Evaluates the possibility of shallow water bathymetry mapping using optical satellite imagery

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SUMMARY

The shallow water depth data is very important for applications in marine engineering, environmental management and hydrological applications. The article studies the method of depth estimation, which evaluates the possibility sea-bed depth mapping of shallow water areas around islands from optical satellite images. The study was experimentally done by using the Lyzenga common method for shallow waters area around the An Bang island of the Spratly archipelago - Viet Nam from the Sentinel-2 multi-spectral satellite image. The results show that the estimated depth from the image is -14.7 m, the depth estimation model achieved a high correlation of 0.89, the possibility of establishing a depth map from the Sentinel 2 satellite image was achieved at a scale Average 1:25,000 - 1:50,000. In addition, the establishment scale of the map depends on many factors to calculate the construction of models such as: image resolution, input points precision, computational model construction, preprocessing algorithm... The research results will be the foundation for step by step researching topographic sea-bed mapping in shallow water area around islands of the Spratly archipelago from satellite imagery.

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1. INTRODUCTION

High resolution and accurate coastal seafloor data is essential for oceanographic studies, particularly in accessing forecasting models for managers about affecting the topographic morphology and the near - shore environment, updating charts information for navigation, livelihood activities and ensuring national defense and security. The shallow waters around offshore islands have complex variations in depth and morphology, greatly influenced hydrodynamics, affects biological processes such as nutrient uptake and light absorption by plants [10], impact on coastal works [18].

Traditional active sensor methods such as multibeam echosounder and light detection and ranging (LIDAR) technology have been used widely nowadays. However, these technologies often have limitations such as: multibeam sounders are often of low spatial resolution, narrow coverage, and have trouble navigating in shallow water areas [15] [11]. Lidar technology with relative accuracy, high resolution, and cost is still too expensive for many applications, especially when updating a depth data set is required at all frequencies [1] for offshore areas. With the development of remote sensing technology, optical remote sensing imagery can provide valuable information for describing and monitoring shallow water. Recent satellite technologies and image processing algorithms have provided opportunities for the development of potential quantitative techniques to improve the disadvantages of conventional image processing methods, in terms of cost , map honesty, and objectivity [3]. Remote sensing images are equipped to establish underwater maps as multi specture images: Landsat [18], SPOT [1], IKONOS [12], Quickbird [21], Worldview-2 [4] and Sentinel-2 [8], [19]… Based on the principle of reflecting, scatering and absorbing light from water, scientists have come up with different methods to estimate the depth of water on the satellite image, some common methods such as: Stumpf Model/Linear Ratio Model [20], Lyzenga Model or Linear Band Model [1], Jupp's Model or Depth of Penetration Zone (DOP) Model [9], inverse and semi-optimized algorithms for hyperspectral (HS) imageries analysis [4], [7], classification and comparison method with LUT lookup table [5].

Linear Band Model is proposed by Lyzenga (1978, 1981, 1985, 2006) and Philpot (1989). Lyzenga extracted spectral radiation values from satellite imagery at points that already know the depth (real ground points) and used linear regression to determine a relationship between radiation and information deep fact area. The mathematical relationship was then used to calculate the depth of the coastal water level from the satellite image [13],[14],[15] Many studies have been successful in determining the depth using the Lyzenga method such as: Clack (1987), Hochberg et al. (2007), Hogrefe et al. (2008), Liu et al. (2010), Deidda and Sanna. (2012), Kanno and Tanaka (2012) ... This is a common and widely used method because it assumes that the depth independent of the optical properties that are difficult to estimate, such as benthic types, atmospheric conditions, water quality, location of the sun and the satellite. In addition, Philpot (1989) show that these characteristics increase the complexity of the model and reduce the reliability of the results. So this method is simpler and more usable. However, this model still has many errors for turbid water areas or there exist some substances that plants absorb high radiation.

