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WAVE SPECTRA OF A SHOALING WAVE FIELD: A COMPARISON OF EXPERIMENTAL AND SIMULATED RESULTS

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SUMMARY

Wave profile measurements made from an aircraft crossing the North Carolina continental shelf after passage of Tropical Storm Amy in 1975 are used to compute a series of wave energy spectra for comparison with simulated spectra. The results of these measurements indicate that, as it moves shoreward, the observed wave field experiences refraction and shoaling effects which cause statistically significant changes in the spectral density levels. Using a modeling technique, these changes in spectral density levels are successfully simulated in all but the most inshore of the six spatial regions that are compared. Total energy levels of the simulated spectra are within 20 percent of those of the observed wave field; however, the shift of the spectral density peak toward lower frequencies, seen as the wave field moves inshore, is not predicted by the simulated spectra. The results of the study represent the first successful attempt to theoretically simulate, at oceanic scales, the decay of a wave field which contains significant wave energies from deepwater through shoaling conditions. The comparison can also be used to establish a minimum level of spectral energy for which simulation would be expected to effectively predict the changing energy levels that occur as the wave field moves inshore. Problems in using this technique for simulation are discussed.

INTRODUCTION

As the waves from offshore weather systems move shoreward, the energy imparted to the waves by the storm is carried with them. Ultimately, that energy is partially dissipated along the shoreline, but in moving from the storm region to the coastline the energy in the wave field may focus or concentrate at new wave frequencies as the waves are modified due to shoaling and refraction effects. These changes are functions of the initial wave height and period, the water depth, the bottom topography, and other factors. The ability to predict these changes would greatly enhance the oceanographers' abilities to predict the effects of shoreward-moving wave systems. A reliable technique could be used as an operational tool for site planning of both shoreline and offshore facilities and, possibly, as the basis of a warning system for regions of high wave activity. Verification of such a technique requires simulation of the wave fields and a comparison of the results with those of the measured wave fields.

A technique to determine these effects was developed by Pierson, Newmann, and James (1955) some years ago. Their technique required the division of a deepwater wave spectrum into an approximating sum of simple sine waves, the assignment of a frequency, direction, and fraction of the total energy to each component, and the refraction and shoaling of each component as it is propagated shoreward. The results were then summed at some point of interest in shallow water in order to determine the effects of shoaling and refraction. The advent of computerized refraction models has made this a more practical technique to use. With certain modifications, the application of this technique has been reported in several recent papers, for example Chao (1974) used it to predict the refracted wave spectrum at a point near the Chesapeake Bay entrance.

A detailed and comprehensive review of the last two decades of research in the theory of water-wave refraction has been given by Meyer (1979). Starting with the classical linear theory of surface waves, Meyer derives and discusses the original ray theory in the geometrical optics version and then discusses the extension to a uniform ray theory, originally due to Keller (1958). Meyer further discusses reflection conditions at a shore, resonant wave trapping, and reflection by seabed topography. Insofar as we know, these advances in our theoretical understanding of wave refraction have not been routinely incorporated in the refraction models used by oceanographers and ocean engineers, nor has there been full experimental confirmation. As Meyer points out, experimental observation of the predicted phenomena is impeded by scale effects and a full test of the theory requires observations at the natural ocean scales.

There are also a number of non-linear phenomena, occurring in wave propagation, which should be incorporated in refraction models for a more representative simulation. (See Phillips (1977) for a very detailed and comprehensive review of these phenomena.) Among these are wind-wave and wave-wave interactions.

Beginning with the work of Miles (1957) and Phillips (1957), a rational theory of wind-wave interaction has been developed and partially tested, both in the laboratory and in the field. At present, the major uncertainty lies in our knowledge of how the variations in the Reynolds stress are generated in airflow over waves. The primary dissipative mechanism at moderate and high winds appears to be whitecapping (Hasselmann, 1974). This phenomenon appears to be less understood than wave generation.

The non-linear energy transfer among wave components is also of importance and has been described by Hasselmann (1962, 1963a, b). The theory is complicated, requiring substantial algebraic manipulations and numerical calculations in order to obtain numerical results. A simple analytical result for a narrow-band spectrum has been obtained by Longuet-Higgins (1976) and applied by Fox (1976) to the mean JONSWAP spectrum. It was found that there was a non-negligible energy transfer among the components near the peak of the spectrum and on the low frequency face of the spectrum.

