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Analysis of The Utilization of Sentinel-2 Imagery for Satellite-Derived Bathymetry Using Lyzenga Algorithm (Case Study: Bali Province)

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***Abstract*—Bathymetric surveys nowadays are often used by the echosounding method. This method has weakness because the range that can be surveyed is limited due to cannot reach areas that have shallow depths. With advances in technology, there are alternative ways that can be done to map the depth of the sea, with the help of satellite imagery or remote sensing. This method uses a mathematical algorithm based on a combination of spectrum channels called Satellite-Derived Bathymetry (SDB). In this research, Sentinel-2 satellite imagery was used with Lyzenga algorithm. Lyzenga (2006) uses multilinear regression which is a combination of an equation that aims to convert pixel values into in-situ depth values. Within research of six locations in Bali Province, which are Sangsit Harbor, Gunaksa Harbor, Amed Port, Keramas Beach, Serangan Harbor and Sawangan Beach produced an R^2 value each of 0.451, 0.747, 0.495, 0.610, 0.451 and 0.676. While the RMSE values were 26,247, 12,377, 31,942, 3,531, 3,000, and 1,992 respectively for water depths of 146 m, 97 m, 183 m, 22 m, 13 m, and 18 m respectively. The parameters that affect the level of accuracy are: water depth, presence of breaking waves, presence of disturbance objects in the waters.**

Keywords— *remote sensing, satellite-derived bathymetry, sentinel-2, lyzenga, bali province.*

I. INTRODUCTION

Indonesia is an archipelagic country that has a very wide water area with 74% of which is water territory or around 5.8 million km^2 [1]. By having a large water area, it is important to know the sea depth map or bathymetry. Bathymetry maps play an important role in determining shipping lanes and in determining the appropriate coastal protection structures for a coastal area or port. Technology related to mapping the seabed is by utilizing the principle of acoustic waves in water so that it can produce accurate depths for deep water but this method is still difficult to apply in shallow waters [2]. On this basis, an alternative technology is needed to support the availability of depth information efficiently and continuously, especially in shallow waters and remote areas. Guenther (1996) [3] proposed the use of remote sensing techniques including airborne LiDAR to be used in bathymetric mapping. Remote sensing is the science of obtaining information about an object, area or phenomenon by analyzing data obtained through a recording device that uses electromagnetic waves as its intermediary medium without touching the object [4]. The ustilization of remote sensing has been widely used in research such as monitoring shoreline changes (Pujianiki, 2021, 2022) [5]–[7]. In principle, satellites are divided into active (radar) and passive (optical) satellites.

In this study optical satellites are used considering that radar satellite waves cannot penetrate the surface of the water. The optical satellite used is Sentinel-2. Sentinel-2 optical satellite was used. Sentinel-2 is a satellite launched by The European Commission and the European Space Agency (ESA) in collaboration with the Global Monitoring for Environment and Security (GMES) program. Sentinel applications have been used in several studies such as Pujianiki et.al 2020, 2021, 2022 and application results show good results. Depth measurements use Satellite-Derived Bathymetry (SDB) technology by utilizing several mathematical algorithms based on spectrum channel combinations. In this study, Lyzenga (2006) algorithm were used. The Lyzenga [8] algorithm uses linear logarithms using one or a pair or three optical image channels. The research location was carried out in the waters of the Bali Province. Bali is a province in Indonesia which has quite diverse water areas based on depth. In this study, tests were carried out at six representative locations, they are Sangsit Port in Buleleng Regency, Amed Port in Karangasem Regency, Gunaksa Port in Klungkung Regency, Keramas Beach in Gianyar Regency, Serangan Harbor in Denpasar City, and Sawangan Beach at Badung Regency. Based on studies that have been done before, a test were carried out again whether the waters in Bali have the same characteristics as one another. Based on this level of accuracy, it can be concluded how far the development of remote sensing technology has been in mapping various waters in the Province of Bali.

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II. METHOD

A. Research Location

The research locations were carried out in six locations in Bali Province representing five regencies and one city. The data collected is in the form of depth/bathymetry samples that have been recorded using an echosounder. At Serangan Harbor the survey was conducted on June 7 2021. At Sawangan Beach the survey was conducted on January 12 2021. At Keramas Beach the survey was conducted on June 1 2022. At Gunaksa Port the survey was conducted on April 16 2021. At Amed Port the survey was conducted on July 18 2021. At Sangsit Port the survey was conducted on November 1 2020.

