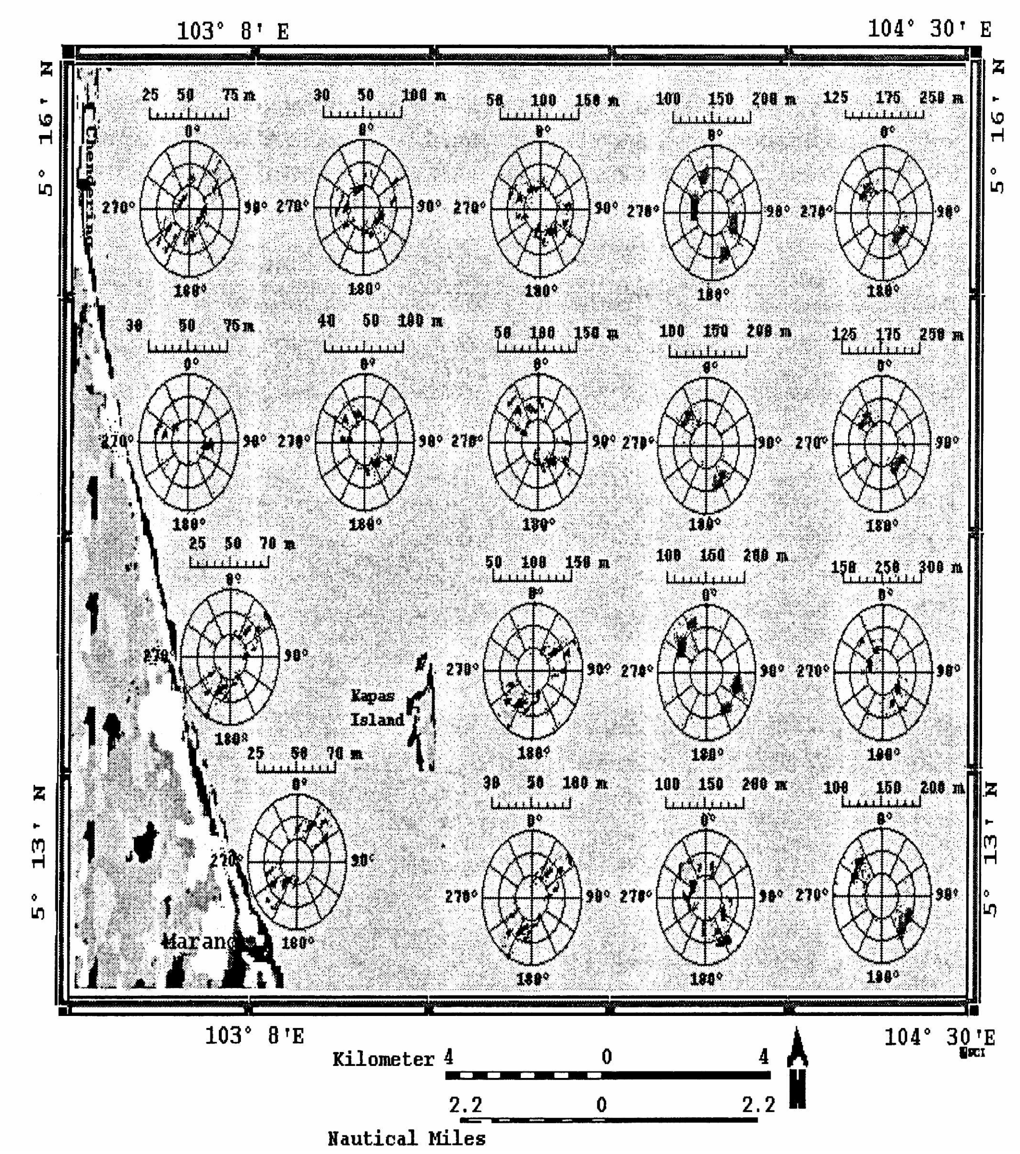

Figure 1. ERS-1 Wave Spectra in August 1993

The wavelengths derived from ERS-1 data during August 1993 in this study contradict the results of Ibrahim and Saumsudin (1996) and Maged and Mansor (1997). Maged and Mansor (1997) found an offshore wavelength, which ranged between 200 to 500 m. This cannot occur in the South China Sea especially during southwest monsoon season because the wind energy input is approximately less than 1 N/m$^2$ (Maged, 1994). This low energy could not generate a storm wave or large swell. However, Maged and Mansor (1997) found that the maximum peak of energy wave spectra was 0.52 $m^2$ sec in August 1993. In general, wavelength derived from ERS-1 data for the different months (August, September and October 1993) are not similar to the findings of Valencia (1978); Morgen