# DETERMINING SHALLOW WATER BATHYMETRY BY STEREO PHOTOGRAMMETRY TECHNIQUE USING WORLDVIEW-2 IMAGERY

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**Abstract**

Bathymetry in shallow-water areas plays an important role in marine environment management, marine economic resource development, and national defense and security. The echo sounding method is currently highly accurate; however, it has to deal with a variety of challenges as a result of the high cost, terrain influence, and meteorological conditions at sea. As remote sensing technology progresses, estimating bathymetry using satellite imagery will help lower measuring costs and expand monitoring coverage, particularly in shallow water, offshore areas, and difficult-to-access areas. In this article, the authors present a technique for determining bathymetry in shallow water regions by utilizing WorldView-2 stereoscopic images. The accuracy of stereoscopic depth measurement using WorldView-2 images is assessed by field depth measurement using the single-beam echo sounder. The study area is Nam Yet Island. The coefficient of determination ($R^2$) between the two datasets (field measurement data and using satellite images) is 0.9. The stereoscopic satellite image method of depth measurement is highly accurate for regions with depths below 5 meters. The accuracy of the stereoscopic measurement decreases as the depth increases by more than 5 meters.

***Keywords:*** *Bathymetry; shallow water; stereo photogrammetry; WorldView-2 stereo images.*

## 1. Introduction

Bathymetry is the study and practice of measuring the depth of bodies of water, such as lakes, rivers, streams, and oceans, from below the surface [1]. The term "bathymetry" refers to the depth of the ocean above sea level, but it can also refer to the depth and shape of underwater terrain. A bathymetric map depicts the underwater topography using an approach similar to that of a topographic map. The deep-water contours and colors represent the topography of the underwater terrain.

Satellite images, depth echo sounding (SONAR- SOund Navigation and Ranging), and airborne LiDAR depth measurement (ALB) are a few of the methods currently available for determining the depth of the ocean. This approach, however, is not suitable

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for usage in shallow water and has big operational expenses. On the other hand, bathymetry that makes use of remote sensing data can determine large coverage, is particularly useful for offshore areas, and lowers the cost of map construction. Presently, there are two primary categories of remote sensing techniques: (1) Active remote sensing techniques, such as the LiDAR method, and (2) Passive remote sensing techniques, such as the determination of shallow water depths along offshore islands with the use of optical satellite images. Researchers are using a wide variety of data and methodologies to study the best way to create bathymetry maps in shallow waters from satellite images. According to that, there are two main methods for estimating the depth of shallow waters using satellite imagery: (1) The interpolation method applied to multispectral images, and (2) The stereoscopic measurement method.

The physical properties of radiation transfer models (RTMs) can be employed to calculate the remote sensing reflection transition model, which is applicable to parameters such as water quality, depth, and bottom reflection. In 1985, Lyzenga [2] proposed a way to use the interpolation algorithm on multispectral images to determine the water depth. The method proposed by Lyzenga [2] is considered incorrect when applied to bathymetry calculations under conditions of variable bottom reflection. Consequently, this approach is incapable of differentiating various forms of reflectance in water [3]. Stumpf et al. [4] offered a new ratio method in order to solve these problems. This method utilizes the ratio of two spectral bands to simulate changes in the reflection coefficient during depth calculations.

Stereo photogrammetry, a new method of bathymetry, has given a way for determining water depth from satellite images [5]. The stereo photogrammetry, in contrast to the interpolation method based on multispectral images, does not require atmospheric correction or field bathymetric data. However, relative orientation and geometrical conditions in water will differ from those on land because of the difference in the refractive indices of air and water. Murase et al. [6] analyzed the differential error in the horizontal direction when two different cameras measured the incident angle of light rays from an underwater point. Current high-resolution satellites like GeoEye-1 and WorldView-2 have offered a new data source that allows for the determination of shallow water depth using the stereo photogrammetry technique. Specifically, the WorldView-2 satellite supports the acquisition of stereoscopic image pairings, which guarantee uninterrupted imagery while reducing fluctuations in the surface ocean [7]. Cao et al. [8-10] studied the scientific basis and errors in determining shallow water depths using the stereoscopic measuring method on WorldView-2 images. At depths ranging from 5 to 20 meters, the results indicate a mean square error of 1.76 meters and a reasonably minor inaccuracy of approximately 14%. The greatest precision is achieved at depths ranging from 0 to 5 meters in shallow water.

