# CHAPTER 8

## THE USE OF IMAGING RADAR IN STUDYING OCEAN WAVES

by

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### INTRODUCTION

Imaging radar can be used to provide information about the two-dimensional character of the wave field. This is especially important near shore where the effects of refraction and shoaling interfere with the simple interpretation of a directional spectrum based on records from a newtork of gages.

Imaging radar has the advantages of providing full two-dimensional information of the type provided by aerial photography and of being available continuously, including night time and during storms.

Imaging radar, of course, also has some disadvantages when compared to other data gathering systems. Specifically, the imaging radar does not provide a measure of wave height. It does not provide as much resolution as aerial photography and the shorter waves of interest may be missed. The most important disadvantage is that short ripples are essential to the detection of long waves, hence swell is not detected outside the breaker zone when the wind is calm or the high frequency waves are inhibited by oil slicks.

Several characteristics of the radar images of waves, as compared to aerial photography, are illustrated in Figure 1. Note the similarity of the wave patterns in the radar image and the aerial photograph. The image does not show any features of the land. The location of the radar is shown on the aerial photography by an "X".

Ijima et al (1964) and Wright (1965) appear to have been among the first to report the use of radar for imaging ocean waves. Oudshoorn (1960), Wills and Beaumont (1971), Evmenov et al (1973) and others have published photographs of a radar scope showing waves. This report differs from earlier papers on this topic by providing a discussion of practical procedures for overcoming some of the more mundane technical difficulties associated with routine data collection.

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Landward of the bar wave breaking due to limited water depth cannot therefore occur before the new generated waves reach the shore of the island or the dykes on the mainland coast (FIG.14).

Fig. 14: Wave Breaking on the Bar in front of the North-western Shore of the Island of Norderney

## 4. Wave height damping on the tidal flats

While the waves passing the eastern part of the bar attack the northwestern shore of the island of Norderney, those which are generated after breaking on the eastern part spread out over the tidal flats. Though they are not high enough to be broken because of the limited water depth a certain wave damping on the tidal flats could be observed. It must be explained as a combined superposing effect of bottom friction, refraction, diffraction and shoaling.

The damping of maximum wave height from the inner part of the tidal inlet can be described as a function of itself in relation to the water depth at the end of the travel distance (FIG.15). One gets a more complicated expression for the damping of the significant wave height (FIG.15), but the influence of water depth can be distinguished too.

The intensity of wave height damping on the tidal flats can be described by another example:

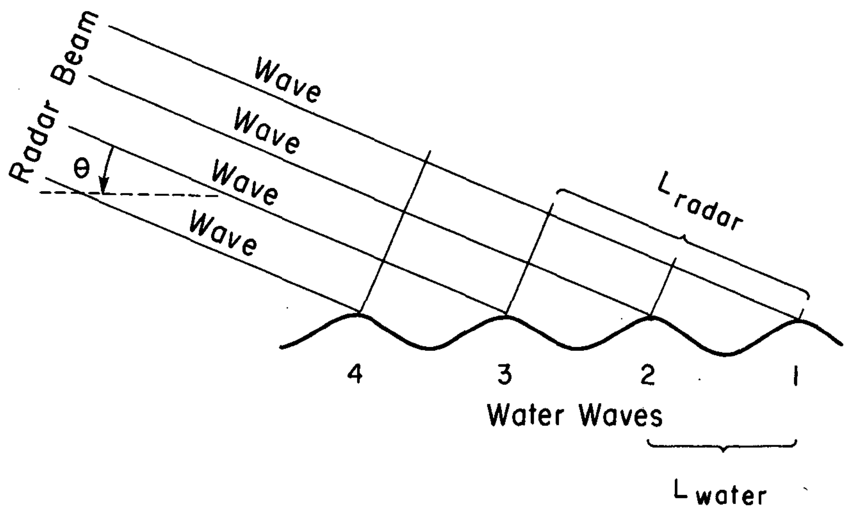



Figure 2. Illustration of first order Bragg Scattering. Each wave acts as a reflector. Reflection from several waves must be in phase for a significant return signal.

are nearly always in equilibrium with the wind. Thus if the wind is calm and the water surface glassy, the swell waves which may exist will not be detected seaward of the surf zone.

