Converting Digital Number into Bathymetric Depth: A Case Study over Coastal and Shallow Water of Langkawi Island, Malaysia

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Keywords: Bathymetric Mapping, Remote Sensing, Satellite-derived Bathymetry, Hydrographic Surveying, Malaysia

SUMMARY

Over the years, hydrographic surveyors have used lead lines, sounding pole, wire drag and sounding machine to collect the bathymetry data. To date, the vessel-based echo sounding surveys such as single beam echo sounder system (SBES) and multibeam echo sounder system (MBES) are widely used in hydrographic surveying around the world. Nonetheless, these vessel-based acoustic sonar methods are constrained by limited ground coverage, difficulties to access shallow coastal water, labour intensive and high operating cost which significantly limits of the frequent repetitions. The advancement of the satellite-derived bathymetry has brought in the new revolution in hydrography. The paper highlights the application of incorporating satellite remote sensing and geographical information system (GIS) techniques to extract bathymetric information from the newly commenced Landsat 8 satellite imagery. In this study, the ratio transform attempt proposed by Stumpf et al. was applied on the newly acquired multispectral images to convert the digital number (DN) over the coastal and shallow water area into bathymetry depth to produce a bathymetry map of Langkawi Island, Malaysia. The average uncertainties obtained was 1.521 m, where the highest RMSE recorded was of 3.758 m, while the lowest RMSE was of 0.024 m. In addition, the correlation coefficient between the estimated depths and endorsed bathymetry data was 0.9054. The results indicated that satellite-derived bathymetry technique can be used as a reconnaissance tool instead of the vessel-based echo sounding survey for shallow water and coastal bathymetric mapping. Bathymetric mapping from optical multispectral images for instance offers a fast, flexible, efficient and economically beneficial solution to map the seabed topography over broad areas.

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1.0 INTRODUCTION

Hydrographic surveying is the fundamental task dealing with the hydrosphere. It is defined as a branch of applied sciences which deals with the measurement and description of the features of the sea and coastal areas. In strict sense, it is defined merely as the surveying of a water area. However, in modern usage it may include a wide variety of other objective such as measurements of tides, current, gravity, earth magnetism and determination of the physical and chemical properties of water. Nevertheless, the primary purpose is to obtain basic bathymetry data to produce nautical charts with emphasis on the features that may affect the safety of navigation. These bathymetry information are also very useful in other marine activities such as marine construction, offshore engineering, oil and gas exploration activities as well as oceanography research.