Thus, this study tested the linear band method proposed by Lyzenga for the shallow waters around the An Bang island of the Spratly Islands - Viet Nam. The research was experimentally proposed to overcome some of the faults of the model due to the turbid waters or the presence of certain substances and plants that absorb high radiation in the coastal area. Moreover, the estimated map results are evaluated, comparing the probability of mapping established depth scales, as a scientific basis for step-by-step approach to producing seabed topographic maps from satellite imagery.

2. METHODS

2.1. The principle of determining the depth of water from remote sensing images

Based on the Beer Law on the attenuation of light passing through an absorbent material and reflected states just below the ocean surface at any wavelength, r_{rs} is a function of the bottom reflectance (albedo) r_B, irradiance reflectance of an optically deep water column r_w, the coefficient α is a two-way attenuation coefficient (i.e., it accounts for losses in both the upward and downward directions), and h is the water level. Lyzenga (1978) [1], Philpot (1989) [3] show their relationship as follows:

$$r_{rs} \equiv \frac{\pi L^{-}}{E_i^{-}} = r_w + r_B^{*} e^{-\alpha h} = r_w + (r_B - r_W)\, e^{-\alpha h} \qquad (1)$$

Upwelling irradiance under the water can be written:

$$L(h) = L_s + L_b e^{-\alpha h} \qquad (2)$$

Where L_s including surface reflections as well as water column scattering effects, and L_b, and L_b including signals transmitted through the water - the air is lost as well as reflections bottom and water column scattering effects. Equation (2) can be rearranged to describe the depth in terms of the reflectances and the albedo:

$$h = \frac{1}{\alpha}\ln(L_b) - \frac{1}{\alpha}\ln(L_h - L_s) \qquad (3)$$

Where L_h is surface irradiance, and L_s is the deep-water medium irradiance.

2.2. Linear band model of Lyzenga

Based on the simple radiation transmission model shown in formula (1-3) above. First, he defines a variable X_j for each band from 1 to N as follows:

$$X_j = \ln(L_{hj} - L_{sj}) \qquad (4)$$

Where L_{hj} is the above-surface radiance in band j and L_{sj} is averaged deep water radiance in the same band j. Lyzenga 1978 computed benthic transformations use multispectral bands and a rotary matrix, similar to the analysis of the main components to calculate the independent variable depth in the radiation values between bands, for an N-band system, transformed radiances fall along a set of parallel lines in N-Space. Thus, a second set of variables can be obtained by rotating the coordinate system so that the Y_N axis is parallel to this direction [13].

$$Y_i = \sum_{j=1}^{N} A_{ij} X_j \tag{5}$$

Where A_{ij} is the i variable in the rotation matrix for band j. If the linear transformation (5) is a pure rotation, there are N – 1 depth-independent variables that could be used as indices of bottom type, only Y_N will be dependent on the water depth, while all the other variables are functions only of bottom reflectance [13]. Although this algorithm accounted for bottom type variability and did not require any existing depth measurements, it failed to account for any heterogeneity in water column properties across an image. This algorithm was updated by Lyzenga in 1985, and again in 2006 by Lyzenga et al., to account for water quality heterogeneity, finally modeling depth as [2],[15]:

$$\hat{h} = h_o - \sum_{j=1}^{N} h_j X_j \tag{6}$$

Where h_o and each h_j are constants defining a linear relationship between X_j, again defined as above, and depth. h_o and all of h_1 - h_j are determined through multiple linear regression between a set of known depths and the log-transformed radiances found at those depths.

In areas with large sedimentation, absorption, reflection is unregulated, leading to $L_{hj} - L_{sj}$ < 0 (in fomular 4) and will cause a calculated model error. Therefore, for different areas, it should be tested with or without minor adjustment or adjustment. I.e $L_{sj} = 0$ or $L_{sj} = L_{\min sj}$, where $L_{\min sj}$ is the smallest radiation value in deep water area. Then the variable X_j taken into regression is calculated as: $X_j = \ln(L_{hj})$ or $X_j = \ln(L_{hj} - L_{\min sj})$.

