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HIGH-RESOLUTION RADAR

PART IV - SEA CLUTTER ANALYSIS

[UNCLASSIFIED TITLE]

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INTRODUCTION

One of the properties of a high-resolution, millimicrosecond, pulsed radar is its ability to display targets separated in range by several feet. With such a radar, sea clutter has been observed to be made up of a series of discrete echoes. This report is concerned with some of the statistical properties of these discrete echoes. Data were taken on a field trip with a millimicrosecond radar at an ocean site one mile north of Boca Raton, Florida.

ELECTRONIC EQUIPMENT

The radar used for this study was an experimental short-pulse model designed and built by the High Resolution Branch of the Radar Division, Naval Research Laboratory. Some of the properties of the radar are listed below:

Frequency	9375 Mc
Pulse length	0.008 μsec
Peak power	15 kw
RF amplifier	X-band TWT
I-F amplifier	2 S-band TWT's
I-F bandwidth	200 Mc
Video bandwidth	100 Mc
Antennas	6-foot (section of a paraboloid of revolution) horizontal beam-width: 1.2 degrees
	8-foot (full paraboloid of revolution) beamwidth: 0.9 degree
PRF	1800 pps
Display	A-scope, B-scope, delayed sweep, range-gated tape recorder
Dynamic range	20 db

METEOROLOGICAL AND OCEANOGRAPHIC EQUIPMENT

The following systems were used to present a history of wave heights and direction and wind velocity and direction. Motion-picture equipment was installed to take simultaneous records of the area of the ocean under study in the radar tests. For tests conducted in daylight, a camera looking at the radar-illuminated area was motor driven in frame synchronism with a camera looking at the radar echoes. The topographical movies of the waves were used along with the recorded optical sightings to determine wave-front directions. Wind-measuring equipment consisted of an AN/UMQ-5 wind gage. The sensing element for this wind gage was located on top of the radar tower 130 feet above sea level. This tape-recording instrument was operated continuously day and night, its tape output indicating both velocity and direction for the local wind.

Wave-measuring equipment consisted of a 25-foot model of the Beach Erosion Board's step-resistance ocean wave gage. The sensing element, or staff, was pile mounted in 25 feet of water at a point 400 yards from the beach. This instrument was also a tape-recording unit, and was operated continuously in such a manner as to sample the waves for a 2-minute period each hour. In addition to the automatic operating features of 2 minutes per hour, manual controls permitted simultaneous operation of the wave gage with the radar for specific tests, and for many of these tests the simultaneous results were recorded on the same dual channel tape (Fig. 1).

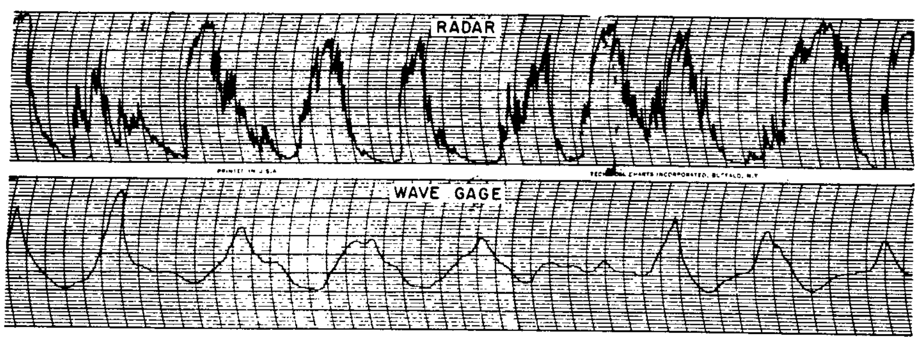


Fig. 1 - Simultaneous radar and wave-gage patterns

OPERATIONAL PROCEDURE

The radar was tower mounted on an ocean beach in such a manner as to permit operation with antenna heights of 27 to 113 feet and to permit approximately 180 degrees of azimuth scan when looking at the ocean. Study of radar sea clutter was thus possible for grazing angles from 1/4 to 6 degrees and from near trough aspects around to head-on aspects of the wave fronts. One of the objectives of this high-resolution radar field trip was the study of some of the basic back-scattering properties of rough sea water.

The majority of the tests were conducted looking into oncoming waves to show characteristics of radar sea clutter while azimuth, range, polarization, and grazing angle were varied. (Since the radar equipment was on the beach, and the waves terminated at the beach, it was not possible to look at the back of waves.) As many different sea states were studied as weather conditions and time permitted. Ranges from just beyond the surf out to 3000 yards were used for these radar clutter studies. Simultaneous records were made

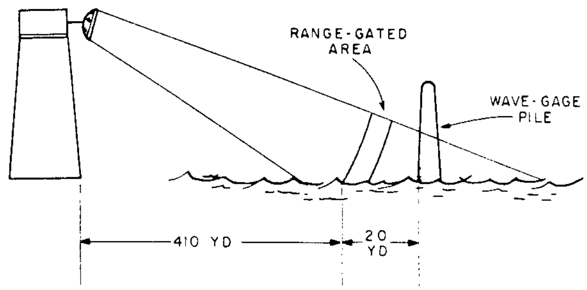


Fig. 2 - Orientation of radar tower and wave-gage pile

of wave profile and range-gated radar echoes. This report is chiefly concerned with those tests conducted on waves passing the pile-mounted wave gage located 430 yards from the tower (Fig. 2).

The use of TWT amplifiers in the radar receiver assisted in the process of range-gating the receiver gain. Normal operation calls for zero bias on the TWT control grid. Operating the grid at -50 volts made it possible to gate the receiver into full gain and out again for a period of time roughly equal to the length of the short pulse used in the transmitter. Thus at the 430-yard range of the wave gage, the effective illuminated area was approximately 22 feet wide and 5 feet deep.

Suitable modifications of the video output circuit permitted its use as an input to one channel of the dual-channel Brush tape recorder. The wave gage supplied the signal for the other channel of this recorder. Independent controls permitted simultaneous or separate operation of these two channels. The sampling time chosen for most of the tests was 2 minutes and the tape speed used in the recorder was 5 mm per second. Calibration marks, provided by a test signal generator, were inserted on the tape for each series of tests conducted. Full-scale deflection on single Brush tape was 50 mm and represented the 25-foot range of the wave-gage staff. For the dual tape records, the signal was amplified by a factor of 2, giving a scale factor of 10 feet for full-scale deflection of 40 mm.

DATA REDUCTION

A preliminary analysis of the Brush tape data consisted of a visual study of the correspondence of radar echo variations with wave slopes, or contour characteristics. Since this was not too conclusive, the data study progressed to an analysis of the first-probability features of the radar echo variations; that is, the percent of time was calculated for which the echo equaled or exceeded specified values of power. A curve tracer having a series of sequentially triggered mechanical counters was used, with each counter set to trigger at progressive power levels as the curve was traced. The reference signal-generator calibration runs were used to set the triggering levels for the counters.

Final processing of this analog-type data from the radar and wave gage consisted of its transformation into digital form. An "Oscar" (Model J) data reader, built by Benson-Lehner Corporation, was available for this job. This reader could be used to record sequentially both functions of the dual tape record for each 1/5-second time interval in the chosen 1-minute sample. The two digital answers were listed beside the time interval number, or line number, by an electric typewriter, while a tape-cutting unit recorded the same information in proper form for use as electronic computer input. The processing of a

1-minute sample of dual tape data, giving two 300-number functions, required from 15 to 20 minutes on the data reader. A total of 130 1-minute samples were processed in this manner for computer analysis.

In cooperation with the Applied Mathematics Branch at NRL, the Narec digital computer was programmed for specified studies of these two functions, the radar function A_1 and the wave-gage function A_2. The following list indicates the nature of the programming:

First differences for both functions

Average value of A_2 in relative units

Average value of A_1 in watts

Standard deviation for both functions

Percentage of time above preselected levels for A_1

Autocorrelation of both functions

Crosscorrelation, A_1 to A_2

Power spectrum of both functions

Fifteen of the 130 sets of answers proved defective on the first processing, but minor corrections to the "Oscar" cut-tapes corrected all of the defects for a second processing of these by Narec. Print-out time of the answers was in general greater than Narec computation time, since the computer first supplies the answers in coded tape.

One of the choices made in "Oscar" data reading was to record the radar function in terms of the signal-generator calibration levels of power. Hence, when this function was used by the computer to derive the power spectrum, a power series was used as the base rather than a voltage series. Spot tests indicated that the error introduced for the range of data in question was slight, so no effort was made to reprogram the computer for corrective processing on this score.