Parasitic capillaries (Longuet-Higgins, 1963) gain energy from longer gravity waves through radiation stress and dissipate this energy by viscous dissipation. This may be the major mechanism for the dissipation of the energy of gravity waves in regions where rays converge in the absence of whitecapping, that is, with low to moderate winds.

All of the non-linear dynamical processes described above were developed in terms of deepwater waves. In order to apply them in refraction models, it is necessary to extend them so as to apply to waves in water of finite depth. This may be easier for some of the processes than for others, but it has not yet been done.

In order to be consistent, a refraction theory for finite amplitude waves must also be formulated. As far as we know, a self-consistent theory describing the refraction of finite amplitude waves does not exist. However, Grosch and Comery (1977) used an ad hoc theory: a combination of the third order expression for phase velocity as a function of water depth, wave number, and "amplitude," together with the linear refraction equation to carry out a number of refraction calculations. They found substantial differences between the results of the usual linear theory and this pseudo-nonlinear theory. In brief, this difference is due to the fact that a decrease in water depth causes a decrease in phase speed to first order, but also an increase in wave "amplitude" and a corresponding increase in phase speed at third order.

The standard refraction models used by oceanographers and ocean engineers do not incorporate any non-linear dynamics in part because the understanding of these phenomena is still incomplete, and also because there have been no critical experimental tests of the linear refraction theory on oceanic scales where non-linear dynamics could be expected to effect the results significantly.

Poole (1976) reported an attempt to compare calculated spectra, using standard, linear refraction theory with those estimated from measurements off the Maryland coast. However, in this experiment, most of the energy in the wave field was at frequencies higher than those for which refraction would take place at a significant number of wavelengths from the shore. As a consequence, the changes in spectral density level as the wave field moved shoreward were not statistically significant, and therefore, could not be attributed to any physical causes.

The present study is of a higher energy wave field associated with the passage of Tropical Storm Amy. The frequencies at which the energy is concentrated lie in the range for which significant refraction takes place. That is, the longer wavelengths (periods) associated with the storm conditions undergo stronger shoaling and refraction effects which increase the likelihood of significant changes in the spectral levels as the wave field moves shoreward.

This paper presents the results of a comparison of wave spectra computed using linear refraction theory to determine nearshore spectral distributions from deepwater wave spectra, henceforth called the simulated spectra, and the wave spectra that are derived from surface profile measurements of the observed wave field using the Blackman and Tukey (1958) method and transformed to a fixed reference frame using the unidirectional transformation technique (Poole, 1976a), henceforth called the experimental spectra. This comparison of simulated and experimental spectra are presented for the wave field associated with the passage of Tropical Storm Amy, July 2, 1975.

TEST DESCRIPTION

For the purpose of comparison, it was necessary to obtain spectra from as strong a wave field as possible, emanating from a distant source, with minimum influence from local winds. It was hoped that this type of wave field would have a strongly long crested seaway that, while passing over a uniformly changing bottom topography, would refract and shoal in a manner that best conformed to the assumptions of the modeling technique. After a series of flight tests where only low sea state conditions were found, these conditions were most nearly met with the passage of Tropical Storm Amy off the North Carolina coast in July 1975. At the time of the experiment (2000-2030 G.m.t.), the storm center was approximately 950 km offshore and had maximum sustained winds of 31 m/s (fig. 1).

During the 48-hour period prior to the wave measurement flight, the storm moved out to sea in a relatively constant direction from the test site. Surface winds in the test area were from the northwest at 2.5 to 5 m/s, perpendicular to the dominant swell direction.

The wave data were taken from a NASA C-54 aircraft stationed at Wallops Island, Virginia. The wave measurement portion of the flight (fig. 2, see insert) began approximately 150 km offshore at an altitude of 152 m and continued in the onshore direction along the path of the dominant swell propagation, as determined from preflight wave reports and visual observation from the aircraft. A continuous surface profile was measured along the line-of-flight using a laser profilometer and the results were recorded on analog tape. Data gathering was terminated at the shoreline over Jennette's Pier, Nags Head, North Carolina. The flight position was periodically recorded by an inertial navigation system.

