Implementation of the algorithm of spectral analysis of waves in bathymetry of coastal waters of Oman Sea

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Abstract

Understanding the characteristics of the seabed and ocean plays a crucial role in coastal management and engineering, exploration of coastal resources, navigation, research on tides and biodiversity, planning for the construction of marine structures and aquaculture. Mapping of shallow coastal areas is necessary to protect the ship in the navigation area. Remote sensing techniques can be an alternative method to reduce the cost of seabed hydrography. Synthetic Aperture Radar (SAR) images are active remote sensing images that are not sensitive to climatic conditions and are able to provide two-dimensional images of the sea surface with global coverage.

This research was conducted by implementing the algorithm of the spectral analysis of swell waves on Sentinel-1 satellite images from coastal waters of Oman Sea, and bathymetry map of the coastal areas was prepared. This method is based on the breaking and changes in the wavelength of swell waves in coastal waters and can measure depth in waters with medium depth. Two-dimensional Fourier analysis was used to determine the wavelength of long waves, and the accuracy of wave peak calculation was increased by applying a frequency filter. Two methods were used to extract the periodicity of swell waves.

After the statistical comparison of the results with the field data, the bathymetry accuracy was 1.125 m, the mean absolute error was 0.811, the mean relative error was 5.051%, and the correlation was 0.853, which confirms the suitability of this method in coastal waters.

Keywords: bathymetry, radar images, spectral analysis, swell waves, Oman coasts.

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Introduction

Water resources have always been considered as one of the vital issues of human life. Meanwhile, coastal areas of seas and lakes have always been considered as the most important sources of water for various needs. These areas are more in contact with human factors, and most human exploitations and applications are related to these areas. At the same time, these sources are highly important for the surrounding areas from the environmental, tourism, economic, political, etc. aspects [1, 2]. Surveying the geographical and geometric features of coastal areas is the first and important step for planning, exploiting, and protecting these natural resources. The depth of water and its physical characteristics in these areas can play a vital role for many applications and projects [3].

Estimating the depth of coastal waters using remote sensing satellite images plays an important role in the management and optimal use of marine natural resources and the first step for planning and protecting them [4, 5]. In the past decades, thanks to image data with suitable spectral, spatial, and temporal characteristics, the use of satellite bathymetric methods in shallow areas has increased [6]. Direct measurements of water depth and physical parameters using direct methods in coastal areas are very costly and relatively time-consuming [7]. Therefore, remote sensing will be a very suitable solution for many research and engineering projects in coastal areas due to its high capability in collecting information in a short time and in a wide geographical area. This subject is of particular importance in a country like Iran, which has a vast expanse of water [8].

In general, there are four methods for bathymetry of shallow coastal areas using remote sensing technologies. The first method is bathymetry using multispectral and hyperspectral images, which is based on the volume (energy) of returning waves in different parts of the electromagnetic spectrum of the water column and its changes due to the water depth (including water surface, water column, and seabed). In practice, the reflectivity of electromagnetic waves depends on the quality of the water column and the type of bed, so the bathymetry method using spectral images has some challenges to determine the depth of turbid and muddy waters [10]. The fact that most of the studies in this field have been conducted in very clear tropical waters is a proof of this claim. The second method is spectral analysis of waves using visible images, which is based on refraction of waves and inferential investigation of the relationship between water depth, wavelength, and angular frequency of waves in shallow waters. The main advantage of this method is not needing to have a certain depth and other environmental parameters, so it can be considered an effective and practical method. The third method of bathymetry is using the changes in the intensity of radar images. This method requires one or more synthetic aperture radar (SAR) images and a limited number of reference depths as input, and bathymetry can be performed in lines 5 to 10 times the traditional hydrographic bathymetry [11]. The fourth method is the spectral analysis of swell waves using radar images, which, due to the low permeability of microwave waves into water, has the ability to depict the unevenness of the water surface [12]. This method is based on the fact that SAR images are able to depict the long waves of the ocean and the linear dispersion relation between their wavelength and depth. The present study will show that this method can be used for bathymetry with desirable precision in Iranian coasts [13].

One of the challenges related to coastal management is understanding the amount of erosion and its impact on coastlines and seabed roughness. Therefore, coastal management needs fast and cost-effective methods for permanent coastal monitoring. Because the conventional methods of coastal mapping and with ultrasonic techniques are very time-consuming and expensive, and therefore cannot meet the need for continuous monitoring. On the other hand, remote sensing data and especially Roman satellite images with high spatial and radiometric resolution are a suitable solution for collecting information in short time intervals. In the coastal areas of Oman, the existing sea currents have caused continuous changes in the depth of these areas, and therefore, the preparation of periodic hydrographic maps of the coastal strip in short intervals is one of the challenges faced by researchers in this field.

