TOPSAR C-band for Three Dimensional Reconstruction of Coastal Bathymetry

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Abstract

This paper reports on a study carried out for the generation of three-dimensional (3D) ocean bathymetry using airborne TOPSAR data. The main objective of this study is to utilize Fuzzy arithmetic for constructing ocean bathymetry from polarized remote sensing data such as a TOPSAR image. In doing so, two three-dimensional surface models, the Volterra model and a fuzzy B-Spline model which construct a global topological structure between the data points were used to support an approximation of real surface. The best reconstruction of coastal bathymetry of the test site in Kuala Terengganu, Malaysia was obtained with polarised C bands TOPSAR acquired with VV polarization. With 10m spatial resolution of TOPSAR data, an accuracy of (root mean square) ± 0.03 m was found with C_{vv} band.

1. Introduction

Operational of Synthetic Aperture Radar (SAR) on coastal bathymetry mapping is of interest for a diversity of end users (Hennings et al., 1989). The coastal bathymetry is considered to provide key parameters for coastal engineering and coastal navigation. The bathymetry information is valuable for economic activities, for security and for marine environmental protection (Vogelzang et al., 1992, Vogelzang et al., 1997, Hesselmans et al., 2000 and Maged et al., 2007). Remote sensing methods in real time could be a major tool for bathymetry mapping which could produce a synoptic impression over large areas at comparatively low cost. The ocean bathymetry features can be imaged by radar in coastal waters with the strong tidal currents. Several theories concerning the radar imaging mechanism of underwater bathymetry have been established, such as big Alpers and Hennings (1984), Shuchman et al (1985) and Vogelzang (1997). The imaging mechanism which simulate under water topography from a given SAR image consists of three models. These models are a flow model, a wave model and the SAR backscatter model. These theories are the basis of commercial services which generate bathymetric charts by inverting SAR images at a significantly lower cost than conventional survey techniques (Wensink and Campbell, 1997). In this context, Hesselmans et al., (2000) developed the Bathymetry Assessment System, a computer program which can be used to calculate the depth from any SAR image and a limited number of sounding data. They found that the imaging model was suitable for simulating a SAR image from the depth map. It showed good agreement between the backscatters in both the simulated and airborne-acquired images, when compared, with accuracy (root mean square) error of $\pm$ 0.23 m within a coastal bathymetry range of 25-30m. Recently, Splinter and Holman (2009) developed an algorithm to map nearshore bathymetry using a single aerial snapshot taken from a plane, unmanned aerial vehicle, or satellite. This algorithm is based on the changing direction of refracting waves which are used to determine underlying bathymetry gradients function of the irrotationality of wavenumber condition. In this context, Splinter and Holman (2009) claimed that depth dependences are explicitly introduced through the linear dispersion relationship. Further, they used spatial gradients of wave phase and integrated times methods between sample locations (a tomographic approach) to extract wave number and angle from images. They found that synthetic bathymetries of increasing complexity showed a mean bathymetry bias of 0.01 m and mean rms of $\pm$ 0.17 m. Nevertheless, refraction-based algorithm has limitations in which it can be applied within 500 m away from the shoreline. In this circumstance, bathymetry of complex seas cannot be determined. This suggests that the refraction-based algorithm is best suited for shorter period swell conditions in intermediate water depths such as a semi-enclosed sea. Further, the refraction-based algorithm cannot be implemented in SAR data. In fact, the shortest wavelength less than 50 m cannot be estimated in SAR data due to the limitation of using two dimensional (2D) Fourier transform (Romeiser and Alpers, 1997). In this paper, we emphasized how the 3-D coastal water bathymetry could be reconstructed from single airborne SAR data (namely the TOPSAR) using integration of the Volttera kernel (Inglada and Garello, 1999) and fuzzy B-spline models (Maged and Mazlan, 2006 and Maged et al., 2007). Three hypotheses examined are: (i) Volterra model can be used to detect ocean surface current from C bands TOPSAR with VV polarization, (ii) the continuity equation can be used to obtain the water depth, and (iii) Fuzzy B-spline can be used to invert the water depth values obtained by the continuity equation into 3-D bathymetry.