Echo-sounding is the predominant technique employed for creating bathymetry maps in Vietnam. The majority of the research, which determines bathymetry by using remote sensing data, has focused on evaluating techniques for interpolating multispectral images. Yen et al. [11] and Phong et al. [12] applied the interpolated ultilizing method by Stumpf and used Landsat 8 satellite image for determining bathymetry. In 2019, Nguyen Ha Phu et al. [13] published the results of their study on stereophotogrammetry depth measurements of shadow waters at Hai Sam Island using WorldView-2 imagery. The experiment results demonstrate that the stereoscopic measurement technique can accurately determine the depth of water to an extent of 42.0 meters [13].

Consequently, there is currently limited research on determining bathymetry using the stereophotogrammetry method with satellite images. As a result, the authors present their research on the bathymetry of shallow water areas using WorldView-2 image data and the underwater stereophotography technique. The study was conducted on Nam Yet Island in Vietnam. The accuracy of the bathymetry determined by stereo photogrammetry is assessed using echo sounding data.

## 2. Study area and materials

### *2.1. Study area*

The Truong Sa Island district, located in Khanh Hoa province, Vietnam, was formed using the Truong Sa Islands' tiny coral islands, sand dunes, reefs, and shoals as its foundation (Fig. 1a).

The study area is Nam Yet Island. Nam Yet Island is an atoll within the Truong Sa Archipelago. This island is approximately 11.9 nautical miles (22 km) from south of Ba Binh Island and 18 nautical miles (33.3 km) from north of Sinh Ton Island. Nam Yet Island is located at 10°10′45″N 114°22′0″E.

Figures 1b and 1c illustrate that Nam Yet Island is situated within a sizable atoll. The Nam Yet’s inner surface (facing toward the sea) is gentle and shallow, whereas the outer surface (south) is extremely precipitous and deep. The Nam Yet area is approximately 3.75 $km^2$. The Nam Yet Island region is mostly affected by the tides at Truong Sa Station. The magnitude (tide amplitude) is influenced by the law of diurnal tides, which results in a substantial increase and decrease in the water level during the high tide months of January, June, July, and December. During the low tide months of March, April, September, and October, the water level experiences fluctuations and the tidal properties are diminished. In fact, in deep-water regions, the transparency of the sea water is visible for up to 30 meters. The transparency of the seawater has substantially decreased at a depth of 15-20 meters in the shadow water area. Salinity is generally consistent, despite its fluctuation with depth and season.