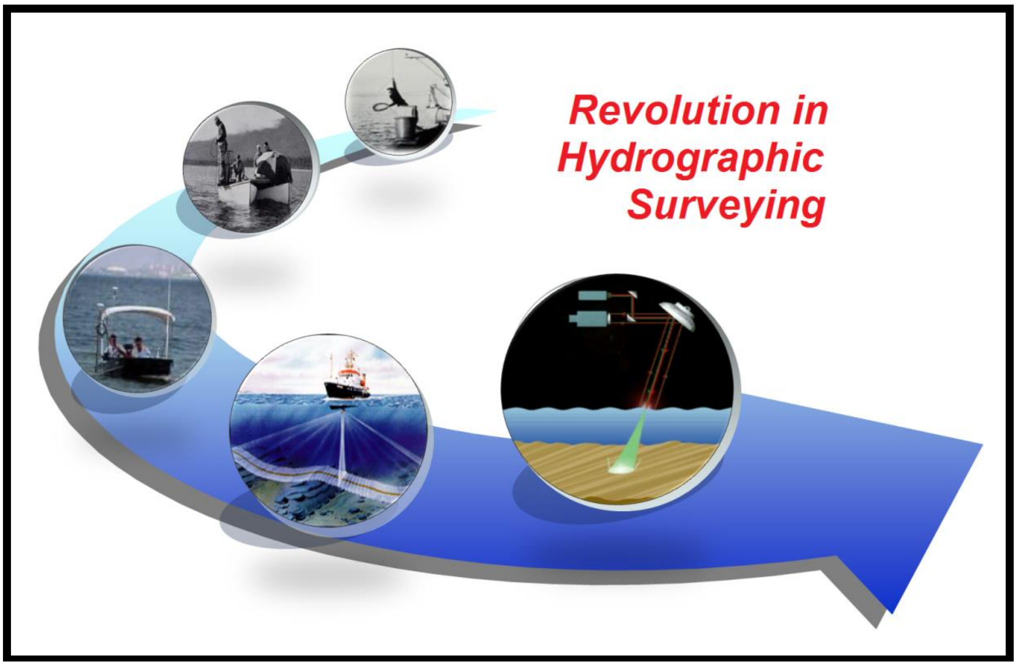

Figure 1: Revolution in Hydrographic Surveying

Bathymetric mapping is essential for port facility management in order to avoid serious disaster. The completeness of the coastal bathymetry information is critical towards monitoring the seabed topography and detecting the emergence of new land in supporting dredging operations through prediction of navigational channel infill and estimating sediment budgets. Over the years, hydrographic surveyors used lead lines, sounding pole, wire drag and sounding machine to collect the bathymetry data. To date, most of the coastal bathymetry mappings are using the sonar or acoustic hydrographic surveying instruments such as single beam echo sounder system (SBES) and multibeam echo sounder system (MBES). Nevertheless, these vessel-based echo sounding methods applied nowadays are constrained by the limited ground coverage, difficulties to access shallow coastal water, labour intensive and high operating cost which significantly limits its frequent repetitions.

Since the past decade, the advancement of remote sensing technology has brought in the new revolution to the hydrographic surveying. The ability of the electromagnetic spectrum (EMR) to penetrate water columns provide the fundamental principle of extracting water depth information using remote sensing and geographical information system (GIS) technology. In fact, satellite remote sensing technology has been introduced as a possible alternative method in the bathymetric data acquisition process. Indeed, the preface of the airborne LiDAR bathymetric (ALB) and satellite-derived bathymetry (SDB) mapping methods of extracting the seabed information from the optical remotely sensed images were increased and ameliorated among the hydrography communities.

Coastal bathymetric information will be very useful in navigational channel management, marine construction and coastal engineering, dredging and reclamation operations as well as supporting other related scientific and environmental studies such as oceanography, marine ecology and marine biology. In certain region, especially the coastal and shallow water areas, the comprehensive seabed topography survey is limited and the coverage is not geographically well-distributed. Therefore, satellite bathymetry can be an alternative tool for facilitating the increasingly demand of hydrographic surveying activities around the coastal and shallow water areas. The main objective of this study is to evaluate the usability of space-borne bathymetric mapping technique and identify the appropriate spectrum channels to be used in extracting bathymetric information from Landsat 8 multispectral satellite data.

2.0 SATELLITE-DERIVED BATHYMETRY

The initial attempts of using aerial multispectral data and radiometric technique to estimate water depth over clear and shallow water was done by Lyzenga (1978). The ability of electromagnetic spectrum (EMR) to penetrate water columns provides the fundamental principle of extracting water depth information using this technology. The physical principle is when light passes through the water column, it becomes attenuated. Shallow water area will appear bright while the deep water areas looks dark on the image. Generally, the solar radiation reflected from the Earth undergoes significant interaction with the atmosphere and in water column before it reaches the satellite sensor. The measured radiance is closely related to the incoming solar radiation, attenuation of radiation in and out of the atmosphere and water column, reflectance properties of the seabed as well as the water depth.

The technique developed Lyzenga was later expanded and further explored by Benny and Dawson (1983), Spitzer and Driks (1987), Jupp (1988), Philpot (1989), Bierwirth (1993), Maritorena et al. (1994) and Stumpf et al. (2003). Through their remarkable efforts, a wide variety of algorithms for bathymetry retrieval have been developed and empirical models have been established to form the statistical relationship between image pixel values and water depth values. However, the ultimate aim is to automatically extracting the water depth information for bathymetric mapping.

3.0 STUDY AREA

Malaysia is known as a maritime country with its coastal area about 63,665.3 km^2 and a total coastline length of 4,492 km. Its Exclusive Economic Zone (EEZ) is approximately 453,186.18 km^2 and there are 827 islands and 273 geographic entities in within the Malaysia's sovereign territorial. Consequently, accurate bathymetric measurements are very vital in producing hydrographic plans and nautical charts which are fundamentally important to support marine navigation, shipping, coastal and offshore engineering, oil and gas industries and research activities.

In this study, Langkawi Island has been chosen as the study area. Langkawi Island is separated from mainland Malaysia by the Straits of Malacca. It consists of 104 small islands and the total area is about 478.48 km^2. The main island spans about 25 km from north to south and slightly more for east and west. Two-thirds of the island is dominated by forest mountainside filled, hills and natural vegetation. Geographical position is located between 06.15°N to 6.37°N and 99.69°E to 99.92°E. The island is complemented with lavishness tropical rainfall forest and fringing beautiful sun-drenched beaches and also blessed by homogeneous seabed topography and tranquil sea in its marine environment. This study will focus on the shallow coastal areas in the southent part of the Langkawi Island.

