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Sensing Water Surface Fluctuations Through Sequences of CCD Images

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ABSTRACT

This study presents the results of sensing remotely water surface fluctuations through images acquired by a charged coupled device (CCD) camera. A transfer function between the gray scales of the images and the actual wave profile was derived. It is shown that, for the case of regular waves, the relative errors estimated from this transfer function are, on the average, 0.16 and 0.006, for wave heights and periods, respectively, as compared with wave gauge measurements. However, the results for the cases with irregular waves are less satisfactory. The relative errors for significant wave heights from CCD images are 0.10, and 0.08 for the periods. Two different regions within the wave basin were used for this study to assess the universality and applicability of the transfer function.

KEY WORDS: Remote sensing, CCD image sequences, wave heights, wave periods.

INTRODUCTION

Measurements of ocean waves are often conducted using "in-situ" devices such as wave gauges and buoys. Generally, it can be said that accuracies of these kinds of measurements are relatively high. However, it should be noted that the underlying assumption of point measurements is that the wave field is homogeneous. These methods will, therefore, not be applicable for regions where wave properties may change considerably. These may include, wave field in a region where there are abrupt changes of the underlying topographies, or where there are man-made constructions nearby. In these circumstances, one has either to carry out measurements in various locations repeatedly, or to deploy a large amount of instruments. Furthermore, these instruments are liable to damages such as those caused by severe sea conditions, fishing activities and the passages of water vehicles. All these can be both time and cost demanding, as well as inefficient.

In recent years there have been considerable interests in applying the technique of remote sensing for the study of ocean waves. As compared with the conventional methods, this technique has the clear advantage in that the spatial information of a large area can be obtained instantaneously. It is therefore an efficient and economic way to monitor the sea state. Furthermore, since there is no direct contact with the water surface, possible interactions between the instruments and the water can thus be avoided.

Remote sensing of water surface is based on analyzing the signals acquired by some devices. Usually, a camera or radar system is employed for the acquisition of these signals. The signals were then recorded in form of images with different color levels showing the variations of the water surface. The color level of each pixel in the image represents light intensities reflected from the water surface, which are then recorded instantaneously by the instruments. Researchers have shown that, both absolute wavenumber spectra, as well as directional information, of the wave field can be obtained from these images (Stillwell & Pilon, 1974; Young et al., 1984). Between these two measuring systems, the costs for radar operation are relative high.

It is noted that when a camera is used for this purpose, the intensities of the color level in the images depend on the wave slopes, not on wave heights (Gangeskar, 2000). Knowledge of the wave field can only be obtained when a suitable relation for the variations of light intensities of the images and that of the slopes of the water surface is derived beforehand.

Even though relatively inexpensive as compared to a radar system, there are still some problems that remain to be resolved. The first one is due to distortions caused by the down-looking angles of the camera, which, quite often, are not perpendicular to the water surface. When this is the case, the scales of the space coordinates in the images will not be constant, and this can lead to errors in the determination of the wavenumber spectrum (Sugimori, 1975). The second one is due to non-uniform illumination to the water surface. As mentioned earlier, the images of wave slopes are based on light reflection from the water surface (Jähne & Riemer, 1990). If the illumination is non-uniform, even if the wave slopes in the region of the image were the same, the relative brightness in the image will not be equal. In passing it is also noted that in the past studies, regions covered by the CCD camera images are rather small (Jähne & Riemer, 1990; Klinke, 1996 and Senent et al., 2000). In this way, the advantages of remote sensing, that is, to acquire information of a relatively large area, will be lost. Finally, it should also be mentioned that, due to lack of the "in-situ" measurements, remotely sensed results are often presented in dimensionless forms. Even though our understandings of the complex wave fields have been improved enormously through previous studies, however, it seems fair to say that, for engineering applications these results are inadequate. A relationship between the gray scale values of the images and the wave heights must be derived.

With these problems in mind, a series of experiments were conducted. Both regular and irregular waves were used. An empirical relation is obtained from the results of the experiments. It is shown that, hydrographic parameters of the water surface can be estimated from the CCD images through this relation.