2.3. Assess the possibility of establishing a depth map

To evaluate the possibility of establishing a depth map of the study area from satellite images, the researcher used empirical methods to compare field measurements with extracted data on maps computed from satellites images for two parameters: point position error and depth error:

- *Point position error:* The accuracy of the test results after the warping image is compared through the external control points, the test position position error is calculated according to the following formula:

$$\Delta_{\text{Vi\_tri}} = \sqrt{\Delta_{goc}^2 + \Delta_s^2} \tag{7}$$

Where $\Delta_s = \Delta X^2 + \Delta Y^2$, ΔX = X(m) – x(m), ΔY = Y (m) – y(m) and (X, Y) is the coordinates of the test point extracted from the warped satellite image, (x, y) is the coordinates of the test point extracted from the map or plane chart image with the scale M or directly measured in the field with the accuracy equivalent to the map with scale M.

Point position error: $m_{xy} = \sqrt{\frac{\sum \Delta_s^2}{n}}$ (mét) (8)

Δ_{goc} is the geophysical point location error allowed from maps or data collected directly in the field, calculated as follows:

Δ_{goc} = 0.5 (mm) * M, where M is the corresponding map scale denominator value.

- *Depth error:* Similar to the accuracy check of position errors, depth points were also tested empirically between the calculated depth values from the remote sensing images and the depth values collected from the map or field surveys with larger scale requirements. The test depth error is calculated according to the following formula:

$$\Delta_Z = \sqrt{\Delta_{zgoc}^2 + \Delta_z^2} \quad (9)$$

Where $\Delta_z = Z - z$ (mét), Z is the depth extracted on the map computed from satellite images, z is the depth collected in the field. Δ_{zgoc} Similar to Δ_{goc} above. The elevation error in the M-scale map is less than one-third the height between the contours. Therefore, Δ_{goc} is calculated = the height between the contours /3.

3. DATA AND STUDY AREA

3.1. Study areas

The Spratly Islands Archipelago are offshore islands, located on the east -southeast coast of Vietnam and south of Vietnam's East Sea. The test area is a shallow water area around an island in the An Bang Island archipelago. This is the area with weather conditions, complex hydrology, all year round with great waves and the most inaccessible vessels among the geographical entities of Truong Sa of Vietnam. Sea water in this area is relatively clear, can see the bottom with a depth of 10-20m (Figure 1).

Figure 1. Research area of Spratly archipelago

The climate can be divided into two seasons: dry and rainy. Dry season from January to May, the rainy season from May to January next year, the average annual rainfall is very large at about 2500mm [16].

3.2. Study data set

Sentinel-2 satellite have driven the design towards a dependable multispectral Earth observation system featuring a MultiSpectral Instrument (MSI) with 13 spectral bands ranging from the visible and nearinfrared to the short-wave infrared. The spatial resolution varies from 10 m to 60 m, depending on the spectral band, with a 290 km field of view and repeat cycle 10 days [6]. With the clear water environment as the Spratly Islands Archipelago, Sentinel 2A image is a good data to study water depth. This study uses bands B2, B3, B4, B8 to estimate the shallow water depth. Image of the study area were taken at 9h 47 'Vietnam time on 16/6/2016, percentage of cloud is 1,214%, sunny weather, visibility over 10 km, northeast winds levels 6-7, high waves of 1.5-2m, tide is starting to descend [17].

Control point data set includes: Collect 8 points of clear geographic coordinates with a map scale of 1: 2,000. Of these, there are 4 points that warp the image, and 4 points that test position position error; Collect 25 depth points that take into the model building and 12 depth points that test the depth mapping capabilities of the model. The depth and position control points are obtained from the direct measurement using the Hidrobox depth meter combined with the GPS Trimble 2008 device and TC 405. Due to the very tidal pattern of shallow water originating from the complexity of coastal seabed terrain combined with continental wind regimes and large fluctuations in flows. So when calculating the tidal correction during the experiment, the authors removed tidal influence over a measuring time range by combining with the tide table and using the TC405 to check the water edge elevation from the high control points in the island.