2. Methodology

2.1 Data Set

The Jet Propulsion Laboratory (JPL) airborne Topographic Synthetic Aperture Radar (TOPSAR) data were acquired on December 6, 1996 over the coastline of Kuala Terengganu, Malaysia between 103° 5'E to 103° 9'E and 5° 20′ N to 5° 27′ N. TOPSAR is a NASA/JPL multi-frequency radar imaging system aboard a DC-8 aircraft and operated by NASA's Ames research Center at Moffett Field, USA. TOPSAR data are fully polarimetric SAR data acquired with HH-, VV-, HV- and VH-polarized signals from 5mx5m pixels, recorded for three wavelengths: C band (5 cm), L band (24 cm) and P band (68 cm) at 10m spatial resolution. A further explanation of TOPSAR data acquisition can be found in Melba et al., (1999). This study is utilized C_{vv} band for 3-D bathymetry reconstruction.

2.2 3-D Coastal Water Bathymetry Model

Two models are involved for bathymetric simulation: the Volterra model and Fuzzy B-spline model. The Volterra model is used to simulate the current velocity from C_{vv} band TOPSAR data. The simulation current velocity is used with the continuity equation to derive the water depth variations under different current values. The fuzzy B-spline is used to reconstruct the two-dimensional water depth to a 3-D dimensional (Figure 1).

2.3 Volterra Model

A Volterra model can be used to express the SAR image intensity as a series of nonlinear filters on the ocean surface current. This means that the Volterra model can be used to study the image energy variation as a function of parameters such as the current direction, or the current waveform. A generalized, nonparametric framework to describe the input–output x and y signals relation of a time-invariant nonlinear system is provided by the Inglada and Garello (1999). In discrete form, the Volterra series for input, $x(n)$, and output, $y(n)$ as given by Inglada and Garello (1999) can be expressed as:

$$y(t) = h_0 + \sum_{i_1=1}^{\infty} h_1(i_1)x(n-i_1) + \sum_{i_1=1}^{\infty}\sum_{i_2=1}^{\infty} h_2(i_1,i_2)x(n-i_1)x(n-i_2) + \sum_{i_1=1}^{\infty}\sum_{i_2=1}^{\infty}\sum_{i_3=1}^{\infty} h_3(i_1,i_2,i_3)x(n-i_1)(n-i_2)x(n-i_3) + \dots + \sum_{i_1=1}^{\infty}\sum_{i_2=1} \dots \sum_{i_k=1}^{\infty} h_k(i_1,i_2,\dots,i_k)x(n-i_1)x(n-i_2)\dots x(n-i_k)$$

Equation 1

where, n, i_1 , i_2 ,...,i_k , are discrete time lags. The function $h_k(i_1, i_2, ..., i_k)$ is the kth-order Volterra kernel characterizing the system. The h_1 is the kernel of the first order Volterra functional, which performs a linear operation on the input and h_2, h_3,...,h_k capture the nonlinear interactions between input and output TOPSAR signals.

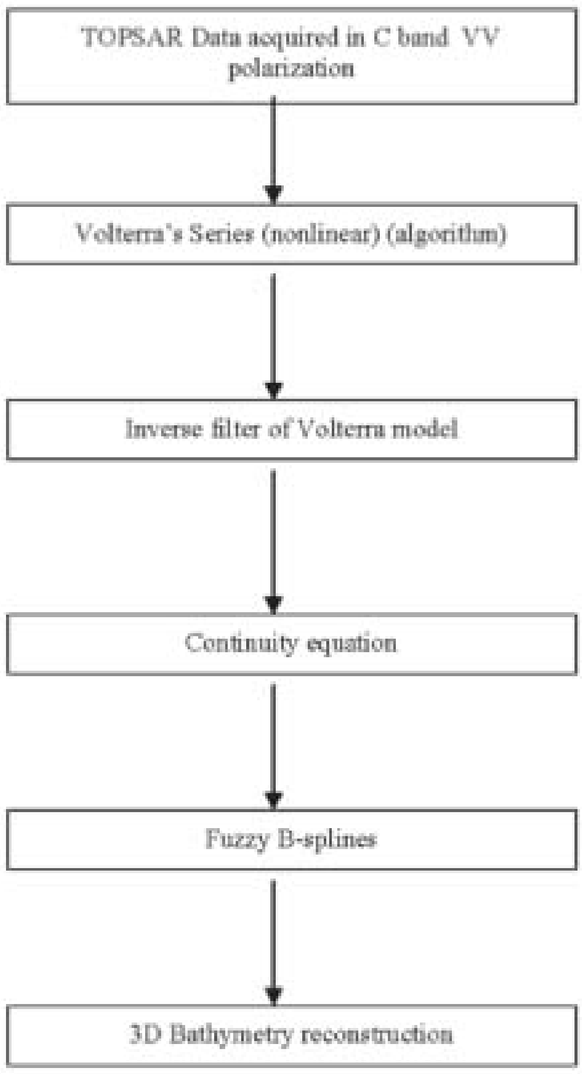

Figure 1: Flow chart of 3-D bathymetry reconstruction

The order of the non-linearity is the highest effective order of the multiple summations in the functional series. Following Inglada and Garello (1999), the expression of the Volterra kernels for the current flow in the range direction can be described as:

