Journal of
Ship&Ocean
Technology

SOTECH Vol. 10, No. 4, pp. 34 ~48, 2006

# The Application of Marine X-band Radar to Measure Wave Condition during Sea Trial

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**Abstract**

The visual observation of wave condition depends on the observer's skill and experience. Also, the environmental conditions such as light and cloud heavily influence the visual measurement. In the speed test of sea trial, the wave measurement should be objective and accurate. In this paper, the problems of visual measurement and their effects on speed test are described. To overcome those problems, we developed the wave measurement system using commercial marine X-band radar, WaveFinder. The system installed at inland base was calibrated by waverider buoy and then the system's operability was defined. Onboard tests had also been performed three times for formal wave measurement to correct the ship speed. The results illustrated very good agreement with visual observation by experts. It can be concluded that the system would be useful to measure wave and swell information for the sea trial, irrespective of day and night.
**Keywords: wave measurement, X-band radar, swell estimation, radar image**

## 1 Introduction

Generally waverider buoy and visual observation are used to measure ocean waves. But the waverider buoy cannot be applicable for the ship moving in deep sea. The usual practice relied on has been the visual observation. But it has several defects and limitation related to environmental condition and observer. To overcome this problem, various wave measurement systems have been suggested. Recently, the wave measurement systems using marine X-band radar have been developed and extended its application to wave height measurement. This paper introduces the wave measurement system, WaveFinder, developed by authors. The system was calibrated and verified with the measurement results of waverider buoy. The system was adopted to measure wave condition during sea trials. The system will be a device to support safe navigation in ship's voyage.

## 2 Analysis procedure and system configuration of WaveFinder

Generally marine X-band radar is used as a device to distinguish any obstacles and/or islands and/or shores from sea. Radar transmits directional microwave pulse and find out obstacles around ship from the reflected microwave signal by obstacles and/or sea surface.

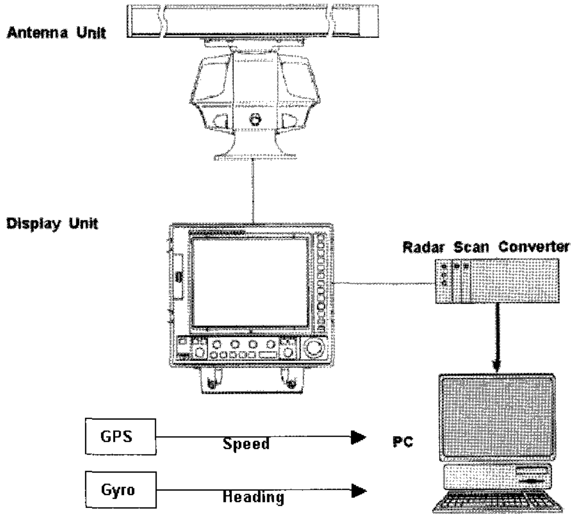
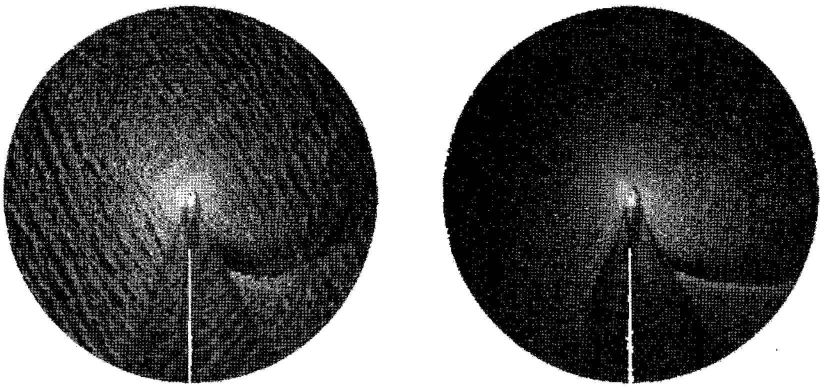



**Figure 1:** System configuration of WaveFinder

For this purpose, the signals reflected by the sea surface (generally called as "Sea Clutter") are considered as noise and removed. Figure 1 shows the system configuration of the Wave Finder. WaveFinder obtains the wave information in real time by three-dimensional FFT to the series of radar images including sea clutter. This kind of system allows the wave measurement on ship's moving situation and also can be free from the disturbance of wave induced by ship's hull by adopting certain portions of radar images sufficiently apart from the ship.