B. Data and Sources

The data used in this study are:

1) Data from bathymetry measurements using a single beam echosounder at the study site. This data was obtained in collaboration with various parties.
2) Sentinel-2 Level 2A satellite image data obtained from the Copernicus Open Access Hub website https://scihub.copernicus.eu/dhus. The satellite imagery data taken has a different time from the measured data using an echosounder. For this reason, it is necessary to carry out a tidal correction by calculating the decrease in water level when the satellite image is captured.

C. Research Tools and Instruments

The tools or software used in this study are:

1) The Sentinel Application Platform (SNAP) is used to process Sentinel-2 image product data, such as resampling, subset, masking and running the algorithm used in this study.
2) Sen2Coral Plugin is a plugin for SNAP software. Sen2Coral can eliminate Sun glint or the effect of reflected sunlight which can interfere with reading bathymetry depth.
3) Admiralty Total Tide (ATT) is software that functions to make tidal corrections to data that has been recorded via an echosounder.

D. Image Pre-Processing

The steps that need to be carried out in processing Sentinel-2 images before running the SDB algorithm are:

1) Resampling is needed because each band have different spatial resolution. The resampling process is carried out by combining multiple band to have same resolution.
2) Subsets are used to crop on the image area to only focus at the research location only.
3) Image Masking functions to separate land and sea parts, it is necessary to run the Math Normalized Difference Water Index (NDWI) band. This stage is carried out so that the land area does not affect the waters when running the SDB algorithm.
4) Sun Glint Correction is used to remove the shine effect of sunlight because it can interfere with the Satellite Derived Bathymetry process. This process uses the Sen2Coral Plugin in SNAP.

E. Water Index Method

The normalized difference water index (NDWI) is used to differentiate open water. This method uses the green band (band 2) and near-infrared/NIR (band 4) to help increase the presence of water, while removing ground and terrestrial vegetation [9]. Xu (2006) [10] proposed a modified NDWI by replacing the NIR band with a shortwave infrared (SWIR) band to eliminate noise from buildup in coastal areas.

$$NDWI = \frac{Green - SWIR1}{Green + SWIR1} \quad (1)$$

F. Sun Glint Correction

The influence of the sun's reflectance needs to be eliminated or reduced by considering that near-infrared waves are completely absorbed in water. The infrared band is used to determine the reflectance of the water surface to get better results. Sunlight correction is performed using the spectral distribution of light, although measurements are considered more precise using donwelling radians on the surface. An algorithm for eliminating the sunburn effect was developed [11] which was later refined by Hedley (2005) [12].

$$R'_i = R_i - bi\,(R_{NIR} - min_{NIR}) \quad (2)$$

where:

R'_i = Channel i value after reduction
R_i = Initial i channel value
bi = Value of the slope of the regression
R_{NIR} = Channel value
min_{NIR} = Minimum value of NIR channel

G. Lyzenga algorithm

The Lyzenga algorithm implements algorithms that use one or a pair of passive satellite wave bands [13]. This method uses the principle of light wave propagation in water where the light intensity decreases as the depth increases due to absorption or known as attenuation. The degree of attenuation is different for each wavelength in the electromagnetic radiation spectrum. In the visible light region, the red part of the spectrum is attenuated faster than the blue spectrum [14].

$$Z = a_0 + \sum_{i-1}^{N} a_i \ln\left(R(\lambda_i) - R_\infty(\lambda_i)\right) \quad (3)$$

where:

Z = Water Depth
ai (i=0,1,…N) = Constant coefficient, N is the number of spectral bands
R(λi) = Reflectance after atmospheric correction for the spectral band λi
R∞(λi) = Average deep sea reflectance in the spectral band λi

H. Multilinear Regression

The simplest and most frequently used SDB model is the multiple linear method or also called multiple linear regression analysis. The difference between Multiple Linear Regression and simple linear regression is that multiple linear regression has more than one independent variable.

$$y = b1\,x1 + b2x2 + b3x3 + \ldots + bi\,xi + a \quad (4)$$

where Y is the variable depth of the echo sounder, X is the predicted variable, a is the intercept, ie the value of Y at X=0, and b is the slope, ie the change in the average of Y to a change in one unit of X.