Research objective

Field bathymetry projects are very costly because they require specialized individuals and vessels and equipment such as single-beam or multibeam echosounder, side scan sonar receiver, differential global positioning system (DGPS) and motion sensor. Also, climatic phenomena, such as storms, and human phenomena, such as dredging, make it necessary to update sea charts and hydrographic operations. The output of this research is the bathymetry of coastal waters, which can be used for low-cost studies, and of course in shallow areas, and the main focus of such research is to investigate the geomorphological structure of the seabed and its changes, or to provide a general zoning of water depth changes for management purposes for the optimal management and exploitation of marine natural resources and it is the first step to plan and protect these resources.

Bathymetry using radar images by swell waves pattern

Another way to determine the bathymetry of the seabed is to observe the pattern of swell waves on the surface of the sea when the shore is approached. This method is based on the fact [14] that SAR images are able to depict long ocean waves and the linear dispersion relation expresses the relationship between their wavelength and depth. The reason for the physical limitations of this method is that the bathymetry range of this method has an upper limit and a lower limit of bathymetry. If the wave moves in the deep part, the wavelength loses its dependence on the depth and so-called wave does not touch the bed. Therefore, bathymetry cannot be performed in this area. When the depth of the seabed is equal to half of the wavelength of the swell waves, these waves touch the bed and it can be assumed as the upper limit of bathymetry [15].

The lower limit of bathymetry is caused by the wave approaching to the surf zone, because in this zone the height of the wave increases until the wave breaks and becomes asymmetric. According to Paul Kachowski and Lehter [6], linear analysis for bathymetry is possible up to a minimum depth of 10 m. Jian et al. [7] developed a new method to calculate wave parameters, including wavelength, wave height, and wave propagation direction, and based on this method, surface waves are divided into two types in terms of wind speed.

First, the wind speed is calculated for each pixel. If the speed is above 6 m/s, waves caused by wind are called Wind Waves, and if the speed is less than 6 m/s, it is classified as swell wave, and due to the difference in their degree of non-linearity, a different algorithm was used for each of them to extract wave parameters, including wavelength, wave height, and propagation direction. The studied area was the coastal areas of Japan and the used 1-ERS and 2-ERS images were VV polarized C-band, which finally calculated the wave height with a bias of 0.09 m and a standard deviation of 0.61 m. Paska Joski et al. [37] performed bathymetry by simultaneous application of Tera SAR-X radar images and QuickBird satellite images. For depths between 100 and 10 m, SAR images were used, and for depths less than 20 m, QuickBird was used, and for depth between 10 and 20 m, both were used. For depths between 20 and 60 m, the accuracy of bathymetry was 15%. Salisios et al. [39] performed bathymetry using Al ALSAR band images on the coastal areas of Naples Bay, Italy, and the calculated depths were consistent with the official Italian sea charts.

Ranga et al. [34] performed bathymetry using COSMO-SkyMed images on the shores of the Gulf of Naples. In this research, an accuracy of 3.1 m was obtained at a depth between 5 and 50 m. Bayan et al. [41] conducted bathymetry in the shallow coastal waters with a depth of less than 10 m using SAR images and the linear dispersion relation. The mean absolute error of the extracted depth was 0.86 m and the mean relative error was calculated, and the study area was Fujian and Miapu provinces of China. Prosh et al. [42] used Terma SAR-X images and linear dispersion relation and wave tracking technique for bathymetry of the deep part to the shore of Port Phillip, which an error of less than 5 m was obtained for 72.2 cases, and an error of less than 7 m was reached for 89.2% of the cases.

Methodology

The research method in the present work is bathymetry using synthetic aperture radar (SAR) images based on the refraction of surface convective waves when propagating towards the coast. Due to the fact that a direct relationship can be established between the propagation pattern of swell waves and the water depth, as a result, unlike the tidal current method, the water depth can be calculated absolutely. In this method, any image can be used for bathymetry as long as there are swell waves at the time of image acquisition. We selected this method for bathymetry. The limitation of this method is that it cannot provide measurements with high spatial resolution for replacing the traditional hydrographic operation. However, this method is a powerful tool for evaluating the need to update sea charts. With thousands of kilometers of coastline, Iran needs to develop a technique that prioritizes which areas need to update sea charts in order to save time and money. From a military point of view, this technique can provide us with basic depth information that can be used for naval maneuvers in strategic and sensitive areas where there is no accurate access to depth information.

Area of study

Due to the arrival of swell waves from the Arabian Sea and the Indian Ocean, Oman Sea is used as the area for bathymetry using the spectral pattern of swell waves. For this reason, the study area was chosen near the Port of Oman, Port of Oman is one of the cities of the Hormozgan province, which is surrounded by coastal waters on three sides and it is a peninsula. The city is connected to the Gulf of Oman from both the east and west sides and is connected to the military areas from the northeast. This position has made the appearance of the city longitudinal and limited its width. The length of the coasts of Hormozgan province is 2,238 km, which made this province have the longest water border in the country, and Oman city, as the widest city in the province, has 320 km of coast and is near the Oman Sea and 320 km east of Bandar Abbas as the capital of Hormozgan province. The coasts of Makran and Oman overlook open waters and the Indian Ocean, and this space has played a minor role in national, transnational and even regional decisions so far.