In the process of programming the computer for correlation and spectrum coefficients, arbitrary decisions were made as to sampling rate and sample length of the data to be analyzed. These decisions were made from a rough guess that the periods of interest in the raw data would be from 3 to 8 seconds. The 1/5-second sampling rate selected in digitizing the analog data was considered short enough to disclose the 3-second components and a correlation integral limit of 40 delay units (1/5 second each) was set to show the 8-second components. One-minute samples were selected as standard for computer inputs, giving a function of 300 digits for both the radar and wave-gage data.

The autocorrelation coefficients were determined by the computer as the average lagged-cross-product of numbers in the 300-digit input function with opposite numbers in the image of this function. By varying the delay between the function and its image from 0 to 8 seconds in 1/5-second increments, a total of 41 correlation coefficients was determined for each 1-minute sample. To derive the crosscorrelation coefficients, the radar function was used opposite the wave function, in place of the image function used to get the autocorrelation. As the delay was increased in this cross multiplication process, the odd end-numbers exposed at each end were dropped, thereby losing information. For this reason, the 8-second limit was set as a reasonable maximum for a 1-minute sample of data.

Since the power spectrum is the Fourier (cosine) transform of the correlation function, the computer was programmed to use the 41 correlation coefficients derived for each data sample to calculate 10 power-spectrum coefficients for each sample. The number 10 was selected here to insure equivalence of the range of frequencies covered when going from correlation function to power spectrum (the range for power spectrum was 1/16 cps to 1/1.6 cps).

RESULTS

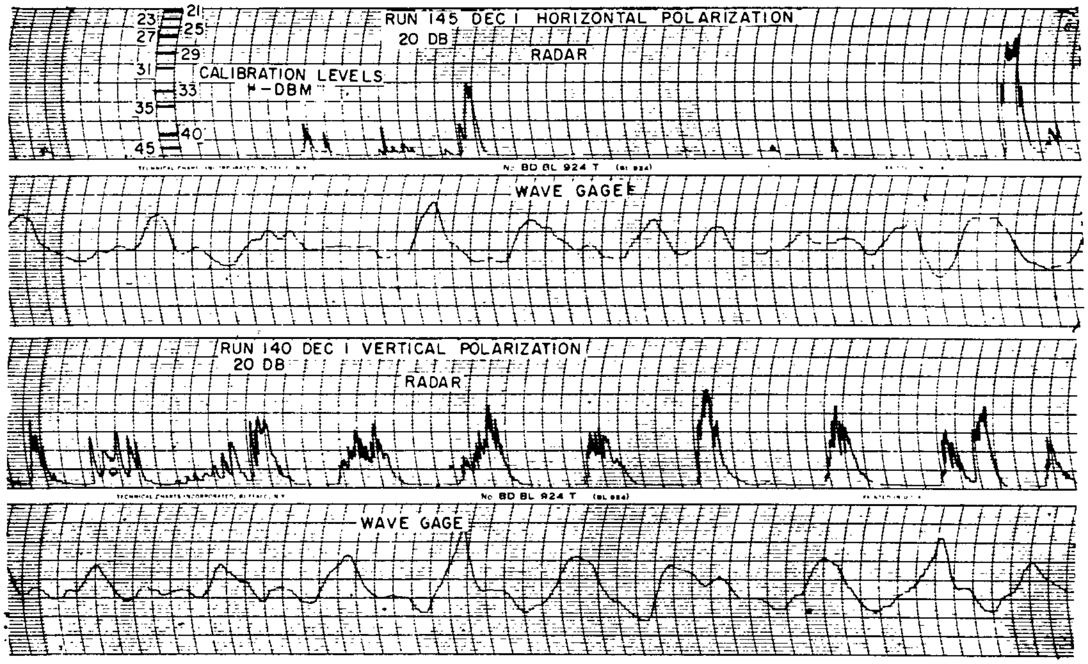
Dual Tape Records

The first approach to data reduction consisted of a visual survey of the original data in Brush tape form. Figure (3a) shows a comparison of a 1-minute vertical-polarization sample with a 1-minute horizontal sample. The wave gage for this test was amplified by a factor of 2, giving a full-scale deflection of 40 mm for 12.5-foot waves, or 3.2 mm per foot. Calibration marks from the test signal generator are included for reference. Both runs had 20-db attenuation in the receiver signal path and both had about the same wave roughness. Figure (3b) shows portions of runs with 10 db in the receiver signal path instead of 20 and with the wave pattern for the vertical test showing a finer structure than that for the horizontal. Figure (3c) compares the two polarizations with similar wave patterns but with 10-db receiver attenuation for vertical and none for horizontal.

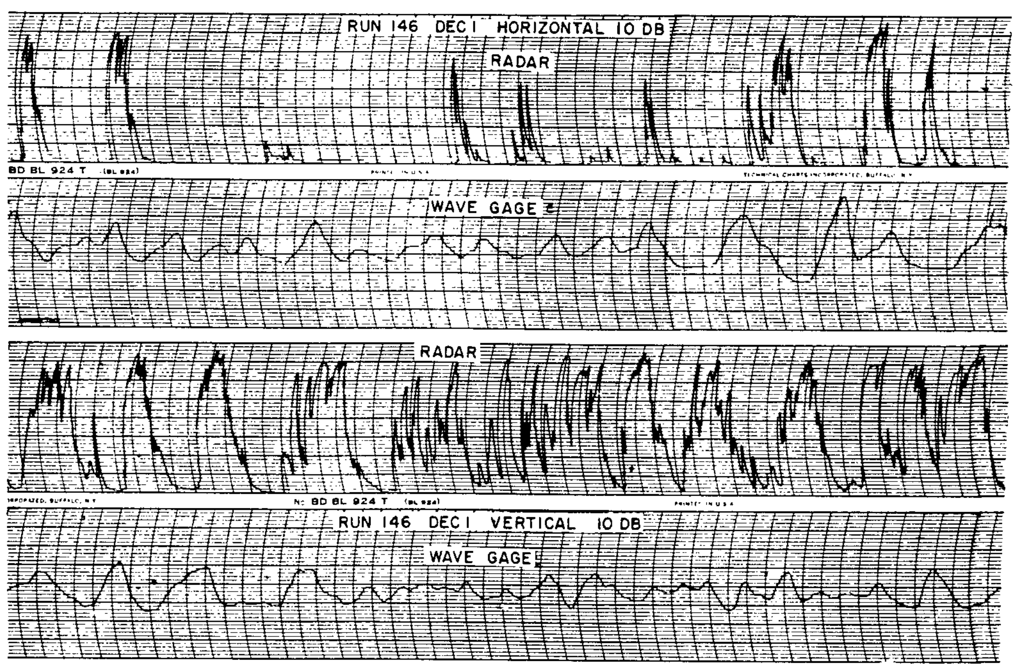
In the next illustration (Fig. (4a)) an attempt has been made to compensate for the time it takes a wave to travel from the wave-gage pile to the area being sampled by the radar. For vertical polarization (Fig. (4a)) the radar was gated to look 10 yards in front of the pile; therefore, the radar record is delayed 1.0 second relative to the wave-gage record to allow for the assumed average crest velocity of 10 yards per second. In spite of the fact that the wave record presents a two-dimensional study of the surface while the radar return represents a three-dimensional study, there is a fair correspondence in this sample of wave-to-radar response. For the horizontal test (Fig. (4b)), an attempt was made to delay the gated area 5 yards in front of the pile. Failure of the minimum echo area in the data to fall to normal noise level between wave responses indicates possible interference by the echo from the wave-gage pile. Correspondence of waves to echoes can be noted here also. As can be seen from previous illustrations, there can be radar echoes opposite areas in the wave record having no prominent wave like pattern, and conversely, there can be no radar response opposite areas in the wave record showing strong wave patterns. The changing nature of the waves as they move from the pile to the radar area would tend to weaken the correspondence for this method of comparing the two functions. This conclusion suggested an attempt to compare the statistical properties of the two time-varying functions.