I. Accuracy test

The method used to determine the accuracy of the resulting bathymetric maps is RMSE (root mean square error) [15].RMSE is the root of the average sum of the squares between the difference in depth values from echosounder measurements and the depth values from satellite-derived bathymetry.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{t=1}^{n} (At-Ft)^2}{n}} \quad (5)$$

Where:
At = The value of the estimated depth of the image
Ft = Field measurement result value
n = Number of depth points used in model validity

III. Results and Discussion

A. Location 1 Sangsit Harbor

The Sentinel-2 satellite image data used for this location was recorded on August 25, 2021 at 02.16 UTC or 10.16 WITA. According to the Admiralty Total Tide application at that time the water level was at +1.30 m. Meanwhile, LLWL is at an altitude of +0.40 m. Therefore, the height correction of the bathymetry data with the echosounder will be added by 0.90 m to equalize the perception with the satellite imagery data.

After the processing of satellite imagery and the application of the Lyzenga Algorithms at Sangsit Harbor, the equations and accuracy values are obtained in Table 1. From the regression equation at Table 1, the comparison graph between the depth of the Lyzenga Algorithms to the echosounder we can see in Figure 1.

The processing results of the Lyzenga algorithms coefficient of determination (R^2) value of 0.451 and the level of accuracy (RMSE) of 26.224. Figure 2 is a comparison of the bathymetry mapping results of the echosounder and the calculation results of the Lyzenga algorithm.

Based on the results of the bathymetry plotting between the echosounder data and the results of the Lyzenga algorithm, there is a difference in the depth level where the results of the Lyzenga algorithm are only able to detect depths of up to -70 m from what should be -150 m. This reveals that depth can affect the results of accuracy in bathymetry measurements using remote sensing.

B. Location 2 Amed Port

The Sentinel-2 satellite image data used for this location was recorded on June 6, 2022 at 02.16 UTC or 10.16 WITA. The nearest station for monitoring tides in Amed Port is located in Labuan Amuk. According to the Admiralty Total Tide application at that time the water level was at +0.80 m. Meanwhile, LLWL is at an altitude of +0.50 m. Therefore, the height correction for the bathymetry data with the echosounder will be added by 0.30 m to equalize the perception with the satellite imagery data.

After the processing of satellite imagery and the application of the Lyzenga Algorithms at Amed Port, the equations and accuracy values are obtained in Table 2. From the regression equation at Table 2, the comparison graph between the depth of the Lyzenga Algorithms to the echosounder we can see in Figure 3.

The processing results of the Lyzenga algorithm have a determination coefficient value of 0.747 and a level of accuracy of 12.377 m. Figure 4 is a comparison of the bathymetry mapping results of the echosounder and the calculation results of the Lyzenga algorithm.

Based on the results of the bathymetry plotting between the echosounder data and the results of the Lyzenga algorithm, there is a slight difference to the maximum limit where the echosounder has a maximum limit of -100 m while the results of the Lyzenga Algorithm are only up to -85 m. This is in accordance with the accuracy limit which reaches 12,377 m. However, on the contours of the shallow sea, the results of the Lyzenga Algorithm have a less flat surface when compared to the echosounder map. This reveals that at a shallow elevation is the position of the breaking waves at Amed Harbor so that the captured image has different band values.

C. Location 3 Gunaksa Harbor

The Sentinel-2 satellite image data used for this location was recorded on June 6, 2022 at 02.16 UTC or 10.16 WITA. The nearest station for monitoring the tides of Gunaksa Port is located in Padang Bay. According to the Admiralty Total Tide application at that time the water level was at +0.70 m. Meanwhile, LLWL is at an altitude of +0.50 m. Therefore, the height correction for the bathymetry data with the echosounder will be added by 0.20 m to equalize the perception with the satellite image recording data.

After the processing of satellite imagery and the application of the Lyzenga Algorithms at Gunaksa Harbor, the equations and accuracy values are obtained in Table 3. From the regression equation at Table 3, the comparison graph between the depth of the Lyzenga Algorithms to the echosounder we can see in Figure 5.

The processing results of the Lyzenga algorithm have a coefficient of determination of 0.495 and a level of accuracy of 31,942 m. Figure 6 is a comparison of the bathymetry mapping results of the echosounder and the calculation results of the Lyzenga algorithm.

Based on the results of the bathymetry plotting between the echosounder data and the results of the Lyzenga algorithm, the biggest difference is in the shallow sea area. Gunaksa Harbor is a port that has high waves. This made the Gunaksa Harbor experience a construction failure at the breakwater before the Port was put into operation. The contours that can be seen in the results of the satellite imagery algorithm are areas where the waves come so that the bands are translated as irregular, making the elevation messy.