Plans and projects have been established in line with the development of the coast of Makran, such as the creation of Oman's energy zone and its transformation into the energy hub of the Middle East, the project of transferring natural gas through a pipeline to Oman, construction of crude oil and gas storage tanks, construction of refineries, petrochemical complexes, and the construction of a power plant, construction of Oman airport, the development of road and rail transportation along the coast (Bandar Abbas-Jask-Chabahar) the establishment of Iran-China industrial estate in Oman and the creation of Jask Free Zone. The port of Oman has high investment potentials and capacities due to being located in the north-south grid connected to the internal road (Bandar Abbas-Chabahar-Jiroft) having the shortest sea distance with Muscat-Oman, the infrastructure of the commercial and passenger activities with the country of Oman has the possibility of developing marine and recreational tourism services with 320 km of coastline. As a result, it is very important to have reliable and up-to-date information about the depth of Oman's coasts.

Choosing the right SAR image

Nowadays, radar images have many applications. Due to the high spatial and temporal resolution, the ability to pass through the cloud, as well as the fact that some products are free, radar images can be easily accessed and each user can perform the necessary processing depending on his needs. One of the main applications of Radar images is to extract water environments, including seas, rivers, flooded areas, and surface waters in general.

Due to the freeness of Sentinel-1 images, a good spatial resolution of 10 m, and a calculation time of 12 days, these images were used for bathymetry based on the spectral pattern of swell waves.

Due to the advantages of synthetic aperture radar (SAR) images, these images were used. Sentinell takes images in the C band with a frequency of 405.5 GHz. The imaging method of this device is different modes, including Interferometric Wide Swath Mode, which is the mode that is taken by default in dry areas. Wave Mode is used to identify the direction of the wave length and height of the wave in the ocean and sea. The Extra Wide Swath Mode is used for the regions of the ocean covered with ice, which requires wide coverage, and the way of imaging is very similar to Interferometric Wide Swath Mode. The last mode is Stripmap Mode, which has a spatial resolution of 5 m with a sampling width of 80 km. The figure below shows the types of image sampling modes in this system.

The data are corrected by the ellipsoidal model of earth and reduced by transforming the speckle noise coordinates. These images are a continuous image in each polarization that only shows the intensity or amplitude. SLC images are taken at the level of coordinates, and no model for ellipsoidal model correction has been applied to them. Unlike the GRD category, each pixel of this image has an imaginary value of intensity and phase.

Swell waves are modulated on the SAR image domain, as a result it is enough for bathymetry based on the spectral pattern of swell waves, and we do not need image phase information. Therefore, GRDH images of polarization 77 were used for bathymetry.

To choose the calculated image for the bathymetry, the condition of the swell waves and the wind at the moment of imaging should be taken into account, as mentioned in the previous chapter [47]. As a result, image was selected on August 17, and the specifications of the image are listed in Table 1. Also, Figure 1 shows the 1-Sentinel image used

Table 1: Characteristics of the selected SAR image

Image id	Date	class
S1A-IWGRDH-1SSV-20150817T141607-20150817T141607-20150817T141636	2015-8-17	SENTINEL-1 Interferometric WideSwath Level-1 Product

Figure 1: Sentinel-1 image taken on 08-17-2015, which was used for bathymetry, and the studied point is marked with a red box

According to the 5-ERA wind and wave model belonging to the European Center for Medium-Range Weather Forecasts (ECMWF), the height of the waves caused by the local wind at the 7th moment of imaging in the studied area is 0.2395 m. Figure 33 shows the height of waves caused by local wind at the moment of imaging in the studied area, while the height of waves caused by swell waves at the moment of imaging is 0.6284 m. Thus, the swell waves dominated the waves caused by local wind at the moment of imaging. Figure 4-3 shows the height of swell waves at the moment of imaging in the studied area. Also, the wind speed at the moment of imaging in Oman is 4.9 m/s, and hence, the spectral information of swell waves can be extracted from the image. The swell waves are visually distinct in the form of clear light and dark lines on the image, which is shown in Fig .

3.3. **Hydrographic data**

In this research, a map or a scale of 1/5000 of the coastal depth of Oman port was used to evaluate the accuracy of the estimated depths. The measured depths are relative to the datum chart, so the water level correction must be applied to the depths. Based on this, the data collected by a tide gauge located in the port of Oman has been used to check the changes in the water level and convert the water height to the average water level, which Table 2 shows the tidal information of the tide gauge. Finally, a 30 x 68 grid of bathymetry points with a distance of 80 meters from each other was selected, which covers the coast of Oman from a depth of 10 m to 25 m. Figure 2 shows the distribution of the points on the image.