(a) (b)

**Figure 2:** Typical radar images

Figure 2 is the radar image obtained by the system when ship's turning. Two images shown in Figure 2 represents the images measured when the significant wave heights were 0.8m (a) and 3m(b), respectively. In general the signal strength of sea clutter in the upstream direction of wind is stronger than the downstream (Nieto Borge 2000). This fact makes the right half of the image (a) look brighter than the left haft of it. Also, a distinct wave direction can be seen in Figure 2 (b). Using these characteristics of radar image, we can get the wave information by analyzing the images obtained by the high speed AD converter.

The paper written by authors (J.S. Park et al 2006) describes the detailed analysis procedure of the wave measurement used in WaveFinder system. The summary of the wave measurement analysis is described below.

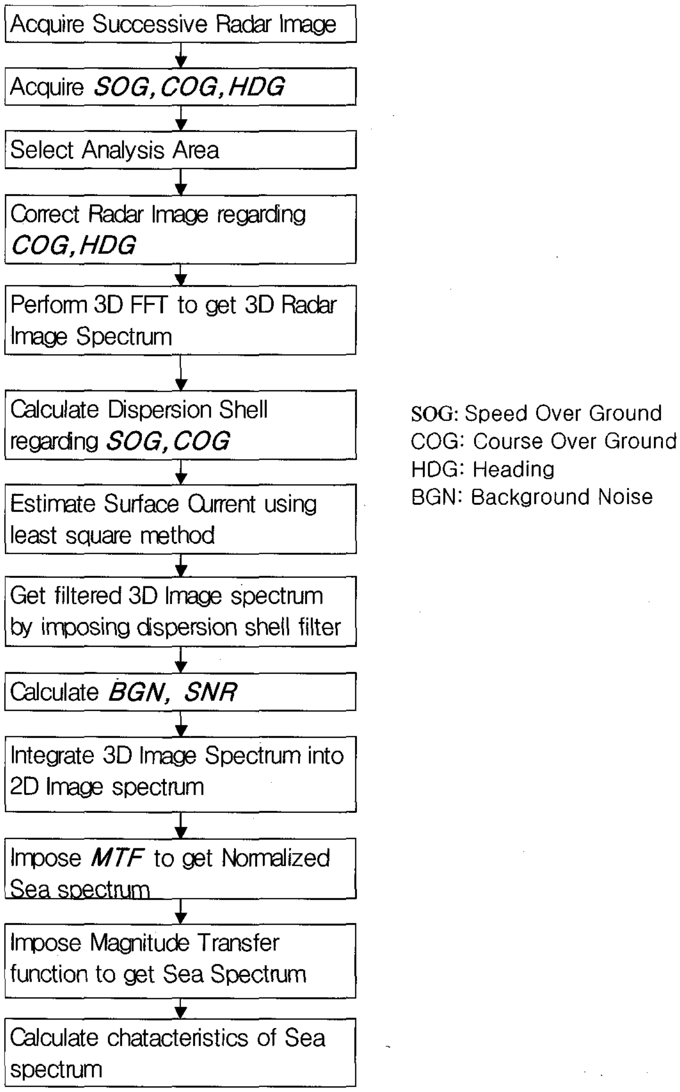



**Figure 3:** Procedure of analysis

Each image obtained at every rotation is converted to the image considering the ship's heading and azimuth. The next step is to select the rectangular area that has the most clear wave pattern from the converted image, and to analyze the selected images to obtain two-dimensional spatial image spectrum. We can get the three dimensional radar image spectrum using two-dimensional spatial image spectra. The dispersion relation in body-fixed coordinate is used to remove the noise imbedded in the radar image spectrum. At the same time the current information is extracted by analyzing the transformation of dispersion shell with least square method. We can get the 2D image spectrum when the directional ambiguity is removed by integrating the 3D radar image spectrum with the positive frequency region. The next step is to adopt MTF (Modulation Transfer Function, Ziemer and Rosental 1987) on the result and then calculate the normalized wave spectrum. The final wave spectrum is determined by adopting the Magnitude Transfer Function obtained in the calibration test to relate SNR (Signal to Noise Ratio) and the significant wave height. Figure 3 shows the summary of the above procedures.

## 3 The calibration and inshore test

The inshore test listed in the Table 1 had been carried out to calibrate the radar image analysis result with the wave measurement from waverider buoy. The wave data of waverider buoy was provided by KORDI.

Both of the measurement and analysis were done acoording to the scheme listed in Table 2.