D. Location 4 Keramas Beach

The Sentinel-2 satellite image data used for this location was recorded on May 22, 2022 at 02.16 UTC or 10.16 WITA. The nearest station for monitoring the tides of Keramas Beach is located in Sanur. According to the Admiralty Total Tide application at that time the water level was at +0.80 m. Meanwhile, LLWL is at an altitude of +0.60 m. Therefore, the height correction for the bathymetry data with the echosounder will be added by 0.20 m to equalize the perception with the satellite image recording data.

After the processing of satellite imagery and the application of the Lyzenga Algorithms at Keramas Beach, the equations and accuracy values are obtained in Table 4. From the regression equation from Table 4, the comparison graph between the depth of the Lyzenga Algorithms to the echosounder we can see in Figure 7.

The processing results of the Lyzenga algorithm have a determination coefficient value of 0.610 and a level of accuracy of 3.531 m. Figure 8 is a comparison of the bathymetry mapping results of the echosounder and the calculation results of the Lyzenga algorithm.

Based on the results of the bathymetry plotting between the echosounder data and the results of the Lyzenga algorithm, differences are seen in the coastal areas where the contours of the echosounder are still quite clear compared to the results of the remote sensing algorithm. Keramas Beach is one of the beaches that is often used as an object for surfing by local and foreign residents. Because the waves are high enough to cause a decrease in accuracy even though the bathymetry profile at Keramas Beach is still in the shallow category.

E. Location 5 Serangan Harbor

The Sentinel-2 satellite image data used for this location was recorded on June 6, 2021 at 02.16 UTC or 10.16 WITA. The nearest station for monitoring the tides of Serangan Harbor is located at Benoa Harbor. According to the Admiralty Total Tide application at that time the water level was at +1.10 m. Meanwhile, LLWL is at an altitude of +0.30 m. Therefore, the height correction for the bathymetry data with the echosounder will be added by 0.80 m to equalize the perception with the satellite imagery data.

After the processing of satellite imagery and the application of the Lyzenga Algorithms at Serangan Harbor, the equations and accuracy values are obtained in Table 5. From the regression equation at Table 5, the comparison graph between the depth of the Lyzenga Algorithms to the echosounder we can see in Figure 9.

The processing results of the Lyzenga algorithm have a determination coefficient value of 0.451 and a level of accuracy of 3,000. Figure 10 is a comparison of the bathymetry mapping results of the echosounder and the calculation results of the Lyzenga algorithm.

Based on the bathymetry plotting between the echosounder mapping and the remote sensing results at Figure 10. The difference is quite clear where the port pool cannot be mapped perfectly by the Lyzenga algorithm. This can happen because when the image is captured there are several obstructing objects which result in misinformation about the separation of land and water parts. This visualization can be seen in the results of the bathymetry mapping using the Lyzenga algorithm where the object looks like a towering rock. This object is actually a ship parked in the harbor pool which was not there before when recording bathymetry using an echosounder.

F. Location 6 Sawangan Beach

The Sentinel-2 satellite image data used for this location was recorded on June 6, 2021 at 02.16 UTC or 10.16 WITA. The nearest station for monitoring the tides of Serangan Harbor is located at Benoa Harbor. According to the Admiralty Total Tide application at that time the water level was at +1.10 m. Meanwhile, LLWL is at an altitude of +0.30 m. Therefore, the height correction for the bathymetry data with the echosounder will be added by 0.80 m to equalize the perception with the satellite imagery data.

After the processing of satellite imagery and the application of the Lyzenga Algorithms at Sawangan Beach, the equations and accuracy values are obtained in Table 6. From the regression equation at Table 6, the comparison graph between the depth of the Lyzenga Algorithms to the echosounder we can see in Figure 11.

The processing results of the Lyzenga algorithm have a determination coefficient value of 0.676 and a level of accuracy of 1.992. Figure 12 is a comparison of the bathymetry mapping results of the echosounder and the calculation results of the Lyzenga algorithm.

Based on bathymetry plotting, the results of the echosounder and the Lyzenga algorithm at Sawangan Beach have a fairly similar level of similarity. Sawangan Beach is a beach located in the south of Bali Island. The composition of this beach is dominated by coral and white sand. It can be seen from the bathymetry profile which tends to be wavy. Even though it has quite high waves, the bathymetric contour profile at Sawangan Beach is still quite clear compared to other locations which also have high waves.