4. RESULTS AND DISCUSSION

The research steps include: (1) image warping, (2) radiation conversion, (3) atmospheric correction, (4) sunglint remove, (5) calculate the Lyzenga depth model parameters, (6) depth estimation, (7) depth map editor, (8) Evaluate the possibility of establishing a shallow water depth map from satellite images. This report does not describe in detail and results step by step but focuses only on the results of steps 5, 6, 7 and 8. However, the steps are still in place to ensure that the noise that affects the accuracy of the mapping is eliminated.

4.1. Bathymetry mapping by Lyzenga method

By testing the L_{sj} component correction cases as analyzed in the above section, it was found that: If not edited L_{sj} component, ie L_{sj} = 0, then the results are the best. Thus, we only need to log the regression band such as ln(B2), ln(B3), ln(B4), where B2, B3, B4 are the corresponding input bands after calibration. Using the Extract Value To Point tool in ArcGIS software, extract the pixel values of the calculated bands at 25 depth points in the input dataset. Perform multi-linear regression of depth with the value of the extracted pixels, the results are the statistical parameters of the Lyzenga model according to the formula (6) are $h_o = -9.47$, $h_{B2} = -16.39$, $h_{B3} = 17.26$, $h_{B4} = -0.13$, The formula for depth calculation is as follows:

$$\hat{h} = -16.39 * \ln(B2) + 17.26 * \ln(B3) - 0.13 * \ln(B4) - 9.47 \qquad (10)$$

Using arcgis software, with inputs such as image bands B2, B3, B4 removed the noise (before the establishment of the model), instead of the formula 10 we can calculate the depth map as follows (Figure 2):