$$H_{1y}(u_x, v_y) = k_y \vec{U} \cdot \frac{\partial x}{\partial u_x}\left[K^{-1}\left[\frac{\partial}{\partial t} + \frac{\partial c_g}{\partial x} + \frac{\partial u_x}{\partial x} + 0.043\frac{(u_w K)^2}{\omega_0}\right]\right]\left[\frac{\partial \psi}{\partial \omega}\right].$$

$$\frac{c_g(K)U + j.0.043(u_w K)^2 \omega_0^{-1}}{[c_g(K)U]^2 + [0.043(u_w K)^2 \omega_0^{-1}]^2} + j.(0.6.10^{-2}.K^{-4})(\frac{R}{V})u_x$$

Equation 2

where $\vec{U}$ is the mean current velocity, u_x is the current flow along the azimuth direction while u_w is the current gradient along the azimuth direction, k_y is wave number along range direction, K is the spectra wave number, ω_0 is the angular wave frequency, c_g is the wave velocity group, ψ is the wave spectra energy and R/V is the range to platform velocity ratio, in case of TOPSAR is 32 s. According to Vogelzang et al., (1997) the current movement along the range direction can be estimated by:

$$U_y(u_x, v_y) = \frac{FT\left[\prod_{j=1}^{i} x(t)\right]}{H_{1y}(u_x, v_y)}$$

Equation 3

where $FT\left[\prod_{j=1}^{i} x(t)\right]$ is the linearity of the Fourier transform for the input TOPSAR image intensity. The inverse filter $P(u_x, v_y)$ is used since $H_{1y}(u_x, v_y)$ has a zero for (u_x, v_y) which indicates that the mean current velocity should have a constant offset. The inverse filter $P(u_x, v_y)$ can be given as:

$$P(u_x, v_y) = \begin{cases} [H_{1y}(u_x, v_y)]^{-1} & \text{If } (u_x, v_y) \neq 0, \\ 0 & \text{otherwise.} \end{cases}$$

Equation 4

Then, the continuity equation is used to estimate the water depth as given by Vogelzang (1992).

$$\frac{\partial \zeta}{\partial t} + \nabla.\{(d + \zeta)U_y(u_x, v_y)\} = 0$$

Equation 5

where ζ is the surface elevation above the mean sea level, which is obtained from the tidal table, t is the time and d is the local water depth. The real current data was estimated from Malaysian tidal table of December 6, 1996.

2.4 The Fuzzy B-splines Method

The fuzzy B-splines (FBS) are introduced allowing fuzzy numbers instead of intervals in the definition of the B-splines. Typically, in computer graphics, two objective quality definitions for fuzzy B-splines are used: triangle-based criteria and edge-based criteria. A fuzzy number is defined using interval analysis. There are two basic notions that we combine together: confidence interval and presumption level. A confidence interval is a real values interval which provides the sharpest enclosing range for current gradient values. An assumption level μ -level is an estimated truth value in the [0, 1] interval on our knowledge level of gradient current (Anile, 1997 and Maged et al., 2009). The 0 value corresponds to minimum knowledge of gradient current, and 1 to the maximum gradient current. A fuzzy number is then prearranged in the confidence interval set, each one related to a assumption level $\mu \in [0, 1]$. Moreover, the following must hold for each pair of confidence interval which define a number: $\mu \succ \mu' \Rightarrow h \succ h'$. Let us consider a function $f: h \to h$, of N fuzzy variables $h_1, h_2, \ldots, h_n$. Where h_n are the global minimum and maximum values water depths of the function on the current gradient along the space. Based on the spatial variation of gradient current, and water depth, the algorithms are used to compute the function f. The construction begins with the same pre-processing aimed at the reduction of measured current values into a uniformly spaced grid of cells. As in Volettra model data are derived from the TOPSAR polarised backscatter images due to the application of 2-DFFT. First of all, each estimated current data along fix window size of 512x512 pixels and lines, is considered as a triangular fuzzy number defined by a minimum, maximum and measured value. Among all the fuzzy numbers falling within a window size, a fuzzy number is defined whose range is given by the minimum and maximum values of gradient current and water depth along each window size. Among all the intervals extremes, and whose central value is chosen as the "best choice" proficient considering the density of data within window size. Then, a membership function is defined for each pixel element which incorporates the degrees of certainty of radar cross backscatter (Maged et al., 2007). In order to evaluate the simulation method quantitatively, the regression model and root mean square were computed for the simulated bathymetry from TOPSAR data and bathymetry points have been extracted from topographic map of 1998 sheet number 4365 of 1:25,000.00 scale.

