CHAPTER 6

WAVE MEASUREMENTS IN OPEN OCEAN

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I. INTRODUCTION

The ability to measure the wave spectra in the open ocean from a moving vessel has met with varying degrees of success. Each sensor to date has suffered in its performance due to environmental conditions or due to its physical placement aboard the vessel for measuring the unperturbed sea. This paper will discuss the utilization of a microwave sensor on a moving vessel for measuring the open ocean wave spectra. Employing microwaves, some of the limitations of other sensors are not experienced.

Tucker [1] developed the Tuckermeter for measuring the wave spectra from a moving ship by sensing changes in water pressure due to surface wave conditions. The Tuckermeter is placed below the water line and thus requires calibration for each wave frequency, ship speed, and depth. Since the sensor operates on pressure, it performs as a low pass filter and will not sense the higher frequencies.

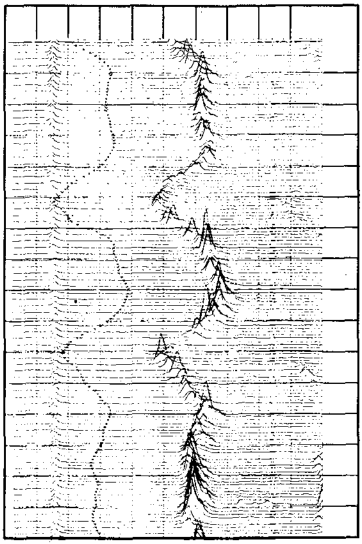
A microwave shipboard wave height radar sensor for measuring the ocean wave spectra was developed by the Naval Research Laboratory (NRL) and was installed on the S.S. McLean in February 1975 and its performance, design, and analysis of data for one data run will be discussed.

II. RADAR SYSTEM

A profile of the ocean waves by measuring their height variations can be used to calculate the ocean wave spectral components. A radar with high angular and range resolution is an ideal sensor for profiling the waves because the narrow antenna beam illuminates a small spot on the ocean surface and the narrow transmitted pulse resolves the vertical height of the waves.

A radar system employing these features was operated from a Coast Guard navigation tower to demonstrate its capability to measure ocean wave spectra as indicated by

Yaplee, et al. [2]. The radar system illuminated a one meter spot with a one-nanosecond pulse permitting a height resolution of 15 centimeters. The radar range measurements were compared with a wave staff mounted around the spot illuminated by the radar. A sample of the radar and the wave staff wave profiles are shown in Figure 1.



WAVE STAFF RADAR

PULSE DATA FROM THE
CHESAPEAKE LIGHT TOWER

WAVE HEIGHTS	1.524 meters
HOR. SCALE	0.762 m/division
VERT. SCALE	1 sec/division
DATE	June 19, 1970

Figure 1 Measurements from Chesapeake Light Tower

The encouraging results of the tower measurements led to a radar system designed to be operated from a ship to profile ocean waves. It was desirable to point the antenna beam out at a slight angle to avoid the ship's bow wake to measure the unperturbed sea. However, since the radar in this look angle is not viewing the nadir, the question arises as to what effect the phenomenon of wave foreshortening will be on the wave spectrum. Therefore, a set of tower radar measurements were made to profile the sea at different look angles between nadir and forty-five degrees. The wave spectra of the tilted radar and wave staff data were obtained and these spectra were almost identical at all look angles from nadir to forty-five degrees [3]. Therefore it was concluded that the results of the shipboard radar would not be compromised as the result of changing look angles.

The principal parameters for the shipboard radar are listed in Table 1. The functional block diagram of the radar system is shown in Figure 2.

TABLE 1

Parameters for Shipboard Radar

Wavelength	3 centimeters
Pulse Width	2 nanoseconds
Peak Transmitted Power	100 watts
Pulse Repetition Rate	10,000 per second
Antenna Diameter	61-centimeter parabola
Receiver Noise Figure	7 db
Equivalent Pulse Processing Rate	100 per second

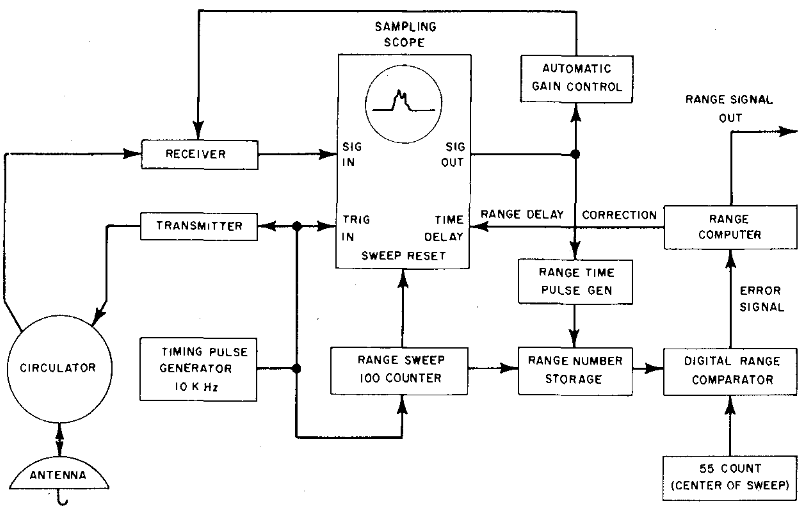
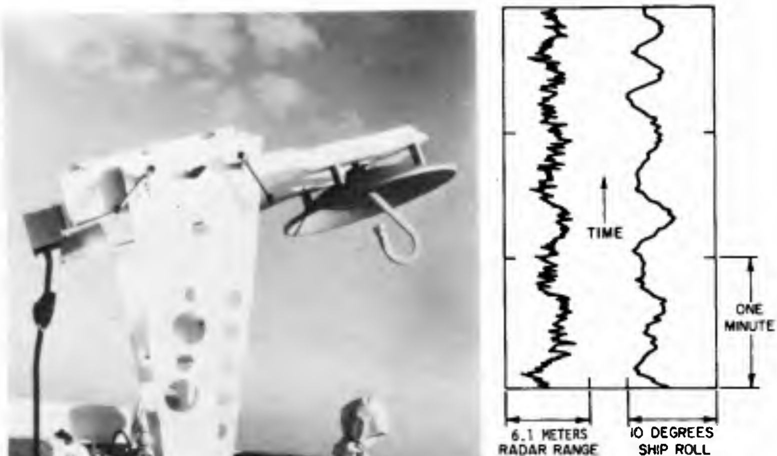