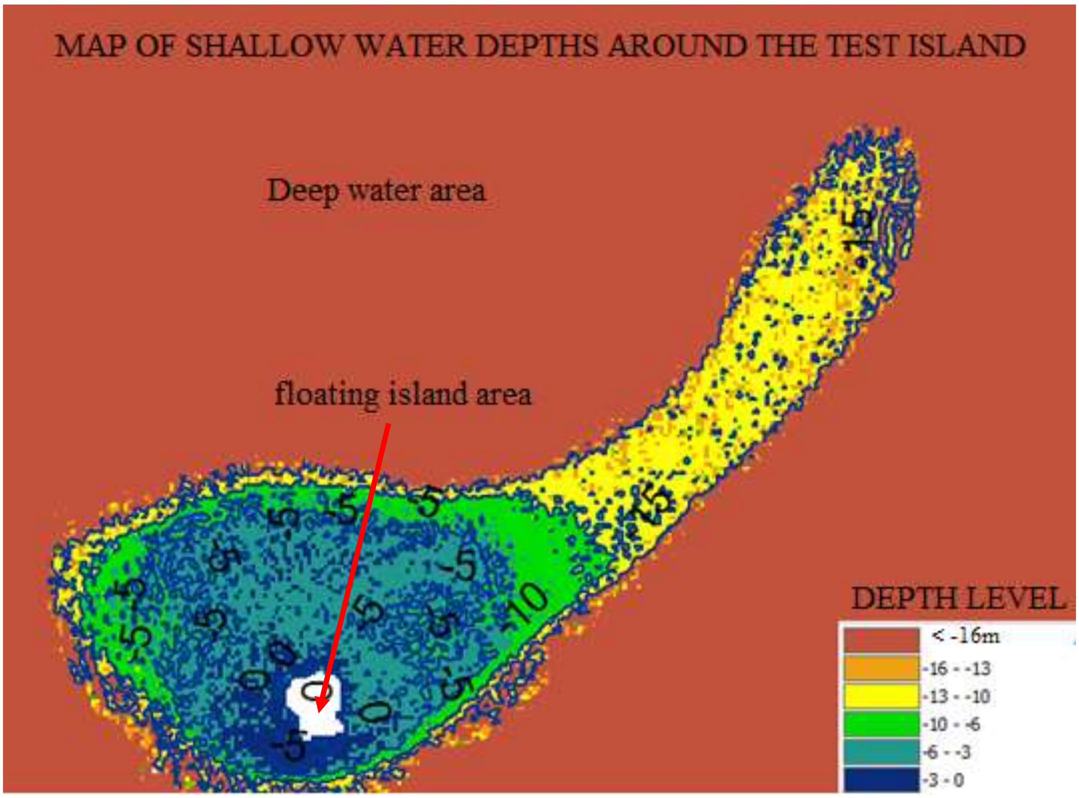

Figure 2. Estimated depth of map from satellite image

The estimated depth for the area is -14.7 m of water, the map shows height between contours of 5m, brown areas are deeper - 15 meters, where the satellite image can not determine the depth of water. The white area is the floating island section, which is the island that emerges from the water surface, not being flooded, the shoreline of the island is often built into embankments to protect the island. Civil works such as houses, roads, playgrounds and trees are often built on the island, which can collect the image wrapping and checks points and evaluates the position error.

The RMSE is the square root of the variance of the residuals. It indicates the absolute fit of the model to the data–how close the observed data points are to the model's predicted values. Whereas R-squared (R^2) is a relative measure of fit (it ranges from zero to one), RMSE is an absolute measure of fit. As the square root of a variance, RMSE can be interpreted as the standard deviation of the unexplained variance, and has the useful property of being in the same units as the response variable. Hight values of R^2 indicate better of model, otherwise lower values of RMSE indicate better fit. RMSE is a good measure of how accurately the model predicts the response, and it is the most important criterion for fit if the main purpose of the model is prediction. The accuracy of the model is very good, the results are shown in Table 1, R-squared (R2) statistic achieved 0.89, the RMSE of the model is 0.995 meters.

Table 1. Statistical parameters of the Lyzenga model

Parameters	Multiple R	R Square	Adjusted R Square	RMSE
Value	0.943376912	0.889959999	0.885175651	0.995499

4.2. Evaluate the possibility of establishing a depth map

The study used 4 image wrapping points and 4 point to check position error, the check position error points after the image wrapping are pixels that can be identified relative in the satellite image. After using the ArcGIS software to extract the coordinates of the test points on the map in figure 2 and take into account the formula (7), (8), the results are shown in Table 2. Where, the coordinates of the collection point of the test have the same accuracy as the scale map of 1: 2.000, inferred Δ_{zgoc}=0.5*2.000/1000 = 1.

Table 2. Parameter check point position error (unit: meter)

TT	ΔX	ΔY	Δs	Δ_{zgoc}	Δ_{Vi_tri}	Noted
1	8.32	9.13	12.3523	1	12.39271	Gain scale 1:25.000
2	8.19	10.24	13.11235	1	13.15043	Gain scale 1:25.000
3	8.77	6.25	10.76919	1	10.81552	Gain scale 1:25.000
4	14.1	13.6	19.59005	1	19.61556	Gain scale 1:50.000

In the current norms, topographic maps in our country stipulate: "the mean square error of the location of the object indicated on the original map against the location of the nearest surveying control point does not exceed 0.5mm to 0.7mm on the map scale for the plain and high mountain areas". Thus, based on the ability of the identification of Sentinel - 2 satellite images with a resolution of 10m can ensure the accuracy of the plane to adjust the topographic map of the scale of 1 / 25,000, because the position error is allowed in the range of 12.5 to 17.5 (meters). However, through experimental testing, there is still one point where the error exceeds the allowed threshold, this depends much on the process of image (wrapping). Because the Sentinel-2 image has a resolution of 10m, the identification of objects on the image is difficult. Therefore, for satellite imagery this data is only used to establish maps with point error at an average scale of 1: 25,000 - 1:50.000.