3. Results and Discussion

Figure 2 shows the regions of interest that were used to simulate the bathymetric information from C-band with VV polarization. The bathymetry information has been extracted from of the 4 sub-images, each sub-image was 512x512 pixels. Figure 3 shows the signature of the underwater topography. Underwater topography is obvious as a frontal line parallel the shoreline. Due to the fact that ocean signature of boundary is clear in the brightness of a radar return, since the backscatter tends to be proportional to wave height (Vogelzang, 1992). This may be provide an explanation for clear bathymetric signatures at C_{VV} band. The finding is similar to that of Romeiser and Alpers (1997).

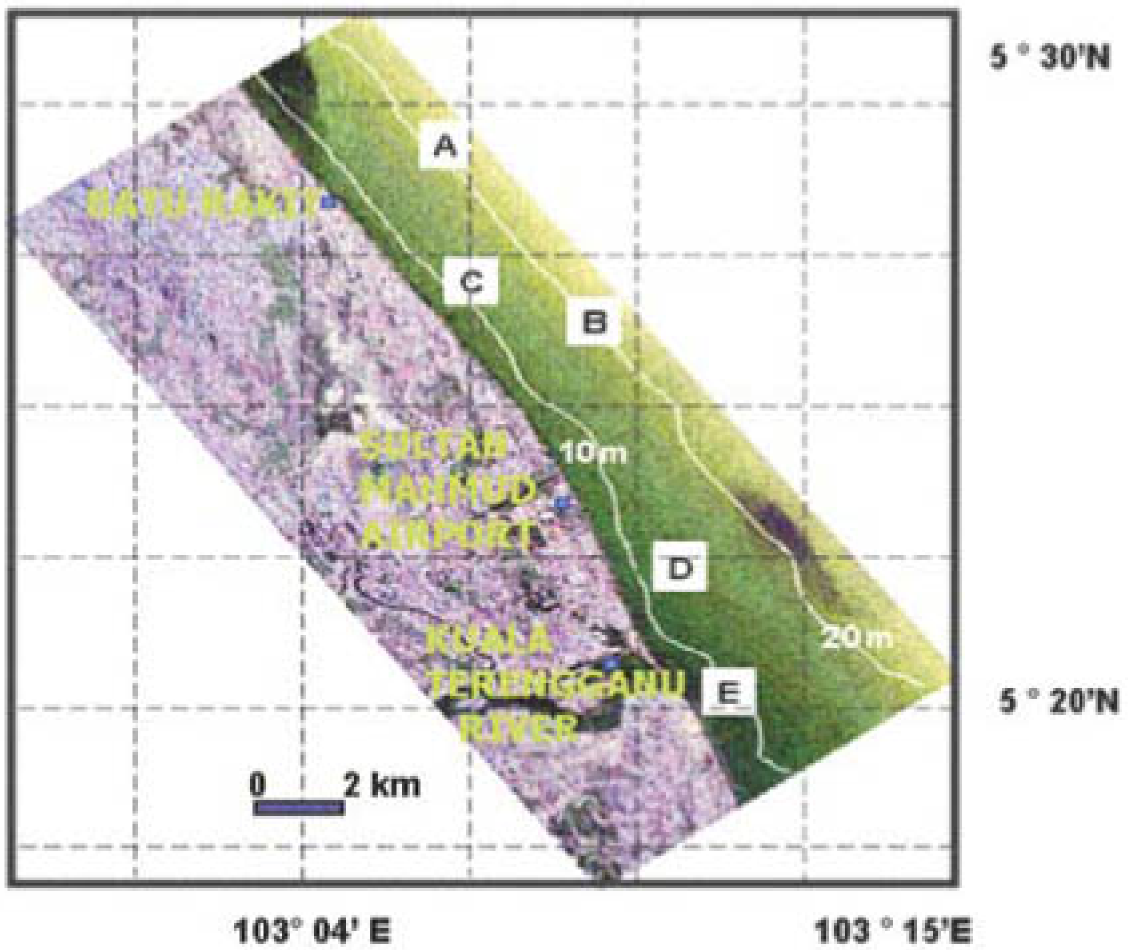

Figure 2: Selected window sizes of A to D with 512 x 512 pixels