At least three processes have been recognized by which the long waves modulate the radar return from the short waves (Lynch and Wagner, 1970 Valenzuela, 1978). It has been known for many years that the convergence zone on the front face of the traveling waves tends to increase the height and decrease the length of the capillary waves and that the divergence zone on the back face of the waves has the opposite effect (Phillips, 1966). This process has been investigated in greater detail and with specific reference to the radar cross section by Keller and Wright (1975), Valenzuela and Wright (1976), Wright (1978), Reece (1978) and many others. This process is illustrated in Figure 3.

The strength of the radar return (generally called the radar cross section) from the sea is a function of the grazing angles, as shown by Skolnik (1970). The slope of the water surface for a distance of many radar wavelengths, varies with the phase of the long waves as shown in Figure 4. The angle is greater for the face of the wave facing the radar than for the opposite face. This process has been investigated extensively by Valenzuela (1970).

When the grazing angle is low the crest of one wave may prevent irradiation of the following trough, producing a shadow zone between successive wave crests as illustrated in Figure 5. This situation produces a maximum contrast in the return from different phases of the

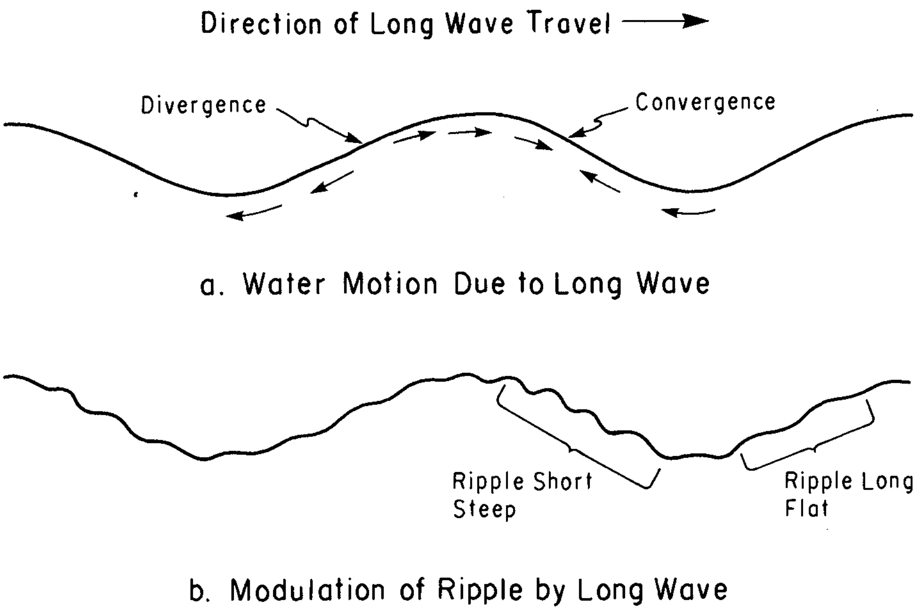



Figure 3. Modulation of short waves by long waves

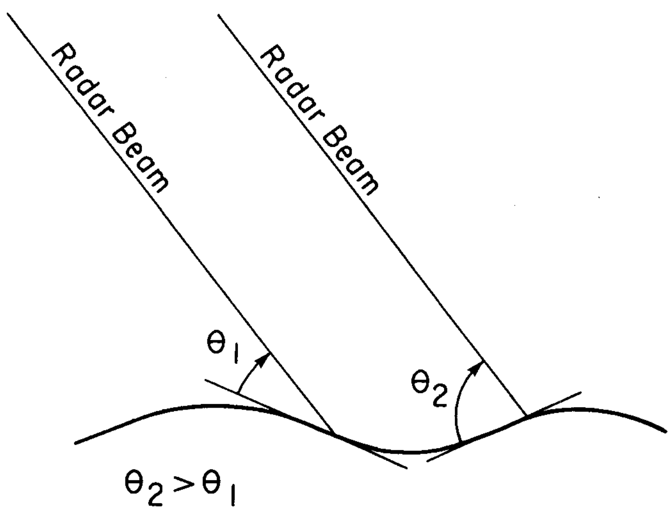



Figure 4. Modulation of the incident angle of the radar beam by the long waves.