**Table 1:** Test condition for calibration

| | |
|---|---|
| Test Location | West of Marado |
| Duration of Test | 2005.5 ~ 2005.9 |
| Items of measurement | Hs,Tz,Peak Wave Dir. by buoy, Radar image by WaveFinder |
| Water depth | 100m (near buoy) |
| Sea Level of scanner | 24m |
| Distance | 2.4km (from Radar to buoy) |

**Table 2:** Scheme of test

| |
|---|
| <u>**Measurement**:</u><br>- 32 radar images files were stored at every ten minute (totally 366 data after Filtering).<br>- Buoy's wave height, period, direction data were recorded at every hour. |
| <u>**Analysis**:</u><br>- The characteristic parameter of radar image were calculated for the analysis area on the directions of 45, 90, 135 deg.<br>- The 1 hour averaged results were used to compare with buoy measurements.<br>- Correlation analysis and data filtering were performed with respect to wave height, period, direction to get magnitude transfer function. |

Among the measured results during the test some undesired cases of data were found and removed from the analysis data. These cases are listed in the Table 3. These problems have been reported by other researchers working with marine X-band radar.

**Table 3:** Cases of analysis failure

| Cause | Effects |
|---|---|
| Wind | Too low echo to analyze radar image: Figure 4-(b) |
| Rain, fog | Unable to be analyzed: Figure 4-(c) |
| Ship and her trajectory | Unwanted noise for wave analysis: Figure 4-(d) |

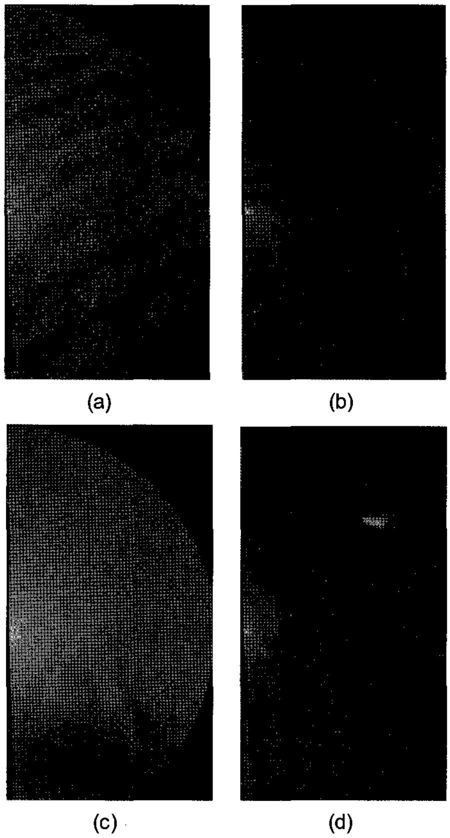



**Figure 4:** Examples of analysis failure

The ripple induced by certain wind speed is the essential source of radar image, representing the reflection from sea surface of waves. Figure 4(a) shows the case in which wind generates enough ripple to detect wave. On the other hand, the wave measurement system can hardly recognize the wave and swell patterns, in case of negligible wind conditions (Figure 4(b)). Generally there is no problem in 'no wind' condition because sea state would be mild also. But sometimes the wave not related to wind such as swell may exist in 'no wind' condition, and then the wave measurement may be impossible. The wave measurement cannot be carried out in the cases of a heavy rain, snow and fog that disturb the radar microwave to travel (Figure 4(c)). The moving object and ship's trajectory also can be obstacles in the analysis (Figure 4(d)).

**Table 4:** Comparison results with buoy measurements

| | Test Range (from Buoy) | Std. Deviation of Error |
|---|---|---|
| Significant Wave Height (m) | 0.42-3.19 | 0.47 |
| Wave Direction (deg.) | 172-233 | 10.76 |
| Wave Period (Tz) (sec.) | 3.45-7.41 | 0.91 |

Table 4 shows the results compared with buoy measurement data except for the cases mentioned above. The cause of differences could be explained with two points of view. The first one is that the measurement area of the buoy and WaveFinder is not exactly matched and the other is the difference of the processing method between two devices. That is, buoy uses time series data analysis method but WaveFinder uses the spectrum analysis method.

