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Simulation of coastal wave spectra energy from ENVISAT satellite data

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Abstract. In the last two decades, scientists have developed several powerful techniques to retrieve energy from natural sources such as a sun radiations, oceans and winds. This study is aimed at stimulating wave energy from large scale synthetic aperture radar (SAR) during different monsoon periods. In doing so, the nonlinear velocity bunching algorithm is used to retrieve the information of ocean wave spectra parameters such as significant wave height, directions, and energy on offshore, midshore, and onshore. Therefore, the maximum peak of the wave energy spectra density of 1.4 m^2 s has occurred during northeast monsoon period. It is clear that the mid-shore and onshore has the highest peak of 0.8 and 1.37 m^2 s, respectively as compared to offshore. In conclusions, a nonlinear algorithm of velocity bunching can be used to retrieve the significant wave height from synthetic aperture radar (SAR). In addition, SAR can be used to map the distribution of ocean wave spectra energy and determined the potential energy zone in Malaysia coastal waters.

1. Introduction

Ocean wave plays significant role in renewable energy industries over the world. It is important to investigate the potential zone of wave energy in coastal zones. The coastal zone is closed area of land and it is easy to supply the generated energy from wave energy farms by cables to land zone [4,6,7,8]. Therefore, the implementation of wave energy farms in coastal zone requires accurate information about the potential wave energy. In this regard, using conventional techniques for wave energy investigation by being a time consuming as it is required to deploy several wave rider buoys over a large scale area of the coastal zone.

Synthetic Aperture Radar (SAR) has been recognized as a powerful tool for modeling ocean waves and forecasting over an area of 300 km x 300 km. Hence, the sediment transport could be modeled by the wave spectra information extracted from a SAR image[1]. Currently, a number of investigations have been carried out on the assimilation of SAR wave mode data into wave forecasting models. This is because the SAR image spectrum has turned out to be far removed from the actual wave spectrum and rather complicated post-processing is necessary for extracting quantitative wave information In this regards, previous studies were carried out by Hasselmann and Hasselmann, [2], and Li et al., [5] by developing an inversion algorithm to map SAR wave spectra into ocean wave spectra. Hasselmann and Hesselman [2] introduced a non-linear algorithm which was developed by Vachon et al.,[11] to model the significant wave height based on the azimuth cutoff. Vachon et al. [11] defined the azimuth cutoff as the degree to which the SAR image spectrum is constrained in the azimuth direction. The azimuth cutoff is affected by the wind and wave condition in a quasi-linear forward-mapping model [11]. Marghany [8] utilized the azimuth cutoff model which was developed by Vachon et al. [11] to estimate the significant wave height. This study is aimed to retrieve the wave energy spectra from ENVISAT ASAR data using the velocity bunching algorithm along the east coast of Malaysia.

2. Velocity bunching algorithm

According to Pierson and Moskowitz [10] the significant wave height spectrum H_s can be related to the one sided directional wave number spectra density $S(\vec{K},\phi)$ by the following formula

$$H_s = 4[\int\int S(\vec{k},\phi)\,dk_i\,dk_j]^{0.5} \qquad (1)$$

where k_i and k_j are the wave numbers in the azimuth and range directions, respectively, and $\vec{K}$ is the wave-number magnitude of k_i and k_j in the azimuth and the range directions, respectively.. The ocean wave spectrum was obtained by input of in situ wave parameters (dominant wave number, wave propagation direction ϕ and significant wave height H_s. The actual ocean wave spectrum density $S(\vec{K},\phi)$ can be calculated from the following equation [6,10],

$$S(\vec{K},\phi) = \frac{\sqrt{S(k_i,k_j)d\vec{K}}\; e^{[-2(5.88U^{-2}/\vec{K}\cos\phi)^2]}}{\left[\vec{K}^2 - (0.5gU^{-2})\vec{K}\cos\phi + 2.4U^{-2}\right]^2} \qquad (2)$$

where U is the wind speed and ϕ is the wave direction. The actual wave spectra contours have been determined by using Eq. 2. Furthermore, Eq. 2 has been used with quasi-linear model to map the ENVISAT ASAR wave spectra onto ocean wave spectra.

