Accuracy Assessment of Satellite Derived Bathymetry Model for Depth Extraction in Sorong Shallow Water Area

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Abstract. Marine research has continuously improved the methods in obtaining the related bathymetric data; not only relying on the conventional methods for i.e. echosounder-based methods, but also by incorporating satellite technology for i.e. passive remote sensing technology, in this case, satellite derived bathymetry (SDB). Regarding the SDB method, as we know, variation of sea bed cover can influence the relation between the spectral reflection of shallow water area and the depth of the sea. In this situation, normalization of the sea bed variation is needed. Previous studies have mentioned that the band ratio can help to normalize the variation of sea bed cover. This research is intended to compare the accuracy of satellite derived bathymetry by using single band and band ratio. Four bands of Sentinel 2A (blue, green, red, and NIR bands) are used along with a single beam echosounder (SBES) measurement data published in 2015 used as training and testing data for the SDB model. Furthermore, the influence of sun glint correction to the results was evaluated and the accuracy of the model was estimated. In total there are four single bands and six combinations of band ratio that are used for this research. The results show that green band outperformed band ratio in term of RMSE value. However, visually, only band ratio of blue/green band that provided a much more representative depth spatial distribution especially for shallow water area below 3 m. In this case, band ratio is effective in normalizing the variation of sea bed cover. Furthermore, the use of sun glint correction in the process is also increase accuracies of the SDB model. The highest accuracy was obtained when using green band after sun glint correction with RMSE value 2.999 m while when using band ratio of the blue band to the green band (blue/green), the accuracy was 3.624 m. In conclusion, SDB model to extend methods in obtaining bathymetry data is promising as more images become available free of charge and in various resolutions.

1. Introduction
An accurate water depth data is essential for a wide range of marine and coastal research, modeling and monitoring. Shallow water depth data has been mapped by various techniques ranging from conventional methods such as using leadline and echosounder-based methods, and more advance techniques for instance using active and passive remote sensing technologies [1]. In this research, we focused on the use of satellite images to derive shallow water depth.

The spectral reflection value of remote sensing image in the optical shallow waters can be used to predict the water depth at the related water area [2,3]. This is based on the concept presented by Lyzenga [2] that the spectral reflection recorded by the sensor called the water leaving radiance ($L_q$) is
a function of bottom reflectance \( (r_{Bl}) \), radiance observed over deep water \( (L_{sl}) \), the effective attenuation coefficient of the water \( (k_i) \), a constant including solar irradiance, transmittance of the atmosphere and water surface, and the reduction of the reflectance due to refraction at the water surface \( (k) \), geometric factor to account for the pathlength through the water \( (f) \), and water depth \( (z) \) as in Equation 1:

\[
L_i = L_{sl} + k r_{Bl} \exp(-k_i f z),
\]

(1)

Water depth information can be obtained by inverting Eq.1 by using single band or more bands of remote sensing image [4]. However, the difficulty with this technique is that changes in the bottom reflectance or water attenuation cause error in the calculation. Furthermore, obtaining the actual \( k_i \) for each water condition is difficult and it requires large samples of water depth from field measurements. Therefore, to overcome the limitation in obtaining field measurement data including water attenuation, the use of empirical data to extract water depth information has widely developed. Vinayaraj [5] mentioned that there are three categories of SDB method, namely analytical models, empirical models and combined models. Analytical models require a number of water optical properties over shallow water (such as absorption coefficient suspended and dissolved materials, attenuation coefficient, scattering coefficient, backscatter coefficient, and bottom reflectance) [6] which are sometimes difficult to obtain due to limited budget and time. Meanwhile, empirical method require training data since the models are developed based on assumption that the total water reflectance is related to water depth [7]. Combined methods are a combination of both analytical and empirical methods.

In this research, we aim to compare the accuracy of satellite derived bathymetry by using single band and band ratio to extract the water depth. Four bands of Sentinel 2A (blue, green red, and NIR bands) were used along with a single beam echosounder (SBES) measurement data published in 2015 that were used as training and testing data for the SDB model. The use of single band is intended to assess the performance of each band in extracting shallower water depth. In literature, the blue band gives the best result and it is able to detect deeper water, however, water turbidity can affect the depth penetration [6]. Meanwhile, the use of band ratio method is intended to see the influence of the method to overcome the variation of sea bed cover [7]. It is important to test the performance of these two methods in Indonesia shallow water. Because Indonesia shallow water vary greatly both in terms of water quality and variation of bottom substrate types. The substrate types are ranging from sand, seagrass to dead and live coral. In this study, the SDB model is implemented on a small island in the bay area of Sorong. The shallow water area is relatively clear with sand substrate and fringing reef, however, anthropogenic influences exist through rivers that flow into the bay. Therefore, it may cause water turbidity in the surrounding location. Furthermore, we evaluated the influence of sun glint correction to the results and estimated the accuracy of the model. It is expected that image with sun glint correction obtains higher accuracy than image without sun glint correction, however, other factors such as water conditions and other environmental situations might cause us to obtain the opposite results.