TABLE 1.
MULTILINEAR REGRESSION EQUATION AND ACCURACY VALUE OF LYZENGA'S ALGORITHM AT SANGSIT HARBOR

Variable x	Correlation Value	Equation	R^2	RMSE
X1 (B1-B2)	0.7699	y = 294.1362x - 252.4367	0.346	28.615
X2 (B1-B3)	0.4578	y = 161.5179x - 315.4919	0.445	26.365
X3 (B2-B3)	0.5478	y = 189.5998x - 279.8712	0.358	28.361
X1+X2+X3		y = -965.5796x1 + 1108.3263x2 - 776.4696x3 - 125.5176	0.451	26.247

TABLE 2.
MULTILINEAR REGRESSION EQUATION AND ACCURACY VALUE OF LYZENGA ALGORITHM AT AMED PORT

Variable x	Correlation Value	Equation	R^2	RMSE
X1 (B1-B2)	0.8717	y = 36.2297x + 21.7862	0.025	24.288
X2 (B1-B3)	0.9085	y = 77.9950x - 39.1515	0.618	15.208
X3 (B2-B3)	0.8633	y = 94.8739x - 39.6550	0.561	16.296
X1+X2+X3		y = -465.5067x1 + 445.7061x2 - 416.6895x3 + 258.1790	0.747	12.377

TABLE 3.
MULTILINEAR REGRESSION EQUATIONS AND ACCURACY VALUES OF THE LYZENGA ALGORITHM AT GUNAKSA HARBOR

Variable x	Correlation Value	Equation	R^2	RMSE
X1 (B1-B2)	0.8632	y = -78.8099x + 84.1516	0.034	44.165
X2 (B1-B3)	0.6835	y = -46.6667x + 103.3168	0.019	44.492
X3 (B2-B3)	0.8046	y = 5.7046x + 37.3027	0.0003	44.924
X1+X2+X3		y = 11288.4944x1 - 11406.5381x2 + 9656.8429x3 + 569.4102	0.495	31.942

TABLE 4.
MULTILINEAR REGRESSION EQUATION AND ACCURACY VALUE OF LYZENGA'S ALGORITHM ON KERAMAS BEACH

Variable x	Correlation Value	Equation	R^2	RMSE
X1 (B1-B2)	0.7800	y = 2.7268x + 6.4903	0.016	5.609
X2 (B1-B3)	0.8154	y = 3.6186x + 6.0024	0.026	5.578
X3 (B2-B3)	0.9135	y = 98.8707x - 38.3870	0.129	5.275
X1+X2+X3		y = -899.5860x1 + 897.5471x2 - 610.3322x3 + 411.4963	0.610	3.531

TABLE 5.
MULTILINEAR REGRESSION EQUATIONS AND ACCURACY VALUES OF LYZENGA'S ALGORITHM ON SERANGAN HARBOR

Variable x	Correlation Value	Equation	R^2	RMSE
X1 (B1-B2)	0.7699	y = 2.3718 * X1 + 3.2906	0.059	3.504
X2 (B1-B3)	0.4578	y = 3.2069 * X2 + 4.2969	0.151	3.329
X3 (B2-B3)	0.5478	y = 8.5030 * X3 + 5.0431	0.184	3.264
X1+X2+X3		y = -106.1917x1 + 107.0419x2 - 95.2791x3 + 17.1366	0.451	3.000

TABLE 6.
MULTILINEAR REGRESSION EQUATIONS AND ACCURACY VALUES OF LYZENGA'S ALGORITHM ON SAWANGAN BEACH

Variable x	Correlation Value	Equation	R^2	RMSE
X1 (B1-B2)	0.9268	y = -4.4629x + 11.2512	0.073	3.363
X2 (B1-B3)	0.8806	y = 1.5093x + 9.6864	0.008	3.478
X3 (B2-B3)	0.8895	y = 22.5368x - 3.8036	0.428	2.641
X1+X2+X3		y = -101.2913x1 + 95.2172x2 - 78.5978x3 + 23.1680	0.676	1.992