In this study, a single ENVISAT ASAR image (Table 1) frame comprising of 512 x 512 pixels and lines was extracted. The ENVISAT ASAR images are a two dimensional sampling of the ocean wave field and thus a two-dimensional (2-D) Fourier transfer has to be utilized [1,6].When the Fourier transfer was selected, the output domain is the two-dimensional frequency spectrum of the input image [6].

Table 1: Physical Parameters of ENVISAT ASAR.

Parameters	Values
Radar Wavelength (cm)	5.6
Ground Resolution (m)	30
Incident Angle (°)	25
Polarization	HH/VV

To map observed SAR spectra into the ocean wave spectra, a nonlinear model was applied. The nonlinear theory is explained below: According to the Gaussian linear theory, the relation between ocean wave spectra $S(\vec{K},\phi)$ and ENVISAT ASAR image spectra $S_Q(\vec{K})$ could be described by tilt and hydrodynamic modulation (real aperture radar (RAR) modulation) and velocity bunching modulation. The tilt modulation is linear to the local surface slope in the range direction i.e. In the plane of radar illumination. The tilt modulation in general is a function of wind stress and wind direction for ocean waves and ENVISAT ASAR. According to Vachon et al.,[11] the tilt modulation is the largest for HH polarization. The hydrodynamic interaction between the scattering waves (ripples) and longer gravity waves produced a concentration of the scatterer on the up wind face of the swell. Following Vachon et al., [11] ENVISAT ASAR image spectra can map into ocean wave spectra under the assumption of the quasi-linear modulation transfer function $S_Q(\vec{k})$ which is given by

$$S_Q(\vec{K})=R(K)H(k_i;K_c)\left[\frac{S(\vec{K},\phi)}{2}\left|\mathrm{T}_{\mathrm{lin}}(k_{i,j})\right|^2+\frac{S(-\vec{K},\phi)}{2}\left|\mathrm{T}_{\mathrm{lin}}(-k_{i,j})\right|^2\right] \qquad (3)$$

where $H(k_i;K_c)$ is an azimuth cut-off function that depends upon azimuth wave number k_i and range wave number k_j, the cut-off azimuth wave number K_c and $R(\vec{K})$ is the ENVISAT ASAR point spread function. ENVISAT ASAR point spread function is a function of the azimuth and the range resolutions [7,11]. According to Vachon et al., [11] $\mathrm{T}_{\mathrm{lin}}$ is a linear modulation transfer function which is composed of the RAR (the tilt modulation and hydrodynamic modulation), and the velocity bunching modulation. The RAR modulation transfer function (RAR MTF) is the coherent sum of the transfer function associated with each of these terms, i.e.

$$T_{lin}(\vec{K})=M_t(\vec{K})+M_d(\vec{K})+M_v(\vec{K}) \qquad (4)$$

The tilt modulation $M_t(k)$ can be described by vachon et al., [11] as follow

$$M_t(\vec{K})=k_j\frac{4\cot\theta}{1\pm\sin^2\theta}e^{(\frac{i\pi}{2})} \qquad (5)$$

where k_j is the range wave number and θ is the local incident angle of the radar beam. Following Vachon et al., [11], the hydrodynamic modulation transfer function can be given by

$$M_d(\vec{K})=4.5\omega K\frac{\omega-i\mu}{\omega+\mu^2}\sin^2\phi \qquad (6)$$

where $\vec{K}$ is long wave number, i is $\sqrt{-1}$, ω is the angular frequency of the long waves, ϕ is the azimuth angle and μ is the relaxation rate of the Bragg waves which is 0.5/s. According to Vachon et al. [11] velocity bunching can contribute to equation 4 (linear MTF) based on the following equation which was given by Vachon et al. [11]