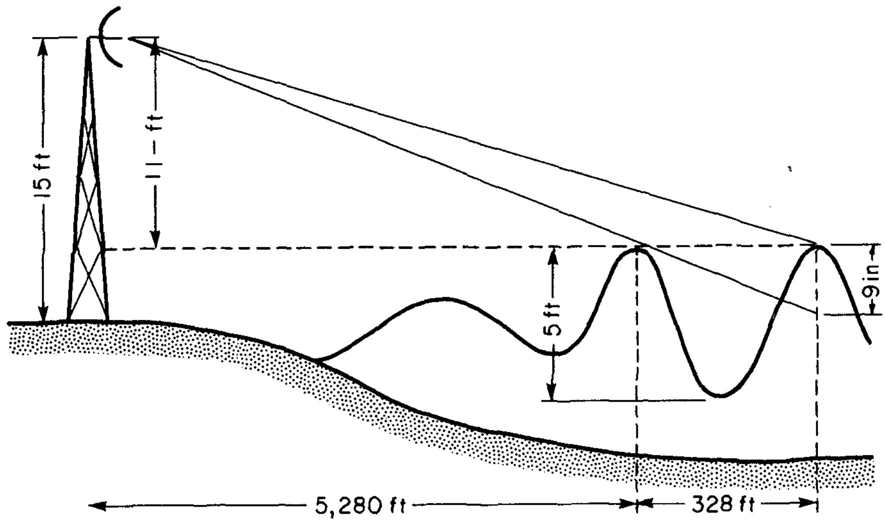



Figure 5. Illustration of the shadowing of a portion of one wave, by a wave nearer to the radar.

wave. When the wave heights are variable, as they usually are, and the grazing angle is small, the crest of a large wave may shadow at least part of the crest of a following lower wave, so that at least parts of some wave crests are missing in the return signals from the longer useable ranges.

The smallest spot which can be distinguished on the radar scope is determined by the duration of the transmitted energy pulse and the ratio of the radar wavelength to the effective length of the radar antenna as shown in Figure 6. The factor of 1/2 in the equation for $\Delta R$ occurs because the radar beam must travel across the spot once in each direction to permit detection. The smallest available pulse length in many radar systems is too long to permit the recognization of water waves. Some commercial marine navigation radars, however, do provide pulse lengths as short as 50 nanoseconds, ($50 \times 10^{-9}$ seconds) for ranges of 5.5 kilometers or less. This pulse length is short enough for the detection of 4-second waves in deep water. Shorter pulses could be used to permit the detection of shorter waves. This would involve a reduction in power and maximum range. Shorter pulses are not generally available in commercial radar systems.

The angular resolution is proportional to the ratio of the radar wavelength to the effective length of the radar antenna. Commercial marine radar manufacturers often provide several optional antenna systems. The shortest, and most widely used, provides an angular resolution of about 2.0 degrees. The longest gives a resolution of about 0.6 degrees. Obviously the longest antenna is preferable for imaging waves.

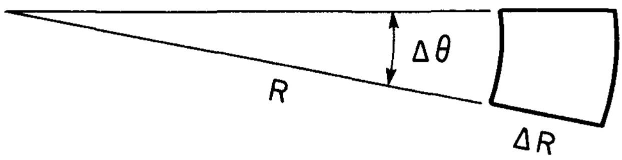



Figure 6. Resolution cell for the radar image. R is the range, $\Delta R$ resolution along the radar beam. $\Delta R = c\Delta T/2$, where c is the speed of light and $\Delta t$ is the duration of a radar pulse. $\Delta\theta$ is the azimuthal resolution.