Figure 2 Radar System

The radio frequency components for the transmitter and receiver are mounted in a watertight enclosure on an antenna pedestal located about 23 meters above the ship's water line. The antenna is pointed abeam and tilted down and out about 15 degrees with respect to nadir. Figure 3 is a photograph of the antenna mounted on the starboard side of the ship's bridge and the figure to the right shows a sample of the measured data before processing.

SHIPBOARD WAVEHEIGHT RADAR ON-BOARD SS-McCLEAN



UNPROCESSED RECORDED DATA

Figure 3

The 10 Kilohertz (KHz) timing generator, shown in Figure 2, triggers the transmitter and synchronizes the receiver signal processing. The radio frequency transmissions consist of 2-nanosecond wide pulses at the 10 Gigahertz (GHz) carrier frequency with a peak power of 100 watts and with a pulse repetition rate of 10,000 per second. The radar pulses reflected by the ocean surface are amplified in the receiver to a usuable level. An envelope detector following the amplifier results in a 2-nanosecond wide video pulse.

Processing the 2-nanosecond wide pulses requires circuitry in the system with bandwidths of 500 Megahertz (MHz). It is desirable to operate at a lower bandwidth where components are more easily used and obtained. By using a sampling scope for display and signal processing, it is possible to make this bandwidth transformation to an equivalent video pulse that is 200 microseconds wide or a bandwidth of 5 KHz. Thus the use of standard low speed logic circuits can be used for signal processing resulting in a simpler and more reliable system. The principle of operation of a sampling scope is well known and will not be discussed. See references [4, 5, 6] for the particular scope used in this radar.

III. EXPERIMENTAL TESTS

The nanosecond radar is located starboard on the bridge of S.S. McLean and adjusted to view the ocean at a look angle of 15 degrees from nadir and away from the bow wake. On February 6, 1975, while the ship was underway from Elizabeth, New Jersey to Portsmouth, Virginia, simultaneous ocean surface data were taken by the shipboard radar while an airborne laser profilometer and airborne nanosecond radar were measuring the same seas. The object of this effort is to establish the validity of the shipboard measured data.

The shipboard radar data were recorded at 30 minute intervals starting at 8:20 A.M. EST on February 6, 1975 and ended at approximately 2:00 P.M. of the same day. Each file of data started with about a minute of zero level setting and followed by a minute of calibrations. The ship was travelling at 14.9 meters per second at 214 degrees heading. Approximately 9:26 A.M. the aircraft intercepted the ship's track at 38°3' N in latitude and 74°41' W in longitude. Airborne data were recorded at 152.4 meters and at 304.8 meters altitude in the immediate vicinity of the ship's path. At 152.4 meters altitude, a laser profilometer [7] and an airborne nanosecond radar were used to profile the ocean surface. At 304.8 meters altitude, NRL's airborne nanosecond radar was operated in the wave spectrometer mode. Aircraft data were recorded continuously at intervals of about 90 seconds as the aircraft was flying at 75.2 meters per second ground speed. Exact coincidence of data taking was not possible and comparison of the data is based on approximate times from the ship and aircraft logs.

IV. ANALYSIS

The dynamics of the two platforms (aircraft and ship) while recording ocean surface data was significantly different. In addition to their peculiar motion characteristics, the data were recorded in different manners. One, is continuously in analog and the other, is intermittently and digitally. To effect a better comparison of the data, it was necessary that the data be reduced to some common base.

The analog shipboard data were recorded in real time, and then sampled and digitized at 8 Hertz (Hz) off-line. This digitizing rate was a compromise, taking into account the longest ocean wavelengths expected to be experienced by the ship and the storage capacity of in-house computers to process the data. The aircraft data were digitized at 90 Hz rate in real time but was utilized at 15 Hz rate off-line. Again a compromise was made with the high frequencies which were not overly significant being truncated and at the same time trying to maintain equal spatial resolution with the shipboard data.

The largest amount of dynamic motion or movement other than forward velocity of a ship is its roll. In Figure 3 was shown a sample of the shipboard radar output and the output of the roll sensor. The magnitude and the period of the roll which affect the determination of the true ocean wave spectra must be removed before any real analysis can be conducted. However other motions also need to be corrected for unless they become second order in magnitude and can be ignored.