The laser profilometer which was used to record the surface elevation was furnished and operated by the Naval Oceanographic Office (NOO). The instrument was a Spectra Physics Geodolite-3 ranging system utilizing a constant wavelength helium-neon laser with a wavelength of 632.8 nm and an output of 25 milliwatts (Ross, Peloquin, and Shiel, 1968).

ANALYSIS

The data from the flight were digitized at 0.02 second intervals and divided into 10 consecutive data segments, as shown in figure 2. Starting from the offshore position, the first 9 segments were each of 3-minute duration (9000 samples) and the 10th segment was 1.727-minutes (5181 samples). The 10th segment was shorter because the data record was terminated at the beach.

Using the method of Blackman and Tukey (1958), the Fourier cosine transform of the autocorrelation function was used to compute the raw power spectrum of each segment, which was then smoothed by the Hamming-Tukey smoothing equation (Bath, 1974, p. 179). A total of 150 lags were used in computing the autocorrelation function. The computed spectral estimates have 114 degrees of freedom. These estimates represent the one-sided cosine transform values in the moving reference frame. For the purpose of comparison, these values were then mapped into a fixed reference frame using the unidirectional transformation technique developed by Poole (1976a).

Spatial segments 1 - 4 consist of measurements made under similar deepwater conditions, and may be regarded as statistically independent and identically distributed random variables. For these tests, local water depths greater than one-fourth the wavelength are considered deepwater. This allows the spectra for these four segments to be averaged to improve the accuracy and statistical stability of the resultant spectrum (Lumley and Panofsky, 1964). The resulting spectrum is then considered the deepwater reference spectrum and is presented in figure 3. By increasing the number of degrees-of-freedom, averaging narrows the width of the confidence bands associated with the data. For this case, having 458 degrees-of-freedom, these bands imply that for repeated tests the spectral density values lie between 0.9016 and 1.086 times the values of the reference spectrum 80 percent of the time.

The aircraft speed was 84 m/sec and so the digitization interval of 0.02 second corresponds to a spatial interval of 1.68 meters. As can be seen in figure 3, the spectral peak lies near 0.100 Hz. The deepwater wavelength for waves of this frequency is 155 m so the spatial sampling interval is 1.1 percent of the wavelength of the waves with maximum energy. It can also be seen from figure 3 that there is negligible energy at frequencies above 0.25 Hz, that is, for waves shorter than about 25 m, for which the spatial sampling rate is 6.7 percent of the wavelength.

SIMULATED SPECTRA

The simulated spectra were computed by first using a theoretical linear refraction computer model to determine the shoaling and refractive coefficients of the wave pattern over the shelf region, then using this information in a modification of the Pierson, Neumann, and James (1955) technique to compute the spectra for the nearshore spatial regions based on changes from the deepwater reference spectrum (Poole, 1976b). The refraction model is standard and does not include reflection, bottom friction, or any of the non-linear mechanisms which were discussed in the introduction. The model initiated wave ray computations in deepwater locations along a crest line perpendicular to the direction of wave propagation such that all computations were referenced to the same initial time and crest location. A small family of wave rays, spaced at 1 nautical mile intervals along the crest bracket the line-of-flight of the aircraft. An initial ray direction corresponding to a flight path of 239 degrees was used to compute a series of refraction diagrams for wave periods ranging from 6 to 14 seconds. These wave periods correspond to the frequency range over which appreciable spectral density levels were observed in the deepwater reference spectrum. Shoaling and refraction coefficients are computed at fixed time intervals along each ray, and tic marks are provided for a visual comparison of the wave crest locations. By overlaying these refraction diagrams with the aircraft flightpath, it was possible to determine the average shoaling and refraction coefficient for each spatial segment over the shelf.

For the linear wave theory used in the refraction model, reflection, percolation, and bottom friction are neglected and it is assumed that no energy is transmitted across wave ray boundaries, i.e., the energy between two rays can be considered a constant. Thus, as the wave rays converge and diverge, the energy density will vary as a function of the shoaling and refraction coefficients. These coefficients can be normalized to their deepwater value to provide an indication of the amplification of the spectral density for each inshore spatial region as a function of wave frequency. By using these results, the simulated refracted spectra were computed by multiplying the deepwater reference spectrum (fig. 3) by the amplification functions as determined by the refraction model for each of the six data segments nearest the shore.