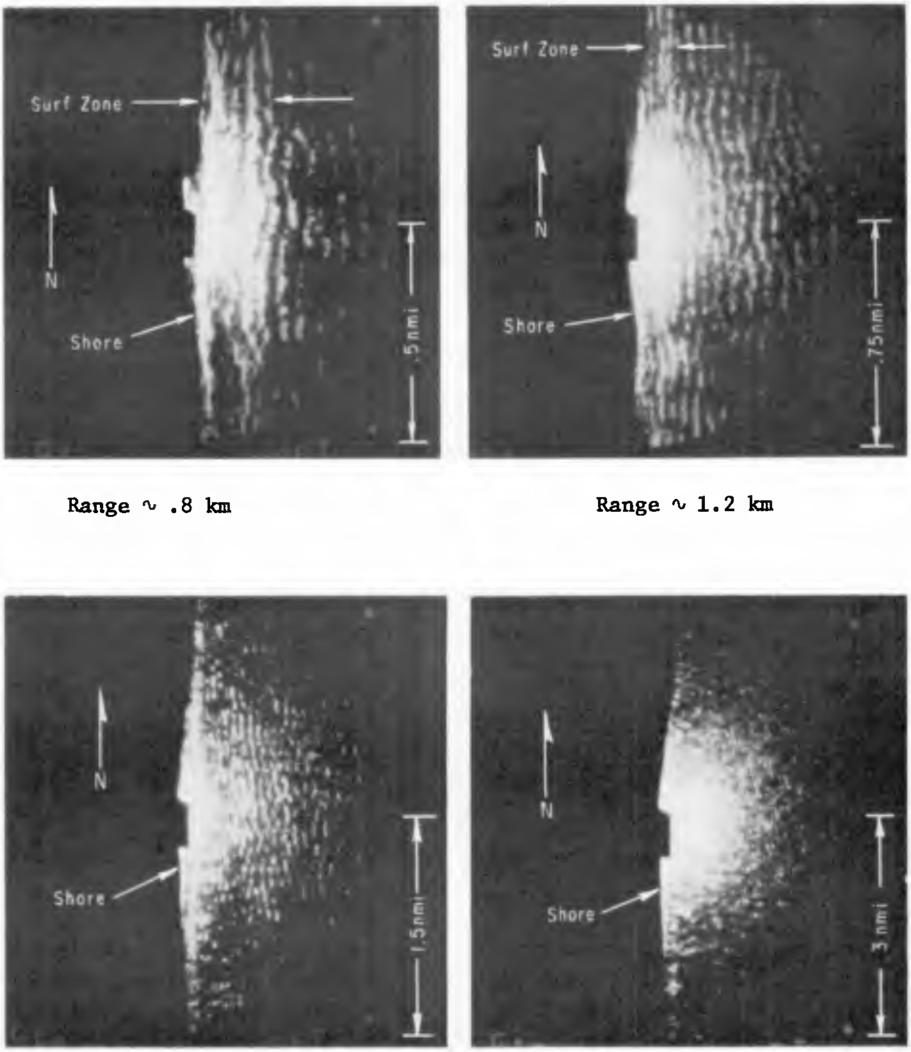
The intensity of the radiated energy decreases with the square of the distance from the antenna. The intensity of the back scattered energy likewise decreases with the square of the distance from the target. Thus the power returned to the antenna, decreases with the fourth power of the distance between antenna and the reflecting surface.

If the signal is strong enough to reveal distant targets, the scope may be saturated by nearby targets, so that no details are revealed. When the signal level is low enough to reveal details near the center of the scope, distant targets may escape detection. Some improvement may be made by using circuits which provide increased amplification at increased distances.