EXPERINENTAL SET-UP

Experiments were carried out in the wave basin ($50m \times 50m \times 1m$) of the Ocean Engineering Laboratory, National Taiwan Ocean University. During the experiments, the water has a constant depth of 0.4 meter, and no other constructions were present. It is hoped that in this way complicated wave phenomena can be avoided. The "in-situ" measurements were conducted with 30 wave gauges formed in a rectangular array. The spacings between the wave gauges are, respectively, 0.4 and 0.8 meters for the short and the long side of the array.

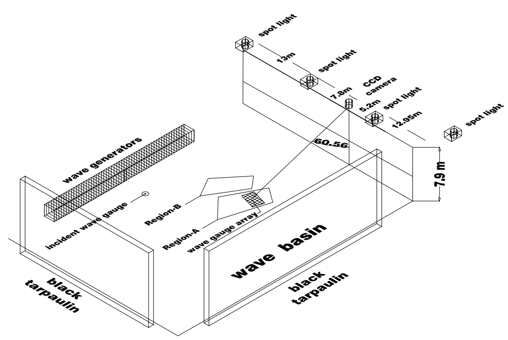

Figure 1 The set-up of the experiments

A CCD camera was used to detect the variations of the water surface fluctuations from a distance. The CCD video camera was installed 7.4 m above the still water level. It has a downward looking angle of 23^0 and 30^o for region A and B, respectively. The rotated angle of the camera to the direction of waves propagate is 30^0 and 35^0 for two regions. Four spotlights were used for the light source and the heights are the same as that of the camera. It also has a slight downward looking angle of 10^0 for the illumination of the area of interest. There are four black tarpaulins placed along the 3 sides, and one atop, of the wave basin. It is hoped that, in this way, the effects of non-uniform reflections of the basin surroundings back to the camera can be minimized. A definition sketch of the experimental set-up can be seen in Figure 1. To simplify the procedures involved in processing the images in later times, video signals were all recorded in monochromatic format. That is to say, light intensities from the water surface are represented in the form of gray values in the images. Figure 2 shows an example of the image. In the figure, generated regular waves have a period of 0.8 second with wave heights of 3 cm. Time series of the variations of the gray values corresponded to the locations of the wave gauges were extracted from the image sequences. These were then used together with the records from wave gauges for the determination of the transfer function.

A total of eight different periods, ranging from 0.6 to 1.3 seconds, were used for the regular wave experiments. For each period of the wave train, six different wave heights were used. On the other hand, all the irregular waves have as targets the JONSWAP type of spectra. All the experimental conditions are listed in Table 1.

Table 1 The wave conditions of the experiments

	Wave Period (T) sec	Wave height (H) cm	Region-A	Region-B
			Numbers of wave height for each period	
Regular Waves	0.6	2.64-5.71	6	5
	0.7	3.42-6.74	6	5
	0.8	3.30-6.74	6	5
	0.9	3.41-6.42	6	5
	1.0	3.10-6.25	6	5
	1.1	2.72-5.77	6	5
	1.2	3.01-6.38	6	5
	1.3	3.10-6.29	6	5
Irregular Waves	$T_{1/3}$	$H_{1/3}$	Region-A	Region-B
	0.6	2.77-4.52	2	4
	0.7	3.19-5.62	0	4
	0.8	3.07-5.17	2	4
	0.9	2.76-5.74	0	4
	1.0	2.71-5.42	2	4
	1.1	2.89-5.36	0	4

Water surface fluctuations were sampled at 20 Hz by the wave gauges. To be comparable, the images were first recorded in AVI format and then digitized by a frame grabber at a rate of 20 frames per second. The recording length is 51.2 seconds for the cases with regular waves, and 102.4 seconds for those with irregular waves. The resolution of the wave images is 240 pixels $\times$ 320 pixels per frame. Two regions in the basin were chosen for this study. Region-A has a length of approximately 762 cm in the direction of the camera, and is 338 cm long in the transverse direction. Region-B, on the other hand, has a dimension of 310 cm by 575 cm. The areas of these two regions are larger than those used by previous studies. The relations between the characteristics of the wave fields measured by the wave gauges and those of the images in region-A are to be used for the estimation of the transfer function. Using this transfer function, the gray values of the image sequences in region-B are then transformed into the characteristics of the waves. As a verification of the transfer function, the results are then compared with those measured by the wave gauges. It is considered that, in this way the applicability of the transfer function in different regions can be assessed.

