USE OF X-BAND RADAR FOR WAVE AND BEACH MORPHOLOGY ANALYSIS

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The present paper reports the observations of waves and beach morphology at two sites in Japan. One is the HORS Research Pier and the other is the Niigata coast where multiple shore protection structures have been installed. An X-band nautical radar system was employed for this study. Radar echo images provided instantaneous distributions of wave crests and waterlines along the shore. They were analyzed to grasp wave dynamics in shallow waters and to capture the changes of coastal features like the positions of bars and shoreline, and the foreshore slopes. The radar measurements were conducted from high to low tides or vice versa to trace the bottom profile and to estimate the foreshore slope in an intertidal range. Furthermore, the radar measurements also revealed a layout of submerged and detached breakwaters, jetties and the shoreline. It is effective for monitoring protective facilities for harbor and beach over a wide area.

1. Introduction

1.1. Purpose of study

Morphological data are the essential item to study and understand long- and short-term behavior of a sandy coast. Traditional in situ surveying like leveling and echo sounding provides precise position data at measured points. It is, however, a costly work that restricts the frequency and density of the measurements. An alternative to traditional surveying is the application of remote sensing technique. Aerial photography was the beginning of remote sensing. The basic idea, to grab a broad area of wave field and water zone as an
image, remains the same in recent remote sensing techniques using video cameras and radars, which are supported by digital technologies.

This paper describes the use of an X-band radar, or a marine radar, for mapping intertidal bathymetry over an area, i.e. alongshore distribution of shoreline positions and foreshore slopes. The methodology and accuracy of the mapping are discussed and then a seasonal change of the coastal morphology is shown to demonstrate the potential of the radar measurement.

### 1.2. Foregoing works

Observations of coastal areas with remote sensing techniques for providing spatial and temporal data at the present are made with sensing in visible light range and sounding backscatters of emitted radars.

In visible light range, use of video techniques in coastal studies has numerous outcomes (e.g.; Lippmann and Holman, 1989; Holland and Holman, 1997; Aarninkhof et al., 2003). Video cameras were mounted on a tower standing on the shore in these studies, providing slanted views, and rectifying and montage of video images from different cameras enable analyses on wave and current dynamics and morphological processes. One of the present authors has also tried to observe the dynamics of surf zones with video cameras attached to a moored balloon allowing for less slanted views (Takewaka et al., 2003). Aircraft mounted video images are also analyzed in the same sense (Piotrowski and Dugan, 2002). Video cameras can provide color images with several scenes per second at maximum rate, which enable to detect wave breaking, suspension of foams and sediments and to trace their temporal and spatial variations. One severe shortcoming is that the video cameras cannot capture images during night times and have difficulties in rainy and stormy conditions.

The X-band radar is a type of imaging radars that is capable of tracking the movements of wave crests over an area of several kilometers, and use of X-band radars in coastal studies is becoming popular in these days. Bell (1999) tried to trace motion of wave crests and to estimat wave phase speeds distributions and water depths using linear dispersion relationship. Borge and Soares (2000) estimated wave spectra of wind waves and swells at Spanish coast. Ruessink et al (2002) reported on detection of a coastal bar system using time averaged radar images. The X-band radar provides distortion-less wave field images of over a broad area with intervals of 2 to 3 seconds. The intensity of a pixel in the radar image corresponds to the relative amount of backscatter signal from the sea surface to the emitted radar beam and hence it is usable during night times and under rainy and stormy conditions. A defect of the radar system is its difficulty in detecting wave breaking state and suspended materials.

The authors regard the advantages of a radar as follows. Because severe erosion occurs under high wave condition lasting for several days usually accompanied with bad weather, use of a X-band radar system is appropriate to observe remotely and continuously the coastal processes under high wave
conditions. In this context, this paper shows an application of radar image data for intertidal foreshore morphological surveys to demonstrate the potential of the radar measurements in capturing the features of coastal morphology.

2. Observation site and experimental setup

2.1. Field of study

X-band radar measurements were conducted at the research pier HORS of the Port, Harbor and Airport Research Institute (PARI) located in Hasaki, Japan (Fig. 1). HORS is located on a 17 km long and almost straight sandy coast stretching from north to south. A 400 m pier facing the Pacific Ocean and a research building on the backshore, which is located approximately 100 m backwards from the mean shoreline position.

The other site where X-band radar measurements were conducted is the Niigata coast, Japan (Fig. 2). Multiple shore protection structures have been installed along the coast. Data were collected during calm and stormy conditions. Radar echo images were analyzed to grasp wave dynamics in shallow waters and to capture the changes of coastal features like the positions of bars and shoreline, and foreshore slopes.

For calculation and analysis of radar images, the coordinate system is employed in this study. The \( x \)-axis corresponds to the longshore extent and the \( y \)-axis is taken in the cross-shore direction, positive toward the offshore.