First Probability

Figure 5 is a summary of one type of analysis of typical range-gated data that was recorded on Brush tape. It is presented in the form of a plot of the percentage of time for which σ_0, the equivalent radar cross-sectional area per unit area, equals or exceeds specific levels. This value is termed here as σ_x (instantaneous σ_0) since in this study no assumption was made of area-extensive conditions. Data was taken for these plots from

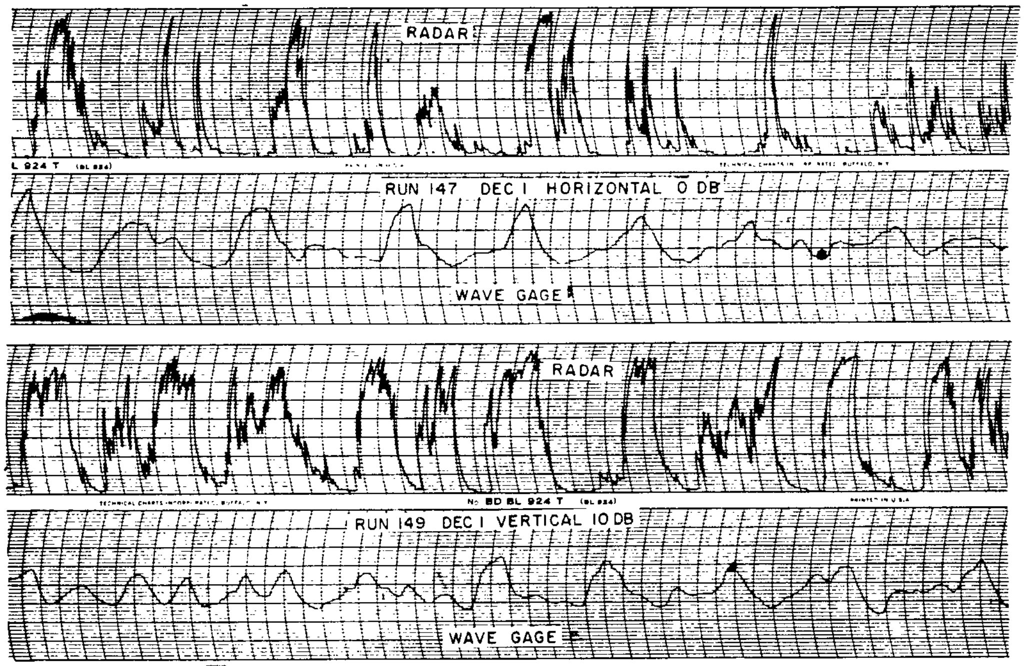


(a) 20-db receiver attenuation



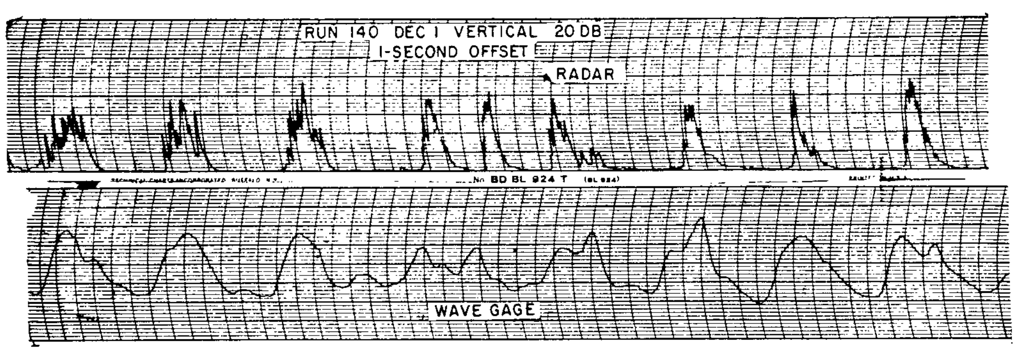
(b) 10-db receiver attenuation

Fig. 3 - Comparison of 1-minute horizontal and vertical polarization samples

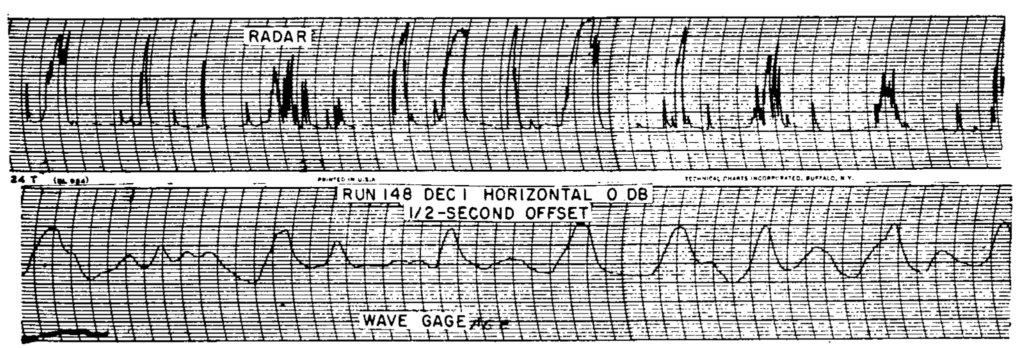


(c) 10-db receiver attenuation for vertical and none for horizontal

Fig. 3 (Cont'd) - Comparison of 1-minute horizontal and vertical polarization samples



(a) Radar gated 10 yards in front of pile



(b) Radar gated 5 yards in front of pile

Fig. 4 - Radar record offset to allow for assumed average

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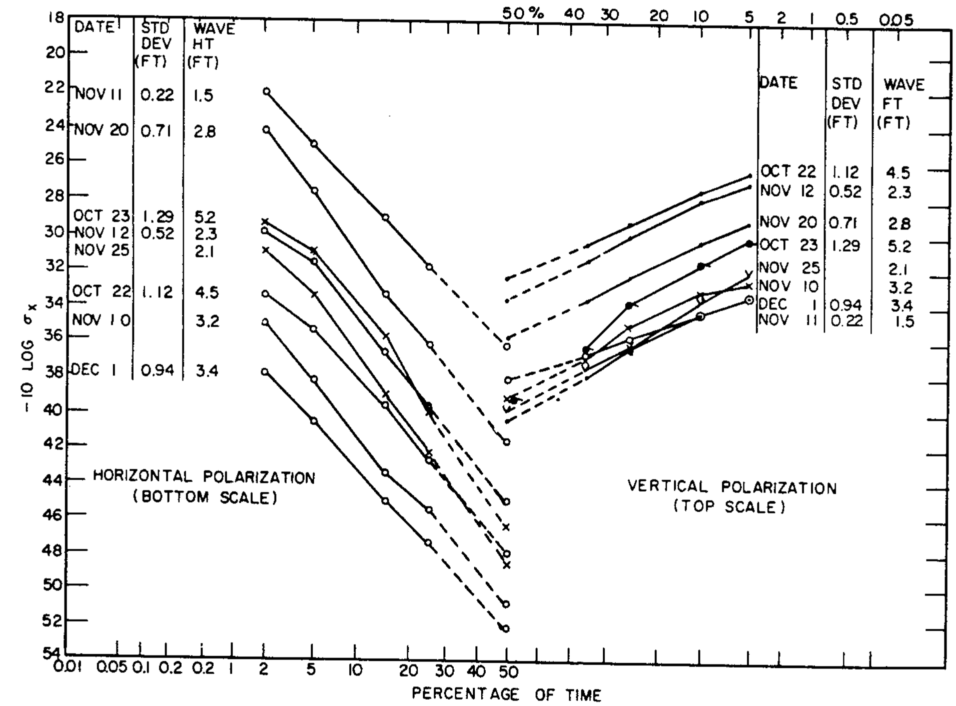


Fig. 5 - Probability plot of σ_x

runs made at low grazing angles (1 to 4 degrees) and at a fixed range of 420 yards (10 to 20 yards in front of wave-gage pile). The variation of σ_x was calculated for 2, 5, 15, and 25 percent of the time for each sample of data, and in plotting, the 50-percent point was derived by extrapolation, as indicated by the dotted portion of the curves. The family of curves was plotted to indicate variations due to wave height, standard deviation derived from wave-gage records, and dependence on polarization. The values for each day represent an averaged value. Wave heights were derived from the average of the highest third of the waves measured for each run made that day. This average in a 2-minute sample was selected as a significant wave height in accordance with techniques outlined by the Beach Erosion Board.

Of particular interest in this plot is the curve representing the average values derived for horizontal polarization on November 11. The significant wave height for this day was 1.5 feet, the lowest height of the series under study. Speculation as to why the smallest waves gave the largest value for σ_x led to the study of the weather conditions at the time of the November 11 tests. Records indicated a calm sea for the night of November 10 (waves less than 1 foot) with the wind blowing from the land at 5 to 7 knots. A calm sea was also indicated for the morning of November 11, with no measurable wind blowing. At 10:00 a.m., a fresh easterly breeze appeared, building up to about 10 knots by the time operations were started at 4:30 p.m. This is the weather history that led to such relatively strong horizontal cross-section coefficients.

Figure 6 indicates the variability of σ_x for 25 percent as a function of standard deviation for each of the two polarizations used. Conditions of operation are the same as those specified for Fig. 5.

