# Simulation of ship speed and direction by using TOPSAR data

**MAGED MARGHANY, ZELINA IBRAHIM, MOHD IBRAHIM MOHAMED**[1] and **SHATTRI MANSOR**[2]

[1]Faculty of Science and Environmental Studies
[2]Faculty of Engineering
Universiti Putra Malaysia
43400, UPM, Serdang, Selangor
Malaysia

**Abstract**. TOPSAR polarized data have many potential applications in coastal waters. One of the most important applications is in ship detection. Ship detection is an important aspect of marine traffic navigation. The main objective of this study is to establish speed and direction of ship movement to enable better traffic control in maritime navigation. TOPSAR L-band data were used for this purpose. Two numerical models were used to detect ship and wake movement. The first model used is based on the Doppler shift effect between sensor and target movement. The second model is based on the relationship between wavelength generated by ship and ship velocity. The statistical analysis of application of the two models has shown a significant correlation indicating high accuracy for ship detection and movement. The work shows that TOPSAR polarized data have the potential for monitoring ship speed and direction. The integration of 2-DFFT with the Doppler frequency shift model has proven useful in identifying the location and speed of the ship in coastal waters.

## 1. Introduction

Monitoring shipping traffic along the coastal waters of Malaysia has taken greater importance for controlling illegal immigration from the neighbouring countries. Radar based data would be useful in tracking the movement of shipping in the waters of the large exclusive economic zone surrounding Malaysia. Monitoring shipping movement with radar data is operationally possible due to the ability of radar signals to penetrate dense cloud cover (Johan *et al.* 1997) which is a dominant feature in tropical regions such as in Malaysia. Besides this, radar pulses have the ability to work during day and night, allowing the monitoring of shipping traffic throughout the day.

The main objective of this paper is to establish the track and speed of the ships in the coastal waters of Kuala Terengganu.

## 2. Materials and methods

### 2.1 Data

TOPSAR L-band data were used in the study. TOPSAR data of Kuala Terengganu were taken on 6 December 1996. The data are relevant to the study area between 5° 21' N to 5° 32' N and 103° 6' E to 103° 15' E. For the purpose of the study, sub-scence of about 300 by 300 pixels were selected relating to an area of 3 km by 3 km.

### 2.2 Preprocessing

TOPSAR image data were loaded into the ENVI V.3 image processing system for image synthesis, antenna correction and geometric correction. The image was then loaded into a PCI EASI/

PACE image processing system for further processing. Four preprocessing stages were performed as follows:

1. Detection of bright pixel areas of ships and their wake
2. Masking the bright pixels of ship from the surrounding area
3. Application of Lee filter
4. Application of 2-DFFT
5. Modelling of the ship speed and direction by using the Doppler shift and Bragg scattering effects.

2.2.1 Detection of ship orientation and wake

According to Johan *et al.* (1997) a ship's track is brighter than the surrounding area. This in effect means that the pixels intensity of a ship is higher (Figure 1). This brightness was examined by detecting the distribution of pixels against the backscattering of the ship's brightness. The ship and wake pixels were masked (Figure 2) in order to have an adequate discrimination between the pixels representing the ship and the background. This approach has been taken based on the backscattering profile as mentioned above.

A low pass filter such as Lee filter was used to determine the linear feature of the ship 's wake. Subsequently, the same low pass filter was applied on the ship pixels to distinguish the ship from its wake and surrounding area. A window size of 3 x 3 was used for this purpose because of the fact that increasing the window size over a small area can lead to migration of the dark pixels into brighter pixels areas. This effect can destroy most of the information from the image. A 2-DFFT was applied on Lee filter image to detect the spectra of the ship wake as described in section (2.2.4).

2. 2.2 Model of ship speed and direction

Ship detection using radar data such as SAR and TOPSAR has a different methodology compared to those based on optical data such as SPOT and Landsat. There are many factors governing ship detection by data derived from radar. The most important factor is the Doppler shift effect. The Doppler shift occurs due to target and antenna movement. The Doppler shift effect occurs when the pulses return from a moving target. This has the effect of shifting the target position azimuthly in SAR images. In the case of a stationary target, the Doppler shift decreases, reaching zero when the SAR reaches the same azimuth direction as the target. If the target is in motion, an extra Doppler shift is observed. The Doppler shift effect falls to zero at different azimuth position and the assigned processor level. Lin and Khoo (1997) estimated the Doppler shift effect of target velocity by using the following formula:

$$U = \Delta V_s / H \tan\theta \cos\phi \qquad (1)$$

where H is the TOPSAR altitude, $\theta$ is the incident angle while $\phi$ is the direction of target movement (Figure 3). Equation 1 shows that target velocity $V_s$ is dependent on the azimuth shift ($\Delta$). Lin and Khoo (1997) calculated azimuth shift as functions of the target movement. The relationship between target movement and aircraft would depend on the change of the aircraft position over the target (Figure 4). In Figure 4 the aircraft will change its position from A to A'. This change will induce change in the slant range R to $R_o$ in time interval dt. This change can induce the Doppler shift between azimuth and target movement. Let the TOPSAR pass the target at closest approach at time t=0 and slant range $R_0$ which is perpendicular to the track when the TOPSAR moves to point A, then the slant range R, changes to

$$R^2 = R^2_0 + (V_s t)^2 \quad (2)$$

Differentiate (2) with respect to time t to obtain

$$2R(dR/dt) = 2\,V_s^2 t \quad (3)$$

Hence,

$$dR/dt = (V_s^2/R)t \quad (4)$$

A signal received at a moving antenna will be altered in frequency according to Doppler shift effect and that the frequency shift will be proportional to the relative speed of TOPSAR,

$$\Delta = (-2/\lambda)\,(dR/dt) \quad (5)$$

Using equations (4) and (5), the Doppler shift is

$$\Delta = (-2/\lambda)\,(V_s^2/R)t \quad (6)$$

Hence, the velocity of the target can be estimated by substituting equation (6) into equation (1). According to Lin and Khoo (1997) the relative velocity of the target with respect to TOPSAR is given by

$$u' = (u \cos \phi,\ u \sin \phi - V_s) \quad (7)$$

Lin and Khoo (1997) did not consider the time change and slant range change in Doppler shift calculations. They considered the change of target speed and position with ERS-1. The location of the ship 's image is recorded as a signal received by the antenna. The Doppler shift recorded in the image is the Doppler frequency shift of the signal received back from the ship to antenna. It is our view that the Doppler frequency shift of signal should have been estimated because of the fact that Doppler shift between the aircraft and target caused the Doppler frequency shift in the image. According to John and Robert (1991) the Doppler shift relative to the transmitted frequency is

$$\Delta' = 2(V_s \sin \theta)/\lambda \quad (8)$$

The variation of Doppler frequency shift $\Delta_f$ can be given by

$$\Delta_f = \Delta' + \Delta \quad (9)$$

Based on the above perspective, the ship 's speed can be estimated by

$$U = \Delta_f V_s / H \tan\theta \cos \phi \quad (10)$$

For TOPSAR H= 7936.99 m and incident angle $\theta$ is 18° within velocity of 250 m/s, resulting in equation (10) being written as:

$$U = -0.06\,\Delta_f / \cos \phi \quad (11)$$

Equation (11) shows the target velocity function on the Doppler frequency shift. The Doppler frequency shift does not exist during the flight time. Nevertheless, it was produced due to the shift of signals received from the target to the antenna. This means that the Doppler shift has an effect on the location of target pixels due to Doppler shift between TOPSAR and the target. In order to determine the speed and

velocity of the target, the magnitude pixel (r) of a ship produced by 2-DFFT time by pixel resolution, results in equation (12) as follows:

$$U = -0.06\, r.\ 10\ \ \Delta_f / \cos\phi \qquad (12)$$

A comparison between equation (12) and (1) shows that equation (12) represents the speed of the target function of Doppler frequency change over the target pixels while equation (1) represents the Doppler change between TOPSAR and the target. This is the reason why the Doppler change should be calculated to include the spatial frequency of the image. Furthermore, equation (12) complies to the Radon transform estimated for the ship's magnitude in spatial domain transform. However, Lin and Khoo (1997) have focused their efforts to calculate wake length to establish ship speed. The pixel of a ship's wake just shows the part of the force momentum put on a ship's power on the water surface but most of the power is found in the ship's magnitude. This is because any object's movement is a function of magnitude of the movement in relation to target, time and direction.

### 2.2.3 Target direction

The target direction was calculated by using the slope of the regression analysis between two different polarizations of TOPSAR. The scatter plot was examined between different polarizations of L-band TOPSAR image. The slope of the regression analysis model was selected from a high correlation between input polarization data. The scatter plot was based on the masked area of the target. The direction location of the target's movement was estimated by using

$$\phi = \tan^{-1}(\text{slope}) \qquad (13)$$

Then equation (13) is used into equation (12) to derive the ship's speed.