From the above results we could confirm WaveFinder could provide the quantitative and objective measurement. And also WaveFinder has the same performance compared with WaMos II, a similar system by Nieto et al., 1999. (Figure 5)

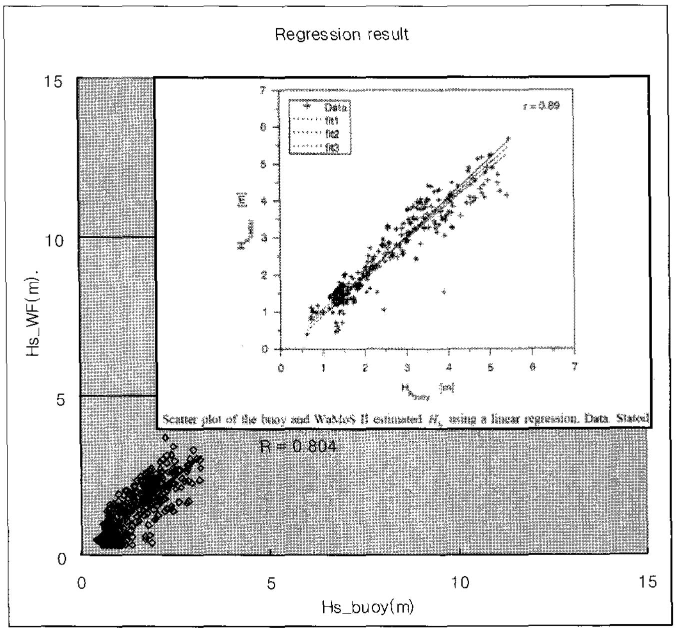



**Figure 5:** Comparison with other measurement system (WaMoS II)

# 4 Validation test and application of WaveFinder in sea trial

Several onboard validation tests have been carried out in sea trials to verify the applicability and performance of WaveFinder.

Before the inshore test, the purpose of the tests was to check the characteristics of radar signals, and to confirm the measurements of wave direction and significant wave height by comparing with visual observation. After inshore test, we focused on the verification of significant wave height measurement by comparing with measurements from buoy, numerical forecasting data and visual observation. In the following section, we show the results of verification tests and some merits of WaveFinder comparing with visual observation in sea trial.

## 4.1 Detection of peak wave direction

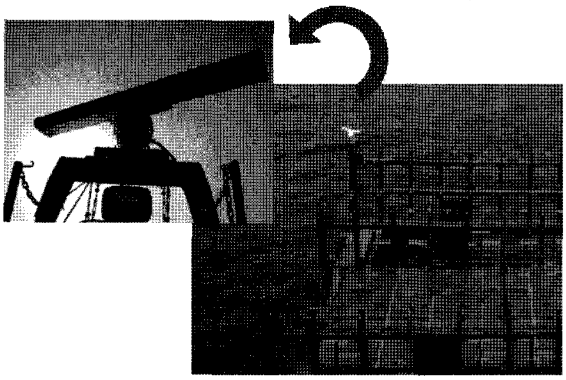
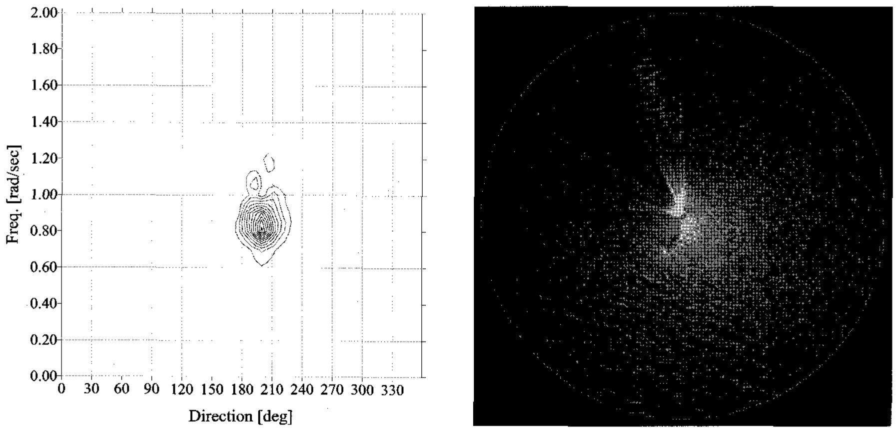
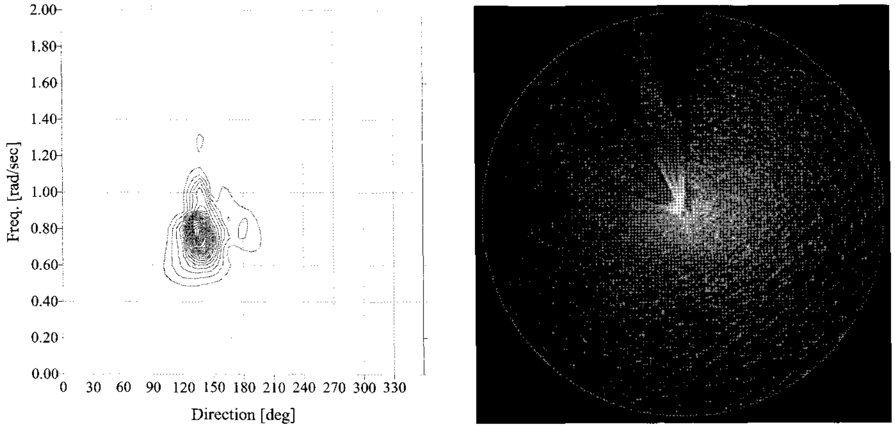