## PRACTICAL CONSIDERATIONS

The optimum settings of the controls on the radar, for imaging waves, depend on ambient conditions and can be found for any given conditions by a little experimentation with the controls. Most wave data collection systems, however, are unattended and the need for frequent adjustment to the radar controls to obtain optimum performance has been a handicap in the exploitation of microwave, ground based radar for the collection of wave data.

A solution to this problem may be obtained by combining a control system which will vary the controls during each observation according to a preset schedule. An off-the-shelf 3 cm (X-band) marine radar has been combined with a control system which turns the radar on at preset times. After a brief warm up period, a series of 1-9 sweeps of the radar over the sea at each of several console settings is photographed. Photographs of the radar scope displaying sea conditions as shown for four range settings are presented in Figure 7. Note that the clearest image of this wave field is found at a range of 1.2 kilometers with 14-15 individual waves being discernable. We find that the clearest images are generally obtained with a range setting between ten and twenty wavelengths. Note also that the radar scope tends to be saturated near the center with faint images near the maximum range.



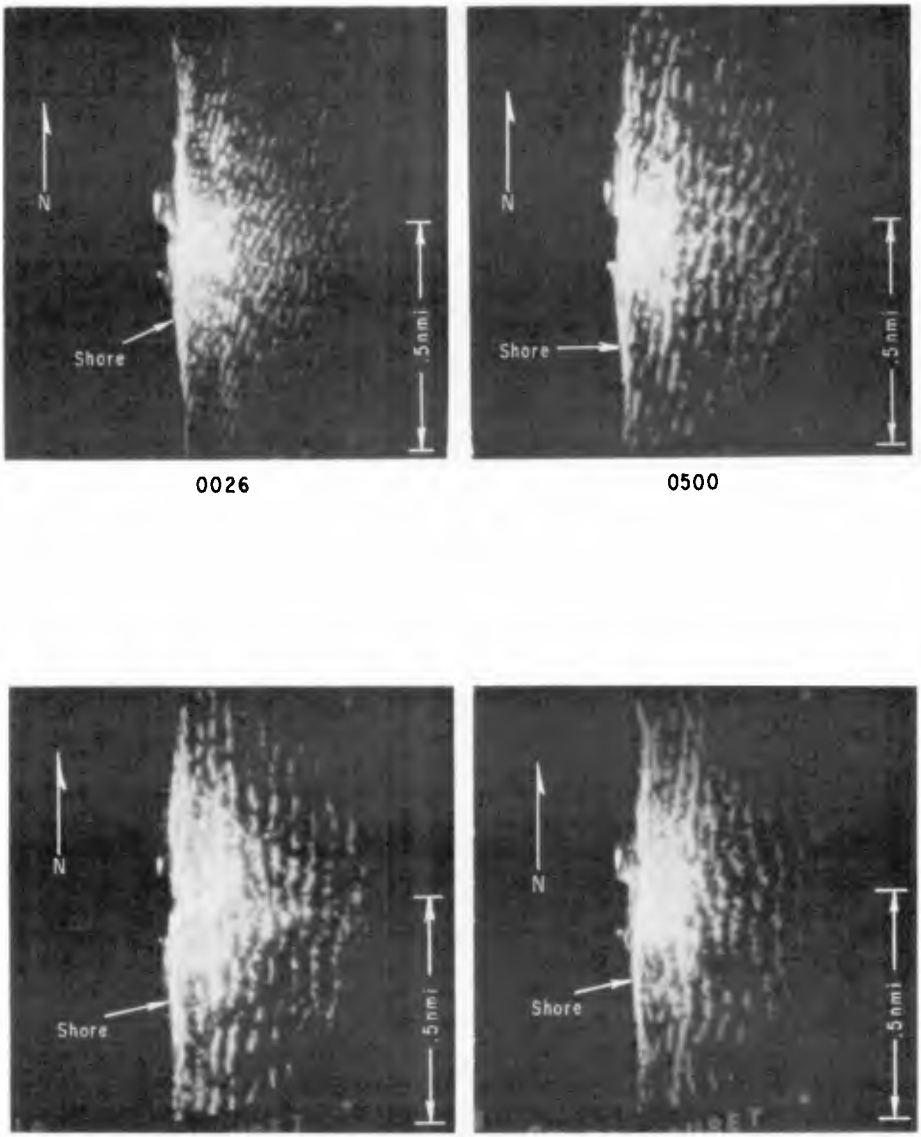

Range ∿ .8 km

Range ∿ 1.2 km

Range ∿ 2.5 km

Range ∿ 5. km

Figure 7. View of the radar images of waves at four ranges. Coast Guard Radar on Nausett Beach, Cape Cod, Mass.




0026 0500

0924 1324

Figure 8. Development of the wave field as revealed by radar

Because of the effects of modulation of the ripples and surface slope on the radar return, it has been seen that longer and steeper waves can be detected at a greater range than short or flat waves. Thus the optimum range setting is seen to be a function of wavelength and wave steepness. This cannot be known in advance. Therefore the system is programmed to take a sequence of pictures at several ranges at a pulse length near 50 nanoseconds as a part of each observation. At present only one level of intensity is provided, but it appears that the addition of two intensity levels to the system would be an improvement. Only the most satisfactory photograph of the set is routinely analyzed.