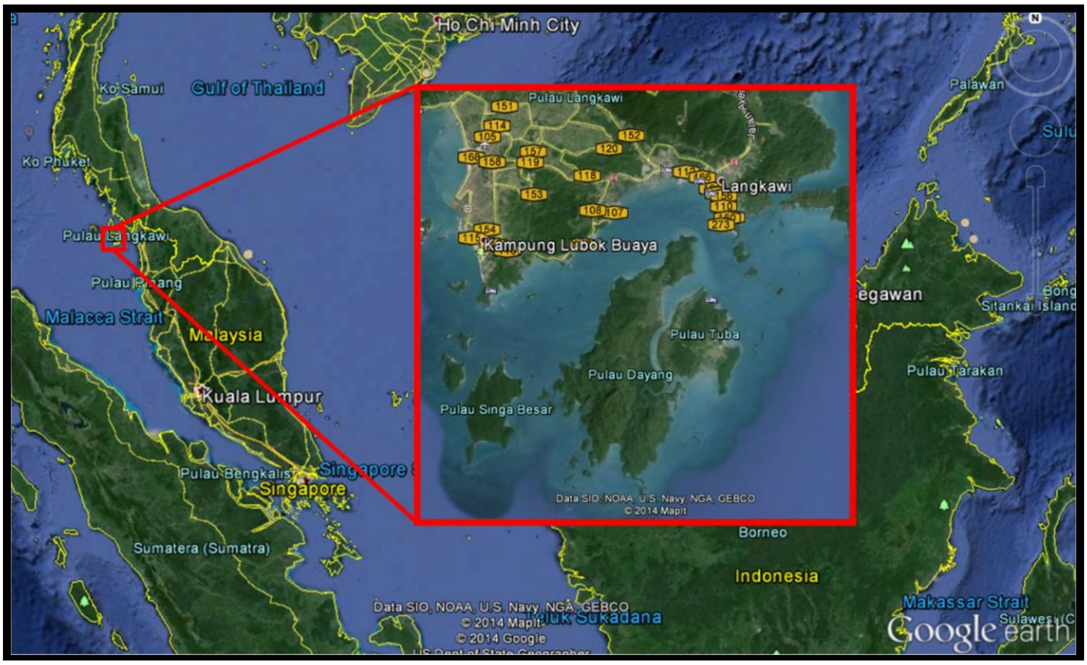

Figure 2: Langkawi Island, Peninsular Malaysia (Source: Google Earth)

4.0 METHODOLOGY

This study incorparated space-borne remote sensing and GIS techniques to extract bathymetric information from multispectral satellite imagery. The selection of data set potentially useable for satellite bathymetry mapping was based on the condition of the satellite image, significantly spectral coverage, spectrum range and ground resolution. In this study, Landsat 8 satellite images were utilised. Figure 3 illustrates the Landsat 8's satellite image (path 128, row 56) which covers the Langkawi Island was captured on 27th February 2014, at 03:34:39hours (UTC Time). Prior attempting to satellite image processing, pre-processing task such as radiometric, atmospheric and geometric correction were carried out in order to eliminate the atmospheric effects, unwanted path radiance, unnecessary sea surface reflectance as well as the distortion of the images.