By assuming rigid body motion the geometry of the radar aboard ship is shown in Figure 4. The upper figure

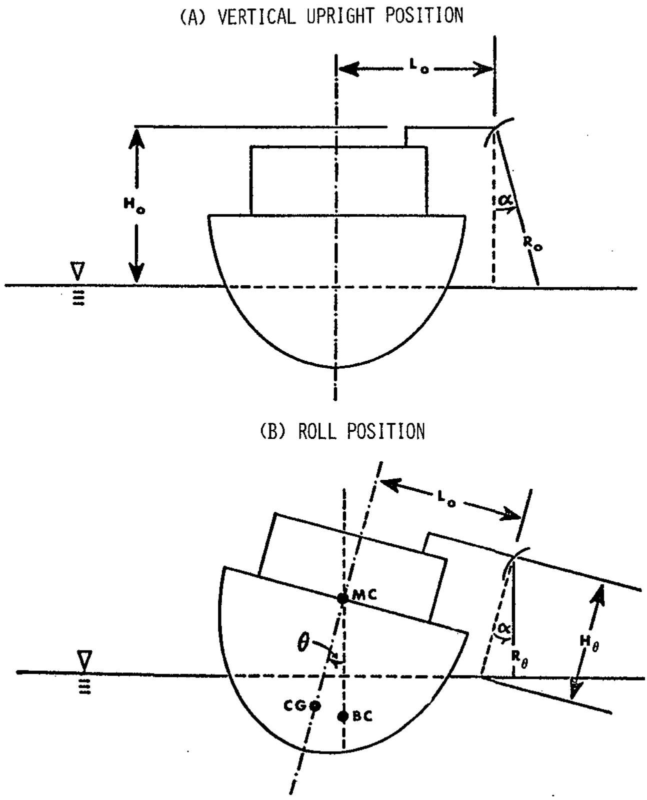


Figure 4 Rigid Body Motion due to Roll

shows the direction of the ship moving into the paper and in still water thus remaining in the upright position. The radar measures $R(t)$, the distance from the radar to the surface of the water at an angle α with respect to the vertical. It is the magnitude and frequency of these radar distance variations that yields information for determining the ocean spectra. As mentioned earlier, ship motions, particularly roll, affects the magnitude of these variations yielding an erroneous wave height change. In the lower illustration of Figure 4 is shown an instantaneous roll position that the ship can assume. In this situation, the change in radar distance $R(t)$ is not due to waves but is due to the ship's motion and the radar then measures the distance R_θ instead of R_o. The magnitude of the change in R_o to R_θ needs to be determined. Symbols used in Figure 4 for determining this change are defined as

H_o - distance from radar antenna to water surface, in the direction of ship's symmetric axis, and 0 degrees roll angle; 23.2 m for H_o in these calculations;

H_θ - distance from radar antenna to water surface in the direction of ship's symmetric axis, caused by θ degrees roll angle;

L_o - horizontal distance of radar antenna from center of gravity of the ship at 0 degrees roll angle; 12.2 m for L_o in these calculations;

θ - angle of roll; positive in clockwise direction, from vertical upright position, by looking into the direction of ship's heading;

R_o - radar distance of 0 degrees roll angle;

R_θ - radar distance at θ degrees roll angle;

α - look angle of radar antenna, 15 degrees;

CG - center of gravity of the ship;

MC - metacenter of the ship;

BC - buoyant center of the ship.

From the Law of Sine's, it can be shown that

$$R_\theta = (H_o - L_o \tan\theta)\,\frac{\cos\theta}{\cos(\theta - \alpha)} \qquad (1)$$

Using Equation (1) the values for $R_\theta(t)$ can be determined from H_o, L_o, α, and θ which can be obtained from the ship's roll sensor.

Using $R_\theta(t)$ in the radar distance measurements, the following relationship can be established:

$$R_R(t) = R_\theta(t) - \zeta(t)\sec(\alpha-\theta) + \Delta R(t) \quad (2)$$

where

$R_R(t)$ - the radar distance measurement to the water surface;

$\zeta(t)$ - the instantaneous apparent wave height, positive in upward direction from the mean sea surface;

$\Delta R(t)$ - the radar distance changes due to ship motion other than roll.

It is worth noting that, as it has been shown by Hammond, et al. [3], for $|\alpha-\theta| \leq 45°$ the term $[\zeta(t)\sec(\alpha-\theta)]$ will indeed give the correct ocean wave spectrum as calculated from $\zeta(t)$. Thus, for simplicity in data processing, Equation (2) can be approximated as

$$R_R(t) = R_\theta(t) - \zeta(t) + \Delta R(t) \quad (3)$$

This relationship shows the effect of ship motion in conjunction with wave motion and their effect on the radar range measurements, but assumes that any flexural and torsional motions which change the distance between the radar antenna and the center of gravity are negligible. All other motion changes such as yaw, pitch and heave, etc. are combined into $\Delta R(t)$. The term of interest, $\zeta(t)$, in describing the sea surface, is small in magnitude and it modulates the distance $R_R(t)$ which is large. The shipboard equipment was designed only to record this modulation and as a result a large distance bias, D, remains.