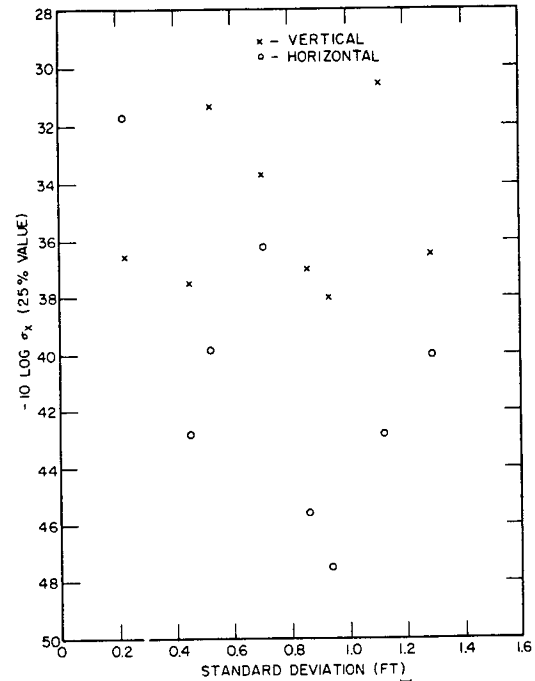


Fig. 6 - The 25-percent values of σ_x (H and V, 4-minute averages) vs wave-gage standard deviation

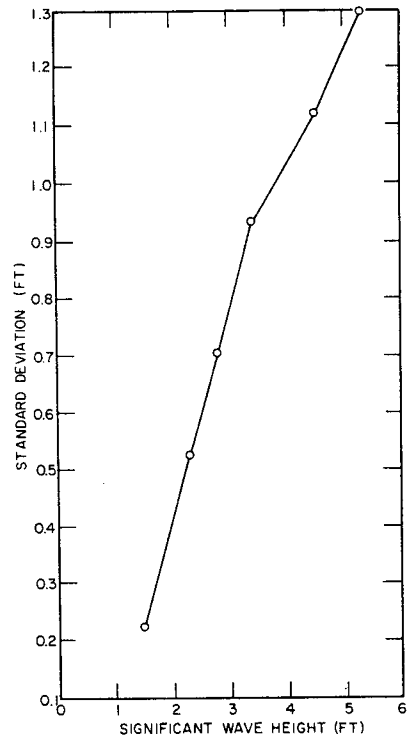


Fig. 7 - Wave-gage standard deviation vs significant wave height (average of highest third)

Figure 7 indicates the relationship between significant wave height (average of the highest third on the wave-gage record for each 2-minute sample) and the standard deviation in feet derived from the computer analysis of the wave-gage records.

Analysis of Wave-Record Sample Length

One of the problems in the study of any more or less random time series, such as the wave-gage record, is determining the sample length that is to be considered as typical or representative of the process under study. In an effort to evaluate the significance of the 1-minute and 2-minute sample lengths of radar data, the arbitrary lengths selected during the field trip, a study was made of the wave spectrum for longer sample lengths. Starting with 16 minutes of data, various combinations were grouped to illustrate variability of the spectrum with sample length. The results of this study are shown in Fig. 8 where, in each case, the high and low extremes are plotted against the average to indicate variability. While this approach does not validate the selection of a "best" sample length for the physical phenomena being studied, it does indicate that 1-minute and 2-minute sample lengths are highly questionable. As a result of this study, data analysis was limited arbitrarily to those consecutive radar runs for which four 1-minute samples were available for averaging.

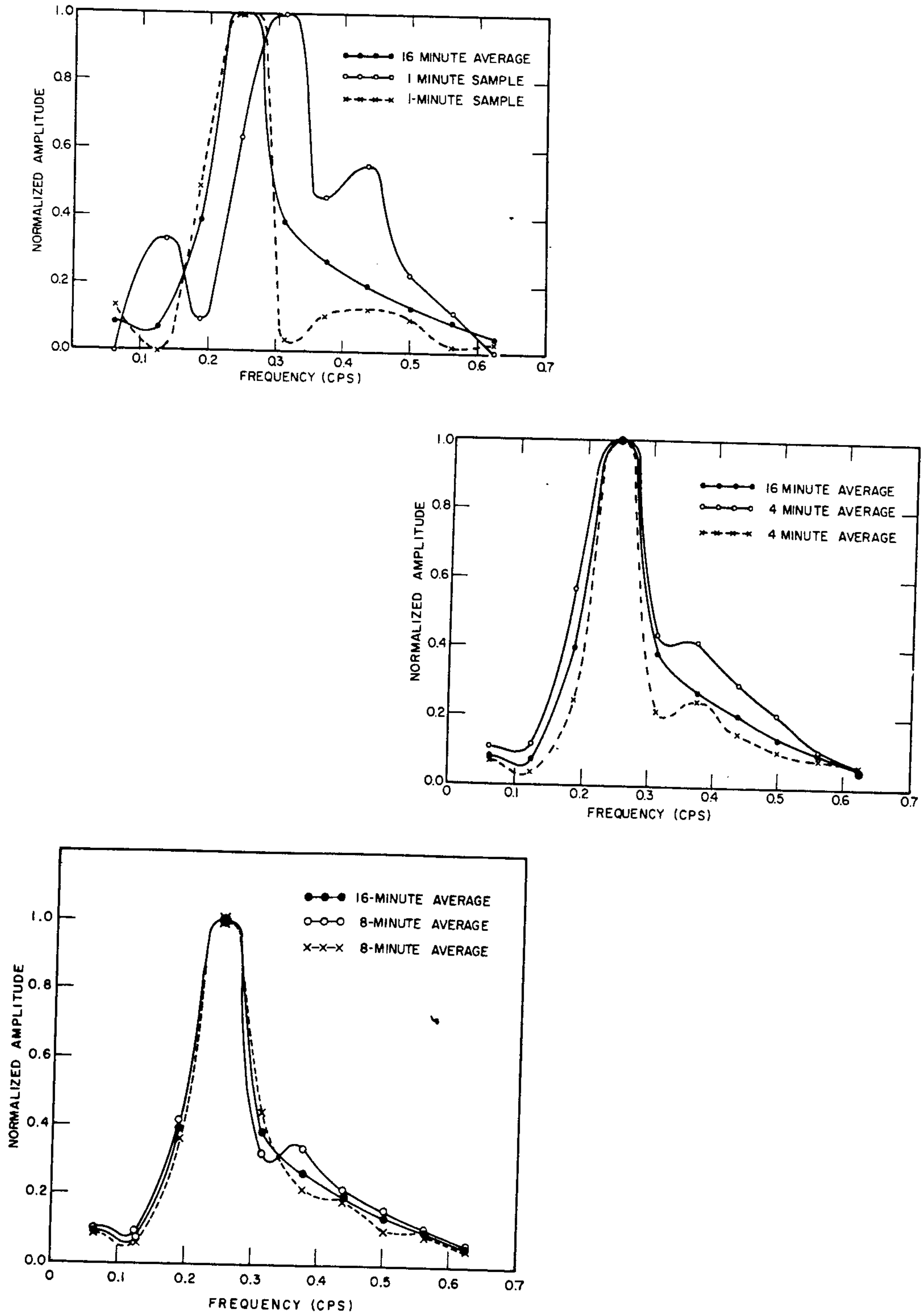


Fig. 8 - Variability of the power spectrum with sample length of wave-gage record

Another measure of the variability encountered in terms of 1-minute samples is indicated in Fig. 9. This shows how the calculated σ_x varied as a function of the percent of time for eight 1-minute samples, taken consecutively.

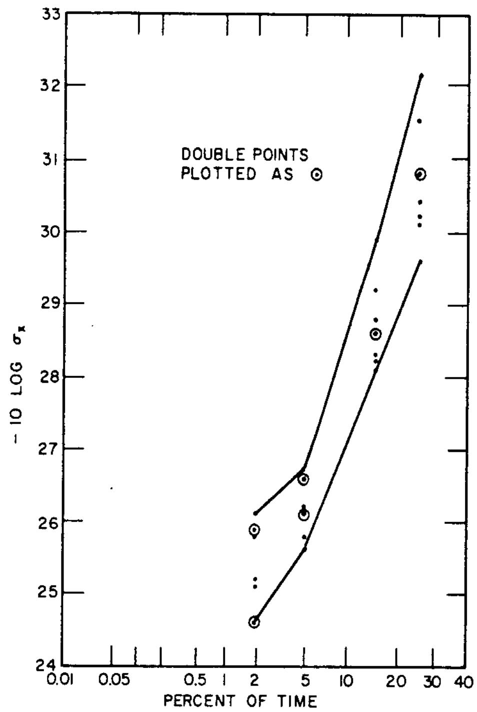


Fig. 9 - Variability study of 8 consecutive 1-minute samples

Narec Readout

One of the answers from each test run analysed in digital form by the computer was the average power back for that run. This power level was derived from the signal level of a reference signal generator fed into the input of the receiver through a directional coupler. Figure 10 shows the variation in echo power received in tests made November 12, 1957, as a function of tilt and the two polarizations used. As can be seen from the noise power level, the average-power answers in the horizontal polarization tests consist of an appreciable amount of noise power along with the sea-clutter power being studied. A greater dynamic range in the receiver would be desirable to add significance to the difference between polarizations since many tests analysed produced the weaker (horizontal) signal just above this limiting noise level.