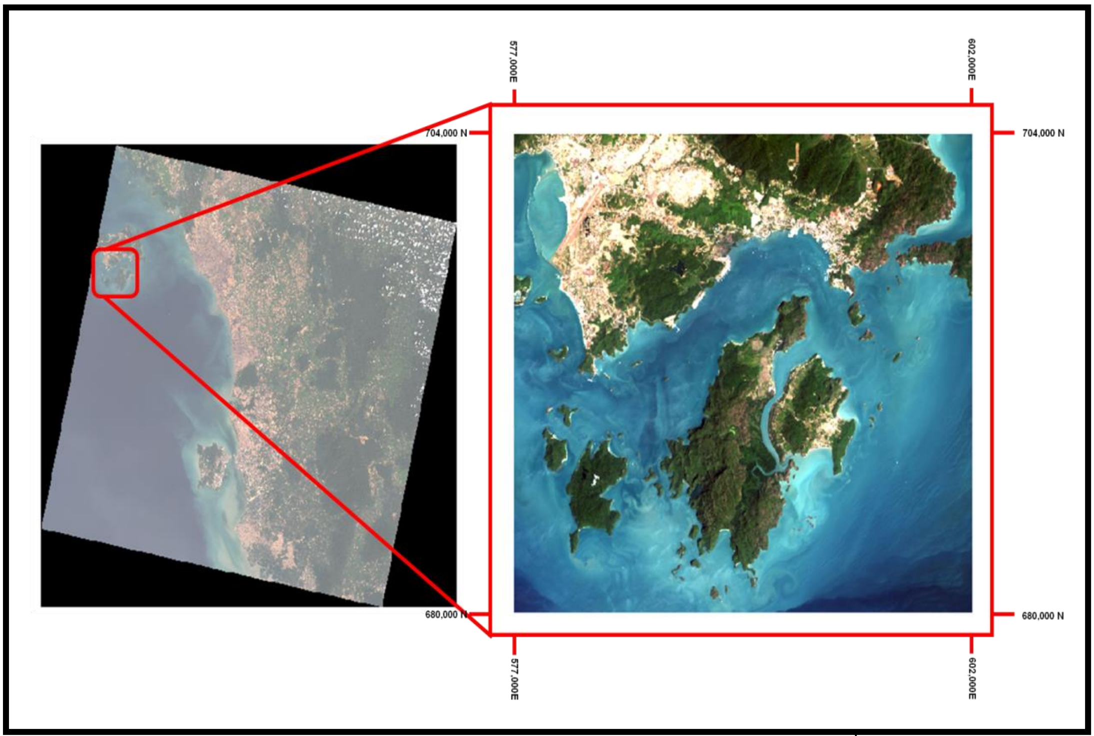

Figure 3: Landsat 8 satellite image of Langkawi Island dated 27th February 2014.

4.1 Radiometric and Atmospheric Correction

Radiometric correction allows the conversion of raw image digital value (DNs) to spectral radiance. Thus, the spectral radiance was calculated from remotely sensed data by using the Spectral Radiance Scaling Method's equation (NASA, 2008) as shown below:

$$L_{\lambda} = \left(\frac{Lmax_{\lambda} - Lmin_{\lambda}}{QCALmax - QCALmin} \right) * (QCAL - QCALmin) + Lmin_{\lambda}$$

(Equation 1)

where QCAL is DN recorded; Lmaxλ is referred as spectral radiance scales to QCALmax; $Lmin_{\lambda}$ is referred as spectral radiance scales to QCALmin; QCALmax is referred as the maximum quantized calibrated pixel value; while, QCALmin is the minimum quantized calibrated pixel value. All the required calibration coefficients and other related parameters were obtained from the metadata of the satellite images.

Subsequently, the spectral radiance values computed from Equation 1 were converted into Top-of-Atmosphere (ToA) reflectance value (P_{λ}). According to the Landsat 8 Calibration guide suggested by USGS (http://landsat.usgs.gov/Landsat8_Using_Product.php), the ToA reflectance value of the 16-bit Landsat 8's OLI band data can be computed via the Equation 2 and Equation 3 (NASA, 2013) as shown below:

$$P_{\lambda}' = M_{\rho} * Q_{cal} + A_{\rho} \qquad \text{(Equation 2)}$$

where, P_{λ}' is the TOA planetary reflectance without the solar angle correction; $M\rho$ is the multiplicative rescaling factor for a particular band; $A\rho$ is the additive rescaling factor for a particular band; while, Qcal is the quantized and calibrated standard product pixel values (DNs) for a particular band.

$$P_{\lambda} = P_{\lambda}' / \cos\theta_{SZ} = P_{\lambda}' / \sin\theta_{SE} \qquad \text{(Equation 3)}$$

where, P_{λ} is the TOA planetary reflectance after the solar angle correction; θ_{SE} is the local sun elevation angle, the scene centre sun elevation angle in degrees; while, θ_{SZ} is the solar zenith angle, can be also calculated from $\theta_{SZ} = 90° - \theta_{SE}$. All the required parameters can be found in Landsat 8 satellite image header file.

Practically, the radiation recorded at the satellite sensor may also be influenced by a range of unpredicted effects when it passes through the atmosphere. Atmosphere properties such as the amount of water vapour, gas molecules, distribution of aerosols, suspended particles of dust and water droplets in the form of clouds may change its transmittance. In order to eliminate the atmospheric errors, Dark Object Subtraction (DOS) technique was applied to derive a good estimate of the true at-ground upwelling radiance and then convert them into reflectance. Atmospheric effects correction algorithm stated by Jensen (1996) was used for the atmospheric correction. The formula for the DOS relative atmospheric correction technique is expressed as below:

$$OutputDN_{ijk} = InputDN_{ijk} - Bias \qquad \text{(Equation 4)}$$

where Input DN_{ijk} is the input pixel value at line *i* and column *j* of band *k*; while Bias is the darkest pixel value, normally refer to water bodies and dark shadows; or can be determined by subtracting the minimum possible DN from the band minimum DN.