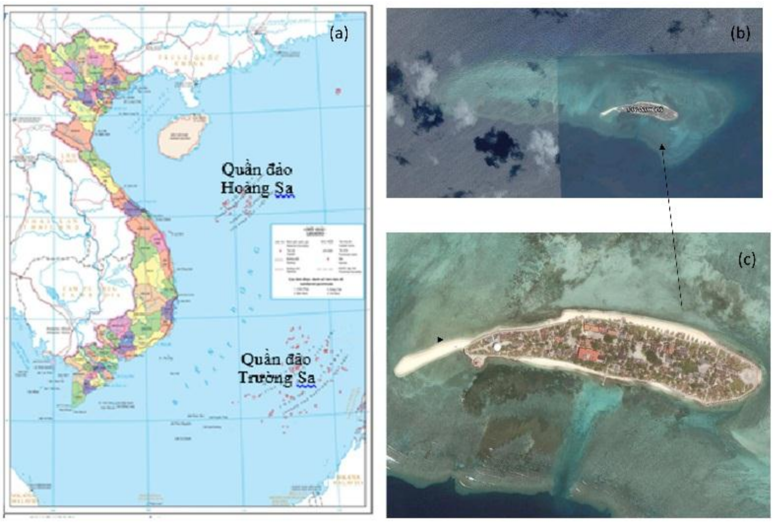


*Fig.1. The study area: (a) Location of the study area (a red rectange); (b); and (c) Nam Yet island in WorldView-2 satellite image.*

### *2.2. Material data and pre-processing*

The satellite image data used in the article is a pair of WorldView-2 stereoscopic images with image characteristics shown in Table 1.

*Table 1. The characteristics of material data*

| **Parameters** | **WorldView-2 satellite images** |
|---|---|
| Name of image 1 | AOI_46_1 |
| Image acquisition | PAN-17APR29025611-P2AS-057202905070_01_P001<br>MS-17APR29025611-M2AS-057202905070_01_P001 |
| Resolution | PAN: 0.5 m; MS: 2.0 m |
| Image acquistion time | 29/04/2017 |
| Name of image 2 | AOI_46_2 |
| Image acquisition | PAN-17APR29025747-P2AS-057202905070_01_P001<br>MS-17APR29025747-M2AS-057202905070_01_P001 |
| Resolution | PAN: 0.5 m; MS: 2.0 m |
| Image acquistion time | 29/04/2017 |

### *2.3. Field measurement data*

Figure 2 shows field measurement data, including 24 data points. The depth of field data was acquired with a Global Navigation Satellite System (GNSS) satellite positioning device, namely Real-Time Kinematic (RTK), in conjunction with a Hidrobox single-beam echo sounder. The depth data is adjusted in accordance with the map reference system and the elevation of the fixed points on the island. The coordinate system is computed and transformed into the VN2000 system, with a projection zone of 6 degrees and a central longitude of $111^o$. The field measurement data is utilized to evaluate the precision of depth points obtained through the stereophotography method.

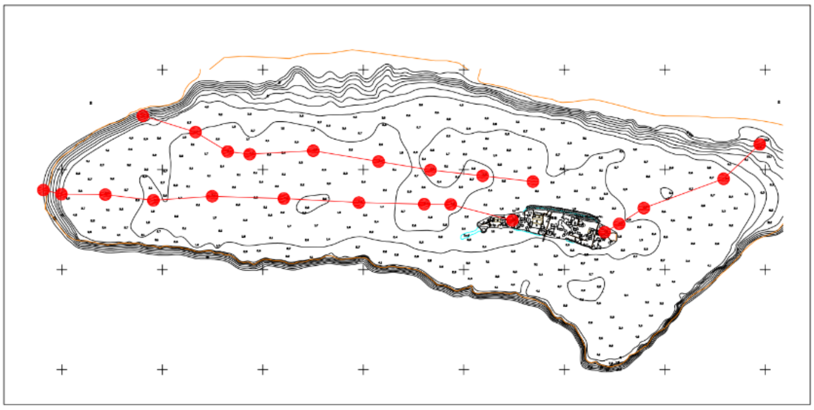

*Fig. 2. The location of the field measurement points.*

## 3. Methodology

### *3.1. The determination of bathymetry using stereoscopic satellite images*

By utilizing sterephophotogrammetry, the spatial coordinates of an object in three dimensions can be ascertained. In principle, measuring stereoscopic images underwater is not dissimilar from measuring them on land; the major difference, however, is the effect of water refraction on the optical parameters.