Table 2: Tidal information of measurement datum

Place	Lat N	Long E	Heights in metres Above datum				
			ML	MHWS	MHWN	MHWNN	MHWS
JASK	25.39	27.39	1.8	2.8	2.2	1.5	0.9

Spectral analysis and calculation of wavelength and propagation direction of swell waves

Before performing spectral analysis, the speckle noise of the image should be reduced. Speckle noise is a point disturbance that is usually modeled as multiplicative noise in monopolarized images. This noise, which is dependent on the signal, is caused by the phase fluctuations of the return signals of electromagnetic waves, appearing as dots. The presence of speckle complicates the interpretation and analysis of the image and reduces the access to image information. Therefore, the selection of the speckle noise reduction algorithm is important. A 5 x 5 median filter was used to remove the speckle noise. Then, a window of 128 x 128 pixels is selected at each bathymetry point and spectral analysis is performed in that window. For more stable detection, the wavelength peak and its propagation direction peak are applied in a 3 x 3 dimensional space to reduce noise, and then the peak wavelength and its propagation direction are calculated. Figure - shows the spectral analysis performed in one window.

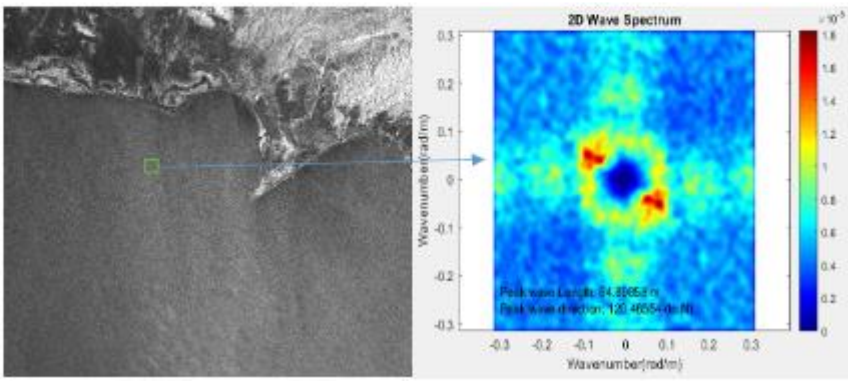

Figure 2: Spectral analysis performed in a window and calculation of peak wavelength and propagation direction

In order to accurately calculate the peak, we must choose a filter for the wavelength and the direction of wave propagation. The minimum and maximum wavelength and its propagation direction are determined according to the linear dispersion relation and the periodicity of swell waves in the bathymetry region. Also, the difference in the direction of wave propagation between two consecutive windows should not exceed 15 degrees.

By performing spectral analysis at all points, a maximum grade of wavelength and propagation direction is obtained. To remove noise from this matrix, a 5 x 5 median filter is applied on this matrix and also a 20 pixel median filter is applied in each row to eliminate possible noises. The figure shows the map resulting from the calculation of the wavelength on the bathymetry points. To calculate the wave peak in the spectral space, the values of the wavelength range in the frequency filter were determined from 40 to 78 m and the wave propagation direction range from 125 to 155 degrees.