Let

$$R_A(t) = R_R(t) - D \quad (4)$$

where $R_A(t)$ is called the relative radar range measurement and D is a constant. Substituting Equation (3) into Equation (4),

$$R_A(t) = R_\theta(t) - \zeta(t) + \Delta R(t) - D\ . \quad (5)$$

Rearranging the terms

$$R_\theta(t) - R_A(t) = \zeta(t) - \Delta R(t) + D. \tag{6}$$

Define

$$R_1(t) = R_\theta(t) - R_A(t) \tag{7}$$

where $R_1(t)$ is the relative radar range without the effect of ship's roll. Rearranging the terms

$$\zeta(t) = R_1(t) + [\Delta R(t) - D] . \tag{8}$$

This results in $\zeta(t)$ describing the sea surface variations. There still exist $[\Delta R(t) - D]$ which has not been accounted for because D is basically a DC term. This however can be removed by filtering the data. The term $\Delta R(t)$, as defined, consist of all the other ship motions affecting the radar range measurements. The high frequency components of $\Delta R(t)$ are of such low magnitude that their effects on the wave measurements are negligible, whereas the low frequency components can be effectively removed with a high pass filter. In the reference by Linnette [8] the filtering process employed to remove the $[\Delta R(t) - D]$ term is discussed. After the process $\zeta(t)$ still contains a Doppler term and it must be taken care of before it is possible to study the ocean surface characteristics.

The term $\zeta(t)$ describing the amplitude variations of the waves as the radar profiles the surface while the ship is underway includes a Doppler term. Due to the velocity of the ship and the Doppler effect, the waves encountered are foreshortened. Thus the wavelengths measured are not the true ocean wavelength but an apparent wavelenth. If the radar's instrumentation had incorporated a coherent radio frequency signal, the effect of the ship's velocity can, by appropriate instrumentation, be subtracted directly. Since this is not the case, it is necessary to correct the apparent spectra to a true spectra. In order to accomplish this, it is no longer possible to operate in the time domain but one must resort to working in the wave number or frequency domain.

It is straight forward to evaluate the apparent wave number spectrum, $\psi_A(k_A)$, from the foreshortened wave height, $\zeta(t)$, where k_A is the apparent wave number because of the Doppler effect. Neglecting the effect of the direction of propagation of the wave component under consideration, it can be shown, in Appendix, that $\psi_A(k_A)$ can be transformed to $\phi(\sigma_T)$ where $\phi(\sigma_T)$ is the true wave frequency spectrum and σ_T is the true wave frequency. The spectra shown in the results were calculated by using Equation (10) in Appendix.

Significant wave heights were determined by employing equation (9), [ref. 9],

$$H_{1/3} = 4\sqrt{E} \tag{9}$$

where $H_{1/3}$ is the significant height and E is the total energy of the waves.

V. SPECTRAL BANDWIDTH WITH SPECTRAL RESOLUTION

The 0.61-meter parabolic antenna illuminates a footprint [10] about 0.95 meters in diameter at a radar range of 24.4 meters. This footprint size can only resolve wavelengths longer than 1.83 meters which is equivalent to an apparent cutoff frequency of 0.908 Hz. The true cutoff frequency is 0.358 Hz after removing the Doppler effect. Translating this true cutoff frequency into a true wave period results in wave period of not less than 2.8 seconds. The high pass filter, discussed earlier, removes waves with periods longer than 7 seconds in the data. The wave spectra shown in the results are calculated for the wave period window of 2.8 to 7 seconds.

If different spectral bandwidths are desired, the upper frequency bound can be raised by increasing the antenna size. The lower frequency bound can also be extended but this requires removing the ship's motions without the use of high pass filter. The analysis requires ship motion sensors at the site of the antenna to record the actual excursions of the antenna. In this manner it is possible to resolve the longer wavelengths of the spectra.

VI. RESULTS

Wave spectra from the shipboard measurements are presented in Figures 5 to 12. The significant wave heights for files 1 to 8 of the data, respectively, are 2.10, 2.22, 2.23, 2.17, 2.16, 1.99, 1.99, and 1.94 meters. Since the sea was not in steady state conditions, it is not possible to make comparison with the Pierson-Moskovitz spectrum [11]. Figure 13b shows the analyzed results from the airborne measurments made by laser profilometer and the nanosecond radar. Laser profilometer registered 1.84 meters and the nanosecond radar registered 1.43 meters as the significant wave height based on data taken at the altitude of 152.4 meters. At the altitude of 304.8 meters, operating the nanosecond radar in wave spectrometer mode