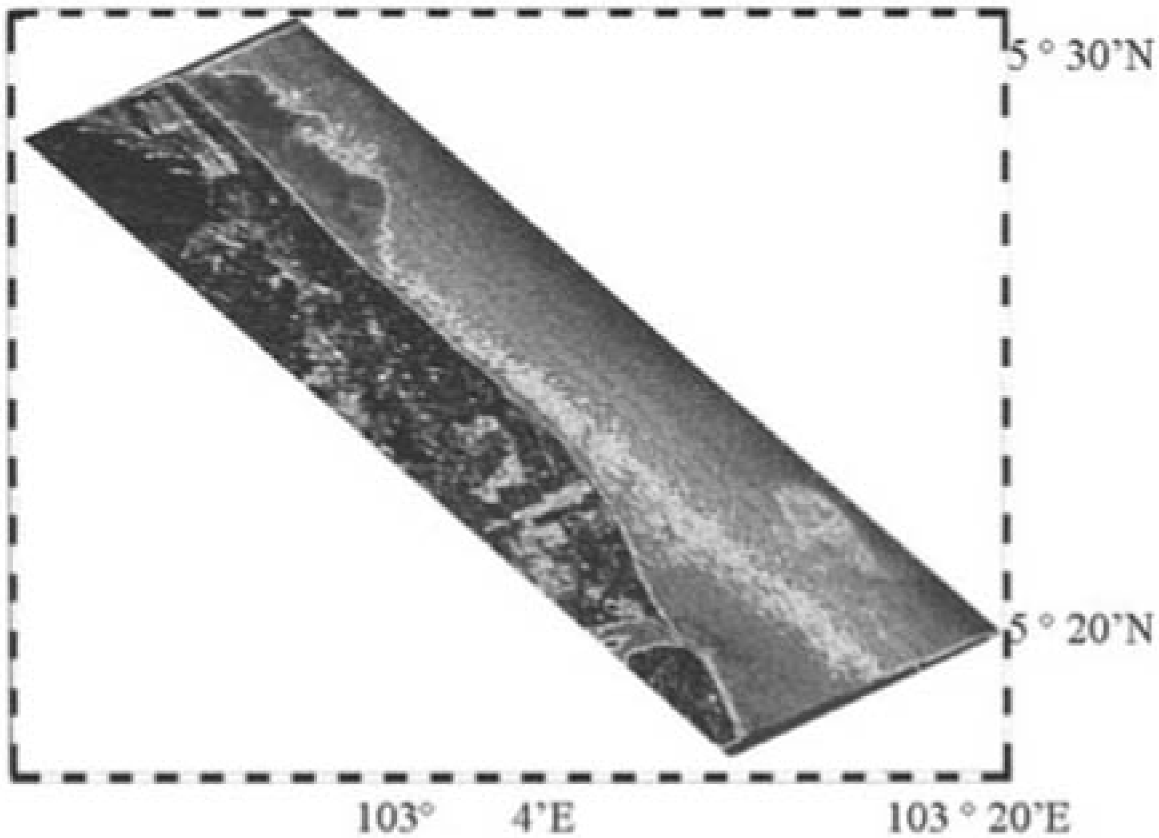

Figure 3: Bathymetry signature with C_{vv} band

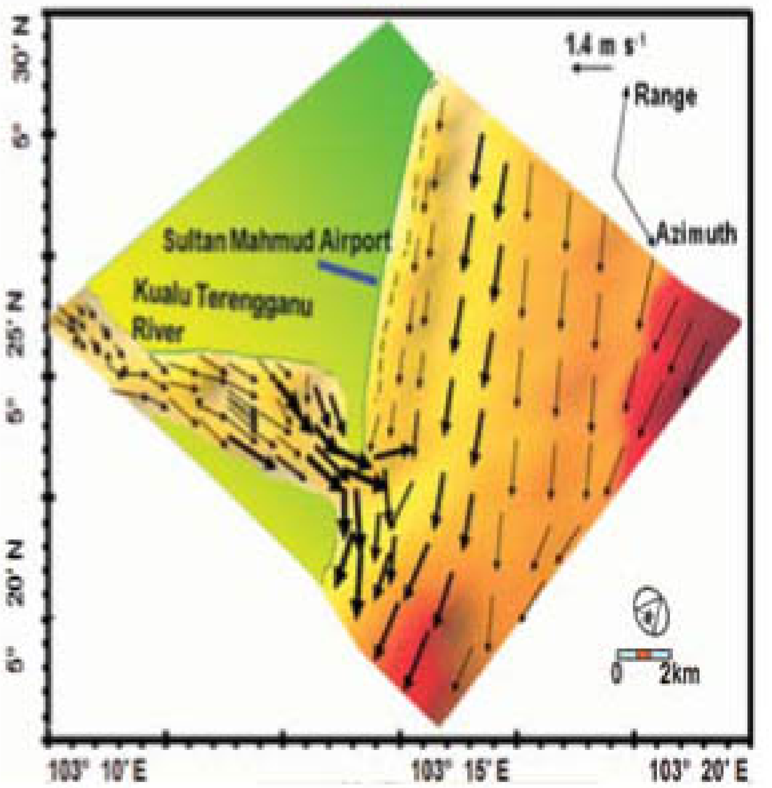

Figure 4: Current vectors simulated from C_{VV} band

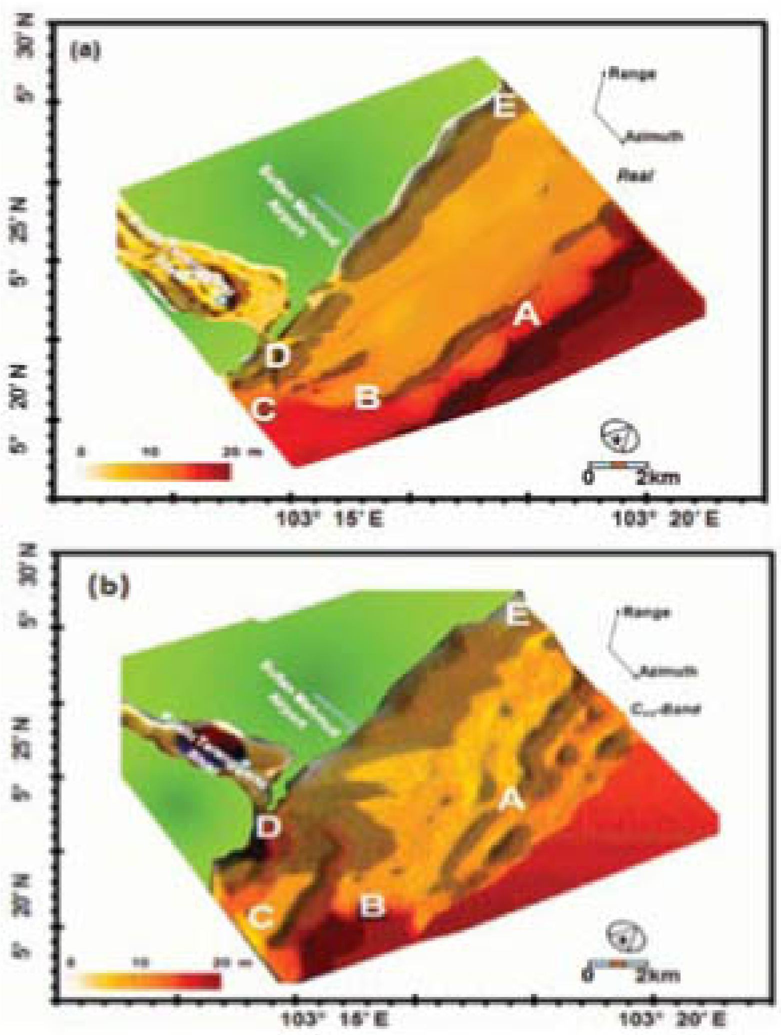

Figure 5: Three-dimensional bathymetry reconstructions from (a) Real topography map and (b) C_{VV} band

The maximum current velocity was simulated from C_{VV} band was 1.4 m/s. which showed northerly current flow along the range direction (Figure 4). This is because that December represents the northeast monsoon period as the coastal water currents in the South China Sea tend to move from the north direction (Maged, 1994). The range travelling current is due to the weak non-linearity due to the smaller value of *R/V* which is 32s. The weak non-linearity was assisted for contribution of the linear kernels of the range current. This means that the range current will be equal to zeros. However, the inversion of the linear kernel of the Volterra model allowed us to map the current movements along the range direction. This result confirms the study of Inglada and Garello (1999). Figure 5 shows the comparison between 3-D bathymetry reconstruction from topography map and the C_{VV} band data. It is obvious that the coastal water bathymetry along the Sultan Mahmad Airport has a gentle slopes and moving parallel to the shoreline. Closed to the river mouth, the bathymetry at location shows a sharp slope. The C_{vv} band captured an approximately real bathymetry pattern. This result could be confirmed with regression model in Figure 6 for bathymetry samples which identified in areas A, B, C, D (Figure 6).