Do the same for deep-level error checking with 12 test points, where Δ_{zgoc}= height between contours of the map at 1: 2,000 scale/3. With height between contours at 1 (m), then Δ_{zgoc} =1/3=0.33 (m), calculated parameters are as shown in Table 3. The calculated results are then compared with the permitted altitude errors on the map, height between contours at 5 (m) then permitted altitude errors is 5/3=1.67 (m), height between contours at 10 (m) then permitted altitude errors is 10/3=3.33 (m). Experimental results show that: the average of Δ_Z is 1.25m that <1.67m. Thus, the Sentinel 2 image data and the depth calculation model such as Equation 10 can be used to establish a depth map with a height between contours of 5m. However, through the examination of each point, there are still 2 points of depth beyond the error threshold 1.67m. Therefore, to ensure accuracy, the model for calculating depth data from Sentinel-2 satellite images, we need to remove the noise caused during image acquisition, the depths involved in modeling must be large enough, and especially the depth collection points must be corrected to make sure the accuracy is as high as possible.These accuracy ranges were also examined and evaluated for sentinel 2 images on July 15, 2016 in the same area [19] and on Landsat8-OLI images in the shallow waters of Truong Sa Island - Vietnam [18].Table 3. Parameters of the depth error check

TT	**Z**	**z**	Δ_z	Δ_{zgoc}	Δ_Z	**Noted**
1	-0.5	-0.1	-0.4	0.33	0.518556	height between contours 5 m
2	-0.3	0.8	-1.1	0.33	1.148434	height between contours 5 m
3	-0.9	-1.6	0.7	0.33	0.773886	height between contours 5 m
4	-1.5	-0.9	-0.6	0.33	0.684763	height between contours 5 m
5	-3.2	-4.7	1.5	0.33	1.535871	height between contours 5 m
6	-4.7	-5.9	1.2	0.33	1.244548	height between contours 5 m
7	-5.5	-7.1	1.6	0.33	1.633677	height between contours 5 m
8	-6.9	-8.2	1.3	0.33	1.341231	height between contours 5 m
9	-9.6	-7.9	-1.7	0.33	1.731733	height between contours 10 m
10	-11.4	-9.1	-2.3	0.33	2.323553	height between contours 10 m
11	-13.6	-13.2	-0.4	0.33	0.518556	height between contours 5 m
12	-15.2	-14.6	-0.6	0.33	0.684763	height between contours 5 m

5. CONCLUSIONS

This research has important implications for the application of remote sensing techniques to the establishment of topographic maps of the shallow water regions of the Spratly Islands. The paper used the Lyzenga method of establishing depth maps from the multi-spectral satellite images Sentinel 2, checking the map data of the depth calculated by the field survey method, we find that: Using Sentinel 2 images can establish a depth map with an average scale of 1: 25,000 -1: 50,000, 5m contour, reaching a depth water of -15m for some test areas according to this approach (An Bang, Sinh Ton and Truong Sa island groups of Vietnam). The study also pointed out: Accuracy of the map depends on many factors such as the input satellite image resolution, the interference effect in the image acquisition process, the control point precision and the calculation model... The research results have solved the set objectives, as a basis for step by step research into the shallow seabed topography mapping from satellite imagery.