2. Methodology

2.1. Study Area

The study area is small islands located at the bay of the Sorong regency (Figure 1). The central point of the study area is at geographical coordinates 0° 54’ 5.75” N and 131° 13’ 59.13” E. The tidal range in this area is ranging from 3 - 6 m and categorized into mixed double tides Furthermore, based on the previous study, wave occurrences generally fall into calm category (81.5%) and rough category for 8.2% (towards the west) and 5.9% towards the southwest [8]. The current speed is 1 m/second and water salinity is ranging from 34.2-34.4 %o [9]. The islands are surrounded by reef formation. It is one of tourist destinations with white-sand beaches and is famous as the leatherback turtle habitat [10].
2.2. Dataset

Datasets used in this study are described as the following:

a) Sentinel 2A with four bands including blue (0.49 µm), green (0.56 µm), red (0.665 µm), and near infrared (0.842 µm) parts of the spectrum [11]. The Sentinel-2A was obtained in level L2A from the ESA website, i.e., Copernicus Open Access [12]. The time acquisition of the image was October 2018 with 10 m spatial resolution. The image was obtained in the format of bottom of atmosphere reflectance (BoA) and has gone through a standard radiometric and geometric correction [11].

b) The SBES points were collected in October 2018. The data has undergone tidal correction and used as an input to build and validate the SDB model in extracting bathymetry information.

2.3. Method

2.3.1. Image correction. For this research, we performed image correction using averaged deep water area [2]. It is assumed that sea-surface scattering (atmospheric scattering) are homogeneous over target area. The observed spectral radiance in deep water is assumed not include bottom reflectance, therefore the water depth only consists of information related external reflection from water surface and atmospheric scattering. In target area, the effect of atmospheric scattering, surface reflection and in-water scattering are eliminated by subtracting the averaged radiance of deep water (see Figure 2).
Figure 2. Spectral radiance components measured by sensor in water; modified from Kanno [13]

Sun glint correction was applied based on the method proposed by Hadley et al. [14]. The relationship between sun glint and NIR band was scaled by using linear regression at a selected region. The region is assumed to have a consistent brightness and low water-leaving radiance (for example in deep water area).

2.3.2. Single band method. This method was applied by utilizing knowledge related to the attenuation of energy that propagates in the water column. As increasing depth, the energy to sensor (water-leaving radiance) decreases until it reaches a point where contributions from bottom reflectance can no longer be detected and longer wavelengths will be attenuated much stronger than shorter wavelengths [15]. Estimating depth by using one band is possible by using assumption that bottom reflectance and water attenuation is constant throughout the image [16]. Single band empirical modeling is implemented by considering depth variations and band selection [7,17].

2.3.3. Band ratio method. This method is based on a concept that different wavelength will be absorbed by waters in various degree based on inherent optical properties of the water [15]. Band ratio was used to reduce the variation effect of bottom reflectance by assuming that the change in spectral reflectance due to variation of objects will influence the wavelength in relatively similar way. However, the changes of depth influence the longer wavelength more. Subsequently, at different depths, the change in ratio is much greater than the change due to variation in bottom covers implying that for different bottom covers at a same depth will have the same ratio [15,18].

2.3.4. Modeling SDB. Before modelling the SDB, the coefficient correlation values ($r$) were estimated between log transformed of surface reflectance value of Sentinel 2A and water depth by using Pearson Product Moment with 95% significant level. For the first method, water depth was estimated by means of linear regression analysis as follows [19]:

$$W_z = \beta_0 + \sum_{i=1}^{N} \beta_i X_i.$$ (2)
where \( X_i = \ln(L_i - L_{si}) \), \( N \) is the number of bands, \( i \) is spectral band, and \( \beta \)-coefficients are obtained from the linear regression with echosounding points. This method works by assuming that spectral bands of the imagery are affected by the bottom reflectance. By using this approach, the field measurement data is considered as dependent variable and the transformed radiance is the independent variable. Both data are used to determine the regression coefficient and to estimate the depth information in shallow water.