RESULTS AND DISCUSSION

In figure 4, the deepwater reference spectrum is compared with data from Phillips (1977, page 146, figure 4.8) for a fully developed sea and with the deepwater reference spectrum from Poole (1976b). A significant portion of the wave energy in the present reference spectrum resides at frequencies lower than those characteristic of the spectrum observed by Poole, while the spectral density levels are an order-of-magnitude higher. The reference spectrum observed in the present study is for an area nearly 750 km from the center of the storm, but seaward of the region of shoaling and refraction that occurs further inshore.

The spectra given by Phillips illustrate the equilibrium range of the frequency spectrum for wind-generated waves. The spectral peak is shown for only three cases (those defined by symbols), in addition to the deepwater reference spectra; otherwise, only the saturated portion of each spectrum is shown. For a fully developed sea as shown in figure 4, each possible frequency band in the spectrum is present with a maximum amount of spectral energy (Pierson, Neumann, and James, 1955, page 41). The shape of the present reference spectrum does not match that for the fully developed sea, as would be expected since the reference spectrum is not in the generating area.

In fact, the wave field was probably not fully developed in the storm. The maximum sustained winds in the storm were about 30 m/sec., that is, approximately 60 knots. For this wind speed, a fetch in excess of 2000 nmi and a duration of about 90 hours would be required for a fully developed spectrum to develop. Neither of these conditions were met. At this distance from the storm, the waves had been spread and dispersed, i.e., filtered, with the longer waves (lower frequencies) arriving at this location before the shorter waves (higher frequencies) that were generated at the same time. Thus, the reference spectrum with which the nearshore spectra are compared is based on a sea state that is not fully developed but is characteristic of the filtered sea that is outside the storm-generating area.

Undoubtedly, the non-linear wave-wave interactions discussed in the introduction are occurring as the waves propagate toward shore. An estimate of the magnitude of the changes in the spectrum due to non-linear transfer among the waves can be made. The fractional rate at which energy is lost by wave components near the peak of the spectrum is (Phillips, 1977, pg. 140)

$$\frac{1}{\phi}\frac{\partial\phi}{\partial t} = -\alpha f \qquad (1)$$

where ϕ is the spectral density,

f is the frequency in Hz,

α is a constant.

Based on the results of Fox's (1976) calculations,

$$\alpha \approx 10^{-4} \qquad (2)$$

near the spectral peak.

From figure 3, we see that the spectral peak is at $f = 0.106$ Hz. These waves have a deepwater group velocity of 7.45 m/second. Each of the first nine segments is approximately 15.1 km long, so it takes 8.1×10^3 sec for the energy near the spectral peak to travel over the first four segments which are all in deepwater. From (1), we have

$$\phi/\phi_o = e^{-\alpha f t}, \qquad (3)$$

whence taking $\alpha = 10^{-4}$, $f = 0.106$ Hz, $t = 8.1 \times 10^3$ sec,

$$\phi/\phi_o = 0.92 \qquad (4)$$

Changes in the spectral level of this magnitude lie within the 80 percent confidence bands and so are not significant. As a matter of fact, no systematic changes in the shape or magnitude of the spectrum were observed in the first four segments.

The deepwater reference spectrum, figure 3, is the result of averaging the first four deepwater spectra to obtain a greater degree of statistical stability. In comparing the inshore spectra with this reference spectrum, small changes in the spectral density levels that result in overlapping confidence bands cannot be considered statistically significant and must be attributed to purely random fluctuations in the data. Changes in spectral density levels which are of sufficient magnitude such that the bands do not overlap are considered statistically significant and are attributed to physical causes such as shoaling, refraction, or a combination of these effects. These comparisons are shown in figure 5.

The experimental spectra show a gradual decrease in the peak spectral density levels to a minimum in segment 7 and an increase to a maximum in segment 9, then a decrease to the lowest level in the most inshore segment, segment 10, which is also double peaked. The experimental spectra are also characterized by a shift in the frequency at which the peak energy density occurs to lower frequency levels as the wave field moves shoreward. It is in spectral segments 7, 8, and 10 (figures 5c, 5d, 5f) that variations in the data occur that exceed the 80 percent confidence bands of the reference spectrum and can be attributed to the effects of shoaling and/or refraction and not considered as due to random fluctuations in the data.