Two sensors at positions S1 and S2 detect incident and refracted rays produced by object P at the interface of two tie points P1 and P2, as illustrated in Figure 3a. Point A, which is the intersection of two projection vectors coming from the tie point, is quantified in the measurement of stereoscopic images. Point P represents the target's actual coordinate value. Snell's law of refraction is complied with by light rays as they traverse two distinct satellites. Typically, a refractive index of 1.34 is used to represent the angle of refraction. Temperature and salinity conditions in the seawater can cause the refraction value to fluctuate by as little as 1%.

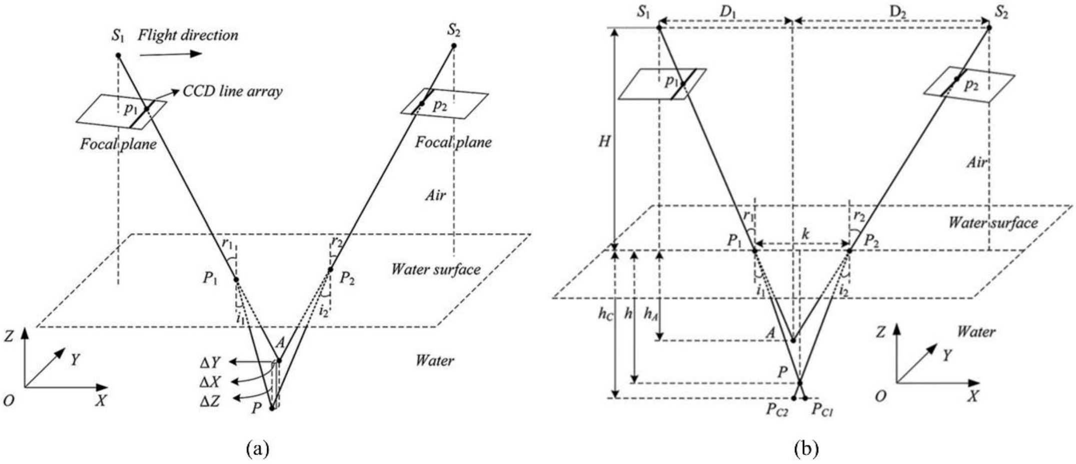


*Fig. 3. (a) Geometric condition of stereo photogrammetry using the satellite images underwater; (b) Geometric condition of stereo photogrammetry using the satellite images underwater with condition D1 unequal D2* [8].

Figure 3b illustrates the difference in horizontal and vertical coordinates between observation point A and true depth point P. The difference of the X value between the actual point P and the point A that is being observed is calculated using the following equation:

$$\Delta X = X_A - X_P = \frac{\tan i_2 \cdot \tan r_1 - \tan i_1 \cdot \tan r_2}{\tan i_1 + \tan i_2} \cdot h_A \tag{1}$$

where $i_1$ và $i_2$ are the incident angles from underwater point P to satellite sensors S1 and S2, respectively; $r_1$, $r_2$ are the corresponding refraction angles; $h_A$ is the observed depth.

In this study, $\Delta X$ is not a significant factor in aerial or satellite photogrammetry. Moreover, as the geometric relationships also indicate, the horizontal differences ($\Delta X$ và $\Delta Y$) between A and P are negligible. The approximate refractive correction model was limited to compensating for vertical deviation in stereometry in previous studies [8]. Fryer and Kniest [14] proved that the geometric parameters of the aerial triangulation have a significant impact on the precision with which stereometry can measure depth. Using the left-hand image as a reference, we can calculate the true water depth $h$ in Fig. 3b as follows:

$$h = \frac{h_A \cdot \left(\tan r_1 + \tan r_2\right)}{\tan\left[\sin^{-1}\left(\sin r_1 / n\right)\right]} \tag{2}$$

### *3.2. The errors in bathymetry measurement by the stereo photogrammetry method using satellite images*

The horizontal direction error, which is caused by the approximate refraction correction model, is shown in Eq. (1). Because of the high flight altitude and limited field of view of sensors, the horizontal direction error computed using Eq. (1) is significantly smaller than that of aerial photography. As a result, it is possible to ignore the horizontal direction error in Eq. (1) that is caused by the approximation model's refraction correction.