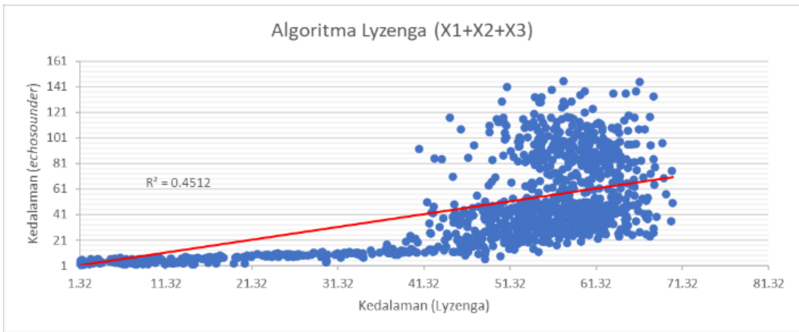

Figure. 1. Depth Graph of Lyzenga Algorithm at Sangsit Harbor

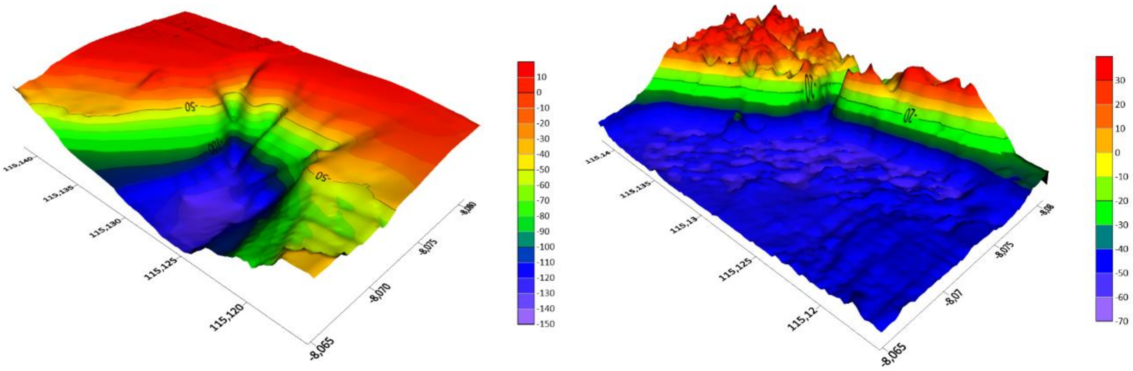

Figure. 2. 3D Bathymetry Map with echosounder (left) and Lyzenga Algorithm (right) at Sangsit Harbor

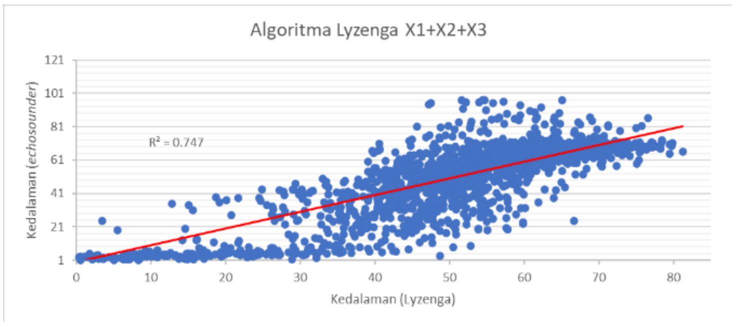

Figure. 3. Depth Graph of Lyzenga Algorithm at Amed Port

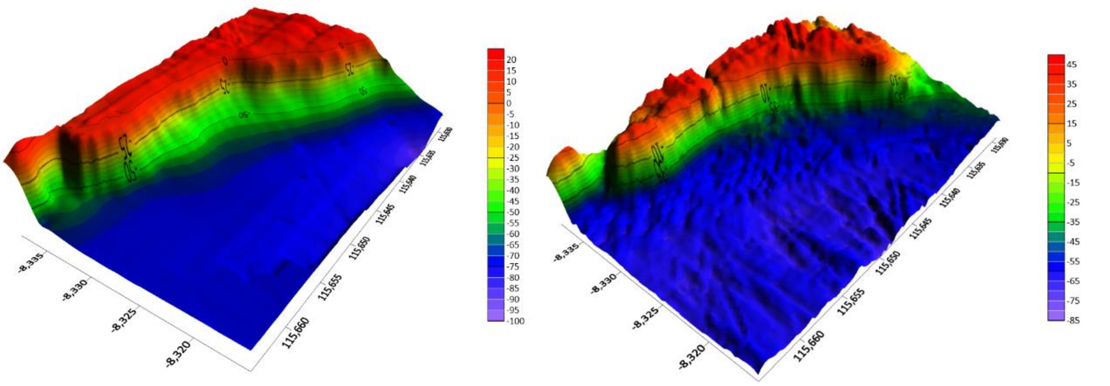

Figure. 4. 3D Bathymetry Map with echosounder (left) and Lyzenga Algorithm (right) at Amed Port