4.2 Geometry Correction & Spatial Sub-Setting

In this case, the selected Landsat 8 multispectral images of the study area was geo-referenced to the MAL Chart by selecting a sufficient number of Ground Control Points (GCPs) which were widely scattered throughout the area of study. These easily identifiable GCPs were utilized to conduct the 1st order polynomial wrapping function using the Nearest Neighbour re-sampling method. Subsequently, the study area was cropped based on the study area.

The near-infrared (NIR) and mid-infrared (MIR) corresponds to the region of the EMR are very sensitive in identifying vegetation biomass, emphasizes soil-crop as well as land-water boundaries. Therefore, in this case, the Band 5 (NIR: 850 – 880nm) of the Landsat 8 OLI was used to differentiate between land features and water surface with the study area. The threshold value (DN/reflectance) for the water features was examined and defined via the 3D profile analysis.

4.3 Deriving Satellite Bathymetry

In order to extract bathymetric information from the satellite images, a linear ratio approach invented by Stumpf et al. (2003) was employed. This method focused on the inversion of the irradiative EMR energy transfer in water column. Indeed, the estimated water depth for each pixel was computed based on the ratio of reflectance in two bands and depth. The optically-derived bathymetry algorithm developed by Stumpf et al. (2003) is given below:

$$Z = m_1 * \left(\frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))} \right) - m_0$$

(Equation 5)

where Z is the calculated depth in meter; m_1 is a tuneable constant to scale the ration to depth, also known as the gain; m_0 is the offset for a depth of 0 m (Z=0); whereas, *n* a fixed value to ensure the logarithm will be positive under all circumstances and that the ratio will produce a linear response.

The water depths within the study area were computed based on the Landsat 8’s Band 2 (blue: 450 – 510nm) and Band 3 (green: 530 – 590nm) images using the above mentioned equation. The water attenuation coefficient value was assuming as the same throughout the whole satellite image scenes. In this case, the m_1 and m_0 are the gain and offset values are scaled based on the nautical chart derived depths to tune the former linear relationship.

4.4 Bathymetry Accuracy Assessment

The data assessment is an important step in determining the usability of the manipulated data or commonly known as the quality assurance as well. Indeed, it is primarily an evaluation of performance against the pre-determined or endorsed data. In this case, 50 bathymetric points were adopted from Malaysian Nautical Chart (MAL) to quantitatively evaluate and assess the accuracy of the satellite-derived bathymetry. The accuracy assessment was done based on the precision uncertainty and correlation coefficient (r^2) between satellite-derived bathymetry data and depths extracted from endorsed nautical chart. Besides that, root mean square error (RMSE) test was also being used to evaluate the satellite-derived bathymetry accuracy. The RMSE can be computed via the Equation 6 below:

$$RMSE = \sqrt{\frac{\sum (X_{known,i} - X_{estimated,i})^2}{n}} \qquad \text{(Equation 6)}$$

where, $X_{known,i}$ is the endorsed depth of the i^{th} point in the dataset; $X_{estimated,i}$ is the estimated depth of the i^{th} point in the dataset; while, n is the total number of test points in the checking area. It is very valuable tool in estimate the common within-group standard deviation of data.

5.0 RESULTS AND DISCUSSION

The result of the extracted dry land areas is shown in Figure 4. Meanwhile, the water areas are shown in blue band (Figure 5) and green band (Figure 6) respectively. These bands were extracted in order to be utilized in computing the water depths within the study area.