Errors in geometric models, relative underwater orientation, ocean waves, and surface ocean elevation are the four most significant factors affecting the precision of water depth, which is determined by stereoscopic methods. Besides, in stereophotogrammetry, relative orientation is a critical factor that is directly proportional to the input image's coordinates. Sun reflection, depth, water turbidity, bottom sediment types, image matching algorithms, and the cumulative error for image matching are all elements that impact relative orientation error underwater.

### *3.3. Determining bathymetry by stereo photogrammetry using WorldView-2 images*

The procedure for measuring bathymetry in shallow water by stereophotometry using WorldView-2 satellite images is shown in Fig. 4.

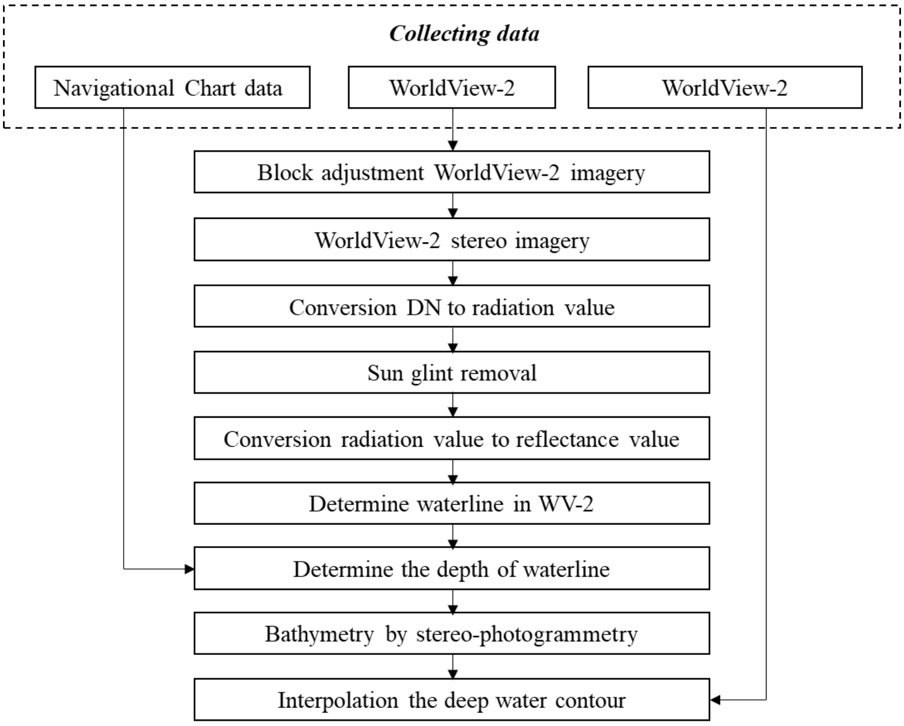


*Fig. 4. Flow chart of bathymetry measurement using stereophotogrammetry.*

## 4. Result and discussion

Topographic surveying will be conducted on an image station using the specialized software ERDAS LPS Automated Terrain Extraction. Hydrological elements, topography and boundaries are among the features of a topographic map that require measurement using the photogrammetry method. The deep-water contour is a representation of bathymetry. The interval elevation of the deep-water contour is 2 m.