and Valencia (1983) and Feng (1994). Valencia (1978) stated that in August the swell wavelength ranged from 16 to 30 m. In September and October, swell wavelength ranged from 24 to 60 m. The resolution of an ERS-1 image is 12.5 m, this means that SAR cannot identify particular areas less than 12.5 m. So ERS-1 cannot detect wavelength less than 25 m.

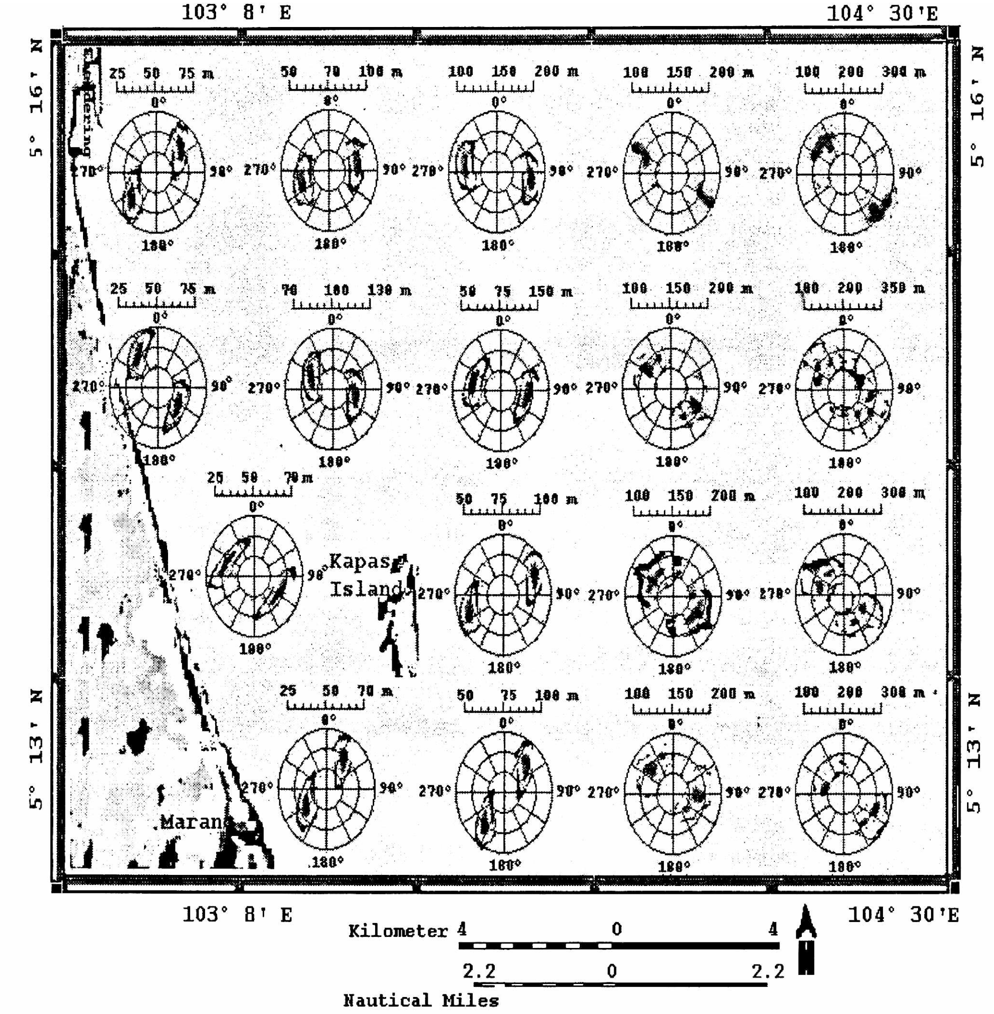

**Figure 2. ERS-1 Wave Spectra in September 1993**

The disagreement between the present study and Valencia (1978) is based on the estimation of the onshore swell wavelength (L) as function of time period (T) by using equation typical of the linear wave theory ($L= 1.56 T^2$). This equation is only valid for deep water (Komar, 1976). In the present study the offshore swell wavelength found to be longer than onshore swell wavelength due to fetch effects.