RESULTS AND DISCUSSIONS

Figure 3 shows the plots of smoothed time series of the gray values (Fig. 3A) and that of the wave records (Fig. 3B) for comparison. Generated regular waves should have a period of 0.9 second and a wave height of 3.5 cm.

It should be stated that, the original series of the gray values contain are zigzagged, i.e., they have many small ripples, which are not seen in the wave records. (Figures not shown here.) A spatial averaging with a 3×3 box-filter, and a temporal 5-point running average, were then used to smooth out these irregularities. Afterwards, the mean value of the gray series was subtracted from the time series. The periods and the "amplitudes" are then obtained by applying the zero-upcrossing method in the usual way. Hereafter, we will denote the "amplitudes" of the gray value series as G and the period is G_T. For all the results, the wave periods estimated from the gray value sequences almost coalesce with those from the records of the wave gauges. The methodology proposed here is to process the signals in the time, rather than in the wavenumber, domain. It is believed that, in this way, the effect of the images distortion can be reduced.

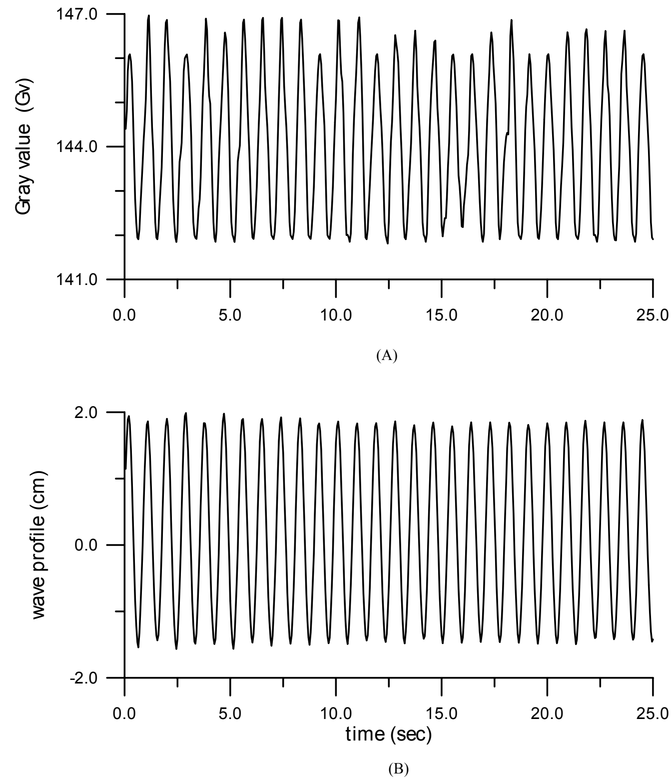

Figure 3 The time series of the gray value and wave profile

The luminance of the water surface depends upon the light intensity it receives. Since the light sources are located at one side of the region of interest, the averaged gray value of each measured points will, consequently, not be the same. This is the main source of non-uniform illumination in this study. Figure 4 shows the averaged gray values and amplitudes of the 30 points in region A for the regular wave experiments. The trend, where the amplitudes of the gray value series decrease with increasing luminance, can be clearly seen. Since there are only regular waves present, all the wave amplitudes of the measuring points should have be equal, a simple formula is therefore used for the correction. In this way, the effects of light source inhomogeneities could be reduced. The proposed formula has the form:

$$G_{\text{modified}} = G \cdot \exp(-G_{avg}all / G_{avg}channel) \tag{1}$$

where

$G_{modfied}$: the modified "amplitude";

$G_{avg}all$: the average gray value of the whole frame

$G_{avg}channel$: the average gray value of the selected point

Experiments with regular waves in region A were carried out first. A relationship between the wave characteristics and the gray values can be obtained through regression:

$$H = 0.0145025 \cdot \left(G \cdot (G_T)^{-1}\right) \cdot \exp(-G_{avg}all / G_{avg}channel) \cdot L \tag{2}$$