Correlation Coefficients

The relative ease with which a computer can supply a set of correlation coefficients leads to the problem of interpretation. Arbitrary selection of 6 significant operational days simplified the problem some, and the averaging of all coefficients of each type of correlation into one value for that day at the range of the wave-gage pile permits a fairly brief graphical presentation of statistical properties available in this type of analysis. Low tilt angles (1 to 5 degrees) and constant range apply to all tests in the series of plots to follow. For autocorrelation, normalized values of the simultaneously recorded radar and wave-gage functions are plotted as a function of delay in seconds. The delay unit used was 1/5 second and data reduction called for 40 slide-over operations to give the 8-second delay limit. Since both horizontal and vertical polarizations were used on all tests, there are two radar curves and one wave-record curve for each day. Figure 11 illustrates the characteristics of these coefficients for each day, showing pertinent meterological data, measured significant wave height, hydrographic data for the general area, average power readout from the computer, and calculated σ_x (15 percent) for the runs in question. Also included is the computer readout of standard deviation.

For any particular 1-minute test featuring simultaneous radar and wave-gage operation, the autocorrelation and crosscorrelation coefficients can be displayed on one plot. A sample of this is shown in Fig. 12, illustrating the weak autocorrelation of the wave record for 2.3-foot waves. In contrast to this, Fig. 13, representing 5.2-foot waves, shows a strong correlation of the wave function, having a value of 0.6 for the first-period peak. In spite

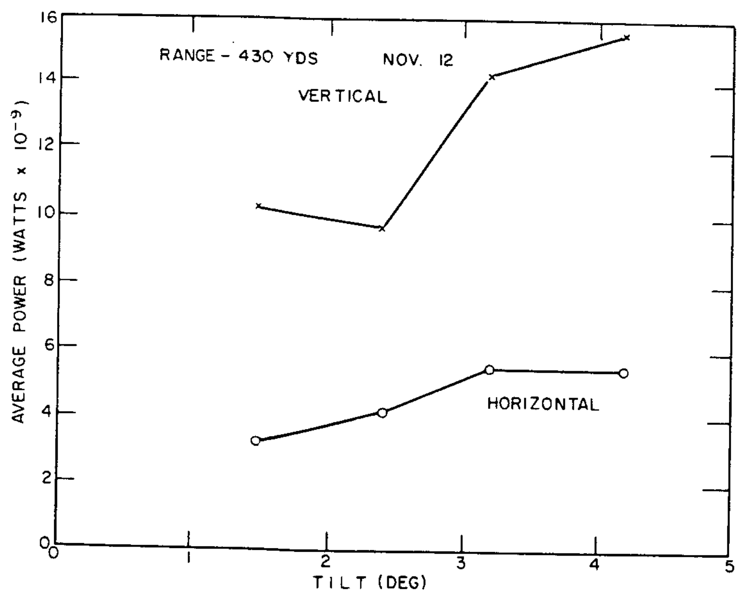
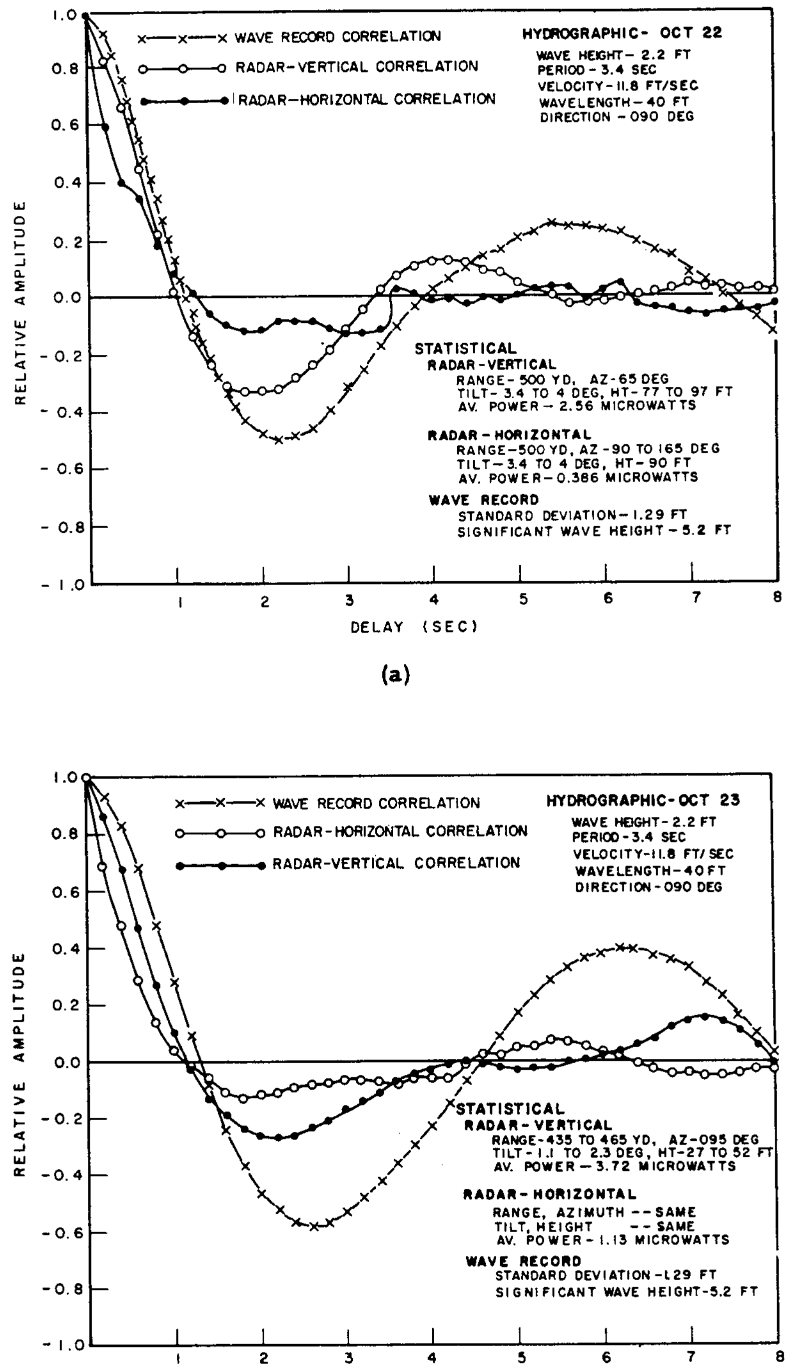


Fig. 10 - Average echo power as a function of tilt angle

of the random pattern of the autocorrelation of the radar that is characteristic of horizontal polarization, the cross correlation of the two functions has definite positive and negative swings. Interpretation of the crosscorrelation function here should include the fact that the wave gage samples the ocean surface at a point some 20 yards away from the area being simultaneously examined by the radar. If wave contours are assumed to be constant while traveling this distance, the first maximum for the crosscorrelation curve in Fig. 13 is a measure of the phase difference for the two functions.

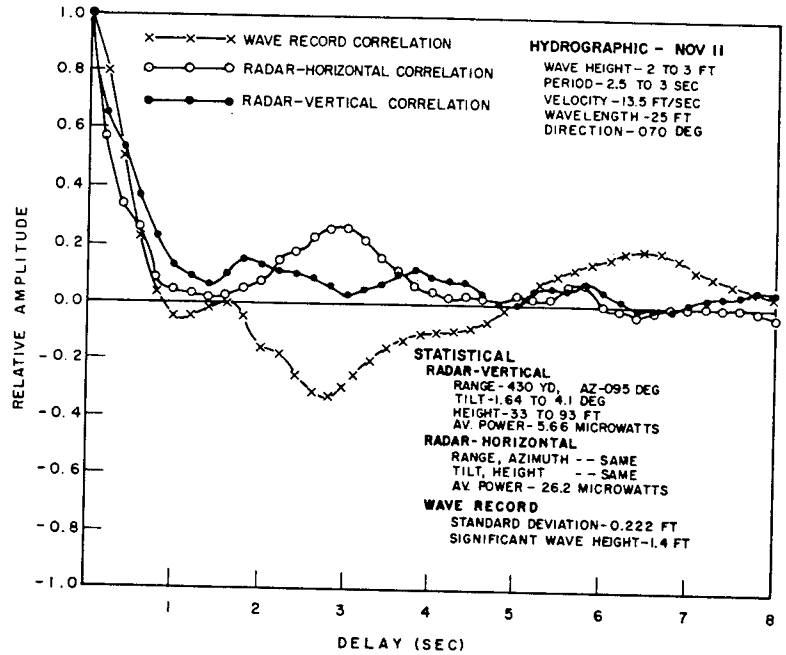
To illustrate the wide variability of results encountered when correlation curves were compared on a 1-minute-sample basis, Figs. 14 and 15 are included. The first is fairly typical and the second, Fig. 15, was selected as the best illustration found of a high degree of correlation between the two functions. Both of these tests were made on November 12 with vertical polarization. Figure 15 can be used to illustrate the potential value of this type of analysis. The first crest for the crosscorrelation curve occurs at 2 seconds delay. If the crest velocity of the waves passing the pile was 10 feet per second, and if the waves traveled 30 feet from the wave-gage pile to the illuminated area, the crosscorrelation curve should have its first maximum at 3 seconds delay when the maximum radar echo is assumed to come from wave crests. Since the predicted and measured delay to the first crosscorrelation crest disagree by 1 second, one or a combination of the above assumptions is in error. If it were possible to validate the crest velocity and the distance between sampling points for the two functions, one could then say that the maximum radar echo occurred 1 second before the crest for waves having a 4-second period.