### 2.2.4 Wake detection

According to Lyden *et al.* (1988) and Lin and Khoo (1997) ship's movement induces an internal wave and turbulent area. These phenomena are proportional directly to the input force of a ship's movement on the water surface. To detect the wavelength of a ship 's wake, 2-DFFT was applied on the masked area of the target. This is because of the fact that 2-DFFT is useful in converting the image in frequency or spatial domain. Frequency domain is useful in removing certain types of noises and identifying the location of the target pixels in the image. Frequency domain can also be used to identify image orientation and periodicity (John 1995). According to this idea, ships and wakes are localised in spatial domain and may also be localised in frequency domain. They can be detected more easily in the 2-DFFT transformed image. Since the ship wakes occupy only a very small fraction of the image, the Lee filter was applied on the masked area to remove all noises surrounding the ship and its wake before 2-DFFT was applied to it.

The 2-DFFT application has split the image into frequency domain carrying spatial location and orientation elements of the frequency domain. In this case, it would be easier to detect the wavelength spectra from a frequency domain image. The wavelength (L) of internal wave caused by a ship 's movement can be estimated from 2-DFFT. Lyden *et al.* (1988) had shown that ship movement generates surface waves. In the case of wave which has a front less than 54° to the ship's track the wave propagation will have a phase velocity equal to the ship's speed. Hence, wavelength of wake spectra could be used to derive ship velocity by

$$L = 4\pi\, U^2/3g \qquad (14)$$

Equation (14) was used to compare ship speed calculated from equation (1) and equation (12). The 2-DFFT was used to estimate the target direction by applying the following formula:

$$\phi = \tan^{-1} \text{ (imaginary frequency/ real frequency)} \quad (15)$$

In equation (15), the target phases function of the frequency distributions are in the spatial domain of the image. The change in frequency along the image could carry information on phase change. According to Shiavi (1991), different signal frequencies have different phase and magnitude. The magnitude (r) of ship spectra is calculated by

$$r = \sqrt{(\text{imaginary frequency})^2 + (\text{real frequency})^2} \quad (16)$$

Then equation (16) can be used with equation (12) to derive the ship's speed.

## 3. Results and discussion

The location of a ship is shown in Figure 1. It is clear that Lee filter can distinguish a ship from its wake as shown in Figure 5. The dark turbulent wake is the feature most frequently observed and it usually extends over a small distance at the back of the ship. It is also clear that the wake's pixels consist of only connected pixels. A similar finding had been described in Deborah (1993). According to Lee (1981), the Lee filter can detect the edge boundary in the image. Furthermore, a ship's wake is considered as a linear feature. According to Maged *et al.* (1996), Lee filter can be used to extract this linear feature from the image.

Figure 6 shows the backscatter profile of the L- band (L-VV, L-HH and L-HV). It appears that the location of ship pixels dominated by higher backscattering has higher values in VV and HH compared to HV polarization. It is also noticed that the backscattering peaks on VV and HH polarizations coincide. This is because the frequency in both VV and HH polarizations are larger than in HV polarization. This can be explained by variations in polarization frequency because at higher radar frequencies less waves can be classified as long waves in composite surfaces. Figure 6 also shows that the backscatter is reduced from around the maximum peaks of the ship. This means that the VV and HH polarizations in L- band can view the ship 's wake while in HV polarization the wake cannot be detected. It may be because of the observed lower frequencies in HV compared to VV and HH polarizations. This also means that L- band HH and VV polarizations can be used to estimate the surface roughness of water such as ship wake. This result is similar to the study of Neil (1994). For that reason, the regression analysis between HH and VV is used to determine the slope of a ship 's location. The regression analysis equation shows that the correlation between L-HH and L-VV is 0.92 (Figure 7) while the correlation between L-VH and both L-HH and L-VV is 0.69 and 0.62 respectively. Based on the slope of the regression model the direction of the ship 's movement is 36°

Figure 8 shows the magnitude spectra of ship 's location. The magnitude was calculated as 42 (Figure 9) and the ship's velocity function of the Doppler frequency shift is 6.4 m/s. Figure 10 shows the frequency spectra domain of a ship's wake. The wavelength of the ship's wake ranged from 10 to 20 m. This means that this particular spectrum showed the decay of the ship's wake behind the ship. Close to the ship, the wavelength induced is larger and then decreases as the distance increases away from the ship. The maximum wavelength was taken into account to estimate the ship's velocity from the wake's wavelength spectra.

The phase extracted by 2-DFFT of the ship and its wake is 53° and 45° respectively. This value is quite different compared to the Doppler shift method. This could be due to the Doppler azimuth shift as a result of movement of ship and TOPSAR. This has probably shifted the location of the ship and its wake to the azimuth direction of TOPSAR.