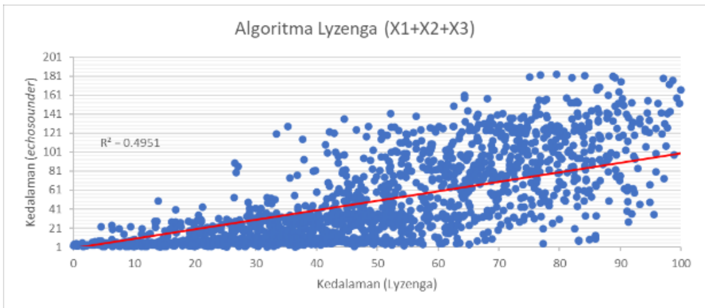

Figure. 5. Depth Graph of Lyzenga Algorithm at Gunaksa Harbor

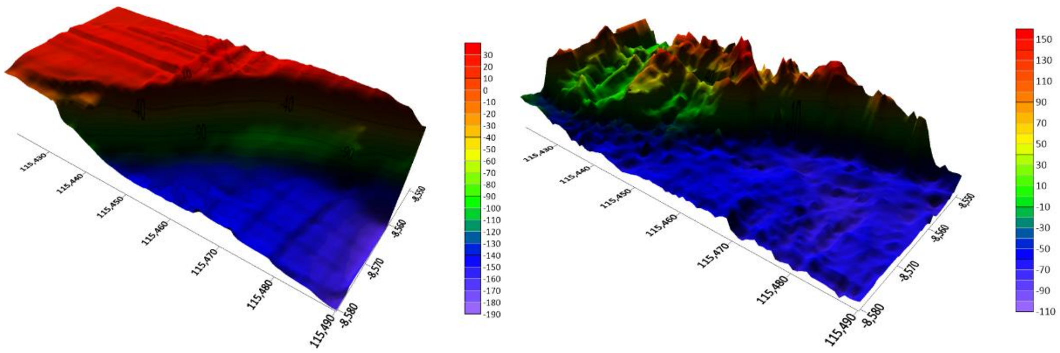

Figure. 6. 3D Bathymetry Map with echosounder (left) and Lyzenga Algorithm (right) at Gunaksa Harbor

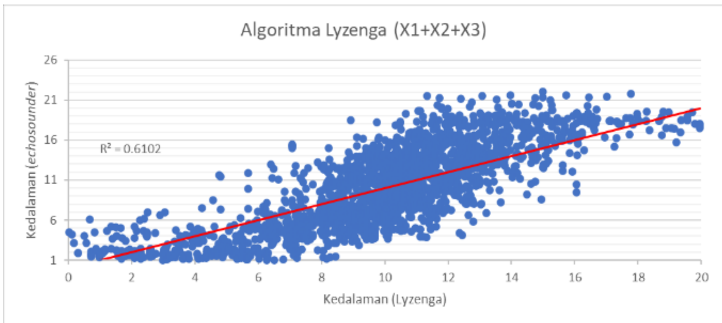

Figure. 7. Depth Graph of Lyzenga Algorithm at Keramas Beach

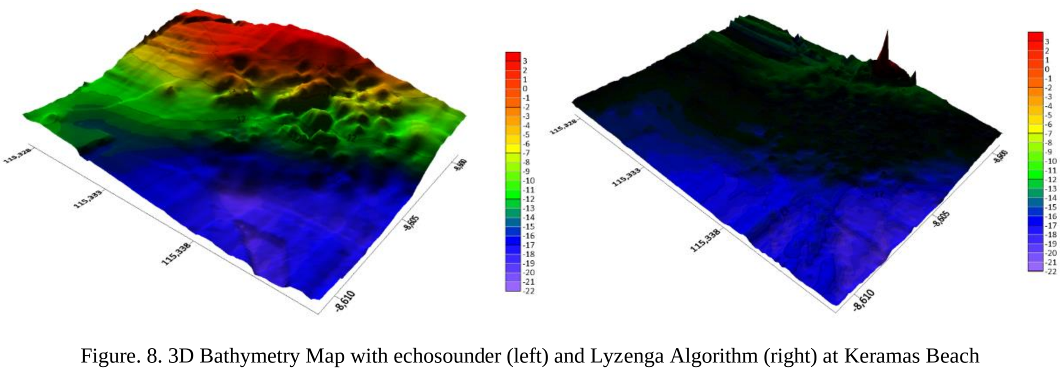

Figure. 8. 3D Bathymetry Map with echosounder (left) and Lyzenga Algorithm (right) at Keramas Beach