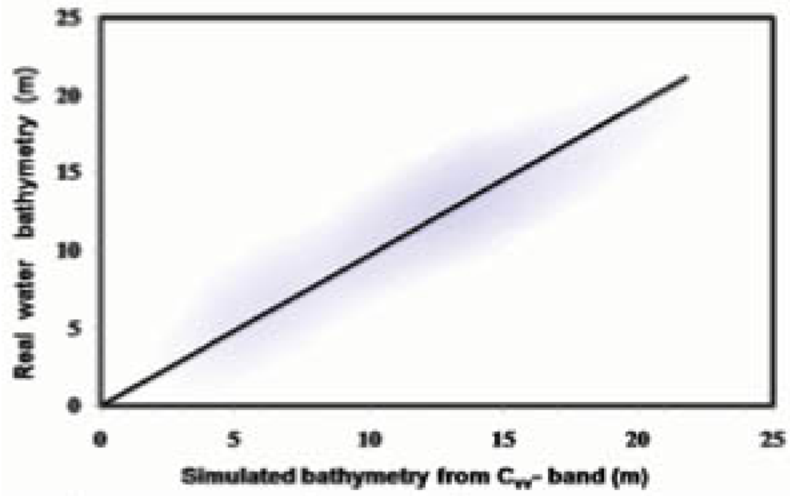

Figure 6: Regression model between real water bathymetry from bathymetry chart and water bathymetry from C_{VV} Band ($r^2=0.85;$ $y=0.95x+1.89$; $rms=\pm0.03$ m)

Consequently, regression model shows r^2 value of 0.85 and accuracy (root mean square) of ± 0.03 m. This confirms studies of Shuchman et al., (1985) and Romeiser and Alpers, (1997) which reported that C_{vv} band might be used to map coastal water bathymetry. The visualization of 3-D bathymetry is sharp with the C_{vv} and real data due to the fact that each operations on a fuzzy number becomes a sequence of corresponding operations on the respective μ -levels, and the multiple occurrences of the same Fuzzy parameters evaluated as a result of the function on Fuzzy variables (Anile, 1997, Anile et al., 1997 and Maged et al., 2007). It is very easy to distinguish between smooth and jagged bathymetry. Typically, in computer graphics, two objective quality definitions for Fuzzy B-splines were used: triangle-based criteria and edge-based criteria (Maged et al., 2009). Triangle-based criteria follow the rule of maximization or minimization, respectively, the angles of each triangle. The so-called max-min angle criterion prefers short triangles with obtuse angles. The finding confirms those of Keppel (1975) and Anile (1997). This can be seen in Figure 5 where the symmetric 3-D structure of the bathymetry of a segment of a connecting depth. Smooth sub-surfaces appear in Figure 6 where the near shore bathymetry of 5 m water depth runs nearly parallel in 3D-space. A rough sub-surface structure appears in steep regions of 20 m water depth. This is due to the fact that the fuzzy B-splines considers as deterministic algorithms which are described here optimize a triangulation only locally between two different points.

4. Conclusion

This work has demonstrated the 3-D bathymetry reconstruction from TOPSAR polarized data. The inversion of Volterra model was used to estimate the water current movements. The fuzzy-B splines were used to reconstruct the 3-D bathymetry pattern. C_{vv} band provides an approximately real 3-D bathymetry. It can be said that the integration between Volterra model and the fuzzy B-splines could be an excellent tool for 3-D bathymetry reconstruction.

References

Alpers, W., and Hennings, I., 1984, A Theory of the Imaging Mechanism of Underwater Bottom Topography by Real and Synthetic Aperture Radar, *J. Geophys. Res.*, 89, 10,529-10,546.

Anile, A. M., Gallo, G., and Perfilieva, I., 1997, *Determination of Membership Function for Cluster of Geographical Data.* Genova: Institute for Applied Mathematics, National Research Council, October 1997, 25, Technical Report No.26/97.