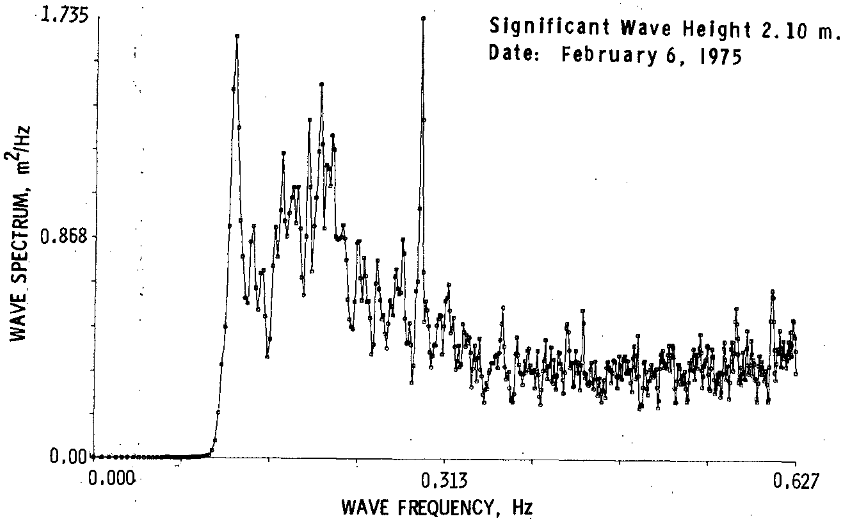


Figure 5 Wave Spectrum from File 1 of the Shipboard Radar Measurements

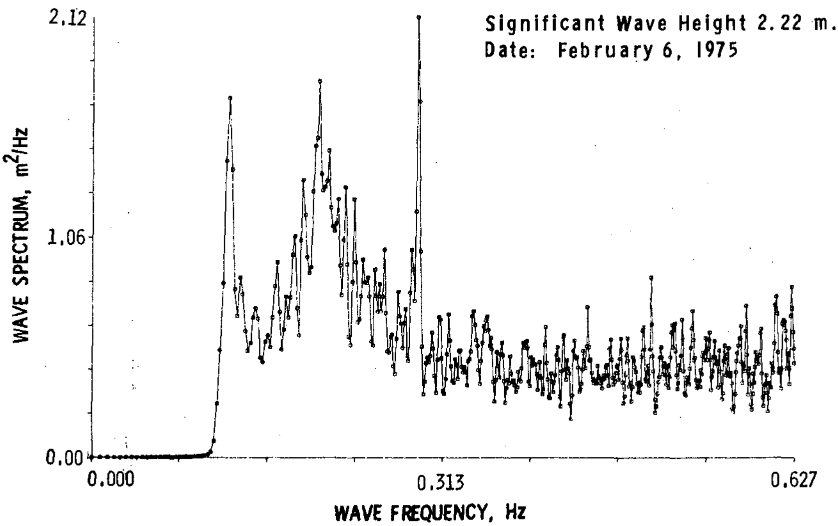


Figure 6 Wave Spectrum from File 2 of the Shipboard Radar Measurements

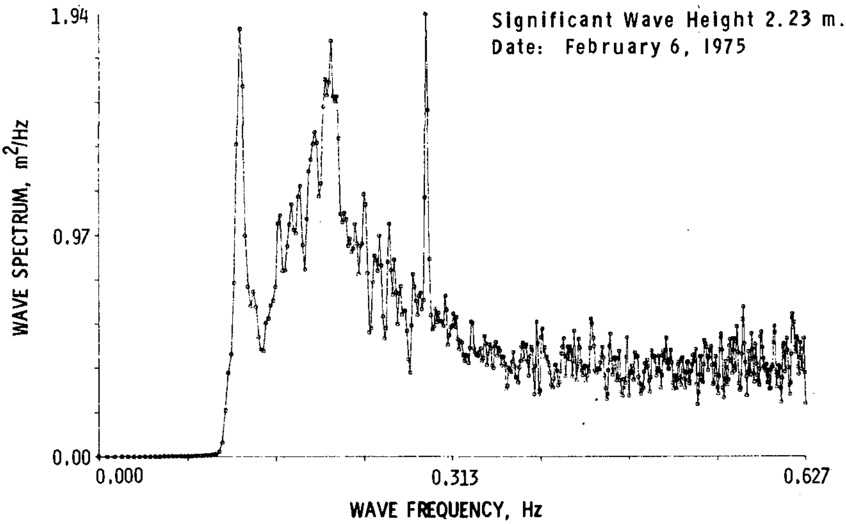


Figure 7 Wave Spectrum from File 3 of the Shipboard Radar Measurements

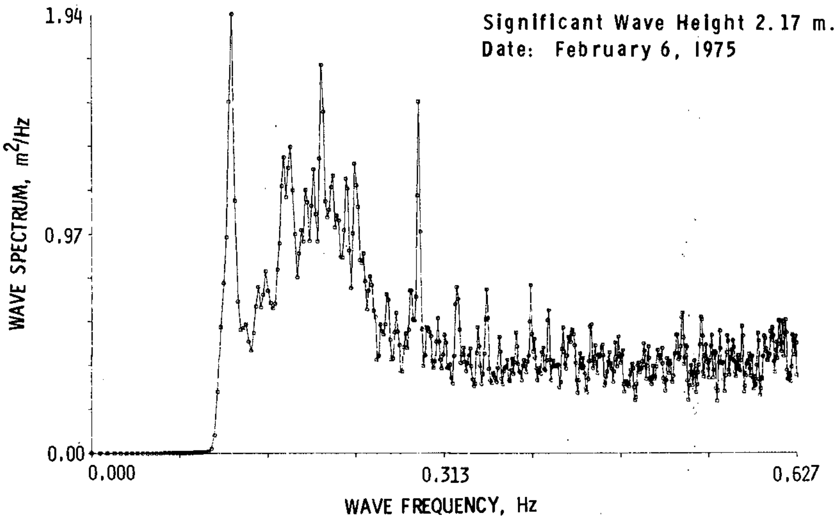


Figure 8 Wave Spectrum from File 4 of the Shipboard Radar Measurements

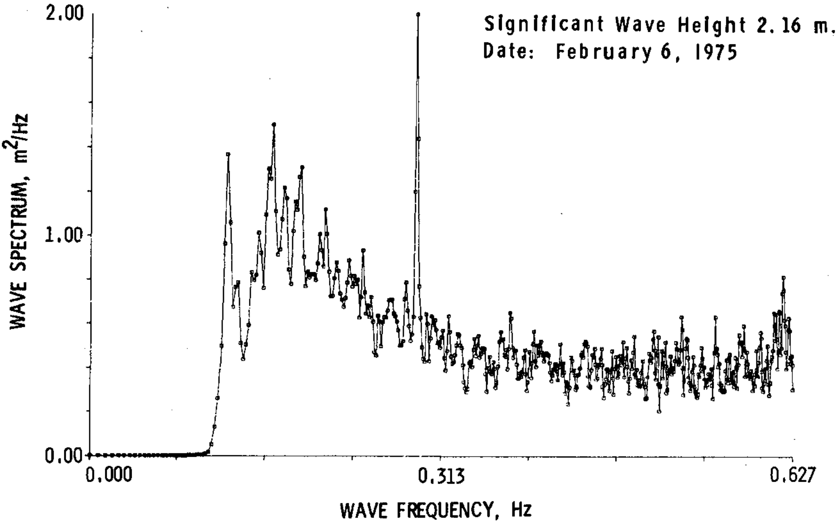


Figure 9 Wave Spectrum from File 5 of the Shipboard Radar Measurements

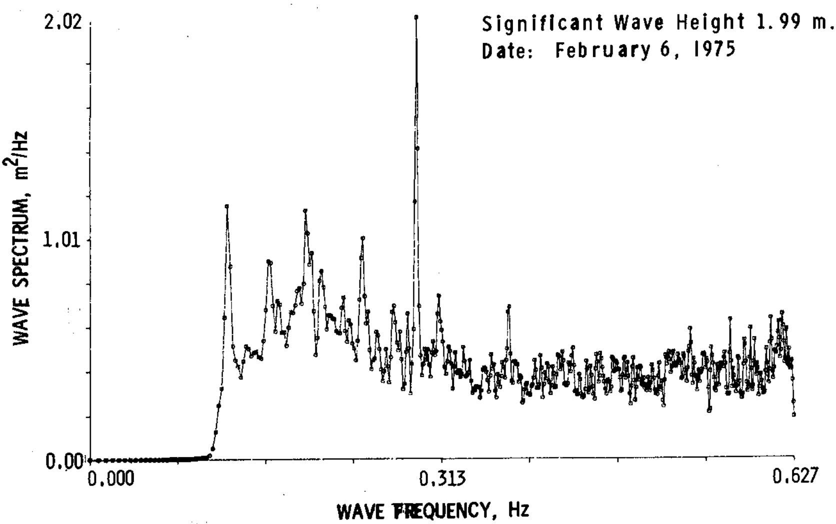