For the second method, water depth was estimated by using band ratio method as follows [7,15]:

\[
W_z = \beta_1 \frac{\ln(nX_i)}{\ln(nX_j)} - \beta_0 \tag{3}
\]

where \( X_j = \ln(L_j - L_{sj}) \), \( L_j \) is water leaving reflectance of band \( j \) and \( L_{sj} \) is reflectance observed over deep water of band \( j \), and \( n \) was set to 1000 based on Bramante et al. [18].

2.3.5. Accuracy assessment. We assessed the accuracy by comparing the SDB model and the in-situ measurements. For this purpose, we calculated the accuracy by using statistic model, the Root Mean Square Error (RMSE).

3. Results and Discussions

3.1. Single Band

Correlation analysis by using Pearson Product moment show that all Sentinel 2A bands used in this study were significantly correlated to the water depth and were able to be used as input for SDB model. In Table 1, for image with glint correction, the highest value of correlation coefficient was 0.855 from the green band. Among the four bands, the lowest correlation was NIR band with only 0.09. Meanwhile, for image without sun glint correction, the highest correlation was also achieved by using green band (0.748) and the lowest correlation was obtained using NIR band (0.137).

By applying linear regression model to each band, for image with glint correction, we can see that the highest accuracy obtained by the green band with RMSE value 2.999 and \( R^2 \) equal to 0.731. This was also indicated by the scatter plot in Figure 3 (upper right) that the depth points mainly spreading around the trend line (red line). The lowest accuracy was obtained when using the NIR band which was also indicated by the scatter plot in Figure 3 (lower right) at which the points were shifting away from the trend line.

Meanwhile, for image without sun glint correction, green band obtained the highest accuracy indicated by the lowest RMSE value equal to 3.825 and \( R^2 \) equal to 0.559. In general, it was obvious that applying sun glint correction demonstrated a higher correlation and higher accuracy were achieved, except for the NIR band.

| Log(band) | Coefficient correlation (r) | R-squared (\( R^2 \)) | RMSE (m) |
|-----------|----------------------------|---------------------|---------|
|           | Glint | No-glint | Glint | No-glint | Glint | No-glint |
| blue      | 0.503 | 0.462   | 0.253 | 0.213   | 5.019 | 5.090   |
| green     | 0.855 | 0.748   | 0.731 | 0.559   | 2.999*| 3.825   |
| red       | 0.743 | 0.569   | 0.551 | 0.324   | 3.882 | 4.706   |
| NIR       | 0.090 | 0.137   | 0.008 | 0.019   | 5.727 | 5.672   |

Note: Asterisk symbol represents the lowest RMSE value
Figure 3. Regression model for each band of Sentinel 2A in estimating the water depth (from upper left to right and lower left to right: blue, green, red and NIR bands). The x-axis represents the log transformed of surface reflectance of Sentinel 2A band and Y-axis represents the water depth obtained from field measurement.

Figure 4. Bathymetry maps as a result of linear regression analysis of green band without sun glint correction (a) and with sun glint correction (b).
Bathymetric map as a result of SDB modelling using green band is available in Figure 4. Image with sun glint correction is more accurate with RMSE 2.999 m compare to image without sun glint correction with RMSE 3.825 m (Table 1). Sun glint correction provided a more visible sub-surface and removed the effect of sun glint and low clouds (see Figure 4 (b) for e.g., grid cell c3).

3.2. Band Ratio
The results of correlation analysis by using Pearson Product moment and linear regression analysis for six combinations of band ratio are available in Table 2 and Figure 5. For image with sun glint correction, blue/green ratio provided the highest value of $r= -0.788$ and the highest accuracy indicated by the lowest RMSE value 3.624 m and $R^2$ equal to 0.621 m. Meanwhile the lowest values of correlation and accuracy are obtained by using green/red ratio with $r=0.157$ and RMSE equal to 5.678 m.