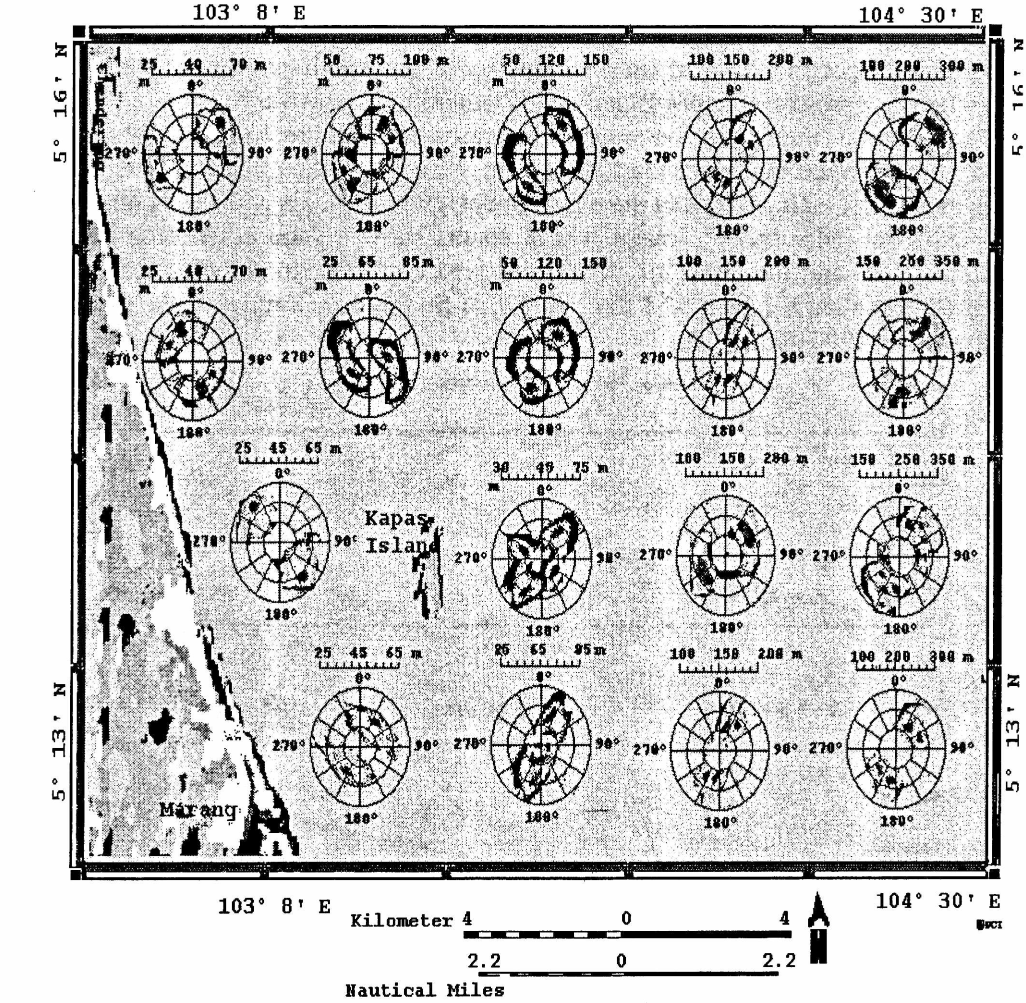

**Figure 3. ERS-1 Wave Spectra in October 1993**

The direction of spectra peaks varied from southwest monsoon and inter-monsoon period and with distance (offshore and onshore). The offshore swell spectra propagated from the southeast direction to the northwest direction in August and September 1993 (figures 1 and 2). However, in October 1993 the offshore swell spectra propagated from the northeast direction to the southwest direction (figure 3). The swell wavelength directions varied between the months. The offshore swell directions during August 1993 were propagated from southeast towards northwest. This result is similar to Wong (1981). August 1993 represent the consitions of the southwest monsoon. In this period, swells are propagated from southerly directions. The month of September and October 1993 represent the transitional period. The swell directions do not have any specific direction. This is because of the variable wind pattern during the transitional period. This result is shown by Maged (1994) and Nasir *et al.* (1995). Obviosly, the dominant feature was that the swell spectra changed their direction when it approached the Kapas Island and the Chendering headland. For instance, in September 1993 the offshore swell spectra with a 200 m wavelength changed its direction from south to the north when it approached Kapas Island and Chendering (figure 3).

The results of the regression models are presented in figure 4 and 5. They show a relationship between the estimated ERS-1 azimuth cut and the simulated one. The x-axis is the cut-off estimated from the wave model, and the y-axis is the azimuth cut-off estimated from radar spectra image. These results show a good correlation between modeled cut-off and measured cut-off. The degree of correlation of between the two model ($R^2$) ranged between 0.61 to 0.78. These findings are similar to the studies of Vachon *et al.* (1994 and 1997a).