Figure 10 Wave Spectrum from File 6 of the Shipboard Radar Measurements

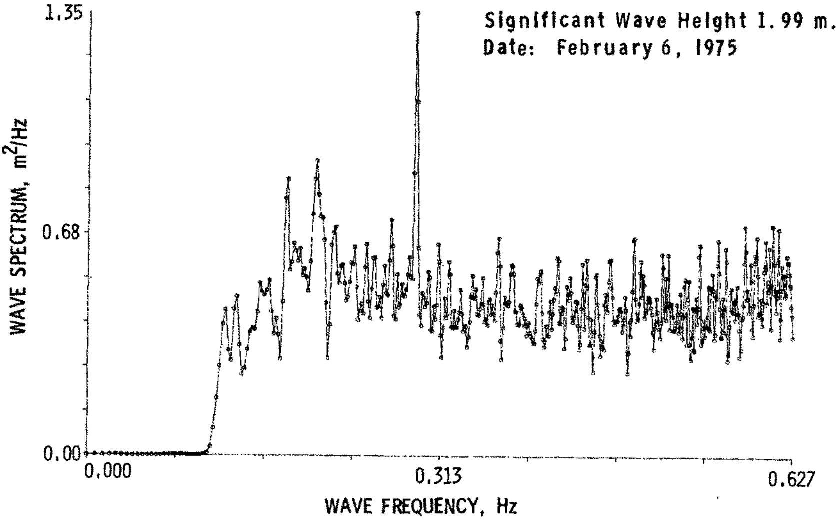


Figure 11 Wave Spectrum from File 7 of the Shipboard Radar Measurements

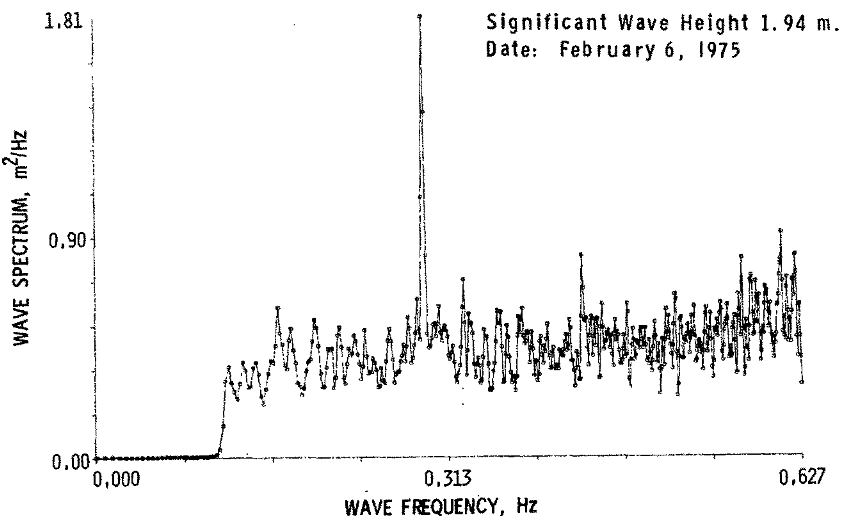


Figure 12 Wave Spectrum from File 8 of the Shipboard Radar Measurements

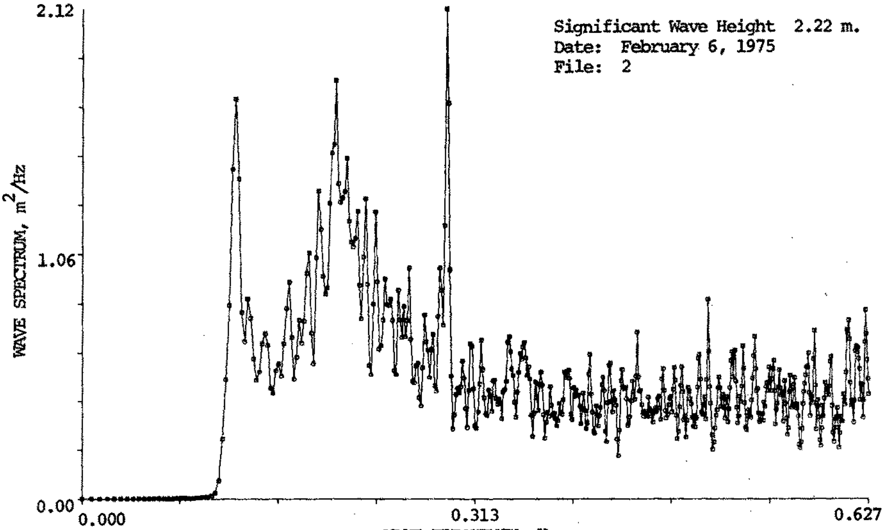


Figure 13a Shipboard Radar Measurements

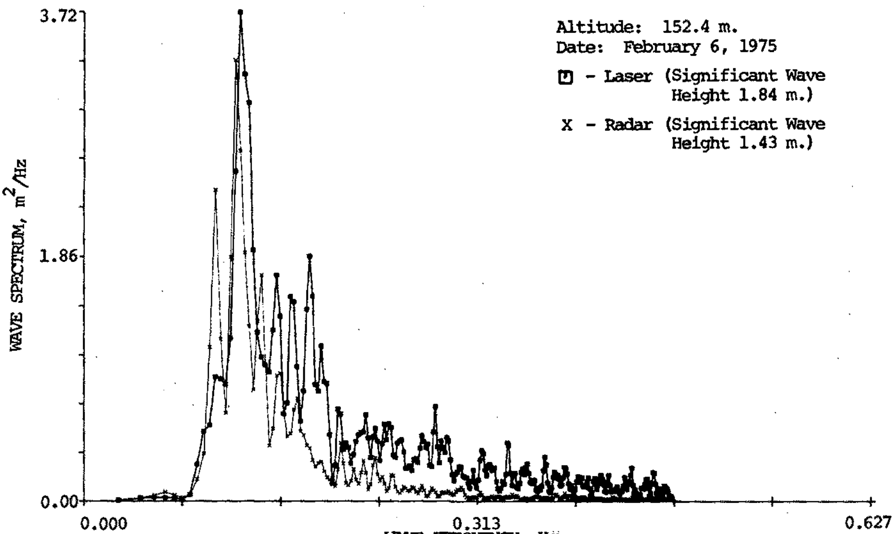


Figure 13b Airborne Measurements

yielded significant wave height of 2.01 meters. All airborne measurements were made in the vicinity of the ship during part of the time the shipboard radar was recording data for file 2. Accordingly Figure 13b, of the airborne