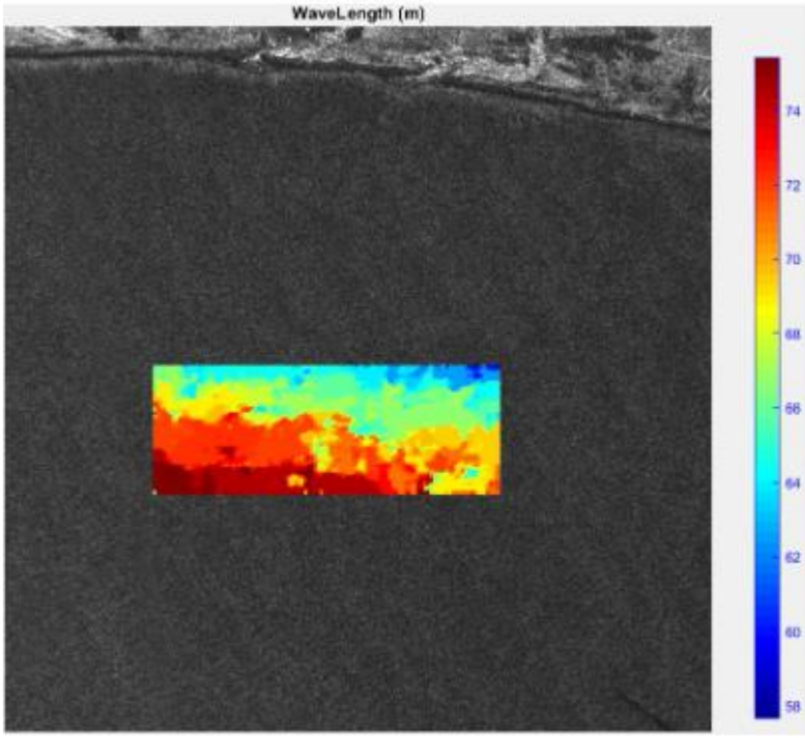

Figure 3: Swell waves' wavelength map in the bathymetry region

Bathymetry using the linear dispersion relation

In order to estimate the depth or use the linear dispersion relation, we need to know the periodicity of the swell waves in the bathymetry region at the moment of imaging. In this research, we extracted the periodicity of swell waves using two methods, and we compared these methods in terms of bathymetry accuracy.

- **Extracting periodicity using the global wave model ERA-5**

The European Center for Medium-Range Weather Forecasts (ECMWF) has provided researchers with almost up-to-date meteorological data, the error rate of which is negligible compared to the data of ground stations in many parts of the world. Thus, these data can be used along with the ground data or even as a substitute for the observation data in the areas without station. The quality and validity of these data for various parts of the world have been controlled by various methods such as coordination with the results of complex atmospheric models.

The latest re-analyzed model of the ECMWF is ERA-5, which replaced the EAR-Interm model. This model provides atmospheric parameters and waves on an hourly basis.

By extracting the periodicity and propagation direction of swell waves in the Oman area from the ERA-5 model, these values were used in the linear dispersion relation. Figure 4 shows the swell wave periodicity in Oman area at the moment of imaging from ER-5-5 model, and Figure 5 shows the direction of swell waves propagation in Oman area at the moment of imaging from ERA-5 model.

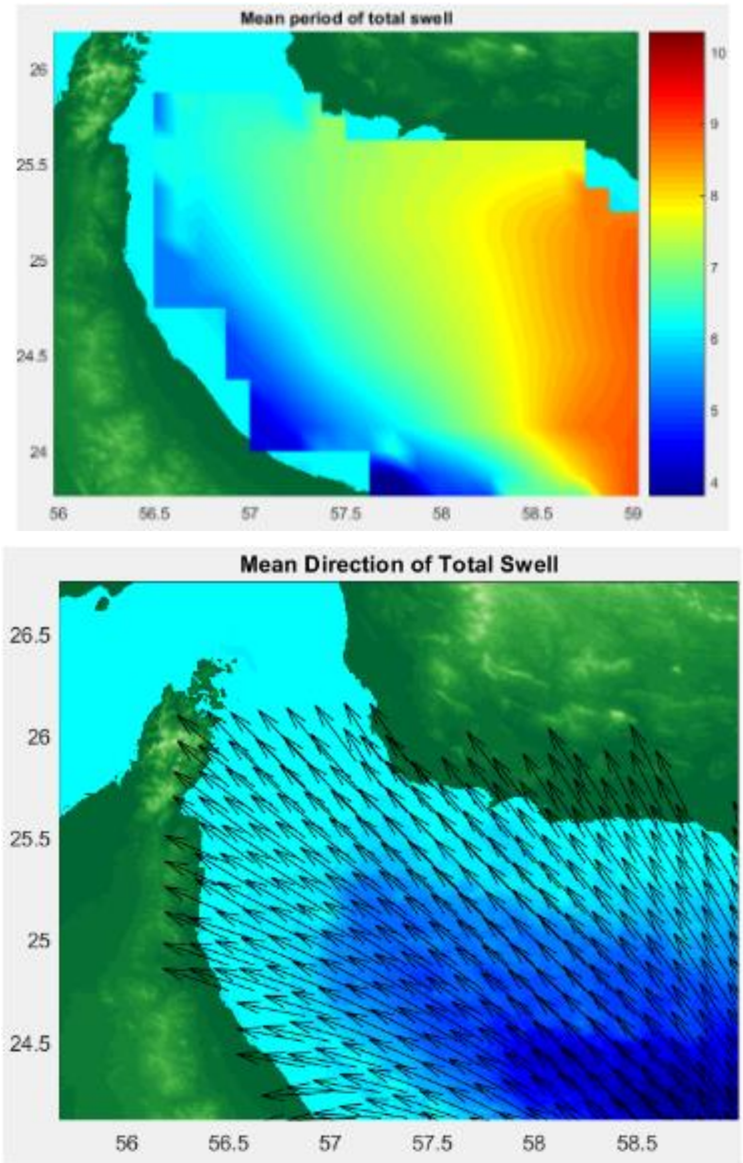

Figure 4: The direction of swell waves propagation in Oman area at the moment of imaging from the ERA-5 model

According to the 5-RA model, the periodicity of swell waves in the bathymetry region is 7.1 seconds and its propagation direction is 137 degrees. According to these parameters, bathymetry was carried out in this area. Figure 3-12 presents the bathymetry map resulting from the spectral analysis method using ERA-5 model and Figure 3-13 shows the bathymetry map resulting from field data, and Figure 6 presents the error section resulting from the depth estimation in using the ERA-5 model compared to the bathymetry data.