The ship 's movement could induce an internal wave or a Kelvin wave. The length of the waves is a function of ship's speed (Lyden *et al.* 1988). The speed modelled by wavelength spectra of ship's wake is equal to 6.8 m/s. The T-test was used to compare the difference between the two calculations. Table 1 shows that there is no significant difference between the two calculations. This means that the two methods used for ship detection can be integrated together to determine the ship's speed and direction. Furthermore, Roland (1994) stated that the Doppler shift is proportional to the Fourier Transform of the auto- covariance function of the backscattered electromagnetic field.

## 4. Conclusion

It can be concluded that TOPSAR data have the ability to detect ships in the coastal waters of Kuala Terengganu. The comparison between the Doppler shift method and the image transformed by 2-DFFT showed a good correlation. It can be said that the 2-DFFT application and the mathematical model can be integrated together to detect ships and their wakes.

Table 1. Simulated statistical analysis of ship detection models.

| $R^2$ | P | T significant > t | conclusion |
|---|---|---|---|
| 0.734 | $P < 0.05$ | 6.3 > 5.2 | No significant difference |

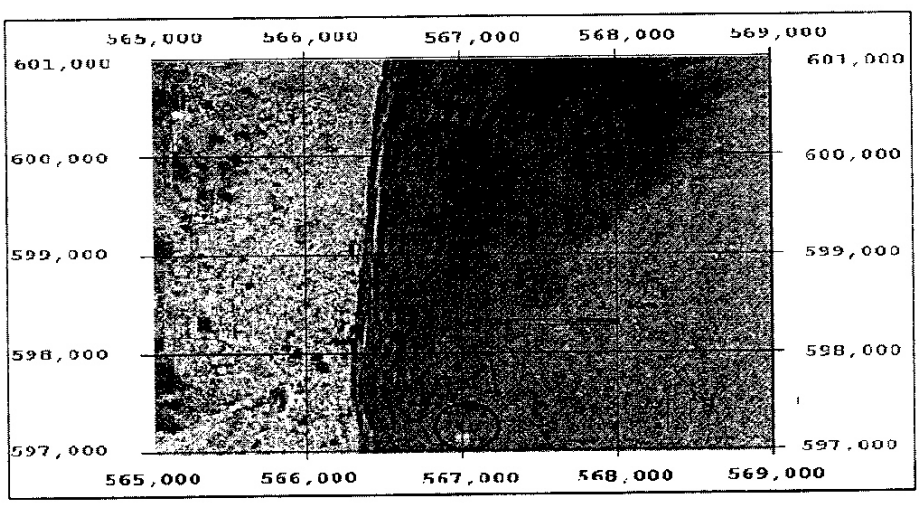


Figure 1. Location of the ship (indicated by dark circle).

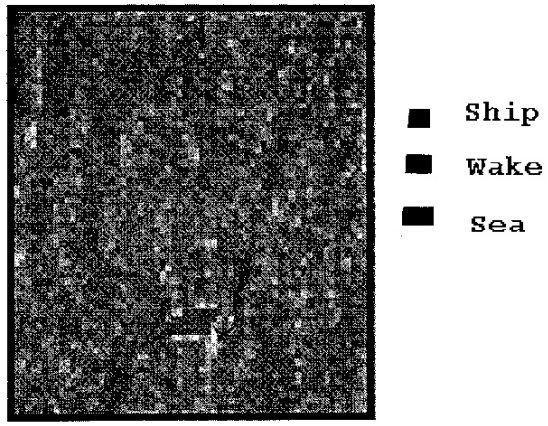


Figure 2. Masked map of ship and its wake.

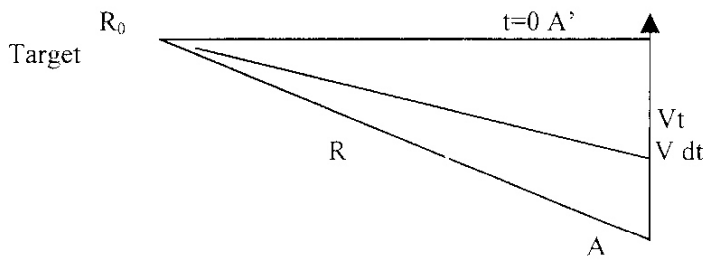


Figure 3. TOPSAR's movement over the target.

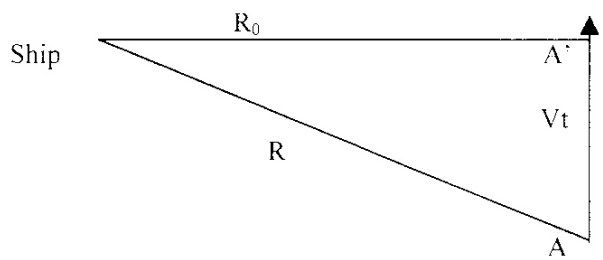


Figure 4. Geometry to derive the relative velocity of TOPSAR and ship.

