Underwater topography detection of Shuangzi Reefs with SAR images acquired in different time

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Abstract

Imaging mechanism of underwater topography by SAR and a underwater topography SAR detection model built on the theory of underwater topography detection with SAR image presented by Yuan Ye are used to detect the underwater topography of Shuangzi Reefs in the Nansha Islands with three scenes of SAR images acquired in different time. Detection results of three SAR images are compared with the chart topography and the detection errors are analyzed. Underwater topography detection experiments of Shuangzi Reefs show that the detection model is practicable. The detection results indicate that SAR images acquired in different time also can be used to detect the underwater topography and the detection results are affected by the ocean conditions in the SAR acquir ing time.

Key words: Shuangzi Reefs, underwater topography, SAR image, topography detection

1 Introduction

Synthetic aperture radar (SAR) is one of the advanced microwave remote sensors of environment and resource. It can observe targets in all weathers and all day and night in a multi-band, multi-polarization and multi-look angle mode. SAR has been used in many observations and researches of the ocean since American Seasat-1 equipped the SAR was launched in 1978 such as internal waves, ocean waves, ships and submarines, sea ices, oil spill and underwater topography. Underwater topography detection with SAR image is one of important applications of SAR. Since De Loor found firstly shallow underwater topography on X-band airborne real aperture radar imagery, many scientists have studied the SAR imaging mechanism and detection model of shallow underwater topography. Alpers and Hennings (1984) presented a simple theoretical model named AH-model of the SAR imaging mechanism of underwater bottom topography in which the topography-tidal current interaction was described by a one-dimensional continuity equation and the current-wave interaction was described by
weak hydrodynamic interaction theory. But the AH-model is one-dimensional and is too simple in many conditions. Yuan (1997) presented an analytical representation of the high frequency spectra of ocean waves which were derived from the wave number spectrum balance equation and built the theoretical basis of shallow underwater topography detection with SAR images. Ma and Zhang (2001) simulated SAR image of underwater topography and analyzed the differences of simulated SAR images in different water depths and in different gradients of underwater topography. In addition, Huang and Zhou (2000) applied the AH-model to study the underwater topography detection capability of SAR images. Jin Meibing (1997a, b) and Jin et al. (1998) utilized the underwater topography detection model presented by Yuan Yeli in practical application researches of underwater topography detection with SAR images. Zhou et al. (1999) and Jin and Zhang (2000) also studied the underwater bottom topography detection with SAR images.

In this paper we detected the underwater topography of Shuangzi Reefs in the Nansha Islands with three scenes of SAR images which were acquired in different time. In this process we used underwater topography simulation and detection models which are built on the SAR imaging mechanism of underwater topography and the damped Newton - row action method. Furthermore, we compared detection results and analyzed errors as well as the reasons for these errors. Detection results show that the detection model and the algorithm of underwater topography are feasible. Detection experiments realize the underwater topography detection of the same area with SAR images acquired in different time and prepare for practical detections of underwater topography of Nansha Islands with SAR images.

2 Detection mechanism of underwater bottom topography with SAR images

2.1 SAR imaging mechanism

SAR can penetrate into seawater only to a depth on the order of centimeter so SAR can not observe underwater topography directly. That underwater topography can be observed by the SAR is because underwater topography modulates radar backscattering of sea surface and the SAR measures radar backscattering of sea surface. It is well known that the main SAR imaging mechanism of underwater topography is hydrodynamic modulation of the short-scale ocean waves by tidal current which flows over underwater topography. This mechanism includes three physical processes: Interaction of the tidal current with underwater topography induces varieties of sea surface currents; short-scale ocean waves are modified by the sea surface current; varieties of short-scale ocean waves induce varieties of radar backscattering.

According to the SAR imaging mechanism of underwater topography detection of underwater topography with SAR images includes two parts: SAR image simulation of underwater topography and detection of underwater topography with SAR images.

2.2 Model and algorithm of simulation and detection of underwater topography with SAR images

A model of simulation of underwater topography with SAR images includes two parts: calculating the tidal current field with the hydrodynamic model and calculating the gray value of simulating SAR images with the tidal current field. The hydrodynamic model used to calculate the tidal current is the Princeton ocean model POM. Gray value expression of simulation SAR images was introduced by Yuan (1997). An algorithm of simulation of underwater topography
with SAR images is to calculate the tidal current field with the program of POM which introduces $\sigma$ coordinate and Arakawa-C gridding then to calculate the gray value of simulated SAR images with the tidal current field.