One might expect the curvature of the earth to be a factor in determining the optimum antenna elevation, but this does not turn out to be the case. When commercial radar is used, the range is restricted to the order of 5.5 kilometers by the weak power return for longer ranges.

At this range an elevation of two meters is sufficient for the radar signal to illuminate the surface at maximum range, even in a vacuum. Refraction by the atmosphere causes radar beams to bend in the direction of the earth. On the average the radar waves propagate along a spherical surface whose radius is 4/3 the radius of the earth. Refraction of the radar beam is greatest when the temperature of the air increases and the humidity decreases with elevation. Propagation parallel to the earth's surface is occasionally observed. The optimum elevation of the radar antenna is a function of the ambient wave conditions. As previously stated, the greatest contrast between wave crest and trough is obtained when the crest of one wave shadows the following trough but does not shadow the following crest. Variation of the antenna elevation to satisfy ambient conditions, however, cannot be accomplished very easily and it is not always possible to obtain an optimum value. Our most successful operations have been obtained with elevations between 20 and 40 meters.

## ADDITIONAL EXAMPLES OF RADAR WAVE DATA

Figure 8 shows the development of a wave field near Cape Cod, Massachusetts. All views were obtained with a maximum range of 925 meters. One can easily follow the gradual change in wave direction from SE to E and the increase in wavelength from midnight to 0900. The wind had been blowing from the SE at 15 m/sec for three hours before the first photographs and varied between 14 and 17 m/sec until noon. The wind had shifted to NE by 1324. Wave refraction near shore can be seen in the first two photographs.

Figure 9 shows even stronger evidence of refraction and the presence of at least two distinct wave trains. Two or more distinct wave trains can be identified in a large fraction of our radar photographs of the wave field.

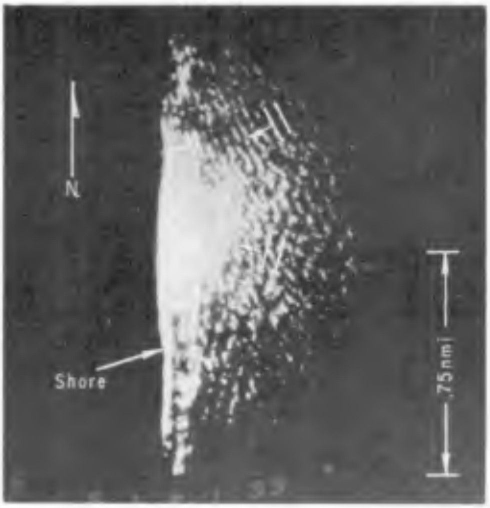



Figure 9. Two wave trains and refraction shown on the Radar Scope. Coast Guard Radar, Cape Cod, Mass., Jan. 8, 1976.