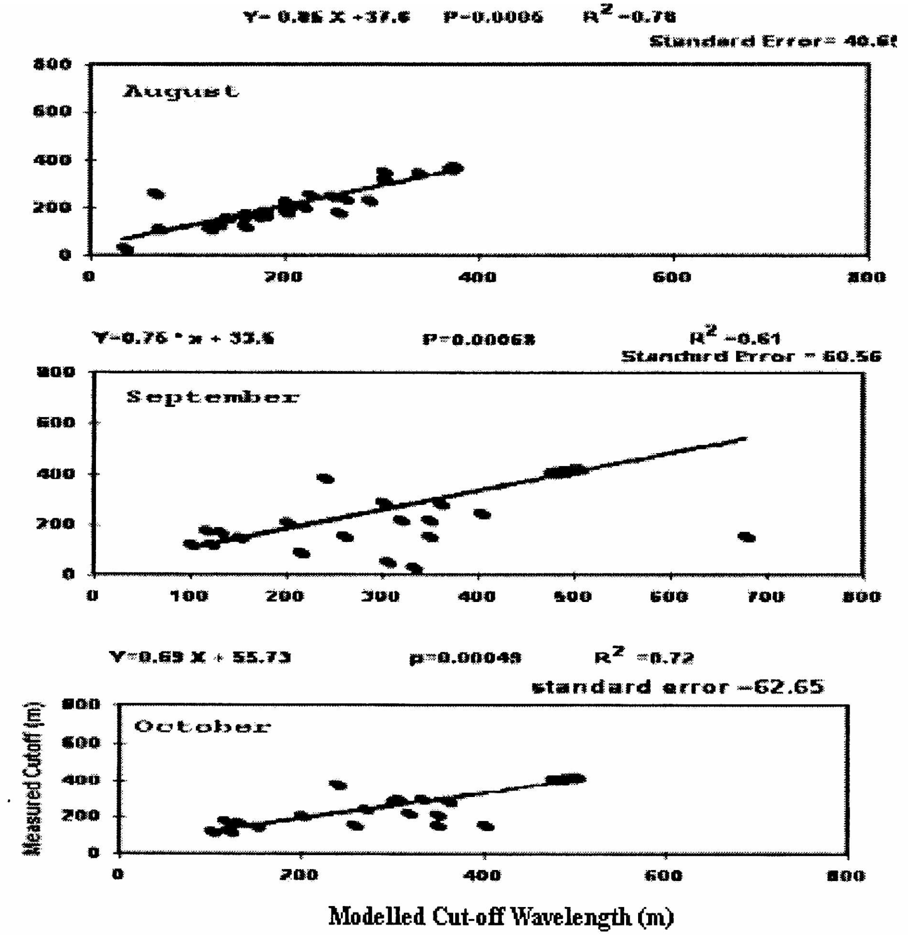

**Figure 4. Azimuth cut-off model during, August, September and October 1993, respectively.**

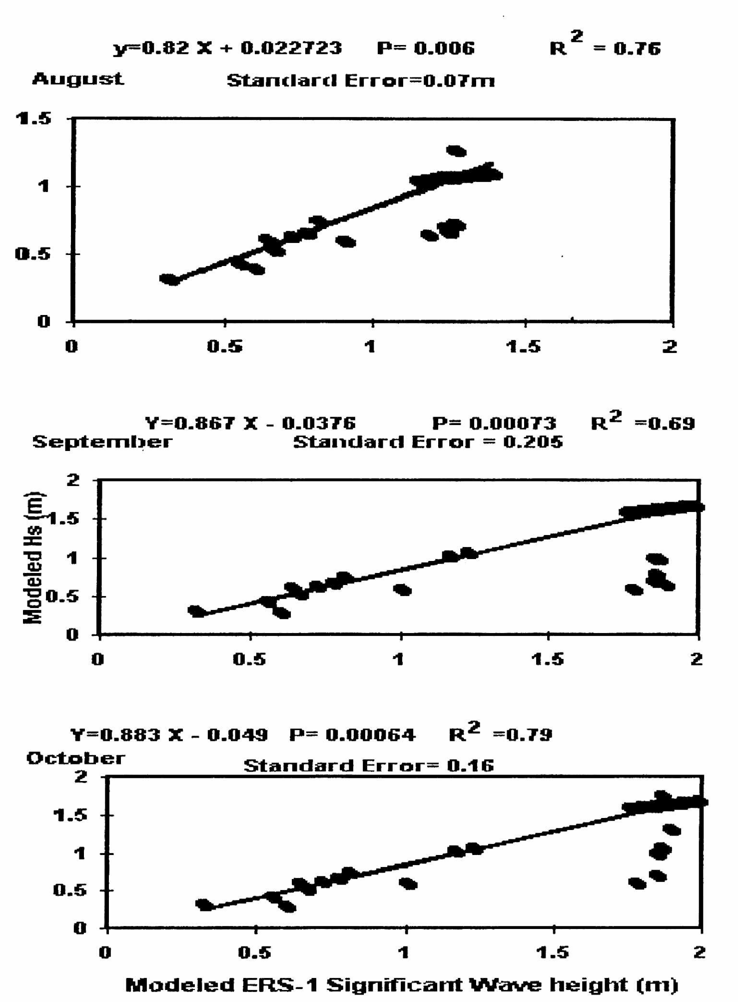

**Figure 5. ERS-1 modelled significant wave Height**

Regression models of ERS-1 significant wave height and wave model (predicted significant wave height from ground data) are in good correlation. The maximum significant wave height occurred in September and October 1993, meanwhile the minimum significant wave height occurred in August. The ERS-1 significant wave height ranged from 0.37 m to 2.0 m in September and October 1993. In August 1993 ranged from 0.25 m to 1.48 m (figure 4). These findings are similar to the studies by Vachon *et al.* (1994 and 1997). The quasi-linear transform reduced the non-linearity between the observed wave spectra by radar data and modeled wave spectra. It can be proposed that quasi-linear transform could be used to estimate significant wave height. The significant wave height simulated from quasi-linear transform agreed with the ground wave field data. These results are approximately similar to the studies by Valencia (1978), Supichai, (1995) and Ooi and Lim (1996). The variation of azimuthally cut-off values between southwest monsoon and inter-monsoon period could be attributed to the effect of different wind pattern.

## 4. CONCLUSION

It was demonstrated that ERS SAR data could capture the variation of offshore and onshore ocean wave spectra. This methodology can be recommended for study the wave transfer. The onshore wavelength ranged between 25 to 70 m while offshore swell ranged from 100 to 350 m. The maximum wavelength (350 m) was found offshore during September and October. The azimuth cut–off based on the quasi-linear model could be used as operational tool to model the significant wave height. The maximum significant wave height was observed in September and October with 1.78 m. The variation of the azimuth cut-off due to the monsoon pattern change because of the change of wind pattern. This suggested that azimuth cut-off could be used in modelling the seasonal variation of significant wave height.

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