**Figure 6:** Validation Test on the Sea Trial of Container Vessel (Dec. 2004)

Figure 7 shows the radar image and its 2-dimensional image spectrum for the sea trial test shown in Figure 6. The peak directions of image spectrum coincided with the wave directions by visual detection. This is the same way for skillful seaman to check the direction of long waves. The measurement can be done with the WaveFinder even during the night. This is one of the nice features of wave monotring system using X-band radar.




**(a)** **(b)**




(c) (d)

**Figure 7:** Examples of analysis results

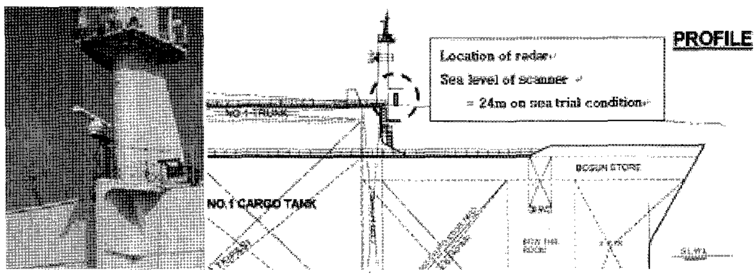



**Figure 8:** Validation test on the sea trial of LNG carrier (July. 2005)

## 4.2 Correlation between wind speed and radar image signal level

Sea clutter relates to wind speed and direction. Figure 9 shows the true wind speed measured in the sea trial (Figure 8), mean and standard deviation of radar signal level in 180 degree's fan-shaped area in front of bow. The correlation between wind speed and radar signal level could be confirmed as shown in Figure 9. Also, the limitation of system operation caused from wind speed could be understood. The minimum wind speed for wave measurement is said to be 3m/s by Nieto et al (2000).

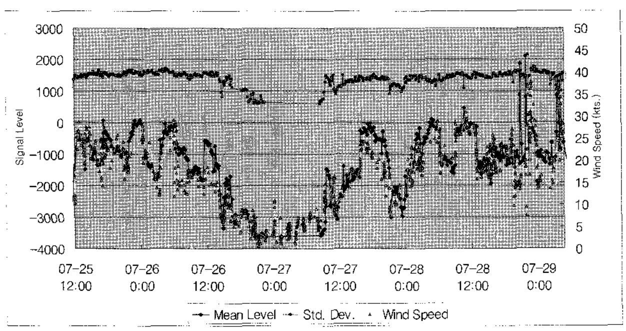



**Figure 9:** Relation between wind speed and radar signal

### 4.3 Comparison with wave buoy

Figure 10 shows the trajectory of the ship in the sea trial (Figure 8) and the location of wave buoy

The indexed (1 to 7) intervals are within 12 miles away from buoy. Figure 11 shows the significant wave heights from waverider buoy (thick line) and from WaveFinder (Solid Circle, Tri-angle). Mostly, these two measurements are similar to each other. For the indexed intervals (Tri-angle), the higher similarity can be seen except 6-th interval. The error in the 6-th interval was caused from rain. And the distance between ship and buoy (dashed line) could cause the difference in the above, because the sea state was under developing. In Figure 11, Hv means the results of visual measurement (Empty Circle). It shows quite big difference from WaveFinder's and buoy's results. And this is an example for the limitation of visual observation.