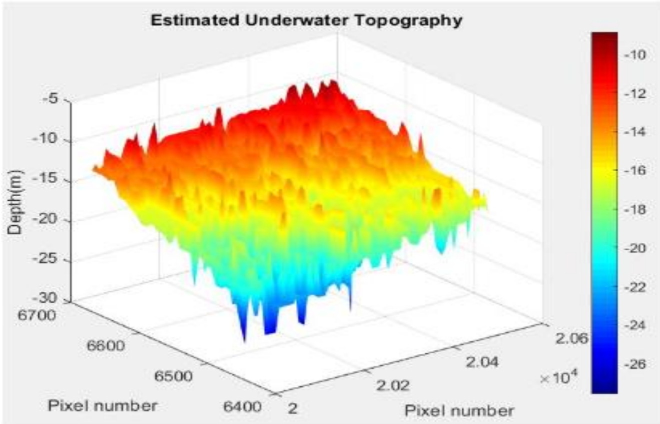

Figure 5: Bathymetry map obtained from the spectral analysis of swell waves using the ERA-5 model

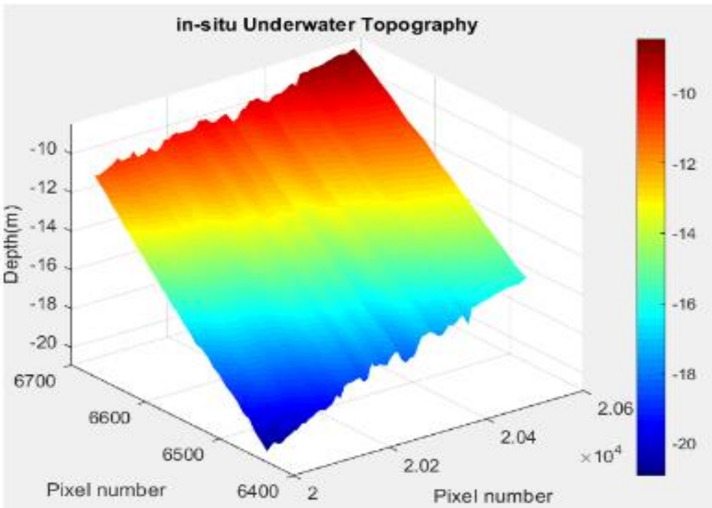

Figure 6: Bathymetry map obtained from the field data

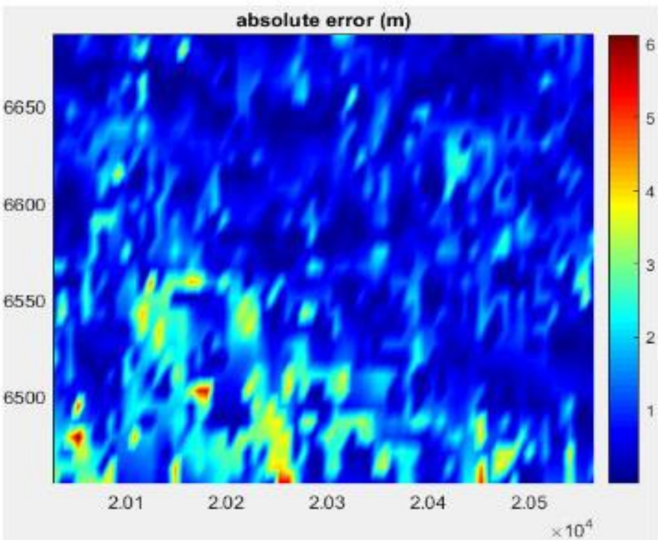

Figure 7: The map of error distribution resulting from depth estimation using ERA-5 model compared to bathymetry data

- **Evaluation of the accuracy of the spectral analysis of swell wave using the ERA-5 model**

After bathymetry using the spectral analysis of swell waves using the ERA-5 model, statistical analysis of the results of the bathymetry with respect to the field data was carried out, which is shown in Table 3.

Table 3: Statistical analysis of bathymetric results using ERA-5 model

Bathymetry limits				Statistical parameters
10 – 25 m	20 - 25 m	15 - 20 m	10 - 15 m	
0.992	1.722	1.125	0.688	Mean absolute error
6.05%	8.209%	6.399%	5.211%	Mean relative error
1.361	2.049	1.518	0.921	RMSE

By analyzing the correlation between the depth of the bathymetry points and the depth of the field data, the R-squared index was calculated as 0.799, and Diagram 1 shows this correlation.