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REFERENCES

1. Laurent Barillé et al. (2010), "Increase in seagrass distribution at Bourgneuf Bay (France) detected by spatial remote sensing", Aquatic Botany. 92(3), tr. 185-194.
2. James F Bramante, Durairaju Kumaran Raju and S Tsai Min (2013), "Derivation of bathymetry from multispectral imagery in the highly turbid waters of Singapore's south islands: A comparative study", DigitalGlobe 8-Band Research Challenge 2010.
3. Jennifer Patch Cannizzaro and Kendall L Carder (2006), "Estimating chlorophyll a concentrations from remote-sensing reflectance in optically shallow waters", Remote Sensing of Environment. 101(1), tr. 13-24.
4. Francisco Eugenio, Javier Marcello and Javier Martin (2015), "High-resolution maps of bathymetry and benthic habitats in shallow-water environments using multispectral remote sensing imagery", IEEE Transactions on Geoscience and Remote Sensing. 53(7), tr. 3539-3549.
5. Claude Flener (2013), "Estimating deep water radiance in shallow water: Adapting optical bathymetry modelling to shallow river environments".
6. K. Fletcher (2012), "Sentinel-2 ESA's Optical High-Resolution Mission for GMES Operational Services", European Space Agency.
7. Nguyen Thi Thu Ha et al. (2016), " First Experience in Modeling Spatial Distribution of Chlorophyll-a Concentration and TSI in the West Lake Water Using Sentinel-2A Image ", VNU Journal of Science: Earth and Environmental Sciences. 32(2S).
8. John Hedley et al. (2012), "Capability of the Sentinel 2 mission for tropical coral reef mapping and coral bleaching detection", Remote Sensing of Environment. 120, tr. 145-155.
9. D.L.B Jupp (1988), "Background and Extensions to Depth of Penetration (DOP) Mapping in Shallow Coastal Waters", Proceedings of the Symposium on Remote Sensing of the Coastal Zone, Gold Coast, IV2(1)-IV2(19).

10. Jaap A Kaandorp, Maxim Filatov and Nol Chindapol (2011), "Simulating and quantifying the environmental influence on coral colony growth and form", Coral Reefs: An Ecosystem in Transition, Springer, tr. 177-185.
11. Ariyo Kanno, Yukio Koibuchi and Masahiko Isobe (2011), "Statistical combination of spatial interpolation and multispectral remote sensing for shallow water bathymetry", IEEE Geoscience and Remote Sensing Letters. 8(1), tr. 64-67.
12. Susan Kay, John D Hedley and Samantha Lavender (2009), "Sun glint correction of high and low spatial resolution images of aquatic scenes: a review of methods for visible and near-infrared wavelengths", Remote Sensing. 1(4), tr. 697-730.
13. David R Lyzenga (1978), "Passive remote sensing techniques for mapping water depth and bottom features", Applied optics. 17(3), tr. 379-383.
14. David R Lyzenga (1985), "Shallow-water bathymetry using combined lidar and passive multispectral scanner data", International Journal of Remote Sensing. 6(1), tr. 115-125.
15. David R Lyzenga, Norman P Malinas and Fred J Tanis (2006), "Multispectral bathymetry using a simple physically based algorithm", IEEE Transactions on Geoscience and Remote Sensing. 44(8), tr. 2251-2259.
16. Nguyen The Tiep et al. (2012), "Types of disasters in the Spratly Islands", Natural science and technology publishers.
17. Center for Oceanography (2016, 2017), "Tide tables - volume II", Natural science and technology publishers-Viet Nam.
18. Phan Quoc Yen et al (2017), " Research Bathymetry Mapping of Shallow Water Areas around Islands in the Truong Sa Archipelago by Deep - Remote sensing technology ", VNU Journal of Science: Earth and Environmental Science. Vol 33 No 4, p. 63-73.
19. Phan Quoc Yen and Nguyen Hieu (2017), " Removing Sun Glint from Optical Satellite Images of the Shallow Water Areas around Islands in the Spratly Islands Archipelago, Vol 34 No 2 ", VNU Journal of Science: Earth and Environmental Science. Vol 33 No 3, p. 8-98.
20. Richard P Stumpf, Kristine Holderied and Mark Sinclair (2003), "Determination of water depth with high resolution satellite imagery over variable bottom types", Limnology and Oceanography. 48(1part2), tr. 547-556.
21. Pramaditya Wicaksono (2012), "The effect of sunglint on satellite-based benthic habitat identification", International Journal of Advanced Research in Computer and Communication Engineering. 1(6), tr. 364-370.

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