The model of detection of underwater topography with SAR images is composed of the shallow water hydrodynamic model and the function expression of radar gray value \cite{Jin and Zhang, 1998}. The algorithm of detection of underwater topography with SAR images is the damped Newton-row action method \cite{Cui et al., 2003}. This method has been testified to be highly efficient, reliable and steady by simulated data.

3 Underwater topography detection of Shuangzi Reefs with SAR images acquired in different time

3.1 Data of underwater topography detection experiments

Three scenes of SAR images are used in underwater topography detection experiments with SAR images. They are ERS-1 SAR image acquired on 19 November 1993, RADARSAT SAR image acquired on 4 June 1998, shorted for RADARSAT1998 SAR, and RADARSAT SAR image acquired on 12 June 2003, shorted for RADARSAT2003 SAR. Original SAR images of Shuangzi Reefs in these three SAR images are showed in Fig. 1.

3.2 Preprocessing of SAR images

Three SAR images of Shuangzi Reefs should be preprocessed before they are used in the underwater topography detection. The preprocessor of SAR images includes the following steps:

1. Geometric correction of SAR images according to geographical coordinates of four corners of SAR images given in the header files of SAR data;
2. Antenna pattern correction of SAR images to eliminate differences of SAR images caused by side-looking of SAR;
3. Calculation of backscattering cross-section of SAR images with correlative parameters of SAR and the satellite;
4. 3 $\times$ 3 pixels averaging processing of backscattering cross-section of SAR images; the resolution of SAR image is much larger than that of detection calculation’s gridding, so we need to reduce the resolution of SAR image, this process can also filter the speckle noise.

![Fig. 1. ERS - left, RADARSAT1998 middle, and RADARSAT2003 right SAR image in Shuangzi Reefs.](image)

3.3 Underwater topography detection of Shuangzi reefs with SAR images

Geographical location of the underwater topography detection of Shuangzi Reefs is $11^\circ 21' \sim 11^\circ 30'N, 114^\circ 16' \sim 114^\circ 26'E$. Gridding introduced
into the detection experiment is 0.02' × 0.02' about 30.74 m × 30.74 m and the number of gridding is 501 × 451.

First tide and tidal current were calculated numerically by the POM and the tidal current field obtained in this calculation was used to obtain the simulated SAR image of underwater topography. The gridding of POM used in this calculation is 0.3' × 0.3'. Tidal current components u and v were inputted to Eq. 1 (Yuan, 1997) to calculate the simulated SAR image of underwater topography of Shuangzi reefs:

\[ G(u,v) = \tan^{-1}(u/v) + \frac{1}{2} \ln \left( \frac{1 + \frac{u}{v}}{1 - \frac{u}{v}} \right) \]

where \( \theta_i \) is the angle of sea surface wind direction, \( \theta_s \) is the direction of sea surface short wave, \( \theta_m \) is the direction of sea surface main wave. \( u, v \) is the tidal current. \( \zeta_{sp} \) is the function of \( \theta_{sp} \) and \( u, v \) (Yuan, 1997).

After the simulated SAR image of Shuangzi Reefs was obtained backscatter cross-sections of three SAR images which were used in the underwater topography detection of Shuangzi Reefs were obtained by Eq. 2 (Jin et al., 1998):

\[ G_{SAR} = \frac{S_{o0}}{S_{o0}} \sigma_0 - \sigma_{om} + G_n \]

where \( \sigma_0 \) is the backscatter coefficient of SAR image; \( G \) is the gray value of the simulated SAR image; \( S_{o0} \) and \( S_{o0} \) are the standard deviation of \( G \) and \( \sigma_0 \); and \( G_n \) and \( \sigma_{om} \) are the average of \( G \) and \( \sigma_0 \).

Second the underwater topography of Shuangzi Reefs was detected by three SAR images with the underwater topography SAR image detection model (Jin et al., 1998) and the damped Newton - row action method (Cui et al., 2003). The initial speed of tidal current inputted into the detection calculation is the speed of tidal current in the SAR imaging time which is obtained by the calculation of POM. The open boundary condition is to input water level in the SAR imaging time. An initial water depth is obtained by interpolation with the coarse - gridding actual water depth. The wind direction of sea surface in the SAR imaging time is obtained by the maximum correlation coefficient of SAR image with simulated SAR image. Underwater topography detection results of three scenes of the SAR images are shown in Fig. 2.

![Fig. 2. Contours of water depth obtained by ERS-1 left, RADARSAT1998 middle, and RADARSAT2003 right SAR images.](image)

### 4 Analysis of detection results

Detection results of underwater topography by three scenes of SAR images are analyzed by comparisons between the water depth obtained by the SAR image detection and the real water depth. Average absolute errors and average relative errors are calcu-
lated. The range of water depth detected by the SAR images is about 2 ~ 60 m, so the detection results in the gridding points where the water depth is in the range of 2 ~ 60 m are analyzed.