$$M_v(\vec{K})=\frac{R}{V}\omega\left[\frac{k_i}{\vec{K}}\sin\theta+i\cos\theta\right] \qquad (7)$$

where *R/V* is the scene range to platform velocity ration. In order to estimate the significant wave height from the quasi-linear transforms, we adopted the algorithm that was given by Vachon et al., [11] and modified by Marghany (2003) to be appropriate for the geophysical conditions of tropical coastal waters:

$$\lambda_c=\beta\left(\int_{H_{s0}}^{H_{sn}}\sqrt{H_s}\,dH_s+\int_{U_0}^{U_n}\sqrt{U}\,dU\right) \qquad (8)$$

where is λ_c cut-off, H_s and U are the in situ data of significant wave height and wind speed. The measured wind speed was estimated at 10 m height above the sea surface. β is an empirical value which results of *R/V* multiplied by the intercept of azimuth cut-off C when the significant wave height and the wind speed equal zero. A least squares fit was used to find the correlation coefficient between cut-off wavelength and the one calculated directly from the ENVISAT ASAR spectra image by equation (8). Then, the following equation was adopted by Marghany [7] to estimate the significant wave height (H_{sT}) from the ENVISAT ASAR images

$$H_{sT} = \beta^{-2} \int_{\lambda_{c0}}^{\lambda_{cn}} (\lambda_c)^2 \, d\lambda_c \qquad (9)$$

where β is the value of $\left(c\frac{R}{V}\right)^{-1}$ and H_{sT} is the significant wave height simulated from ENVISAT ASAR images. The significant wave height H_s is estimated by using the velocity-bunching model. Finally, the in situ wave spectra measurements have been collected using AWAC wave rider buoy during the ENVISAT ASAR overpass on 28 December 2010.

3. Results and discussions

Figure 1 shows the ENVISAT ASAR satellite data along the coastal waters of Johor. This data was acquired on 28 December 2010 (Figure 1). The study area is located along the coast of Johor in the southern, eastern part of Peninsular Malaysia. The area is approximately 20 km of Johor (Figure 1), located in the South China Sea between 1° 57´ N to 2° 15´ N and 103° 51´ E to 104° 15´ E. Further, the coastline is bordered with varying width of alluvial plains. Consistent with Mastura [9] and Zelina et al., [12], this area lies in an equatorial region dominated by two seasonal monsoons and two transition monsoon. The southwest monsoon lasts from May to September while the northeast monsoon lasts from November to March. The transition monsoon periods involve April which is between end of northeast monsoon and the beginning of the southwest monsoon periods. Further, the second transition monsoon is October which is between the end of the southwest monsoon and beginning of northeast monsoon periods [6,12].

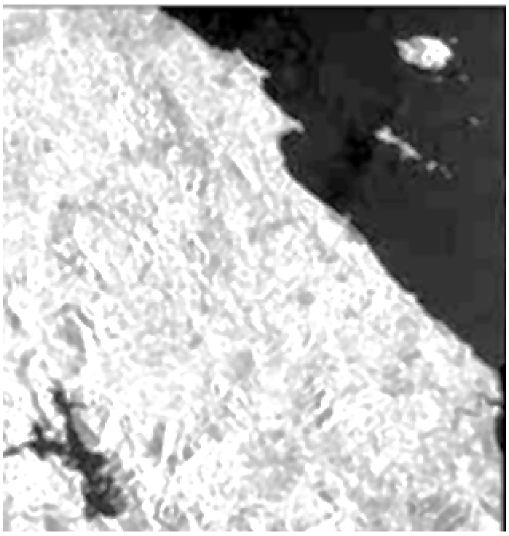

Figure 1. ENVISAT ASAR data were used in this study.