measurements and Figure 6 of the shipboard measurements are combined in Figure 13 for comparison. The shapes are very similiar. The significant wave heights of all the measurements are shown in Figure 14. The data are in reasonable agreement, expecially when time coincidence of the data is not possible and the aircraft covers such large area about the ship.

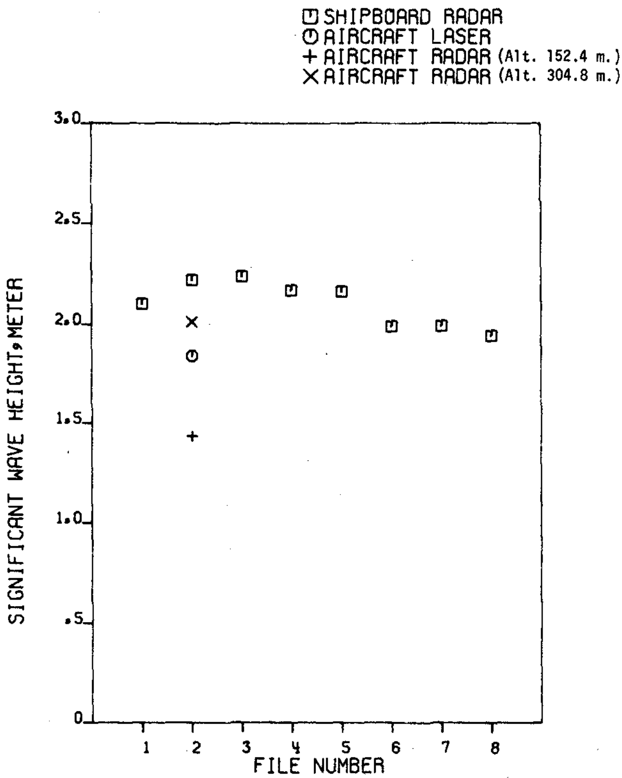


Figure 14 Significant Wave Height Measurements, Feb. 6, 1975

VII. DISCUSSIONS

In any system, one can always find areas for improvement, and this radar is no different. After conducting the analysis of the data, several points should be noted.