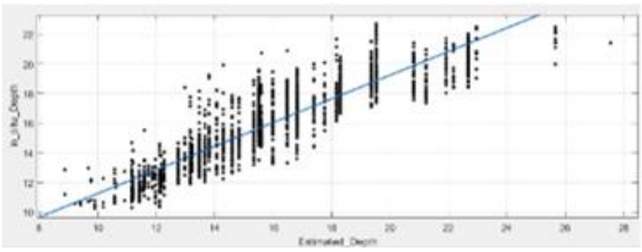

Figure 8: shows this correlation

Extraction of periodicity using spectral analysis of swell waves in deep water range

In the deep water range, the minimum periodicity of swell waves can be calculated by calculating the wavelength or using the relation . Then, at a point with a known depth, we measure the depth by using the obtained periodicity, and by increasing the periodicity value, we reduce the depth error at that point to a minimum, in this way, we will reach the exact value of the periodicity. Thus, it was calculated as 7.232 seconds and the propagation direction of swell waves was obtained as 140 degrees. According to these parameters, bathymetry was done in this area. Figure – shows bathymetry map obtained from the spectral analysis of swell waves using the spectral analysis of swell waves in the deep water area, Figure – shows the bathymetry map obtained from field data, and Figure – shows error section map resulting from the bathymetry in the spectral analysis of swell waves in the deep water range compared to the depth data.

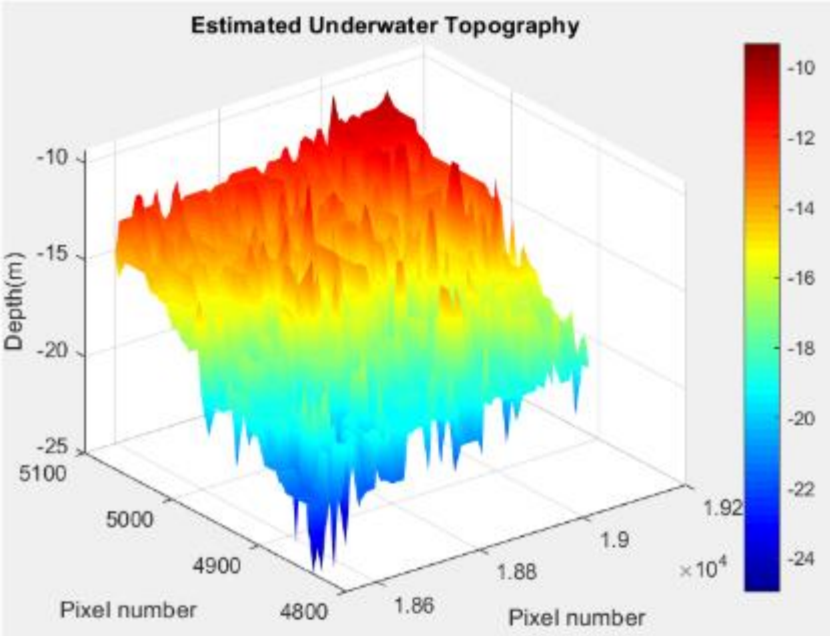

Figure9: Bathymetry map resulting from the spectral analysis of swell waves using the spectral analysis of swell waves in the deep water range