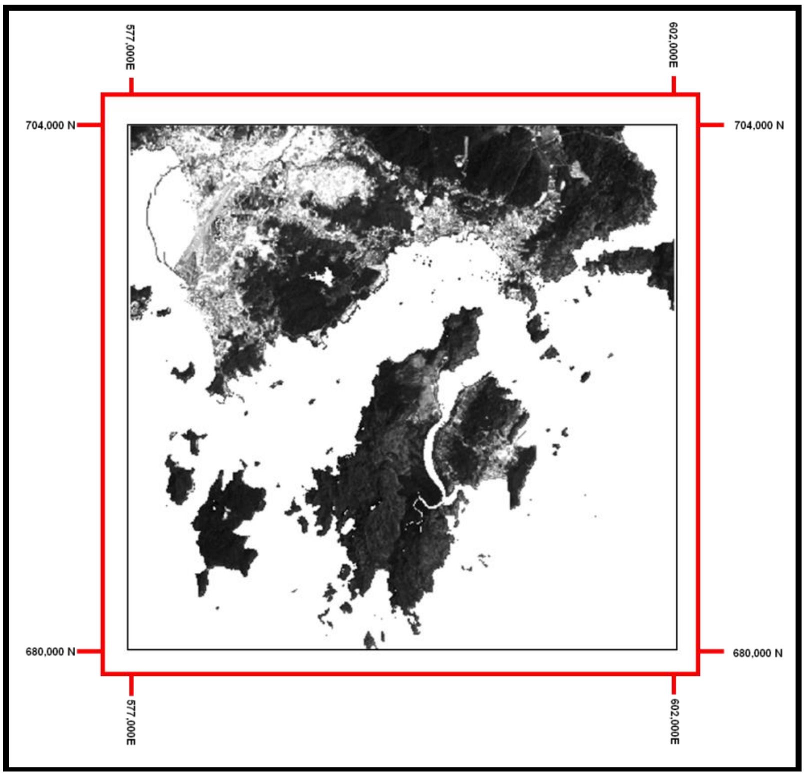

Figure 4: Dry Land Areas extracted from the Landsat 8 (Band 5).

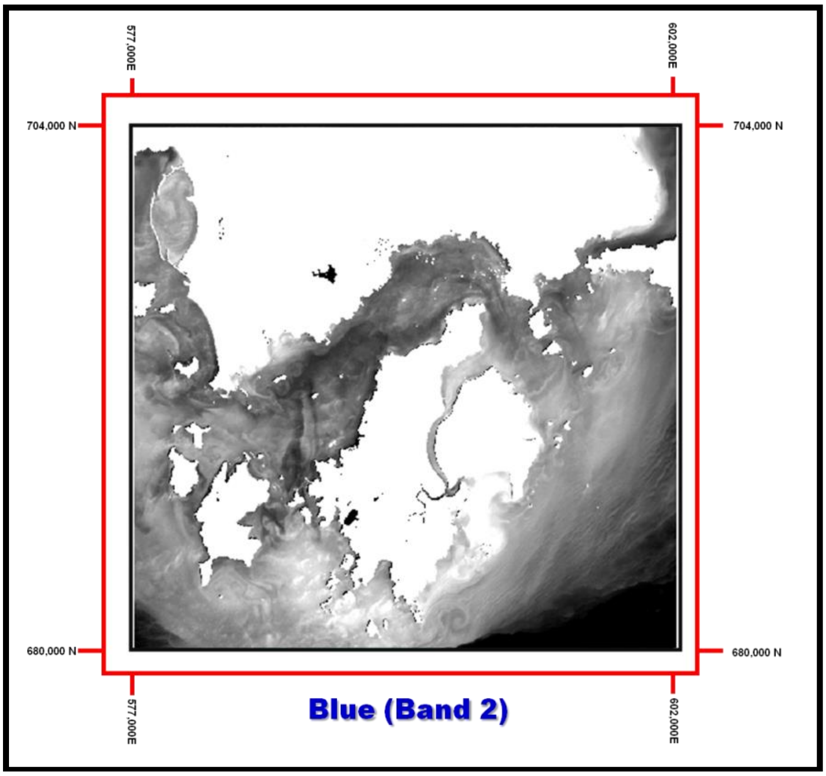

Figure 5: Water Surface Area extracted from Landsat 8 (Band 2).