where H: wave height and L: wave length

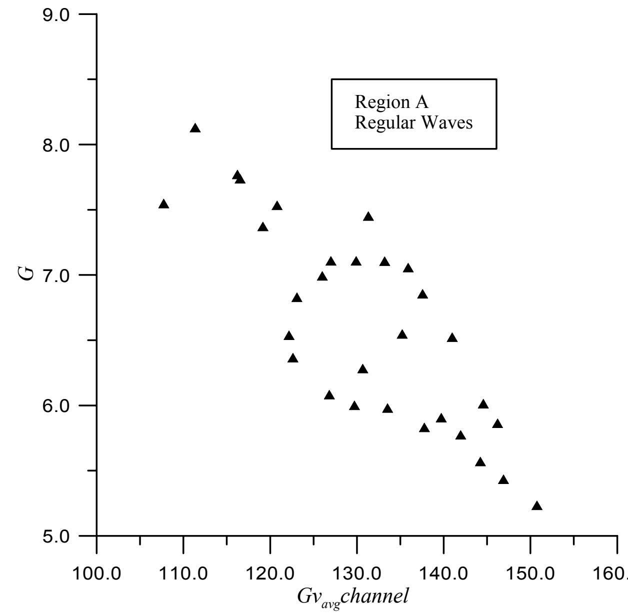

Figure 4 The averaged gray values and their amplitudes

The result is shown in Figure 5, where values shown on the abscissa are estimated from the images, and those of the wave gauges are on the ordinate. In the figure, we have used different symbols for different wave periods for clarity.

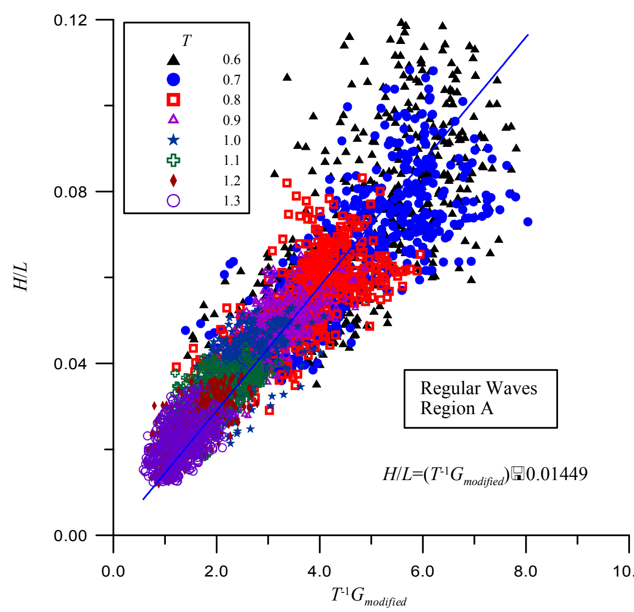

Figure 5 The results of the regression

Wave Height

Figure 6 compares the two sets of wave heights as estimated through image sequences and the wave gauges. The data are from region-A. Values shown on the abscissa are the wave heights actually measured by the wave gauge arrays, whereas those on the ordinate are estimated from image sequences via the transfer function. When wave heights estimated from image sequences are equal to those measured by the wave gauges, they should fall on the straight line shown in the figure. It can be seen that the symbols are distributed alone the line. The relative errors have a mean of 0.15.

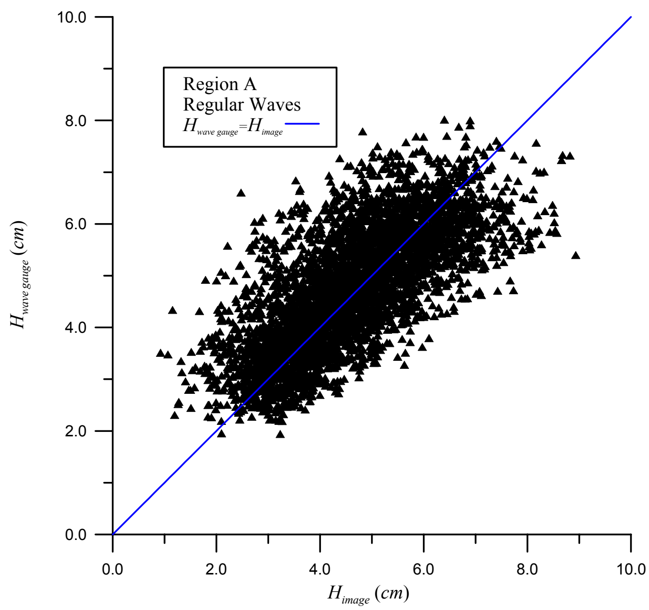

Figure 6 The comparison between the wave heights estimated by the image sequence and those measured by the wave gauges of Region-A