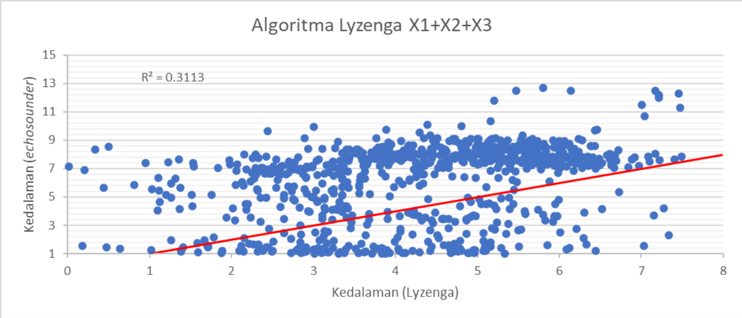

Figure. 9. Depth Graph of Lyzenga Algorithm at Serangan Harbor

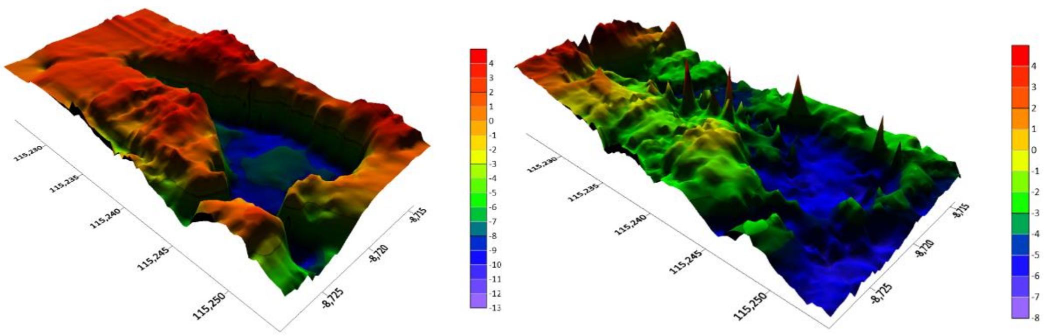

Figure. 10. 3D Bathymetry Map with echosounder (left) and Lyzenga Algorithm (right) at Serangan Harbor

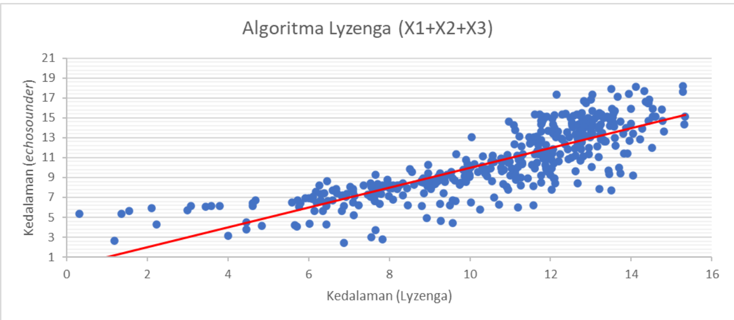

Figure. 11. Depth Graph of Lyzenga Algorithm at Sawangan Beach

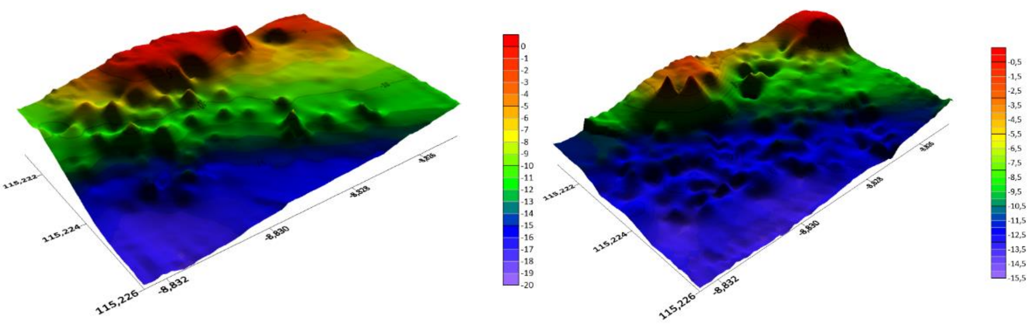

Figure. 12. 3D Bathymetry Map with echosounder (left) and Lyzenga Algorithm (right) at Sawangan Beach

IV. Conclusion

Based on the results and discussion that has been done, it can be concluded that depth has an effect on testing the accuracy of satellite imagery in reading bathymetry. This can be seen from the bathymetric contours at Sangsit Port where there are troughs up to 150 meters deep which SDB was unable to map perfectly. bathymetry is low. This can be seen in shallow water areas that tend to have unstable bands. Serangan Harbor, which has a shallow depth and calm wave conditions, has a low accuracy value. This is due to disturbances in the waters in the form of ships and also the high level of water turbidity.

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