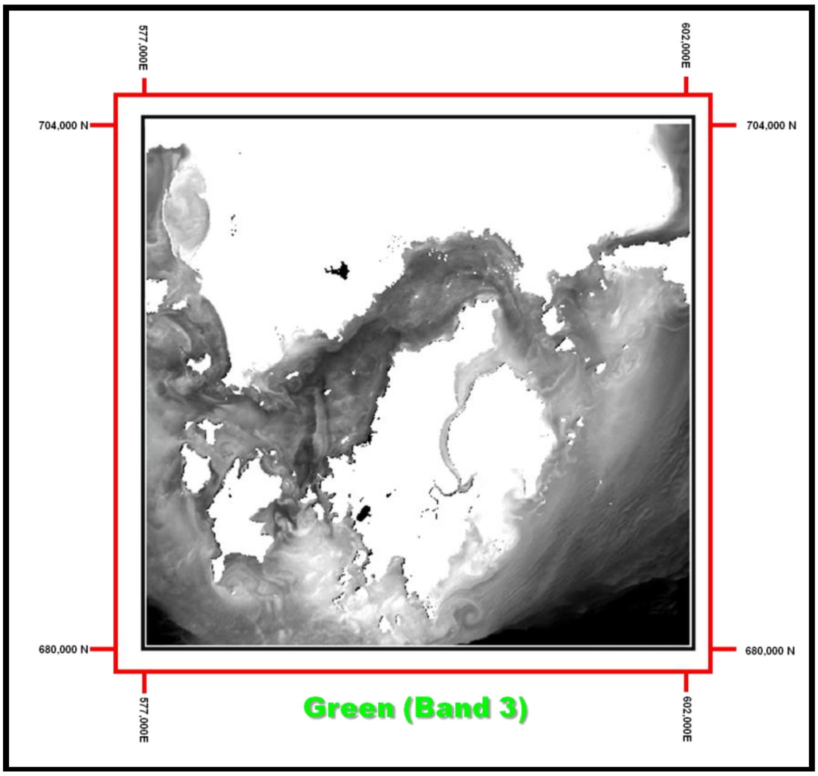

Figure 6: Water Surface Area extracted from Landsat 8 (Band 3).

Meanwhile, Figrue 7 illustrates the estimate water depths computed via the above mentioned satellite bathymetry model developed by Stumpf et al. (2003) using two respective visible bands, Band 2 (Blue) and Band 3 (Green) from the selected Landsat 8 satellite images. Base on the satellite-derived bathymetric data, the depths of the seabed vary with locations. The result depicted that the water level recorded around the study area were between datum level to more than 25m below the chart datum (CD).

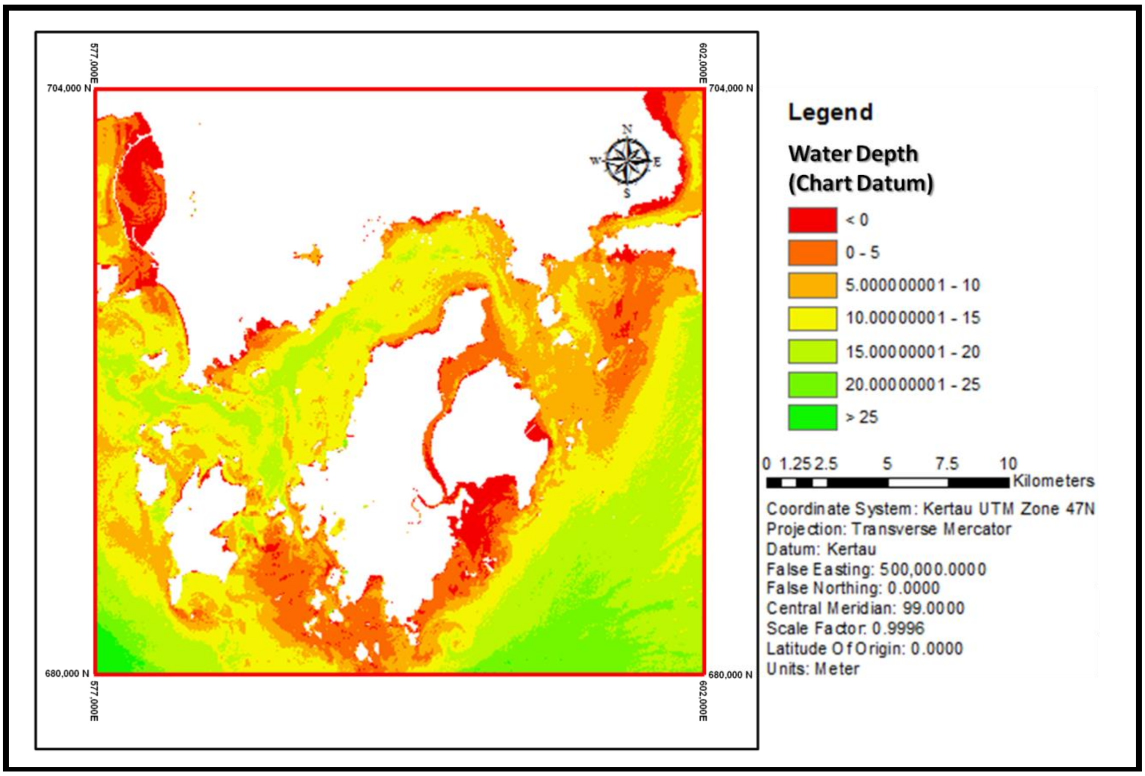

Figure 7: Satellite-derived Water Depth (CD) from Landsat 8.