![Figure 1 X-band radar measurements at the research pier HORS, of Port, Harbor and Airport Research Institute located in Hasaki, Japan](image-url)
2.2. **Radar system**

The radar was installed in HORS and Niigata coast (Fig. 1 & 2). The radar employed in this study is a marine X-band radar for commercial use (JMA-3925-9 Japan Radio Co. Ltd., 3 cm wavelength, transmitting power 25 kw, HH-polarization, radar pulse length 0.08 µs), which is usually installed on a fishery or pleasure boat. The 2.8 m antenna rotates with a period of approximately 2.6 s and transmits with a beam width of 0.8° in horizontal and 25° vertical.

Backscatters or echo signals from the sea surface, so-called sea clutter, are grabbed with a specially designed AD-board with the sampling rate of 20 Mhz, installed on a Windows PC. The echo signals were sampled with 8 bits along the radial direction and then converted to a rectangular image with 1024 pixels in horizontal and 512 pixels in vertical. Each pixel corresponds to a square of 1.8 m wide, which is smaller than the theoretical spatial resolution 7.5 m of the radar system determined from the pulse length of the emitted beam. Figure 4 shows samples of radar echo image for stormy and calm conditions. The radar is located at the center of the bottom of the diagram. The horizontal extent of the image is 1,852 m, or 1 Nautical Mile (NM), and the vertical extent is 926 m. The gray images have pixel intensities between 0 and 255, with brighter pixels corresponding to points with higher signal returns. The meaning of pixel intensities is discussed in the next section.

These image samplings are done with 2 s intervals; part of the image is not renewed since the imaging intervals are shorter than the rotation time of the antenna. This may arise high frequency noises in time domain but does not affect analyses for wave motions, since they have lower dominant frequencies in time.

2.3. **Echo signals**

There are two main scattering mechanisms providing backscatters or echo signals from the sea surface as response to transmission of the radar pulses (e.g.
Skolnik, 1990). The first is the Bragg scattering from capillary roughness on sea gravity waves. Bragg scatters occurs when the length of the roughness is half of wavelength of radar beam, which is 1.5 cm in this study. The second is specular spikes that come from steep and breaking waves. In an horizontally polarized radar, or an HH-polarization radar, sea spikes cause stronger backscatter signals than the Brag scattering.

3. Measurement of wave dynamics

White pixels in the image correspond to regions where reflection or echo of the emitted radar beam was intense (Fig. 3 & 4). The white lines composed by the white pixels are known as the wave crest lines.

Figure 3. Echo images observed in the Niigata coast on 9:00 hours of 22nd January.

Figure 4. Echo images observed in the Niigata coast on 9:00 hours of 23rd January 2004.
Figure 3 and 4 show examples of echo images on the days of stormy conditions, which were observed on 22nd January 2004 and 23rd January 2004. They show that echo signals following reasonably well the passages of waves. The wave directions are from the west on 22nd January 2004 and from the northwest on 23rd January 2004. It is, however, hard to find systematic relationship between wave height and echo signal intensity. This implies that we can find location of wave crests from echo signal variation, but it is difficult to estimate the wave height of individual waves. Ziemer (1995) estimated the wave height by using the empirical equation based on the surveying data. By accumulation the surveying data, the wave dynamics can be estimated in detail.

4. Measurement of beach morphology

4.1. Time-averaged image

Individual echo images are averaged to yield a time-averaged image or the time exposure so-called by other researchers. Figure 5 shows time-averaged images of 15 minutes at a high tide and a low tide observed at HORS on 9th August 2002, which was a day of calm condition. Incident waves were small during the day and wave breaking occurred only in the vicinity of the shoreline. The vertical streak close to center of the image is the pier. Individual waves vanish in the time-averaged image and an edge line extending in the alongshore direction becomes visible. As this edge moves toward the offshore with fall of the tide level, the water line must be located in the vicinity of this edge.
An overlay of averaged ecoh image and the result of bathymetric survey conducted by others, the Niigata coast, is shown in Fig. 6. As an isoline of the contour map follows the longshore distribution of the bright pattern and beach structures in the averaged image, the high return region along the longshore direction must be a proxy of bathymetric feature, or more directly, the waterline at the period of the measurement.

4.2. Determination of shore position

As shown in Fig. 5, a horizontal edge line appearing in a time-averaged image may be related to instantaneous waterlines corresponding to a certain tide level. To explore this, pixel intensities extracted along a cross-shoreline from time-averaged images, the mean water level measured at $y = 380$ m (the root of pier is $y = 0$ m) at 6 and 10 hours, and the surveyed bottom profile are shown in Fig. 7. The location of the maximum value in pixel intensity distribution coincides to the intersection of mean water level and bottom profile. Thus, we can determine the waterlines by searching peaks in the cross-shore pixel intensity distributions.

Figure 8 shows shoreline position determined from the time-averaged images of the Niigata coast observed at a high tide and a low tide during a calm condition day of 22nd January 2004: the tidal range of the day was 0.28m. It is confirmed that the shoreline position moves offshore-wards with the fall of the tide level.
Figure 7. Pixel intensities extracted along a cross-shore line from time-averaged images of HORS during a calm condition day of 9th August 2002, mean water level measured at \( y = 380 \) m, and surveyed bottom profile.