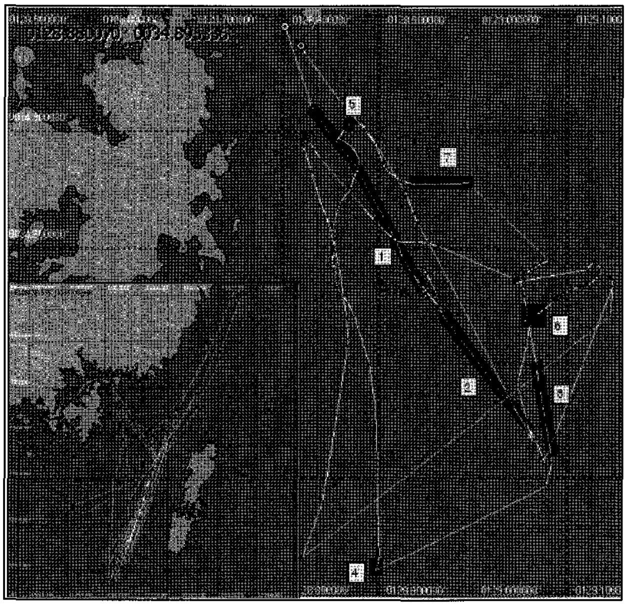


**Figure 10:** Trajectory of LNG carrier and buoy location

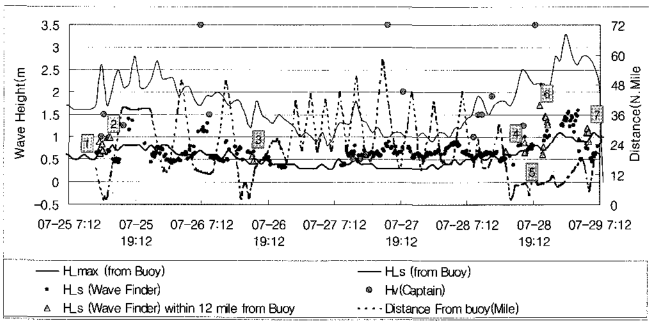



**Figure 11:** Comparison of wave height

## 4.4 Recent application results

The most recent application test was carried out in the sea trial for a LNGC. Since the buoy data was not available, the forecasting wave data were used. According to forecasting, the significant wave height would be 1.5-2m and the wind direction is for NNE from 12:00 July 16th 2006 to 18:00 (GMT+9h). The test was carried out for two heading angle (20,200 degree). In 20 degree's heading from 13:00 to 14:00, the ship was in the following sea condition. In 200 degree's heading from 14:20 to 15:20, the ship was in head sea condition (Figure 12).

Figure 12 shows the measurement results of significant wave height, mean period and peak direction for the test. The total wave spectrum was decoupled into wind wave spectrum and swell spectrum. The significant wave heights of each spectrum were calculated. The measured significant wave heights of total wave spectrum were slightly higher than forecasted. The measured wave direction (about 210 degree) shows good agreements with forecasted value.

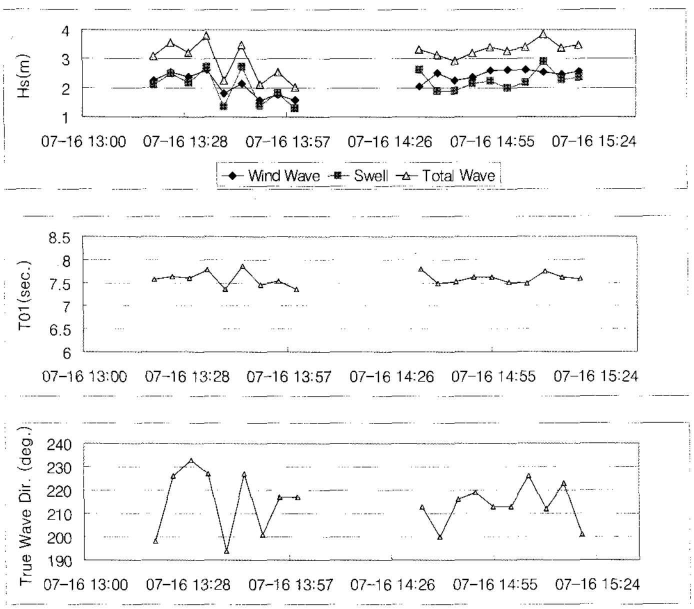



**Figure 12:** Wave measurement results in LNG carrier (2006-07-16 13:00-16:00)

Figure 13 and Figure 14 show the dispersion shell, 2-dimensional wave spectrum and point wave spectrum for each direction. The thick line in the first figure represents the dispersion shell for peak wave direction. The contour shows the energy density of radar image. If some energy comes from sea waves, the energy should be located on the dispersion shell (Young et al, 1985). To get more direct comparison for wave height, we used the radar shadow length as shown in the next section.