1. Future radars for this purpose should record the total range as well as the range modulation by the waves. The advantage is to enable one to make absolute corrections for the ship motions; otherwise, only relative corrections can approximately be made for ship motions, and still leave the DC offset as an unknown quantity.

2. A shipboard radar measurement of wave spectra permit viewing the undisturbed area of the sea. With better time and spatial resolution and by employing accelerometers on the antenna, the ship motion effects can be removed directly. Three accelerometers and three angular sensors at the site of the radar are recommended for future measurements.

3. Shipboard radars can operate in all types of weather, twenty-four hours a day.

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APPENDIX

The changing pitch of the sound from, say, a fire-engine siren as it moves by at high speed is familiar to all; this effect, the Doppler effect, is one of the most obvious influences of relative motion between the source and the medium. Similarly, if a wave train of ocean waves propagating at the surface of the ocean is observed by a radar in motion, a Doppler change of frequency also will result. The Doppler effect is purely a kinematic phenomenon and can be evaluated without resorting to dynamical equations of wave motion. By kinematic argument [12], it can be shown that

$$\sigma_T = \sigma_A + \frac{\sigma_T^2}{g} \cdot v \cos\xi \tag{10}$$

where

σ_T - true wave frequency, $2\pi/T$ or ck_T;

k_T - true wave number, $2\pi/\lambda_T$;

λ_T - true wavelength;

σ_A - apparent wave frequency;

k_A - apparent wave number, $2\pi/\lambda_A = (\sigma_T{}^2/g) + (\sigma_T/v \cos\xi)$;

T - wave period;

λ_A - apparent wavelength;

ξ - angle between the ship's heading and the direction of the wave propagation;

v - speed of the ship;

c - phase speed of wave component;

g - gravitational acceleration.

By employing Equation (10) and Jacobian transformation from the apparent wave number domain to true wave frequency domain in Euclidian space yields

$$\phi(\sigma_T) = \frac{2\sigma_T}{g} \left(1 + \frac{1}{2} \frac{g}{\sigma_T \; v \cos\xi}\right) \psi_A(k_A) \tag{11}$$

where $\phi(\sigma_T)$ is the wave frequency spectrum and $\psi_A(k_A)$ is the apparent wave number spectrum.

Since data is already digitized, the equations are modified to take into account that the information is sampled at some rate and not continuous. Thus following changes are incorporated to perform the calculations:

by defining

M - total number of lags;

J - lag number;

Δx - distance between observations; $v \cos\xi \, \Delta t$;

Δt - time between observations, then

$$k_A(J) = \frac{J}{M \, \Delta x} = \frac{\sigma_T^2(J)}{g} + \frac{\sigma_T(J)}{v \cos\xi}$$

and also

$$\sigma_T(J) = -\frac{g}{2v \cos\xi} + \left[\frac{g^2}{4(v \cos\xi)^2} + \frac{g\pi J}{M \, \Delta x}\right]^{1/2}$$

from Equation (10).

REFERENCES

1. M. J. Tucker, "A Shipborne Wave Recorder," Transactions, Institute of Naval Architects, XCVIII, 236-250, London, 1956.

2. B. S. Yaplee, A. Shapiro, D. L. Hammond, B. D. Au, and E. A. Uliana, "Nanosecond Radar Observations of the Ocean Surface from a Stable Platform," Institute of Electrical and Electronics Engineers, GE-9(3), 170-174, 1971.

3. D. L. Hammond, E. A. Uliana, K. J. Craig, and B. S. Yaplee, "Ocean Wave Height Measurements with a Shipboard Radar System," Proposal submitted to U. S. Coast Guard (FSP-13/72), Naval Research Laboratory, 1971.

4. "Dual Trace Sampling Unit, Type 3S-1," Instruction Manual, Textronix, Inc.

5. "Oscilloscope, Type 568/R568," Instruction Manual, Textronix, Inc.

6. "Programable Sampling Sweep Type 3T5," Instruction Manual, Tektronix, Inc.

7. Spectra-Physics Geodolite 3A Laser Profilometer.

8. H. M. Linnette, "Statistical Filters for Smoothing and Filtering Equally Spaced Data," Defense Documentation Center, NEL Report 1049, 1961.

9. G. Neumann and W. J. Pierson, Jr., Principles of Physical Oceanography, Prentice-Hall, Inc., Englewood Cliff, N.J., 1966.

10. M. L. Skolnik, Introduction to Radar Systems, McGraw-Hill, Inc., 1962.

11. W. J. Pierson, Jr., and L. Moskovitz, "A Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S. A. Kitaigorodskii," J. Geophysical Research, 69 (24), 5181-5190, 1964.

12. O. M. Phillips, The Dynamics of the Upper Ocean, Cambridge University Press, 1966.