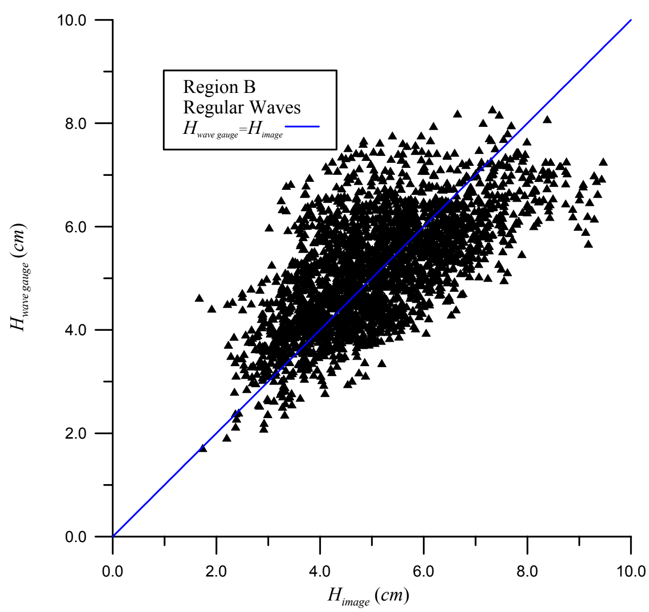

Figure 7 The comparison between the wave heights estimated by the image sequence and those measured by the wave gauges of Region-B

To test its universality, the transfer function was used for the images of region-B. The results are shown in Figure 7. It is clears that for this case the intensities of the reflections received by the camera must now have different values. This is because that the camera now has different orientation as for region A. However, it can be seen that the transfer function still performs well in estimating wave heights, and the relative errors do not increase even when the observing regions has been changed. It can be shown that, the mean value for the relative errors between the estimated and measured wave heights is 0.15.

For the cases of irregular waves, the time series of the gray values were first zero-upcrossed. All these "waves" are then treated individually, with the transfer function applied to them, and a series of wave heights was thereby obtained. Figure 8 shows the significant wave heights estimated by the wave gauges and those from the image sequences for region-B. It is seen that, even for the case of irregular waves, estimated wave heights are still distributed closely around the line where these two wave heights should be equal. The mean values of the relative errors are, respectively, 0.108 for region-A, and 0.11 for region-B. These values are smaller than those for regular waves. The results seem to indicate that, our proposed transfer function can be used directly to estimate the wave heights of an irregular wave field, and no further calibrations are necessary. Further studies are, however, needed to confirm this.

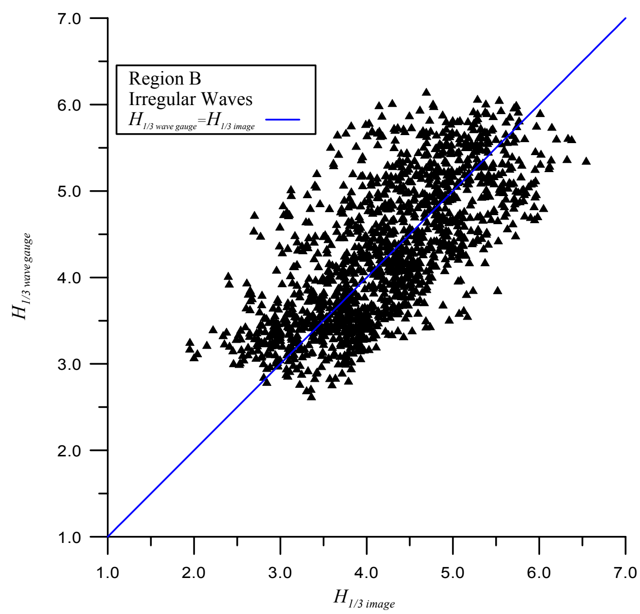

Figure 8 The comparison between the significant wave heights estimated by the image sequence and those measured by the wave gauges of Region-B