Data quality assessment was done by using 50 check points randomly picked out from the MAL5529 (Kuah/Bass Harbour). The selected checking areas are located in the southern part of the Langkawi Island. The selected bathymetry points are ranged from -0.5m to 20.8m in depth with relative to the CD.

A plot of the satellite-derived depths along the Y-axis and the endorsed depths along the X - axis was drawn as presented in Figure 8. The uncertainties are ranged from -3.18m to 3.76m. The highest RMSE recorded was of 3.758m, while the lowest RMSE was of 0.024m. Total RMSE calculated based on the endorsed 50 reference points was 1.521m and the correlation coefficient (r^2) between the estimated depth and check data was of 0.9054.

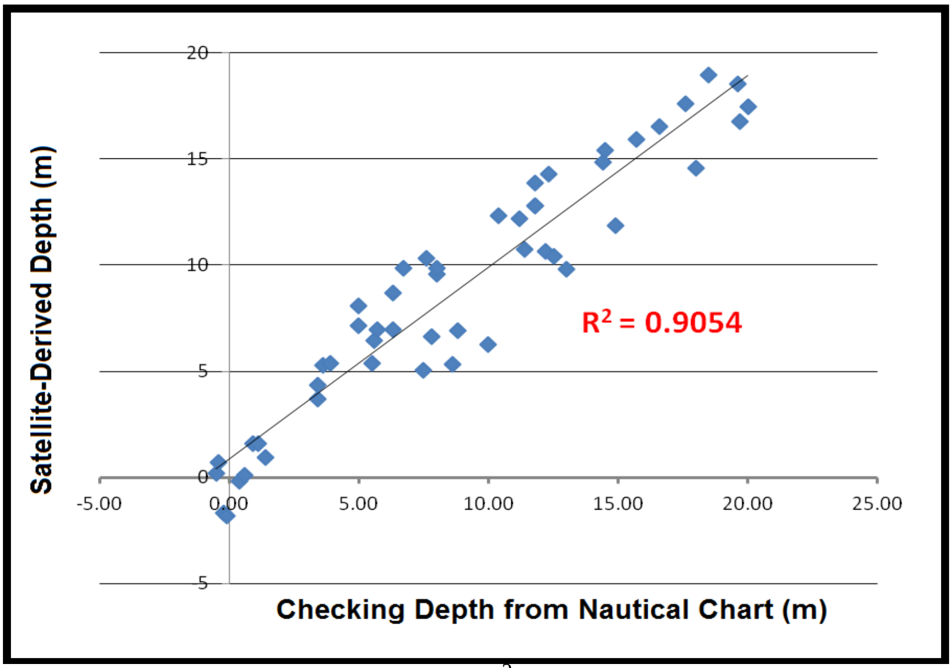

Figure 8: Correlation Coeeficient (r^2) between the Satellite-Derived Depth and Endorsed Depth.

In general, the water depths derived from freely downloadable Landsat 8 satellite imagery (30m spatial resolution) were depicted to be statically accurate and able to provide realistic seabed terrain profiles. This method can be an alternative survey sources to complement the medium resolution (profiling interval 25-30m) sonar sounding surveys. Apparently, it is possible for low-cost, low-accuracy and low-risk bathymetry charting mission. Most of the tiny or small features may not be visible from the low spatial resolution imagery. Therefore, it is not advisable to be applied for jobs that require high accuracy and precision.

Even though satellite-derived bathymetric mapping is an innovative solution to supplement the traditional vessel-based survey techniques, however, more research works still need to be conducted. In order to achieve better results in the future, continued efforts shall be focused on creating new processing algorithms and workflows which can derive greater water depths beyond the coastal area. A properly designed satellite bathymetry model could bring significant new resolution in hydrographic surveying.

6.0 CONCLUSION

In this study, a shallow water bathymetry map has been successfully mapped via the remote sensing approach. The proposed deviation method which gauging the relative attenuation of the blue band and green band radiations were examined and verified. The results showed that the high compatibility satellite-derived bathymetric mapping was able to offer a fast, flexible, efficient and economically advantageous solution to map the seabed topography. It is also proven to be more cost-effective, less labour-intensive and time-saving method of acquiring bathymetry comparing to the conventional sonar sounding surveys as well as allows significant repetitions of bathymetry mapping over broad areas. Perhaps, the satellite-derived bathymetry can be an alternative method and reconnaissance tool in facilitating the increasingly demand of hydrographic surveying activities around the coastal and shallow water areas.

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BIOGRAPHICAL NOTES

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