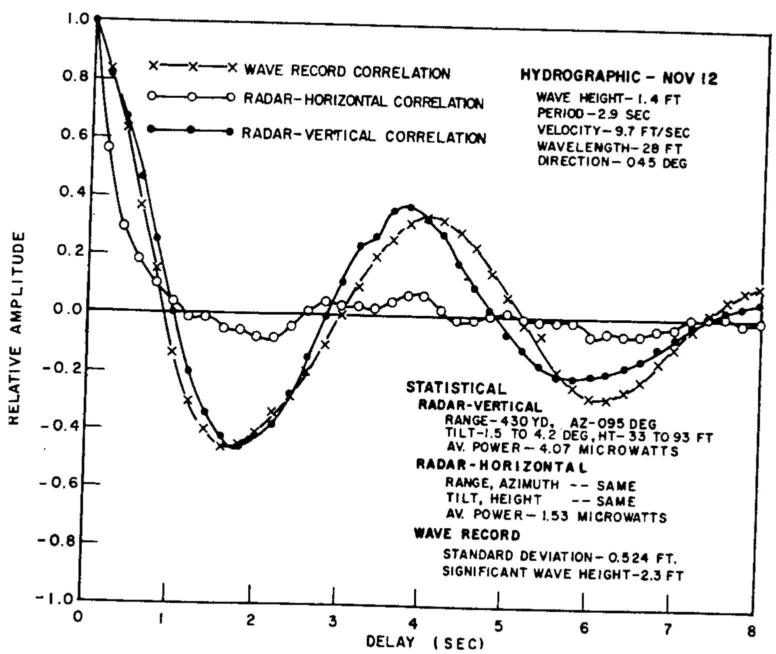
(a)

(b)

Fig. 11 - Variability of the correlation coefficients for different weather conditions

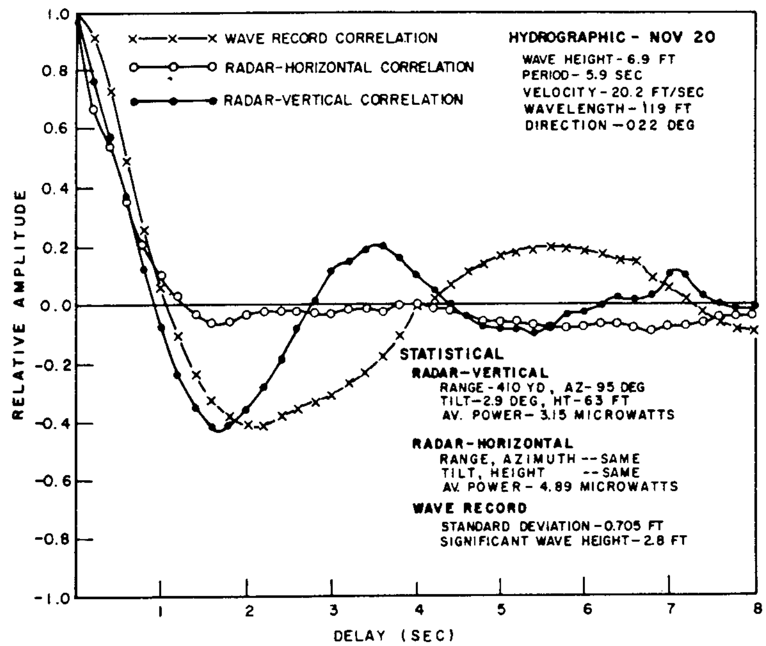


(c)

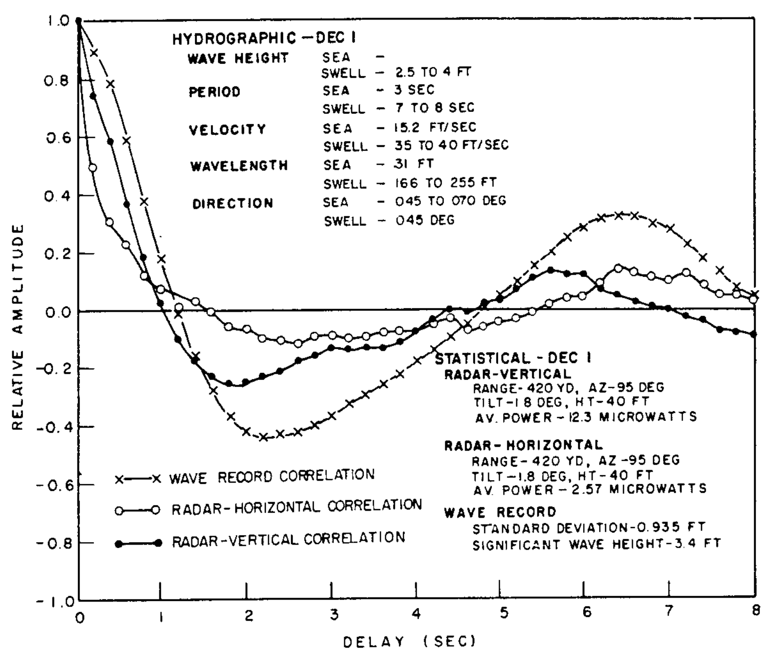


(d)

Fig. 11 (Cont'd) - Variability of the correlation coefficients for different weather conditions



(e)



(f)

Fig. 11 (Cont'd) - Variability of the correlation coefficients for different weather conditions

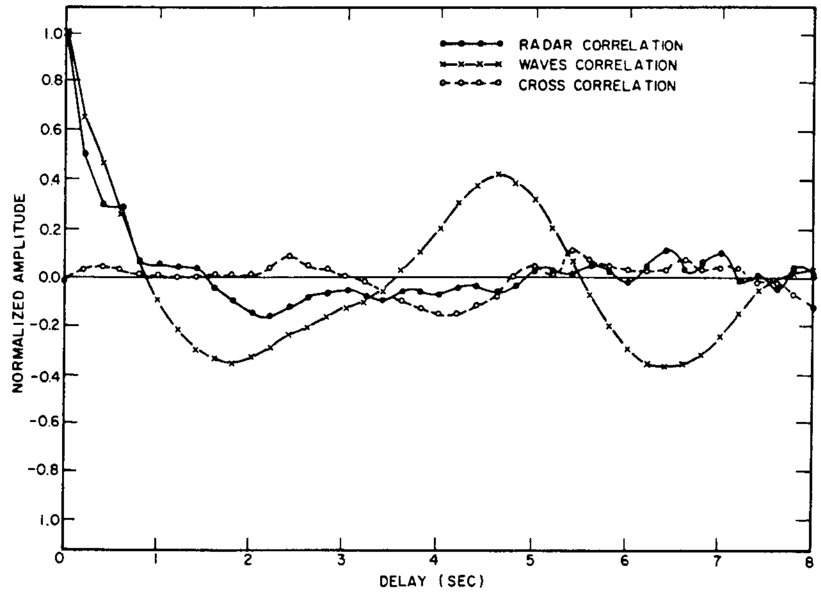


Fig. 12 - Normalized correlation functions, wave height 2.3 ft (1-minute sample, Nov. 12, #70)

