Observation of Stormy Wave Fields by X-band Radar

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X-band radar observation for the region of HORS research pier – located at Kashimanada coast – is conducted within October 2013 when three typhoons, namely 201326, 201327 and 201328, approached the area. Through FFT analyses of the radar images, variations of dominant frequencies and incident wave directions are estimated to illustrate the transition of the wave field during the storm sequence. Since the typhoons travelled quickly along the island, wave field shows drastic changes that are discussed in details.

Key Words : *X-band radar, frequency spectrum, wave field, band pass filtering*

1. INTRODUCTION

(1) Objectives

Radar images are precisely examined to calculate the dominant frequencies and incident wave directions of the stormy wave fields. For comparison, measured and predicted wave data (such as period and direction) are collected. The radar-inferred wave values are juxtaposed with them and probable reasons behind matched/mismatched data are explained.

(2) Previous studies

Decisive and pivotal are wave measurement methods when it comes to sea surface monitoring and sea-state observation, specifically during storms. Shore protection, coastal resources management, harbor management and floating structures' safety are just some examples of various cases for which a continuous estimation and understanding of the currents and waves is essential. Available wave measurement methods can be summarized into three categories: 1) Point measurement methods; 2) Optical methods and 3) Remote sensing. The focus, herein, is on the latter group: Remote sensing measurement, specifically through X-band radars. For a general understanding of the other two groups, refer to Yusheng Qi thesis¹⁾.

Nowadays, X-band radars – due to their affordability and versatility – have been increasingly used to observe and map sea surface, particularly

during harsh weather conditions. X-band radars alike high frequency (HF) radars use bragg effect to capture waves, but they implement short wavelength electromagnetic waves which interact with ripples on top of gravity waves²⁾.

Among all the established application of X-band radars, regular observation and continuous monitoring of sea/ocean state is the prevailing one, as the system can tirelessly perform for long periods during days and nights; Hasan and Takewaka³⁾, filtered X-band radar images of an on-shore area through FFT and MEM (Maximum Entropy Method) and extracted dominant frequencies, eventually calculating wavenumbers and their supposed directions. They also used linear theory for depth inversion.

2. RESEARCH SITE AND INSTRUMENTS

(1) HORS pier

HORS, the 400 meter research pier of the Port and Airport Research Institute (PARI), is located in Kamisu, Hasaki, Japan. A research building is located nearly 108 m backward from the mean shoreline position. The almost straight sandy coast of the region covers approximately 17 km between Choshi Fishery Port (south) and Kashima Port (north). The pier is distanced about 4 km from Kashima Port (**Fig.1**).

Fig.1 Aerial view of the pier (top); radar image example, wave angle definition and position of the 512 pixels chosen for Fourier analysis (bottom).

(2) Radar system

The implemented radar system is a none-coherent nautical X-band radar. Installed on the roof of the research building, the 2.8 m antenna is 17 m above the mean sea level. Each antenna's rotation takes just under 2.5 seconds which transmits with a beam width of 0.8° horizontally and 25.0° vertically. Echo signals from the sea surface, called sea clutters, are captured with a specially designed A/D board installed on a computer⁴⁾.

(3) Radar images

Radar images, sampled every two seconds, are gray-scale with 512 vertical and 1024 horizontal pixels, covering an area of 2778 and 5556 m in cross-and long-shore directions, respectively. Each pixel is a square of 5.4 m side. The gray images have pixel intensity from 0 to 255 with brighter pixels corresponding to stronger backscatter. Wave field angle definition used in this study is illustrated in **Fig.1**.

3. STORMS AND WEATHER CONDITION

In October 2013 the region experienced three major typhoons with associated numbers; 201326, 201327 and 201328. The first typhoon reached the region on October 16th, and the other two were close

Fig.2 Track of typhoons and location of HORS, circled numbers represent each typhoon's location on that day.

Fig.3 Measured wave heights at Kashima (NOWPHAS).

to the area on 26th. **Fig.2** depicts the typhoons' tracks and position of the research pier. Wave height variation at Kashima is also presented by NOWPHAS (**Fig.3**).