Figure 2 shows the simulated wave spectra that derived from AWAC wave rider buoy, ENVISAT ASAR data, and modeled by using the velocity bunching model. Clearly, the wavelength is varied from 100 m to 200 m. The main direction of the wave spectra is the northeast. The monsoon winds affect the direction and magnitude of the waves. Further, Marghany [8] stated that strong waves are prevalent during the northeast monsoon when the prevailing wave direction is from the north (November to March), while during the southwest monsoon (May to September), the wave directions are propagated from the south. According to Marghany et al., [6] the maximum wave height during the northeast monsoon season is 4 m. The minimum wave height is found during the southwest monsoon which is less than 1 m [6,8].

(a) **(b)** **(c)**

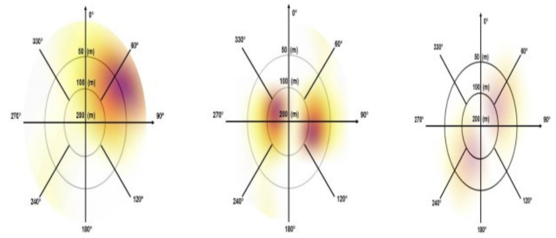

Figure 2. Ocean wave spectra derived from (a) AWAC, (b) ENVISAT ASAR and (c) velocity bunching model.

According to Marghany [7] velocity bunching model produces precisely the information of wave spectra. Indeed, it is able to solve the matter of non-linearity between SAR observed spectra and ocean wave spectra. In other words, it can be used to map SAR observed spectra into real ocean spectra. This result confirms that studies of Vachon et al., [11]; Marghany [8] and Marghany et al., [6]. Figure 3 shows the wave energy density spectra simulated from the velocity bunching model. It is interesting to find that the offshore and onshore wave spectra energy is 1.4 m^2s and 1.37 m^2s, respectively that are larger than midshore. According to Komar [4] offshore is the first region of ocean which received highest wind stress and that caused a high frequency of wave fluctuations. Therefore, the increment of wave spectra energy on shore is due to that the wave is experiencing the breaking status. It can be said that, the ENVISAT ASAR data can be used to simulate the pattern of the wave spectra energy.

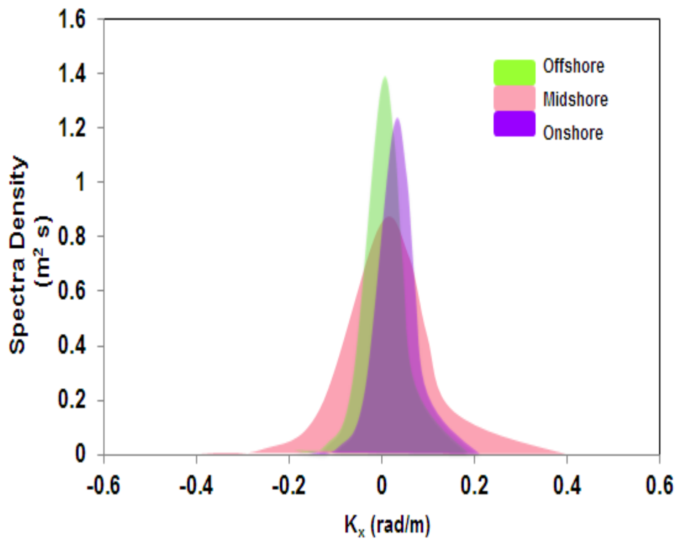

Figure 3. Wave spectra energy simulated from the velocity bunching algorithm.

4. Conclusions

The paper has demonstrated a method for retrieving wave spectra energy from ENVISAT ASAR satellite data. In doing so, nonlinear velocity bunching algorithm is implemented to retrieve significant wave height. The study shows that the maximum peak of the wave energy spectra density of 1.4 m^2 s has occurred during northeast monsoon period. In addition, wave spectra energy are varied along coastal water. Clearly, the mid-shore and onshore have the highest peak of 0.8 and 1.37 m^2 s, respectively. In conclusions, a nonlinear algorithm of velocity bunching can be used to retrieve the significant wave height from ENVISAT ASAR satellite data. In addition, ENVISAT ASAR data can be used to map the distribution of ocean wave spectra energy and determined the potential energy zone in Malaysia coastal waters.

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