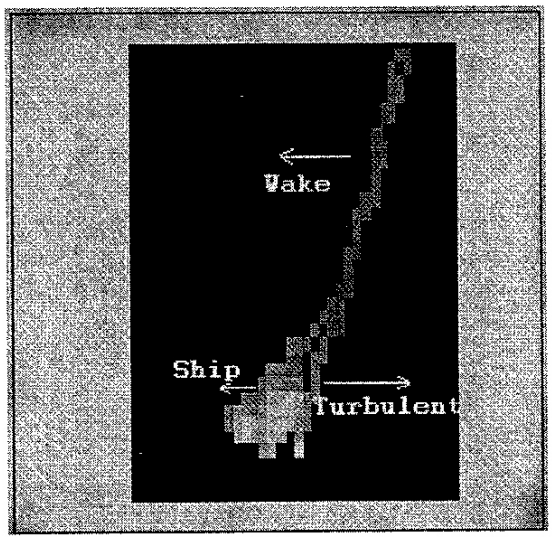


Figure 5. Lee filter map.

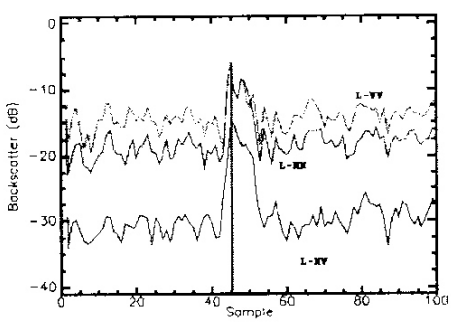


Figure 6. Backscatter profile of ship.

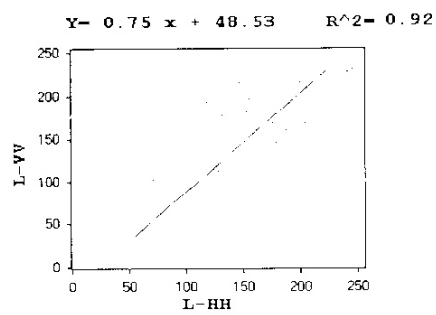


Figure 7. Regression analysis between L-HH and L-VV polarizations.

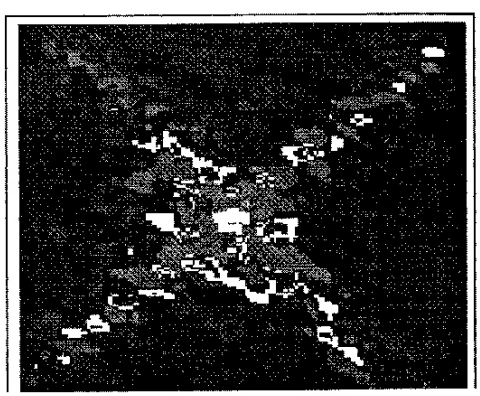

Figure 8. Magnitude spectra of ship.

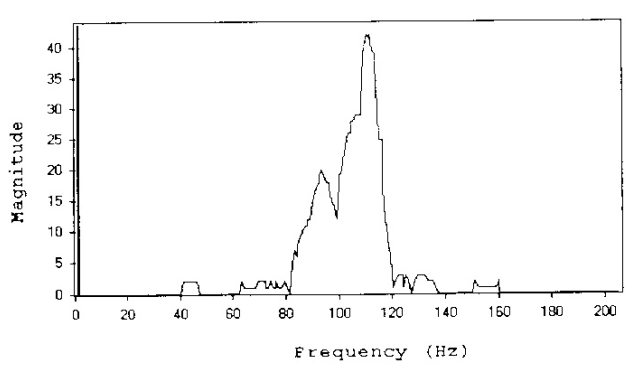


Figure 9. Ship spectra frequency is shown by maximum magnitude peak.

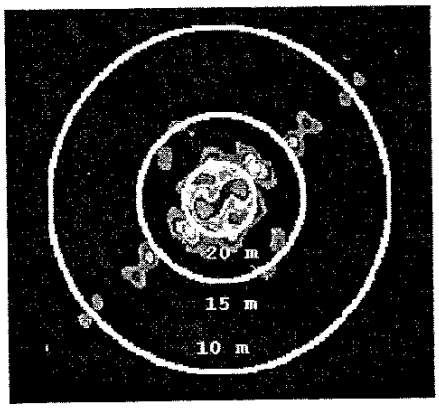


Figure 10. Ship's wake spectra.

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