*Table 2. The difference in the depth of the check points*

| No. | $H_{TD}$ (m) Field data | $H_{LT}$ (m) Stereo-scopic | $H_{TD} - H_{LT}$ (m) | No. | $H_{TD}$ (m) Field data | $H_{LT}$ (m) Stereo-scopic | $H_{TD} - H_{LT}$ (m) |
|---|---|---|---|---|---|---|---|
| 1 | 1.50 | 1.5 | 0.00 | 13 | -1.70 | -2.0 | +0.30 |
| 2 | -1.62 | -2.8 | +1.18 | 14 | -1.45 | -2.4 | +0.95 |
| 3 | -1.58 | -2.9 | +1.32 | 15 | -1.45 | -2.3 | +0.85 |
| 4 | -1.79 | -1.8 | +0.01 | 16 | -1.46 | -2.3 | +0.84 |
| 5 | -1.53 | -2.4 | +0.87 | 17 | -1.51 | -2.3 | +0.79 |
| 6 | -1.52 | -2.1 | +0.58 | 18 | -1.50 | -2.5 | +1.00 |
| 7 | -1.57 | -2.0 | +0.43 | 19 | -11.5 | -15.0 | +3.50 |
| 8 | -1.50 | -2.6 | +1.10 | 20 | 1.60 | 1.5 | +0.10 |
| 9 | -7.50 | -5.0 | -2.50 | 21 | -1.98 | -2.1 | +0.12 |
| 10 | -23.50 | -20.5 | -3.00 | 22 | -1.55 | -2.7 | +1.15 |
| 11 | -1.34 | -2.2 | +0.86 | 23 | -1.50 | -3.1 | +1.60 |
| 12 | -1.83 | -2.9 | +1.07 | 24 | -11.5 | -17.5 | +6.00 |

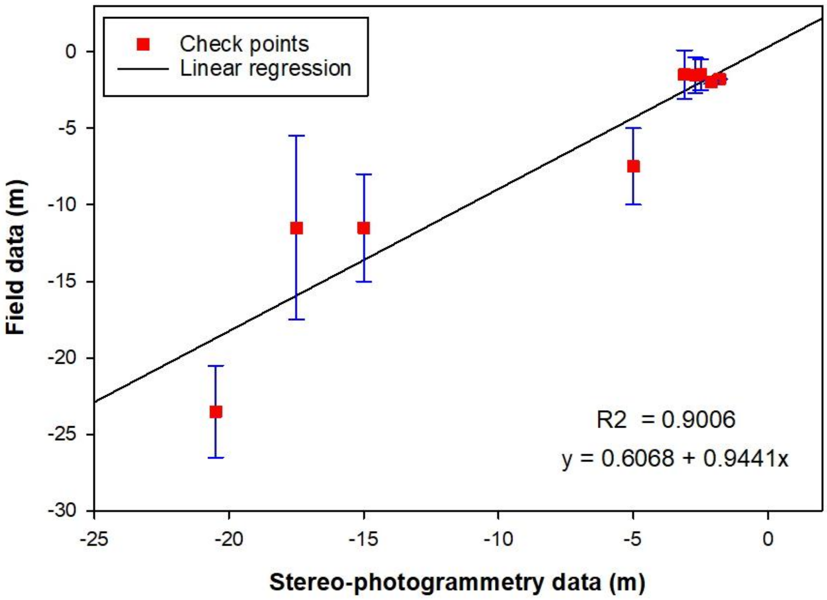


*Fig. 5. Assessing the correlation between depth using the stereoscopic method and field measurements.*

The accuracy of bathymetry determined by stereo photogrammetry is assessed using 24 field data points, as detailed in Table 2. The checkpoint arrangement encircled Nam Yet Island and covered the entire coral reef (Fig. 2). In this article, we used the coefficient of determination $R^2$ to evaluate the precision of depth values, which are determined by the single-beam echo sounder method and the stereo photogrammetry method. Fig. 5 illustrates that the $R^2$ value between the two data sets was 0.9006. Hence, it is evident that the field measurement value correlates highly with the depth measurement value obtained using stereophotogrammetry. Figure 5 illustrates the deviation between the stereoscopic measurement point and the field measurement point. The results indicate that the difference between the two sets of values is negligible for points with depths below 5 meters. With increasing depth, the deviation becomes larger. At depths ranging from 10 to 15 meters, the greatest deviation value occurs (Fig. 5).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(y_i - y_i'\right)^2}{N}} \tag{3}$$

where $y_i$ is the $i^{\text{th}}$ depth of field data; $y_i'$ is the corresponding the depth by stereophotography value; $N$ is the number checkpoints.