It is obvious that wavelength could be measured in many of the radar pictures and that the wavelength decreases as the shore is approached. By following a single wave train such as that indicated by the arrow in the two pictures shown in Figure 10, it is also possible to measure the phase speed of a wave. The straight vertical line on the image is an offshore breakwater. The elapsed time between these two pictures is 5.46 seconds. Two intermediate frames have been omitted.

One of the remarkable features noted in many of the radar photographs is the persistence of individual waves. It is often possible to identify a single wave crest from the time it appears at the edge of the scope until it breaks against the shore. The wave patterns are very consistent from frame to frame. There appear to be perturbations in intensity and direction along many wave fronts, but the wave pattern, taken as a whole, gives the appearance of continuity for the full distance over which the waves can be followed.

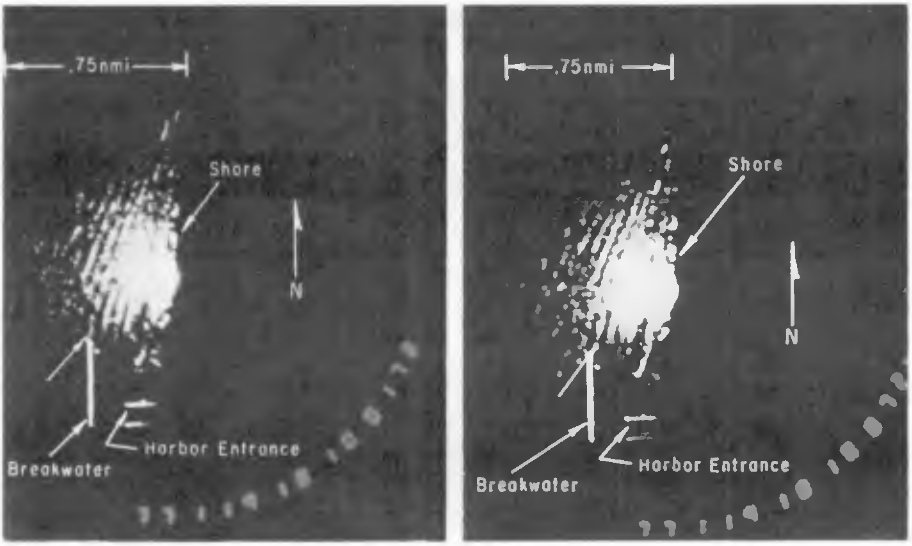



Figure 10. Two views of the radar scope separated by 5.46 seconds illustrating technique for measuring the phase speed of water waves from photographs of the radar scope. CERC radar Channel Islands Harbor, CA, April 29, 1977.

## ANALYSES OF THE PHOTOGRAPHS

The device which we have found to be most convenient for analyzing small quantities of radar film is shown in Figure 11. A 16 mm analytical projector is mounted to the left of the viewing screen. This projector can advance the film frame by frame, or automatically, at various speeds between 1 and 24 frames per second. A mirror is used to extend the light path and to form the image by rear projection on a ground glass screen. This arrangement permits the operator to review the film rapidly and select the best frame from each observation for evaluation. The protractor and ruler mounted over the display screen permits rapid determination of the direction of selected waves. When the only information wanted is the direction of the prominent wave trains at a selected point, evaluation of each observation requires only about a minute. In general, however, the radar record shows systematic variation of wave direction with location. A few frames may be selected for enlargement to reveal perspective about the wave field that is not provided by a network of wave sensors within a small area.

Figure 11. Device used for the analysis of radar film.