In figure 6, the simulated spectra are compared with the experimental spectra. Both show the same undulating variation in peak spectral values with a minimum near segments 7 (figure 6c) and 8 (figure 6d); rising again in segment 9 (figure 6e); and decreasing again in segment 10 (figure 6f). The overlapping confidence bands in all cases except segment 10 indicate good agreement between the simulated and measured spectra for all but the most inshore segment.

In figure 7, the total energies are compared and, as in the spectral comparisons, the energy levels of the simulated spectra follow the general trend of those of the experimental spectra. A comparison of the frequencies at which the peak spectral density occurs is shown in figure 8. There is a general decrease in the experimental value of the frequency of the spectral peak from 0.106 hertz (9.42 second period) in the reference spectrum to 0.091 hertz (10.96 second period) in spectral segment 9. This shift of the peak spectral density toward lower frequencies (longer wave periods) as the waves move inshore is not duplicated by the simulated spectra and may be due to non-linear interactions among the waves. With this exception, the modeling technique described by Poole (1976b), when applied to the data from Tropical Storm Amy, simulates the changes in the spectrum caused by shoaling and refraction over most of the shelf area.

An examination of the behavior of the shoaling and refraction coefficients over the test region may help in understanding the observed spectral changes in the wavefield as it moves shoreward. The energy in the wave field is directly proportional to the square of the product of the shoaling and refraction coefficients. The variation of the shoaling coefficient with bottom depth, as shown in Kinsman (1965, p. 159) for the wave frequencies and depths associated with the test, indicate that the shoaling coefficients for the first nine segments are all less than 1. The effect of this is to decrease the spectral density as the wave field moves inshore, reaching a minimum value near segments 8 and 9. Only in segment 10 does the depth become sufficiently shallow so that the shoaling causes an increase in the spectral density levels. Therefore, any increase in energy levels in the first nine segments above the reference level is due to the variation in the refraction coefficient.

The value of the refraction coefficient is dependent on the separation of wave rays that bracket the flightpath and can have values which range from less than 1 for diverging rays to greater than 1 for converging rays. From an examination of figure 5, it is clear that the combined effect of the shoaling and refraction coefficients shifts the energy density toward the lower frequencies as the wave field moves inshore. This is as expected since the longer waves (lower frequency waves) are the first to be affected by the bottom topography and show the effects of shoaling and refraction. As the wave field moves inshore, these effects spread toward the shorter waves (higher frequency waves) which also begin to be affected by the bottom. This shoreward progress can be observed by comparing the experimental spectra with the reference spectrum. These observations are also consistent with the shift of the frequency of peak spectral density shown in figure 8.

The spectra of segment 10 are unique relative to the spectra of the other data segments. The experimental spectrum is based on only slightly over half the total number of data points that are used to calculate the offshore spectra, and about 8 percent of these are taken through the surf zone. The assumption of homogeneous wave conditions is probably violated in this region as this is the area of maximum change in the waves due to shoaling and refraction effects. The extent to which this invalidates the technique is not known. For this reason, the resulting spectra might be expected to show some anomalies. Yet the double peaked nature of the experimental spectrum is similar to the spectra recorded by the U.S. Army Corp of Engineers Research Center's (CERC) shoreline gauge located at Jennette's Pier, Nags Head, North Carolina (Personal communications, D. L. Harris, CERC, 1975), and shown in figure 9. The experimental flight was co-ordinated with CERC personnel and was designed to pass directly over the recording station. The CERC spectra were generated from data recorded before, during, and after the flight passed overhead. Spectra 9b and 9c bracket the overflight. Nearly all the spectra have similar double peaks with the major peak near 0.08 hertz and the secondary peak near 0.15 hertz. This compares with 0.085 hertz and 0.153 hertz, respectively, for the experimental spectrum. As an indication of total energy, a significant wave height of 1.70m was computed from the measured spectrum by trapezoidal integration of the area under the curve with the assumption of a Gaussian distribution of wave amplitudes. This compares well with the 1.86m and 1.74m for the CERC spectra measured nearest to flight time. Both the data obtained from the CERC measurements and the remotely sensed data may contain significant amounts of wave energy reflected from shore. Even though measured by two different techniques, the remotely sensed spectrum and the CERC spectra still have similar characteristics regardless of the cause. The experimental spectrum appears then to be an accurate description of the energy distribution in the most inshore area.