Wave Period

It was mentioned previously that, estimate of the wave periods through image sequences are rather accurate. This is true for the cases of regular waves, where the mean relative errors are less than 0.006. However, the mean relative errors increased to a mean value of 0.08 for the cases with irregular waves. Figure 9 compares significant wave periods ($T_{1/3}$) measured by the wave gauges and those estimated from image sequences for the wave field in region A. It is found that the periods estimated from images are shorter than those from the "in-situ" measurements. Figure 10 is a segment of the time series of the gray values. It can be seen that, there are small-scale oscillations or ripples in the records. It is conjectured that, when these undulations happen to appear close to the zero-line, the numbers of the wave counts will increase, and this leads, consequently, to a decrease of the number of $T_{1/3}$. To resolve this problem, further smoothing or windowing of the image sequences would be necessary. This has, however, not been carried out in the present study.

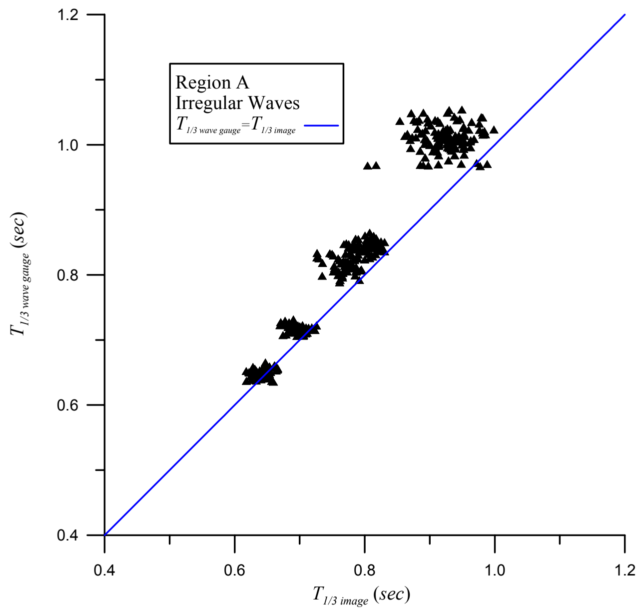

Figure 9 The comparison between the significant wave periods estimated by the image sequence and those measured by the wave gauges of Region-A

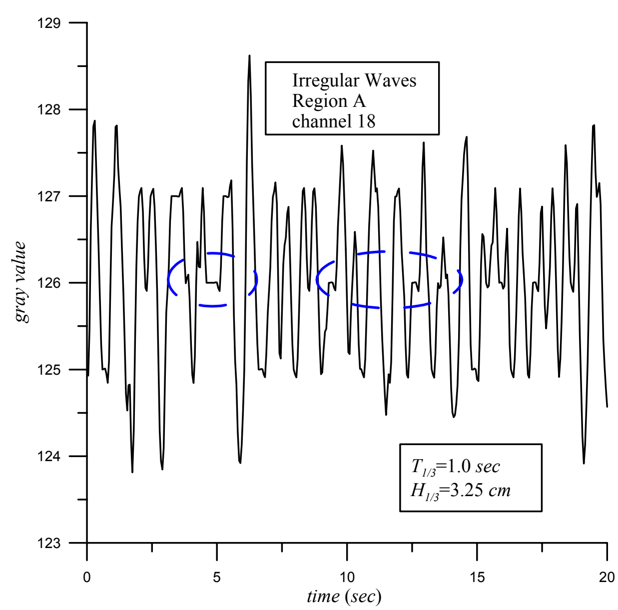

Figure 10 The time series of gray values of irregular waves

CONCLUSIONS

In this paper we have studied the possibility of using CCD images in analyzing the wave fields. As compared with the more conventional methods, a CCD camera has the clear advantage in acquiring the information of the whole wave field at one instant. Furthermore, they can be mounted with relatively ease. Estimates from the images were compared with the data of the "in-situ" wave gauge array. It is found that the mean relative errors between the measured and estimated wave heights are, respectively, less than 0.16 for the case of regular waves, and less than 0.11 for the case of irregular waves. The mean relative errors of the wave periods are less than 0.006 for regular waves, and less than 0.08 for irregular waves.

The series of the gray values are often seen to have small ripples imposed upon large fluctuations. While the latter is due to waves, the former are due to electronic noise. When the waves are small, the signal-to-noise ratio will be relatively high. It is believed that this is the main reason that caused the deviation in the estimation of wave parameters.

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