Anile, A. M, 1997, *Report on the Activity of the Fuzzy Soft Computing Group*, Technical Report of the Dept. of Mathematics, University of Catania, March 1997, 10.

Inglada, J., and Garello R., 1999, Depth Estimation and 3D Topography Reconstruction from SAR Images Showing Underwater Bottom Topography Signatures. In *Proceedings of IGARSS'99.*

Hennings, M. M., and Calkoen, C. J., 1998, Island Connected Sea Bed Signatures Observed by Multi-Frequency Synthetic Aperature Radar. *International Journal Remote Sensing*. Vol. 19(10):1933-1951.

Hesselmans, G. H, Wensink, G. J., Koppen, C. G. V., Vernemmen, C., and Cauwenberghe, C. V., 2000, Bathymetry Assessment Demonstration off the Belgian Coast-Babel. *The hydropgraphic Journal*. No.96. 3-8,

Keppel, E., 1975, Approximation Complex Surfaces by Triangulations of Contour Lines. *In: IBM Journal of Research Development*, 19:2.

Maged, M., 1994, *Coastal Water Circulation off Kuala Terengganu*, Malaysia". MSc. Thesis Universiti Pertanian Malaysia.

Maged, M., 2005, Fuzzy B-spline and Volterra Algorithms for Modelling Surface Current and Ocean Bathymetry from Polarised TOPSAR Data. *Asian Journal of Information Technology.* 4, 1-6.

Maged M., and Hashim, M., 2006, Three-Dimensional Reconstruction of Bathymetry using C-band TOPSAR Data. *Photogrammetrie Fernerkundung Geoinformation*. 469-480.

Maged, M., Hashim, M., and Crackenal, A., 2007, 3D Bathymetry Reconstruction from AIRBORNE TOPSAR Polarized Data. In: Gervasi, O and Gavrilova, M (Eds.): Lecture Notes in Computer Science. Computational Science and Its Applications – ICCSA 2007, ICCSA 2007, LNCS 4705, Part I, Volume 4707/2007, Springer-Verlag Berlin Heidelberg, 410–420, 2007.

Maged, M., Mansor, S., and Hashim, M., 2009, Geologic Mapping of United Arab Emirates using Multispectral Remotely Sensed Data. *American J. of Engineering and Applied Sciences*. 2, 476-480.

Melba, M., Kumar, S., Richard, M. R., Gibeaut, J. C., and Amy, N., 1999, Fusion of Airborne Polarimteric and Interferometric SAR for Classification of Coastal Environments. *IEEE Transactions on Geoscienceand Remote Sensing*, vol. 37, 1306-1315.

Romeiser, R., and Alpers, W., 1997, An Improved Composite Surface Model for the Radar Backscattering Cross Section of the Ocean Surface, 2, Model Response to Surface Roughness Variations and The Radar Imaging of Underwater Bottom Topography, *J. Geophys. Res.*, 102, 25,251-25,267.

Shuchman, R. A., Lyzenga, D. R., and Meadows, G. A., 1985, Synthetic Aperture Radar Imaging of Ocean-Bottom Topography via Tidal-Current Interactions: Theory and Observations, *Int. J. Rem. Sens.*, 6, 1179-1200.

Splinter, K. D., and Holman R. A., 2009, Bathymetry Estimation from Single-Frame Images of Nearshore Waves. *IEEE*

Transactions on Geosciences and Remote Sensing, 47, 3151–3160.
Vogelzang, J., Wensink, G. J., de Loor, G. P., Peters, H. C., and Pouwels, H., 1992, Sea Bottom Topography with X band SLAR: the Relation between Radar Imagery and Bathymetry, *Int. J. Rem. Sens.*, 13, 1943-1958.
Vogelzang, J., 1997, Mapping Submarine Sand Waves with Multiband Imaging Radar, 1, Model Development and Sensitivity Analysis, *J. Geophys. Res.*, 102, 1163-1181.
Vogelzang, J., Wensink, G. J., Calkoen, C. J., and van der Kooij, M. W. A., 1997, Mapping Submarine Sand Waves with Multiband Imaging Radar, 2, Experimental Results and Model Comparison, *J. Geophys. Res.*, 102, 1183-1192
Wensink, H., and Campbell, G., 1997, Bathymetric map production using the ERS SAR. *Backscatter*, 8, 1, 17-22