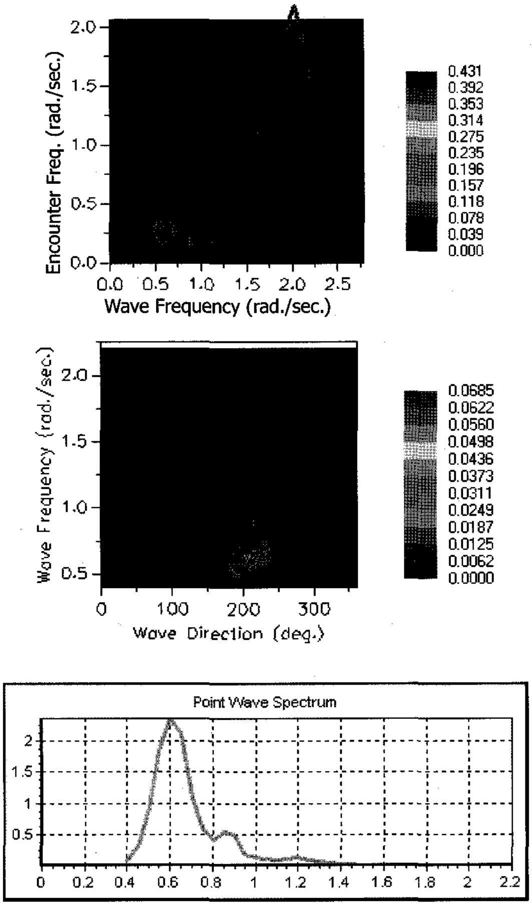
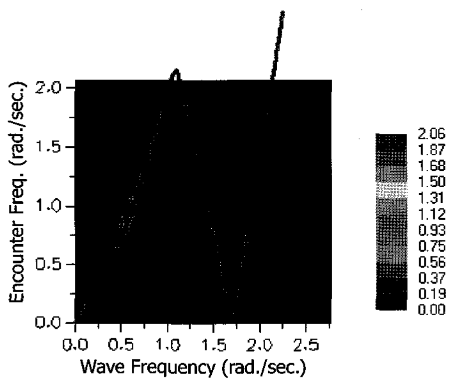



**Figure 13:** Wave measurement results in following sea condition

## 4.5 Verification of wave height using radar shadow length

Figure 15 shows the shadowing mechanism of radar image for sea surface. To simplify calculation, we consider a unidirectional regular wave with the measured peak period and peak direction. The radar shadow length depends on the distance from radar and wave height.



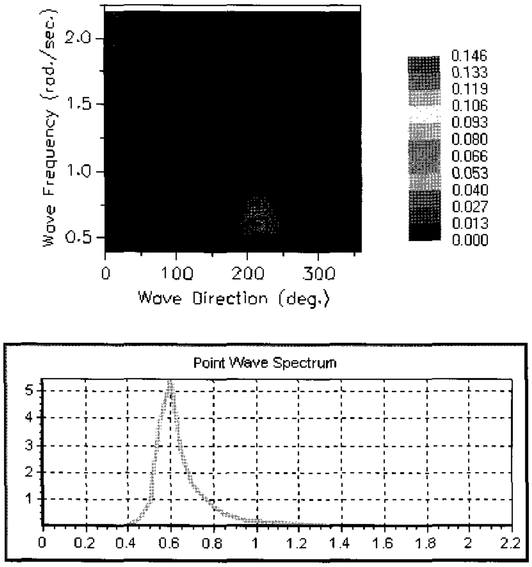



**Figure 14:** Wave measurement results in head sea condition

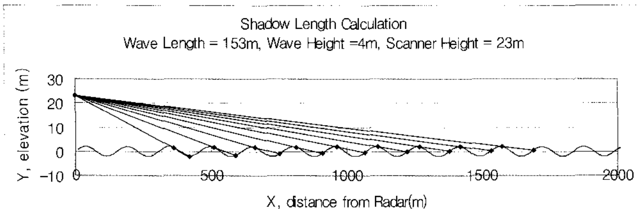



**Figure 15:** Mechanism of shadowing

In Figure 16, the calculation results of shadow length for wave height 2m, 4m are shown as two lines. The peak wavelength is 153m. We measured the actual lengths of the radar shadows that were regarded to come from peak wave direction with peak wave period. We plotted the results on the same figure. The measurement results show the distribution between 2m and 4m. From this, we concluded that the measurement of significant wave height by WaveFinder showed the good agreement with real one.