The root mean square error (RMSE) is the standard deviation of the residuals between two data sets, as determined by Eq. (3). The RMSE is ±0.877 m for regions with a depth of less than 5 m. The RMSE is ±3.984 m for regions with depths exceeding 5 m. Therefore, the determination of depth from stereophotography will result in larger errors as the depth increases due to the influence of light refraction and bottom reflection.

## 5. Conclusion

The results indicate that the accuracy of the method of determining bathymetry in the shallow waters of the Nam Yet Island area is guaranteed by the use of WorldWiew-2 stereoscopic satellite images. The accuracy of the stereoscopic depth measurement results on WorldView-2 satellite images is assessed using single-beam echo sounder depth measurement points. The coefficient of determination $R^2$ between the two data sets, as determined by the stereophotogrammetry method and field measurements, reached 0.9.

Additionally, the RMSE value for areas with depths less than 5 m is ±0.877 m, while for areas with depths greater than 5 m, it is ±3.984 m. For depths below 5 meters, the results indicate that the stereophotogrammetry method produces minimal depth measurement errors. The error in measuring depth using the stereoscopic method increases as the depth increases. In areas larger than 10 m, the stereoscopic depth measurement and the single-beam echo depth measurement methods have the highest difference.

Nevertheless, it is imperative to further refine the approach and eliminate the consequences of inaccuracies when employing stereoscopic measurements of satellite images at sea to determine bathymetry. To assess the applicability of the stereoscopic depth measurement method in the East Sea region, it is also necessary to evaluate the accuracy at various depth levels and in different bottom regions.

## Acknowledgements

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# NGHIÊN CỨU XÁC ĐỊNH ĐỘ SÂU ĐÁY BIỂN KHU VỰC NƯỚC NÔNG BẰNG KỸ THUẬT ĐO LẬP THỂ SỬ DỤNG ẢNH WORLDVIEW-2

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**Tóm tắt:** Độ sâu vùng nước nông có vai trò quan trọng trong quản lý môi trường biển, phát triển tài nguyên kinh tế biển và quốc phòng, an ninh. Hiện nay, phương pháp đo sâu hồi âm cho độ chính xác cao. Tuy nhiên, phương pháp đo sâu hồi âm có chi phí cao, chịu ảnh hưởng của địa hình và điều kiện khí tượng trên biển. Với sự phát triển của công nghệ viễn thám, việc ước tính độ sâu bằng hình ảnh vệ tinh sẽ giúp giảm chi phí đo đạc và mở rộng phạm vi giám sát, đặc biệt ở vùng nước nông, khu vực ngoài khơi và các khu vực khó tiếp cận. Trong bài báo này, các tác giả trình bày phương pháp xác định độ sâu ở vùng nước nông sử dụng ảnh lập thể vệ tinh WorldView-2. Độ chính xác của phương pháp đo độ sâu lập thể bằng ảnh vệ tinh WorldView-2 được đánh giá dựa trên các điểm đo độ sâu bằng máy đo sâu hồi âm đơn tia. Khu vực nghiên cứu là đảo Nam Yết. Hệ số xác định ($R^2$) giữa hai bộ dữ liệu (dữ liệu đo đạc thực địa và phương pháp đo ảnh) là 0,9. Phương pháp đo độ sâu bằng ảnh vệ tinh lập thể có độ chính xác cao đối với những vùng có độ sâu dưới 5 m. Độ chính xác của phương pháp đo lập thể giảm dần khi độ sâu tăng hơn 5 m.

***Từ khóa***: *Địa hình đáy biển; vùng nước nông; đo ảnh lập thể; ảnh lập thể vệ tinh WorldView-2.*

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