4. ANALYSIS

(1) Wave frequency spectrum and filtering

In this article, Fast Fourier Transform (FFT) is applied on various sequences of 128 radar images, during days from 15th to 26th of October 2013, to calculate wave frequency spectrum and subsequently extract the dominant wave frequencies. Intensity variation of a specific pixel over the sequence of images ascribes to backscattering strength changes and therefore wave-height fluctuation. A horizontal line of 512 pixels is selected (**Fig.1**, bottom panel). Each pixel intensity variation, for the described 128 sequence of images, provides a temporal time series on which FFT analysis is performed and, afterwards, averaged spectrum is computed.

Computed frequency spectrums differ in type; some demonstrate one dominant frequency while some others show two or more (**Fig.4**). Knowing the prevailing frequencies of pixel intensity variation, the images are then filtered for those specific frequencies and band-pass-filtered images are processed to determine the incident wave directions of the dominant waves.

(2) Wave periods (frequencies)

Not all the suspected dominant frequencies stand for real wave fields, as there are occasional

Fig.4 Frequency spectrum for 2013 Oct. 21,00h and 23,17h

Fig.6 Frequency spectrum for 2013 October 16,02h.

Fig.5 From top to bottom: original image of 2013 Oct. 23, 17h, and relevant filtered images for first, second and third dominant wave fields with their calculated direction and period in degree and second, respectively.

Fig.7 From top to bottom: original image of 2013 Oct. 16, 02h, and relevant filtered images for first, second and third dominant wave fields with their calculated direction and period in degree and second, respectively.

misinterpretations for tracking some noise effects – including rain – instead of true wave patterns; for this reason, filtered image sequences of all the probably-major frequencies are produced and visually verified.

For instance, the frequency spectrum of Fig.4 includes 5 local peaks whose filtered image sequences are then evaluated for possible wave fields: subsequently, circled frequencies numbered 1 to 3 are verified for three wave fields with respective periods of 12.80, 10.67 and 16.00 seconds (displayed in Fig.5) while the others root from noise effect. For October 16th 02h, that experienced the closest

typhoon to the region, the frequency spectrum contains great power for a very low frequency (Fig.6) which stems from rain noise in the images. The frequency values, numbered 1 to 3, correspond to real wave fields whose band-pass-filtered images are presented in Fig.7.

(3) Wave directions

As shoaling process changes the wave direction, the waves have to be studied far enough from the shore to estimate the correct propagation angle. The radar covers up to 2.7 km off-shore and the wave

Fig.8 Variation of incident wave directions: radar estimation, JMA prediction and NOPHAS measurement

Fig.9 Variation of wave periods: radar estimation, JMA prediction and NOPHAS measurement

directions are calculated at the farthest place from the shoreline. But still, in some cases, shoaling seems to have an effect on the result. Bright white curves in the band-pass-filtered images (Fig.5 and 7) denote the wave crests extent. Thus, choosing the uppermost part of each filtered image, the area with almost 23 m depth, a line is manually adjusted to a wave crest and its angle is regarded as the wave direction.

5. RESULTS AND DISCUSSION

(1) Wave directions

From 15th to 27th of October 2013, radar images of the study area were collected; yet, unfortunately, due to power failure, an important portion of data from early hours of 16th to midday 19th was lost. The available data is carefully analyzed and prevailing wave frequencies with their directions are estimated.

Figure 8 depicts JMA (Japan Meteorological Agency; wave forecast data for every 6 hours), NOWPHAS (Kashima port observed data of every two hours) and radar-derived wave directions (analyzed for selected available hours). As mentioned before, the frequency spectrum of every sequence of X-band radar images might include one, two or more major frequencies. The calculated angles

for the most prevailing wave frequency are shown by the 1st-Direction series in Fig.8. Attributed angles for the other dominant frequencies, if exist, are called as 2nd-Direction and 3rd-Direction – according to their relative importance in the frequency spectrum.

It should be borne in mind that JMA uses a mesh grid to simulate the waves' characteristics on an extensive area and the chosen grid here, positioned at 35° 51' 00" N, 140° 48' 00" E with a water depth around 30 m, is close to the pier's location but more off-shore. It also implements NOWPHAS data during the prediction process. The presented data for NOWPHAS is measured by in-situ instruments near Kashima port, at 35° 53' 46" N, 140° 45' 32" E with approximately 24 m water depth, which is distanced around 6 km from our site northward. Looking at the incident wave directions (Fig.8), no reasonable judgment can be made over probable shoaling effect on differences between radar, JMA and NOWPHAS results; as if it could, because JMA and NOWPHAS stand for deeper water, would have resulted in greater angles for them in comparison to our estimation. But, as Fig.8 illustrates, in some cases our estimation exceeds theirs.