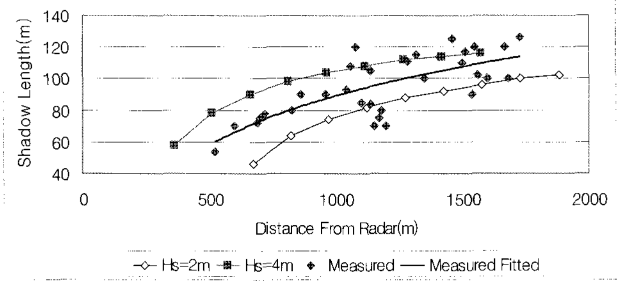



**Figure 16:** Example of shadow length calculation for LNG carrier

## 4.6 Separation of wind wave and swell

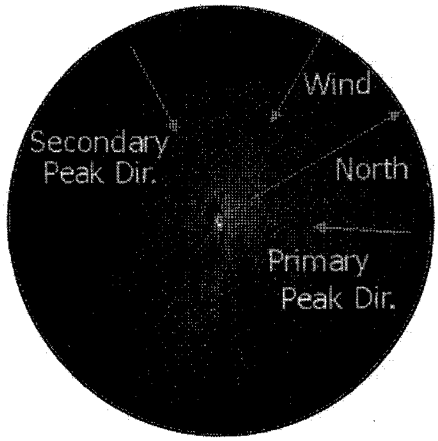



**Figure 17:** The radar image showing two different wave systems (primary, secondary)

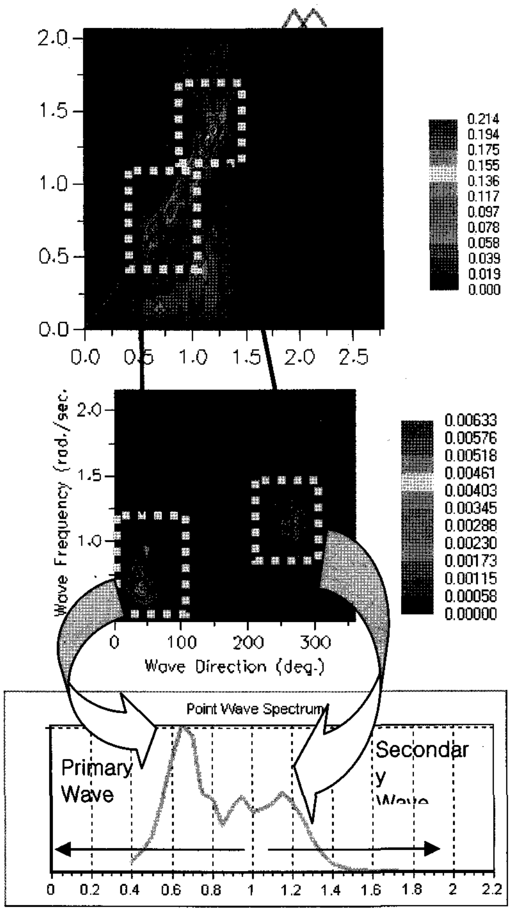



**Figure 18:** Wave measurement results for the wave system that has two peak directions

As shown in section 4.1, WaveFinder can detect swell easily. This feature is useful for sea trial because the measurement of swell is difficult with visual observation. Figure 17 shows a radar image captured on a ship which was moving for 300 deg with the speed of 1.36kts at 12:05 Nov. $30^{th}$ 2005. The true wind speed was 7.5m/s from 333 degree.

The significant wave height by WaveFinder was 1.5m and peak direction was 33 degree. But visual observation could detect only wind wave and the results were 0.7-1m of height and 275 degree of direction. Figure 18 shows the analysis results by WaveFinder. It shows that the two different wave fields existed at that time. From this we can conclude that visual observation may not be effective in the detection of swell with small wave height.

## 5 Concluding remarks

This paper describes the wave measurement system based on commercial marine X-band radar and developed program to analyzing radar image to extract wave and swell components of height and direction. The brief summaries are the following.

- WaveFinder, the developed system, has been calibrated in Marado coast and tuned to have reasonable measurement quality.
- The operability conditions are clarified through the calibration process. That is, the system cannot give reasonable results due to the bad radar images coming from heavy rain, snow and fog etc. Hence, the information from enough reflection from sea surface is the fundamental requirements. It was also found that the wind speed above a certain threshold level is essential to have enough reflection from the sea surface.
- Several onboard tests have been performed using the calibrated wave measurement system and the reliability was confirmed by buoy data. This comparison illustrated the both wave data have reasonable agreements at near distance only. That describes the wave information is definitely function of space and therefore this wave measurement system have to be used to extract surface-average-wave information.
- The wave directions and wave heights have also been compared with the forecasting data from weather-company and the proposed method based on shadow length due to the wave pattern, respectively. These comparisons describe reasonable agreements.
- The Wave Finder was able to subtract the swell component imbedded in the radar signal. This feature can be very helpful in ISO ship-speed correction.

The aforementioned remarks conclude the system's usefulness to measure the wave and swell information during sea-trial for day and night.

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