Figure 8. Shoreline position determined from time-averaged images of the Niigata coast observed at a high tide and a low tide during a calm condition day on 22nd January 2004.
4.3. Determination of foreshore slope

Waterlines at different tide levels and intertidal foreshore slope are estimated as shown schematically in Fig. 9, where the intertidal zone refers to a region between high and low tide levels. We can determine the horizontal positions of the waterline from the radar measurement and a common vertical position estimated from direct measurement of the mean sea level. After measuring the waterline positions at different tide levels, the foreshore slope is defined here as the slope of linear regression of waterlines from high- to low-tide.

Results at two different dates, 9th August 2002 and 16th January 2003, are shown in Fig. 10 and 11 to demonstrate the potential of the radar measurements. In the autumn of 2002, a high wave condition lasted for several days resulting in extensive erosion. Figure 10 shows the bottom profiles along the pier of HORS in August 2002 and January 2003. The berm on the foreshore of August 2002 was eroded totally away and the bottom elevation decreased over 1 m at the foreshore and in the subsequent offshore part.

Shoreline positions were defined with almost the same mean water level for both August 2002 and January 2003, and the alongshore distribution of the intertidal foreshore slopes is shown in Fig. 11. Shoreline positions retreated landwards from August to January in overall. Some morphological features are preserved during this recession, however. The shoreline position of $x < -200$ m ($x = 0$ m on the pier of HORS) retreated almost uniformly due to storm events, but the shape of the coastline as well as the foreshore slopes were preserved during this recession. On the other hand, foreshore slopes of $x > 0$ m had changed in a complex manner. Some part of the foreshore has flattened and some part has steepened.
4.4. Validation of the estimation

Figure 12 shows comparisons of intertidal morphology derived from radar measurements at HORS and surveyed bottom profiles: the former was obtained during an ebb tide at 9 August 2002, from high tide (6h) to low tide (10h) as shown in Fig. 5. Solid points in the figure are positions of waterlines at different times whose horizontal locations are determined from the radar data and the vertical locations from the mean water level measured with wave gauge at the pier. The points follow reasonably well the surveyed bottom profile: the horizontal locations of waterlines vary in a wider range where the foreshore slope is relatively mild and vice versa where foreshore slope is steep.

Determination of shoreline positions using a remote sensing technique encounters the problem of correction of wave set-up, which shifts the waterline position landwards, especially at stormy high wave condition. There are
proposed formulas to predict amount of set-up at waterline positions. For this estimation, however, several data like wave period, height etc. of the incoming waves are necessary, which are sometimes difficult to measure than the mean water level or tide level. For the relaxation of this wave set-up effect, radar measurements should be conducted at a calm wave condition to determine waterline positions.

Figure 12. Pixel intensities extracted along a cross shoreline from time-averaged images of HORS during a calm condition day on 9th August 2002, mean water level measured at \( y = 380 \text{ m} \), and surveyed bottom profile.

Figure 13. Horizontal locations of shoreline observed by radar measurements and survey.
Accuracies of the estimation of waterline positions shown in Fig. 12 are summarized in Fig.13 by plotting horizontal locations of radar measurements and survey, assuming that mean water level measured at the pier meets the waterline and neglecting the effect of wave-setup. Scatter of data points is within a range of 10 m, which is almost the same of spatial resolution of radar measurements as described before.

4.5. Radar measurements applied to a beach with complex multiple structure layouts

The radar measurement technique was applied to the coast of Niigata Port. Figure 14 is an averaged image under stormy condition, which reveals a layout of submerged and detached breakwaters, jetties and the shoreline. It was effective for monitoring protective facilities for harbor and beach over a wide area. And the radar measurements were applicable during not only stormy conditions but also nighttimes. It was also observed that the shorelines of nourished beaches are located between the jetties.

5. Conclusion

An X-band nautical radar system has been employed to determine shoreline positions and intertidal foreshore slopes over an area of approximately 1.9 km in longshore at research pier HORS located in Hasaki and an area where multiple shore protection structures have been installed along the coast in the Niigata coast, Japan. An X-band radar provides instantaneous distributions of wave crests and waterlines along the shore. Ensembles of radar images in consecutive scenes yield time-averaged radar images, which were analyzed to estimate
horizontal positions of waterlines or shorelines. Simultaneously, the water surface level was measured. Radar measurements are conducted from high to low tides or vice versa to trace the bottom profile and to estimate the foreshore slope in an intertidal range. Horizontal positions of the shoreline were measured. Change of shoreline positions and intertidal foreshore slopes after an attack of high waves were shown to demonstrate the potential of the radar measurements in capturing characteristics of coastal morphology. Radar measurements are applicable during not only stormy conditions but also nighttimes. It may be a powerful tool for tracing continuously morphological features of sandy coastlines. Furthermore, the radar measurements also reveal a layout of submerged and detached breakwaters, jetties and the shoreline. It is effective for monitoring protective facilities for harbor and beach over a wide area.

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References

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