Some features complicate the inspection of wave directions: 1) Having two or more dominant waves with totally-different directions; 2) Existence of

Fig.10 An example of band-pass-filtered image with wave direction ambiguity. (2013 Oct. 24, 04h, second dominant wave field with period of 9.48 s).

dominant wave fields with short wavelength which are commonly short-crested; 3) Wave directions which are running almost normal ashore.

Having these aspects in mind, the whole period is divided into 5 periods (**Fig.8**). From a field of multiple waves, both JMA and NOWPHAS condense the data into one direction and period at each time, whereas we extract the prominent waves. In case of having, at least, two wave fields with great difference in their directions, the super-positioning of the waves in JMA/NOWPHAS data might have noticeable effect.

Period 1 and 2 involve similar angles for the 1st and 2nd dominant wave directions, whose attributed periods are close. Thus, the judgment on overall direction is rather simple and the decreasing trend is alike to JMA and NOWPHAS data. On the other hand, period 3 and 5 involve many hours during which two fundamentally-different wave directions exist. As **Fig.8** implies, a plausible combination of these directions would reasonably match the JMA or NOWPHAS data. Yet, we cannot simply replace them with their average as there are other directions involved to build the overall pattern.

The waves with longer length, contrary to shorter waves, have a relatively broad continuous crest (long-crested waves) which is clearly distinguishable on the band-pass-filtered images. It makes it easy to attribute them with a specific propagation angle. Furthermore, it is almost-impossibly difficult to measure the correct direction for wave patterns which are not only short-crested but also seem to be normal to the shoreline. In such cases, filtered images include many narrow striped swathes that each one's assumed angle looks different (**Fig.10**). Such ambiguity can create substantial uncertainty in angle measurement: the whole period 4, for example, suffers from this uncertainty.

(2) Wave periods

Figure 9 demonstrates estimated wave periods versus predicted and measured data. The naming rule, for the period series like 1st-Period, is the same as wave direction comparison. At the first glance,

disagreement of some data at the beginning and the end is remarkable. The data is separated into 3 periods: A, B and C. The pivotal difference, herein, is their proximity to the arrival time of the two typhoons. Thus, great changes with unstable wave fields for the periods nearer to 16th and 26th (period A & C) at the expense of well-lasting wave patterns for the other (period B), are expected.

Period A and C include significantly-differed estimation for the 1st and 2nd dominant periods; as the time gets closer to 26th (typhoon occurrence), the gap become more tangible. In the beginning and middle of period C, the 1st or 2nd dominant wave pattern well matches the JMA. During period B, the 1st and 2nd dominant wave periods are close together and tantamount to JMA predictions – mostly between 9 and 12 seconds.

Nonetheless, some estimated wave periods, in order of 15 to 18 seconds, do not accord with either JMA or NOWPHAS; these frequencies are correctly extracted from relevant radar images and do exist. Yet, we have no idea to explain this contradiction.

6. Conclusion

The inspected stormy condition would definitely deter a comprehensive observation by traditional methods, since the cost would be prohibitive. Land-based X-band radar, however, empowered us to detect and distinguish the main wave fields with their characteristics such as period and direction.

All in all, FFT-derived wave directions and periods acceptably accord with predicted/measured ones, although, irregularity of the sea-bed, co-existence of wave fields with opposing directions, and visual complications to estimate the wave propagation angles, cause the occurred disagreement in some parts. Computation of relevant wave lengths (wave numbers) and implementation of depth inversion method to define the seabed topography might be the right motivation to further this study.

REFERENCES

- 1) Yusheng, Q. : Sea surface wave reconstruction from marine radar images, MS. thesis, *Massachusetts Institute of Technology*, 2012.
- 2) Valenzuela, G.R. : Theories for the interaction of electromagnetic and oceanic waves - a review, *Boundary-Layer meteorology*, Vol. 13, pp. 61-85, 1978.
- 3) Robert, H. S. : Introduction To Physical Oceanography, Department of Oceanography, *Texas A & M University*, September 2008.
- 4) Hasan, G. M. J. and Takewaka, S. : Observation of a stormy wave field with X-band radar and its linear aspects, *Coastal Engineering Journal*, Vol. 49, No. 2, pp. 149-171, 2007.