## VALIDATION

In order to illustrate the agreement between data obtained with this radar and by other techniques, a few samples of radar images coincident with other independent wave measuraments are presented in Table 1. The data were obtained during the West Coast Experiment which was a preflight test in preparation for SEASAT. The aerial photographs were obtained by NASA. Copies are available from U. S. Geological Survey EROS Data Center, Sioux Falls, South Dakota. The SAR images were provided by JPL. The procedure employed for analysis of SAR data has been described by Elachi (1978).

In interpreting the data in Table 1, it should be noted that the observations are not exactly synoptic and that the data appearing in any of the aerial photographs were collected within a few milliseconds.

A more extensive comparison of wave direction as determined by the CERC radar and a pressure gage array is in preparation. Publication by Mattie, Hsiao and Evans in the Journal of Geophysical Research sometime in 1979 is planned.

Table 1. Comparison of Information From CERC Radar Images With That Obtained With Other Direction Measuring Devices.

| Date (1977) | Time | Wave Direction at NUC | Wave Length | Wave Period (Sec) | Wave Direction | Wave Length | Wave Period (Sec) | |
|---|---|---|---|---|---|---|---|---|
| | | CERC RADAR | | | U2 AERIAL PHOTO | | | |
| March 14 | 11:30 | 283° ± 4° | 84 ± 11m | 8.6 ± .9 | 284° ± 2° | 80 ± 16m | 7.6 ± .9 | |
| | | 261° ± 4° | 168 ± 22m | 15.5 ± 2 | 264° ± 3° | 120 ± 16m | 10.2 ± 1 | |
| | | | | | 316° ± 2° | 40 ± 16m | 5.1 ± .5 | |
| March 29 | 11:00 | 282° ± 4° | 107 ± 21m | 9.2 ± 1.4 | 288° ± 2° | 89 ± 16m | 8.1 ± .9 | |
| | | 256° ± 4° | 160 ± 22m | 14.7 ± 2.2 | 257° ± 3° | 109 ± 16m | 9.4 ± 1 | |
| | | | | | 320° ± 2° | 30 ± 16m | 4.4 ± 1 | |
| | | | | | | SAR Direction Refracted to NUC | Wave Length | Wave Period |
| March 28 | 18:00 | 285° ± 4° | 136 ± 22m | 10.8 ± 1.5 | 286 | 283° | 138m | 9.4 ± .1 |
| | | 261° ± 4° | 105 ± 22m | 9.9 ± 1.4 | 259 | 262° | 208m | 11.5 ± .2 |
| | | 242° ± 4° | 182 ± 22m | 15.2 ± 1.5 | | | | |

1. Photographs of the radar scope and the corresponding portion of the aerial photograph are shown in Figure 1.

2. The CERC radar images and the U2 photos for March 14 and 29 were taken within a 10 minute period on each day. The CERC radar measurement at 18:00 hours on March 28 is an average of three images taken within $\pm$ 30 minutes of the SAR data. The 285° direction wave train appeared on all three images. The 261° and 242 direction trains each appear on only two of the three images used in the average.

3. Wave direction and period for SAR data were obtained from direction plots generated from the fourier transform. These were provided by JPL.

4. Periods estimates were obtained from wave length and depth through airy wave theory.

5. Wave length measurements were not all made at the same depth.

## SUMMARY AND RECOMMENDATIONS

It has been shown by means of examples that it is often possible to obtain useful images of the nearshore ocean wave field with X-band based radar. The physical principles involved in the use of radar to image the wave field have been simply described. A comparison of wave direction, wavelength and period estimates obtained with the surface based radar and similar data obtained by other more expensive means shows that the information obtained with radar is comparable in quality with similar data obtained by other means. The surface based radar does not provide wave height information. This paper is a summary of a longer report on this topic by Mattie and Harris (1979).

It is recommended that if only a single wave sensor is to be used at any location, a good gage whose record permits the computation of one dimensional energy spectra should be used. If two or more sensors can be utilized, the second should be an imaging radar which can provide direct information about the two-dimensional nature of the wave field most of the time.

## ACKNOWLEDGEMENTS

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