**Table 2.** The results of linear regression model and the correlation analysis using band ratio of Sentinel 2A (95% confidence interval)

| Log(band)     | Coefficient correlation ($r$) | R-squared ($R^2$) | RMSE (m)     |
|---------------|-------------------------------|-------------------|--------------|
|               | Glint | No-glint | Glint | No-glint | Glint | No-glint |
| blue/green    | -0.788 | -0.528  | 0.621 | 0.279    | 3.624* | 4.878   |
| blue/red      | -0.545 | -0.372  | 0.297 | 0.138    | 4.853 | 5.294   |
| green/red     | 0.157  | -0.067  | 0.025 | 0.004    | 5.678 | 5.712   |
| green/blue    | 0.783  | 0.522   | 0.613 | 0.272    | 3.666 | 4.901   |
| red/blue      | 0.544  | 0.379   | 0.296 | 0.144    | 4.855 | 5.281   |
| red/green     | 0.158  | 0.068   | 0.025 | 0.005    | 5.677 | 5.712   |

Note: Asterisk symbol represents the lowest RMSE value

For image without sun glint correction, blue/green ratio provided the highest value of $r= -0.528$ and the highest accuracy indicated by the lowest RMSE value 4.878 m and $R^2$ equal to 0.279. Meanwhile the lowest values of correlation and accuracy are obtained by using green/red ratio with $r=0.157$ and RMSE equal to 5.678 m. Similarly, applying glint correction obtained a higher correlation and accuracy value. In Figure 4(a and d), the relation of blue/green and water depth was linear indicated by a steep gradient implying that every small change in depth significantly changes the value of the ratio.

Bathymetric map as a result of SDB modelling using band ratio of blue/green band is available in Figure 6. Image with sun glint correction is more accurate with RMSE 3.624 m compare to image without sun glint correction with RMSE 4.878 m (Table 2). The results of the blue/green ratio (Figure 6b) show a much more representative depth spatial distribution especially for shallow water area below 3 m. Meanwhile, the results of other models failed to show the depth distribution in shallow waters, for example Figure 4a (for e.g., grid cells B3, C2 and C3), Figure 4b (for e.g., grid cells B2, B3 and C3) and Figure 6a (for e.g., grid cells B2, B3 and C2, C3). The results of the blue/green ratio (Figure 6b) is able to describe the fringing reef.
Figure 5. Regression model for each band ratio combination of Sentinel 2A in estimating the water depth: a) blue/green, b) blue/red, c) green/red, d) green/blue, e) red/blue, and f) red/green. The X-axis represents the band ratio of surface reflectance of Sentinel 2A band and Y-axis represents the water depth obtained from field measurement.

Figure 6. Bathymetry map as a result of band ratio analysis of blue/green without sun glint correction (a) and with sun glint correction (b).
Figure 7 provides the depth variation of the SDB models at three different locations. Bathymetric profiles in Figure 7a show that SDB models which used sun glint correction were able to represent deeper area better than any other models with good accuracy (see blue and green lines in Figure 7a). Bathymetric profile in Figure 7b shows that images with band ratio fit with SBES data in shallow water area, however, in deeper area, images with sun glint correction could penetrate to deeper water close to 15 m. Meanwhile, cross profile in Figure 7c presents that band ratio image with sun glint correction fit with the SBES data only at the beginning of the transect (point 1 – 35). On the other hand, the SDB models from the green band (in blue and red line) have quite a good agreement with the SBES data started from middle of the transect (after point 35). Images without sun glint correction were overestimated the depth in the deeper water area (see black and red lines in Figure 7a).

Although in literature it was stated that blue band has the ability to penetrate depths close to 30 meters [6], however, in this research green band demonstrated the best accuracy for bathymetric mapping in deeper area up to 15 m (see the blue line in Figure 7a). The accuracy values provided by green and blue bands differs quite significantly (see Table 1). Moreover, the use of green band model outperformed all models. For the band ratio, the blue band to the green band (blue/green) provided the greatest accuracy and generated more accurate estimate of bathymetry (see the green line in Figure 7a-c). Even though the band ratio application has a slightly lower accuracy value than the single green band, it is also able to describe the depth distribution well (see green and black lines in Figure 7a-b). The three-dimensional appearance of the bottom topography of the study area is presented in Figure 8.
Figure 8. 3D view of the topography of the benthic habitat of some part of the study area. Depth data taken from the green band bathymetric modelling with ten times vertical exaggeration.

4. Conclusions
This research provided an evaluation of SDB model accuracy by using single band and band ratio. The use of sun glint correction increased the accuracy by 28% for green band model while for band ratio, the accuracy increased by 35%. In this research, the use of band ratio as input for SDB model apparently not always obtained a better accuracy. The highest accuracy provided by band ratio model was 3.624 m by using the blue band to the green band (blue/green) model while by using green band, we obtained 2.999 m.

The use of SDB model to extend methods in obtaining bathymetry data is promising as more images become available free of charge and in various resolutions. Challenges for future study include (a) extending the experiment with other area to check the consistency of the SDB model, and (b) using other SDB algorithm to obtain better accuracy.

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