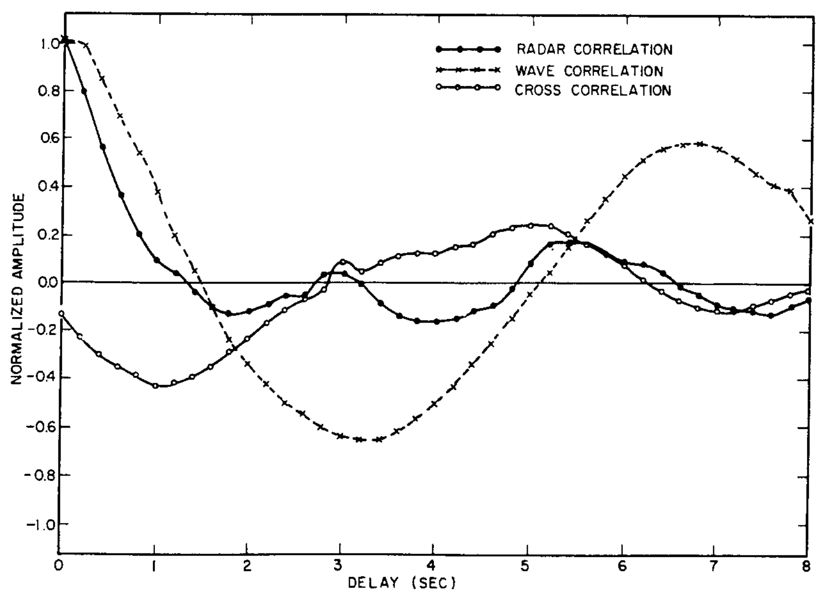


Fig. 13 - Normalized correlation functions, wave height 5.2 ft (1-minute sample, Oct 23, #51)

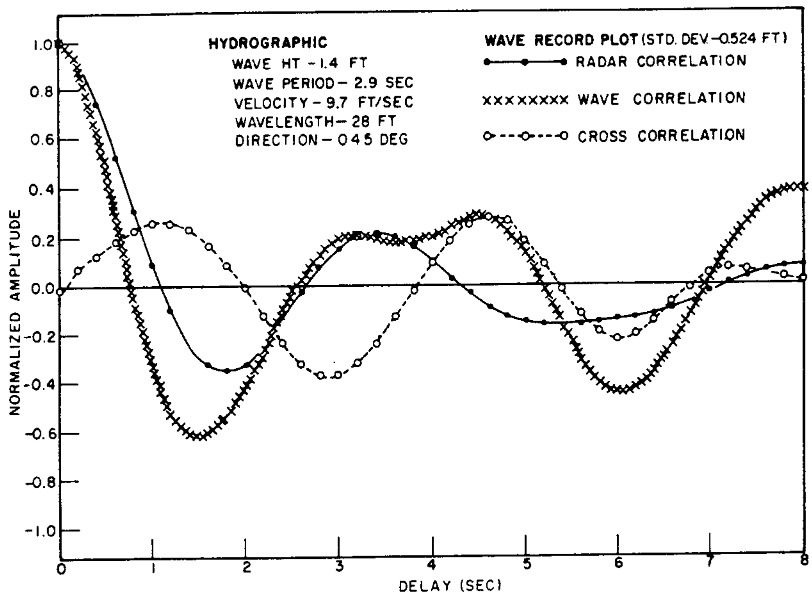


Fig. 14 - Normalized correlation functions, (1-minute sample, Nov. 12, #86)

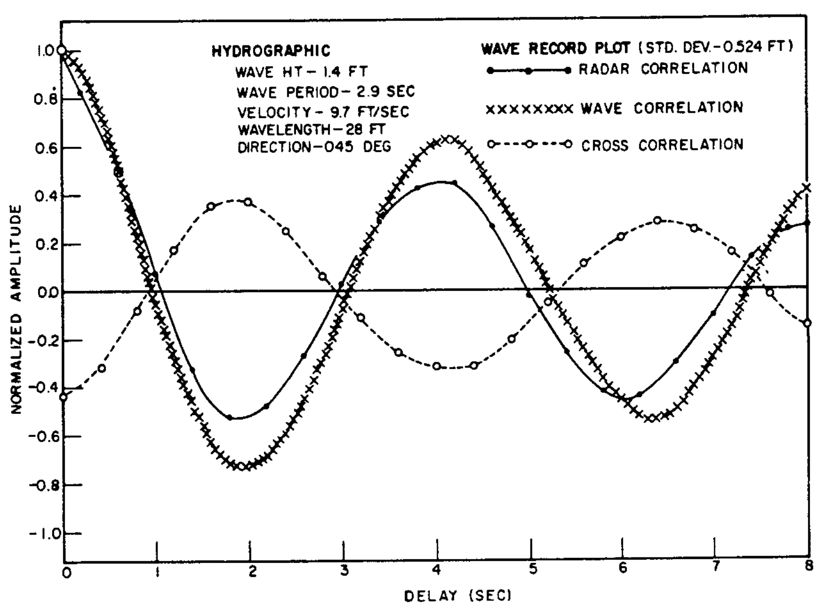


Fig. 15 - Normalized correlation functions, (1-minute sample, Nov. 12, #76)

Power Spectrum

Of interest also is the print-out answer for the power spectrum as given by the digital computer. It was indicated earlier in this report that proper procedure calls for a voltage series (instead of the power series used) as the computer input for a power spectrum operation, but since the difference between the spectrums is slight and predictable over the range plotted, it is felt that the plots derived from the power series will be of interest.

Figure 16 illustrates a 1-minute sample showing a corrected spectrum along with the power-series spectrum. Again it was decided to show the results in terms of one average for each of the six operational days. Figure 17 shows these results with a curve for the wave spectrum and one curve for each of the two polarizations used. Vertical-radar, horizontal-radar, and wave-record spectrums are plotted for each day with normalized amplitude as ordinates and frequency as abscissas. The 1/5-second sampling rate limits the 1.6-second end of the spectrum, and the 40-unit slide-over limit arbitrarily set in data analysis limits the 16-second end of the spectrum.

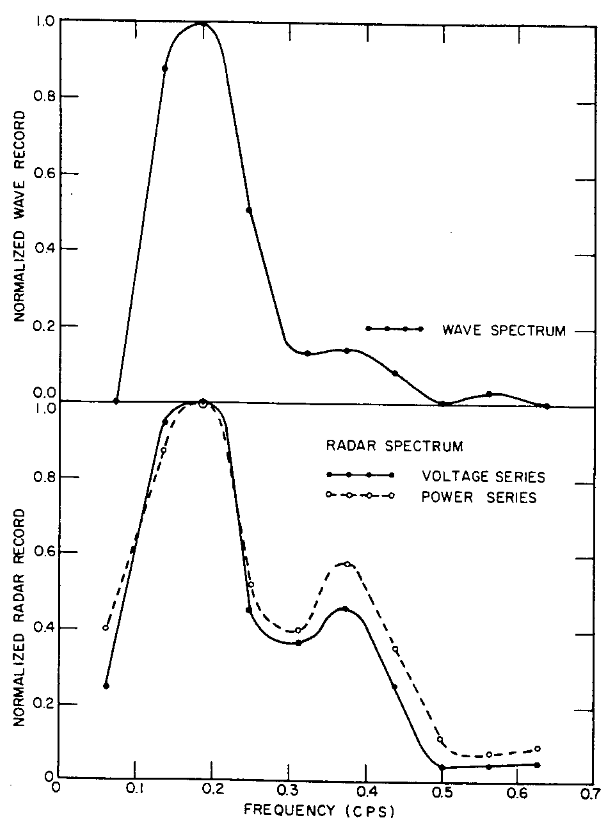
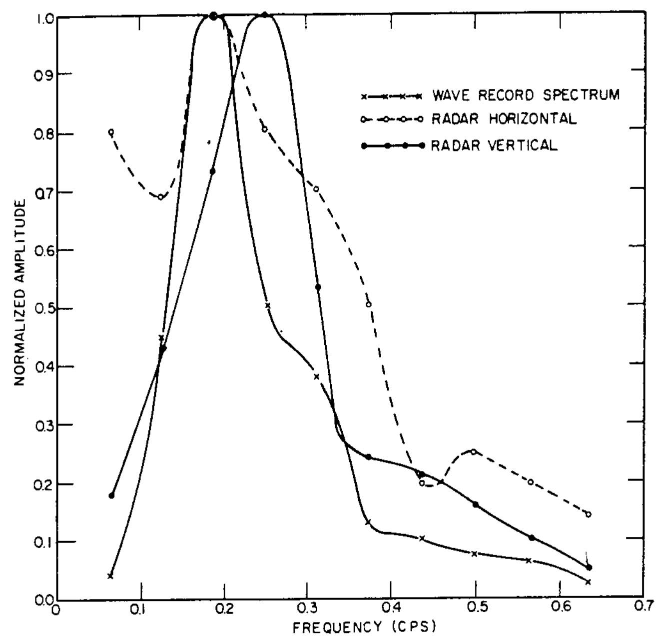
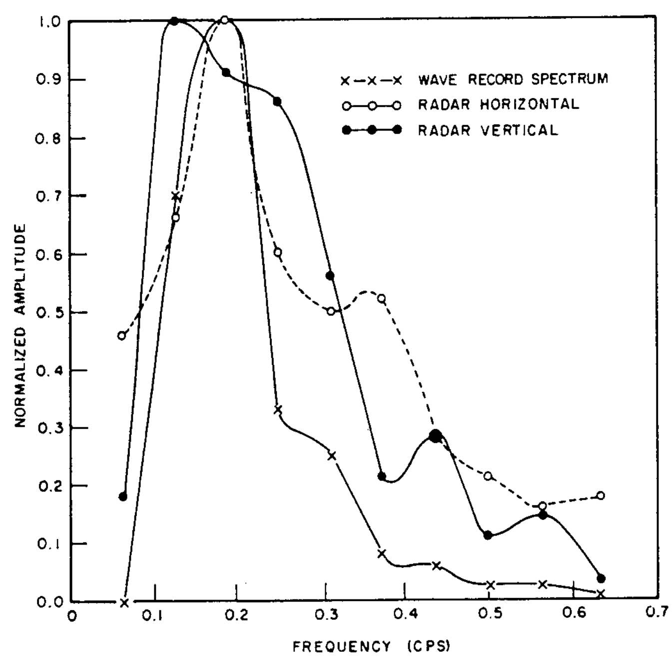