4.1 Analysis of the detection result of ERS-1 SAR image

Detection result of ERS-1 SAR image is shown on the left of Fig. 2. Contours of the whole area of islands and reefs are clear and four islands and reefs are visible. Varieties of water depth in the middle area of islands and reefs are small and accord with the real status. All of these are consistent with observation results of SAR images with eyes and these show that the detection results are good. To compare the detected water depth and the real water depth, we can obtain that the average absolute error is 4.36 m and the average relative error is 17%. One small section paralleling with the latitude line shown in Fig. 3 is selected to testify the reliability of model and algorithm of underwater topography detection with SAR images. The comparison of the detection result with the real water depth in this section is shown in Fig. 4. In order to testify further the detection model and the algorithm are good, the detection results in the range of 2 ~ 20 m are compared because the varieties of water depth in the range of 2 ~ 20 m are obvious. The comparison is shown in Fig. 6a. In this figure, one can see that the detection result of water depth is consistent with the real water depth.

![Fig. 4. Comparison of the real water depth and the detection result of ERS-1 SAR image.](image)

4.2 Analysis of the detection result of RADAR-SAT 1998 SAR image

Detection result of RADARSAT1998 SAR image is shown in the middle of Fig. 2. Contours of islands and reefs are visible and the trend of varieties of water depths from islands and reefs to the middle area is also visible. But varieties of detection results of water depths relative to initial water depths are equal and small. The detection results of RADARSAT1998 SAR image are not good relative to ERS-1 SAR image and this is because ocean conditions in the RADARSAT1998 SAR imaging time are not good. It is known that good ocean conditions of SAR detecting water depth are that the tidal current is changing from the minimum to the maximum or form the maximum to the minimum and that the wind over the ocean surface is about 3 ~ 10 m/s (Huang et al., 2000). To compare the detecting water depth and the real water depth, we can obtain that the average absolute error is 4.47 m and the average relative error is 18%. The comparison of some detecting water depths with the real water depth is shown in Fig. 6b.
4.3 Analysis of the detection result of RADARSAT-2003 SAR image

Detection result of RADARSAT2003 SAR image is shown on the right of Fig. 2. Contours of islands and reefs are clear and visible and the trend of varieties of water depth around islands and reefs is also visible. Water depth in the middle of detection area changes complicatedly and equally. All these are consistent with the results obtained from the SAR image with eyes. To compare the detecting water depth with the real water depth, we can obtain that the average absolute error is 3.41 m and the average relative error is 12%. Comparison of some detecting water depths with the real water depth is shown in Fig. 6c.

Fluctuation of underwater topography is presented as bright-dark stripe in SAR images. From above analyses, one can see that the detection results of ERS-1 SAR image and RADARSAT2003 SAR image are much better than the detection result of RADARSAT1998 SAR image. This can be testified by the observation result with eyes. The main reason why errors of detection result are large is that the detection results of underwater topography with the SAR images rely much on the initial water depth. Otherwise, the ocean condition in the SAR imaging time also affects the detection result. The imaging time of two scenes of RADARSAT SAR images is June when summer monsoon is prevailing, the wind speed of sea surface is large and changes frequently and this weakens the information of underwater topography in the SAR image. The imaging time of ERS-1 SAR images is November when winter monsoon is pre-
vailing the wind speed of sea surface is small and changes little and this makes the information of underwater topography in the SAR images clears.

5 Conclusion

In this paper, three scenes of SAR images acquired in different time were used in underwater topography detection experiments of Shuangzi Reefs in the Nansha Islands. These experiments testify the practicability of model and algorithm of underwater topography detection with the SAR images in the underwater topography detection of Nansha Islands and analyze the feasibility of SAR images of the same area acquired in different time which can be used to detect the underwater topography respectively. This prepares for the practical detection of underwater topography in the Nansha Islands with the SAR images. From this paper we can draw the following conclusions:

1. Model and algorithm of underwater topography detection with the SAR images are feasible and effective in the underwater topography detection of reef region in the Nansha Islands.

2. Detection result of underwater topography with the SAR images is affected by the ocean condition in the SAR imaging time.

3. Rationality of choice of the initial water depth affects the final detection result in the detection calculation of underwater topography.

Work in this paper is the first an application of the underwater topography detection with the SAR images in the reef region and it is helpful to practical detection of underwater topography with the SAR images in the reef region in the future.

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