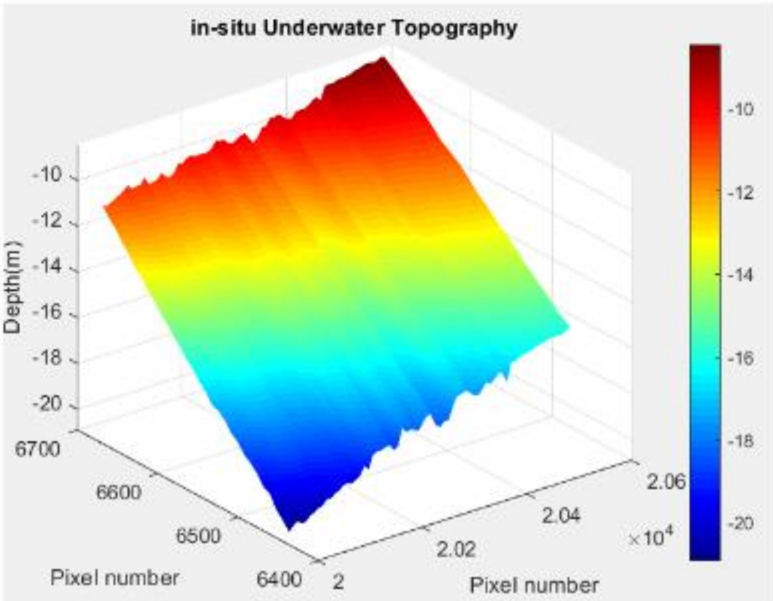

Figure 10: bathymetry map obtained from field data

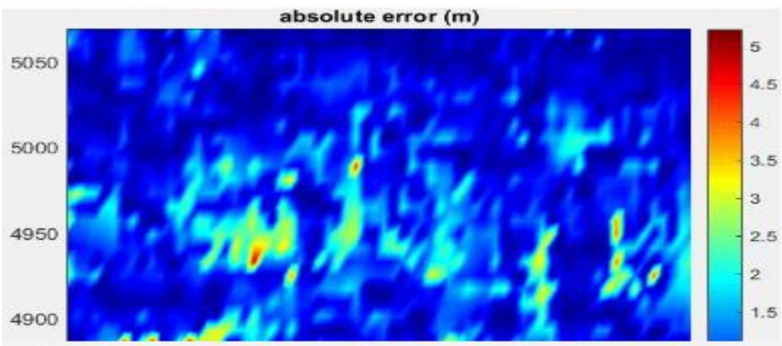

Figure 11: Error distribution map resulting from the depth estimation in the spectral analysis of swell waves in the deep water range compared to the depth data

Evaluation of the accuracy of the spectral analysis of swell waves in deep water

After the bathymetry by the spectral analysis of swell waves using spectral analysis of the swell waves, statistical analysis of the results of bathymetry was carried out compared to the field data, which is shown in Table 3.

Table 4: Statistical evaluation of bathymetric results using the analysis of swell waves in deep water

Bathymetry limits				Statistical parameters
10 – 25 m	20 - 25 m	15 - 20 m	10 - 15 m	
0.811	1.128	0.934	0.594	Mean absolute error
5.051%	5.4%	5.477%	4.432%	Mean relative error
1.125	1.444	1.268	0.819	RMSE

By analyzing the correlation between the depth of the bathymetric points and the depth of the field, the R-squared index was calculated as 0.82, which Graph - shows this correlation.

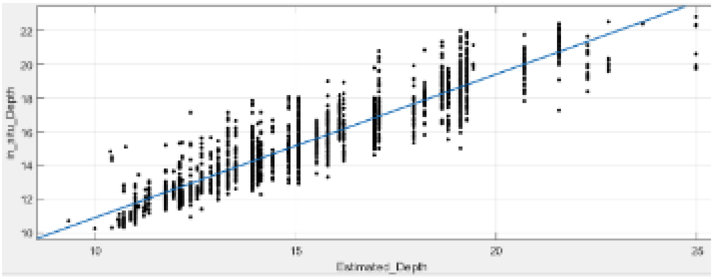

Figure 12: Analysis diagram of correlation between the depth of bathymetry points and depth of field

Conclusion

In this research, after stating the challenges and goals and reviewing the previous studies on remote sensing methods in extracting depth or using satellite images, the way of bathymetry of coastal areas was discussed by analyzing the propagation pattern of swell waves in radar images. Then, it was tried to perform the spectral analysis algorithm of swell waves on 1-Sentinel satellite images. On the coasts of the Oman Sea, a bathymetry map of the coastal areas was prepared. This method is based on the breaking and changes in the wavelength of swell waves in the coastal waters, and it has the ability of bathymetry in waters of medium depth. Linear dispersion relation in medium-depth waters establishes the relationship between the depth of the wavelength and the periodicity of the swell waves. Two-dimensional Fourier analysis was used to calculate the wavelength of swell waves, and by applying a frequency filter, the accuracy of wave peak calculation increased. Two methods were used to extract the periodicity of swell waves. In the first method, by using the 5-RA global wave model, the periodicity of the swell wave and the its propagation direction at the moment of imaging were obtained and used for bathymetry. It is 0.799. The second method of extracting the periodicity was performed using the spectral analysis of long waves in the deep water range. After the statistical comparison of the results with the field data, the bathymetry accuracy was obtained as 1.361 and its correlation was 0.799. The second method was the extraction of periodicity using spectral analysis of swell waves in deep water range. After comparing the statistical results with the field data, the bathymetry accuracy was obtained as 1.125 and its correlation was 0.853. Using spectral analysis of swell waves in the deep water range to estimate the periodicity improved the bathymetric accuracy compared to extracting the periodicity from the ERA-5 global wave model in the range of 10 to 25 m and a percentage improvement in the range 20 to 25 m. The reason for the further improvement in the deep area is the greater sensitivity of the linear dispersion relation with respect to the wavelength and the periodicity at greater depths, which Diagrams 13-33 and 23 show it. Consequently, the SAR images of the Sentinel 1-satellite, are able to identify the reduction in wavelength and breaking of swell waves and bathymetry in the depth range of 10 to 25 m.

It is suggested to calculate the periodicity of the waves in the bathymetry area using the oscilloscope buoy, because the presence of the oscilloscope buoy in the area to measure the periodicity of swell waves can improve the bathymetry accuracy.

It is recommended that by modeling the waves in the bathymetric area using hydrodynamic models, a comparison should be made on the improvement of the use of local models compared to global models.

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