Fig. 16 - Voltage-series spectrum compared with power-series spectrum, Dec. 1, #107

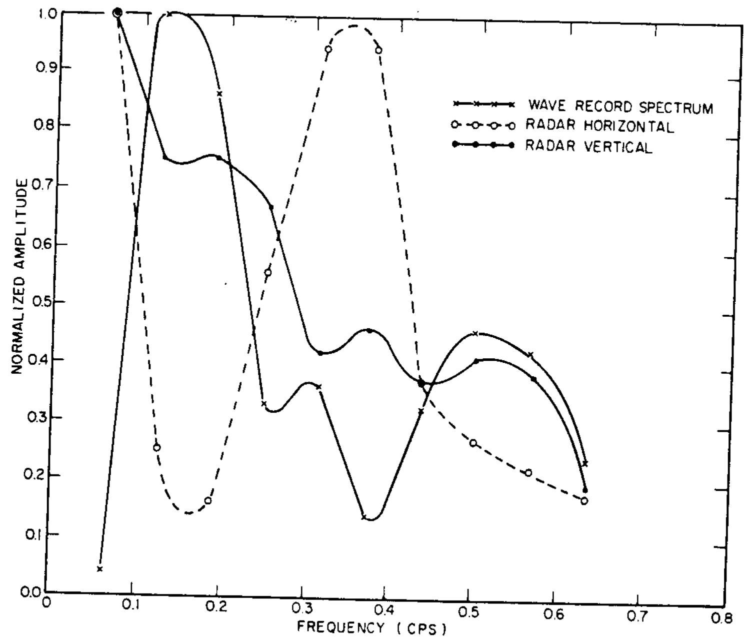


(a) Oct. 22

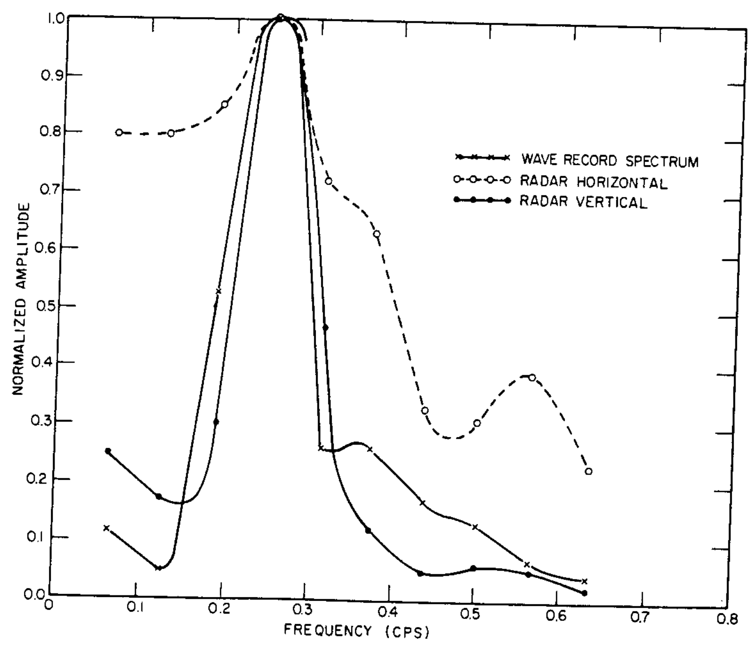


(b) Oct. 23

Fig. 17 - Normalized power spectrum

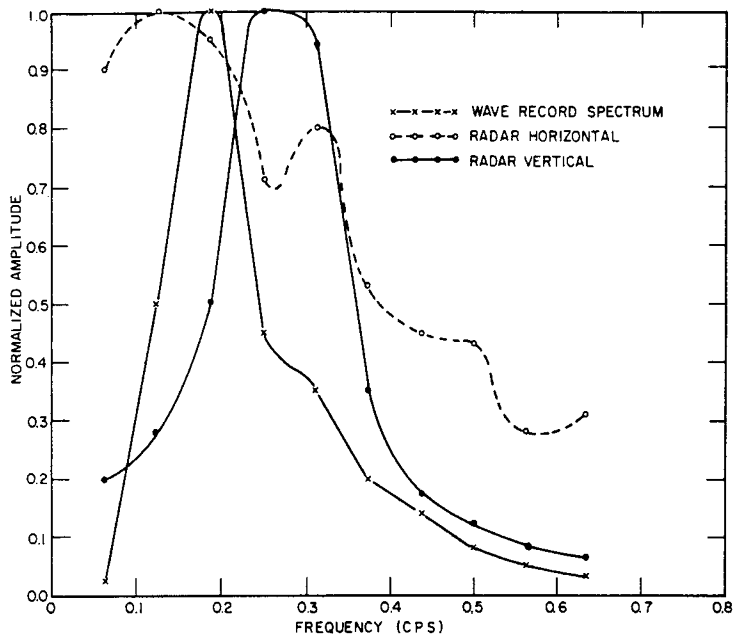


(c) Nov. 11

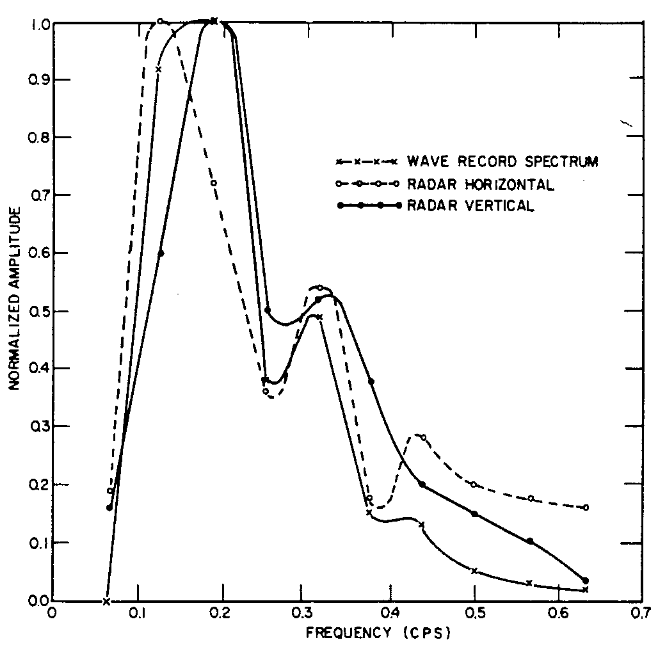


(d) Nov. 12

Fig. 17 (Cont'd) - Normalized power spectrum



(e) Nov. 20



(f) Dec. 1

Fig. 17 (Cont'd) - Normalized power spectrum

CONCLUSIONS

The vertically polarized radar data exhibited properties very similar to those found in data taken by an ocean wave gage placed in the area under study. This similarity suggests the use of a high-resolution radar as a method of deriving the sea properties indirectly without the aid of a wave gage. One thing very clear in this study is that great care should be taken in determining critical or typical sample lengths for both wave-record and radar-record analysis. These tests indicated that a sample less than 4 minutes was inadequate, and that for some operating conditions, even a 4-minute sample was doubtful.

Horizontal-polarization spectrum plots indicate that the energy is spread out over a wider range of frequency than for vertical. While the vertical spectrum plot usually indicates energy in a single narrow frequency range very similar to the plot for the wave-gage spectrum, the horizontal plot usually starts with a strong point below the predominant frequency of the wave-record plot and varies about a gradually sloping line through and past this frequency band. The limited nature of these tests is such that no clear relationship can be concluded between the standard deviation derived from the wave record and the properties of the radar record. There is some agreement between the standard deviation of the waves and the measured third-highest wave average. In the study of the first-probability plots of the radar records, the horizontal-polarization curves were found to be consistently steeper than the vertical-polarization curves, with the plots for both polarizations approaching a straight line when plotted on standard probability paper.

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