Although the experimental spectrum derived from the aircraft data compares well with the CERC spectra, the simulated spectrum fails to match this distribution (figure 6f). The significant wave height of 1.79m for the simulated spectrum compares well with 1.70m significant wave height for the experimental spectrum, but the simulated spectrum is single peaked and has a significantly higher level of energy density.

In this region of high wave activity, a number of assumptions on which the simulation model is based are probably not valid. The small amplitude assumption requires wave height to be small relative to wave length and water depth (Kinsman 1965, p. 125), but in the shoaling water the wavelengths shorten and wave height increases. Also, the equations used to compute refraction are strictly valid only for a constant water depth, but have been used successfully in areas with a mild slope (Dobson, 1967, p. 8). In segment 10, the depth goes to zero, and the slope can no longer be considered mild. It may be that non-linear, wave-wave interactions, dissipation due to bottom friction, and reflection of wave energy from the shoreline have significant effects in this innermost segment. The refraction model is a standard one and does not include any of these effects. For these reasons, the simulated spectrum might not be expected to match the experimental spectrum.

It is an assumption of wave refraction theory that the energy between wave rays remains constant and does not cross the ray boundaries. Thus, when rays diverge, the energy density decreases and, when they converge, the density increases. If the wave rays cross, a "caustic" is formed, indicating that the waves in this region have become so high they are unstable and are breaking (Kinsman 1965, p. 158). The practical application of this theory requires a decision on how to treat the energy associated with the wave rays which form the "caustic." In most of the offshore spatial segments, few rays cross, and the energy from these rays was included in the calculation; that is, it was assumed that no energy was dissipated in the "caustic." The spectrum in spatial segment 10 (figure 6f) was also computed in this manner. However, because there are many "caustics" in segment 10, this spectrum was computed a second time using an approach in which the energy from the crossed rays was not included in the computations (Morris, 1979). The results of this second computation are shown in figure 10. The simulated spectrum using this approach is double peaked and provides a better match with the experimental spectrum than does the standard technique. Since the same probable violations of model assumptions are present in the second computation as were in the first (figure 6f), one would not necessarily expect the comparison of experimental and computed spectra to improve. Whether this is a technique that better simulates the loss of wave energy due to breaking and dissipation in this region, or simply is a fortuitous result cannot be assessed from this single experiment. However, the promise shown in the results obtained using the modified approach suggests a new area for future research.

Another obstacle which must be faced by any further researcher in this area concerns adequate definition of the remotely sensed wave spectrum over the low frequency range in which resides most of the energy associated with the passage of storm systems such as Amy. When the experimental wave spectrum is transformed from the moving aircraft reference frame to a stationary one, the frequency resolution becomes nonuniform, with the worst resolution occurring at low frequencies. Very high data digitization rates may be required in order to obtain adequate definition of the spectrum at low frequencies, leading ultimately to a tradeoff between spectral definition over the frequency range of greatest interest and the computer resources expended in obtaining the final product.

Although this experiment did not have the ideal conditions required for verification of the theoretical modeling technique, the wave climate is probably typical of the conditions for which it can be used. The results of the study by Poole (1976b), illustrated in figure 4, apparently represent a minimum sea condition for which the model can be applied. The results of the present experiment (figure 4), with more energy residing at lower frequencies, establish a level at which the model shows a sensitivity to the shoaling and refraction effects which is distinguishable from purely random fluctuations of wave energies. Additional studies of wave conditions which fall within the energy bounds of a fully developed sea and that of this experiment should help to establish the degree to which the model is sensitive to these changes.

CONCLUDING REMARKS

The deepwater wave field associated with Tropical Storm Amy was not that of a fully developed sea, but is probably typical of a wave field outside the wave generating area. High frequency waves had been filtered and the energy was concentrated toward the low frequencies. In comparison to the spectrum of the deepwater wave field, several of the nearshore experimental spectra show a statistically significant change in spectral density levels, which can be attributed to shoaling and refraction effects. The spectra also show a consistent shift of energy toward the lower frequencies as the wave field moves shoreward which cannot be attributed to shoaling and refraction, but may be due to non-linear wave-wave interactions which were not simulated in the model. The most inshore experimental spectrum is in good agreement with the results of CERC shoreline spectra which were measured simultaneously with this experiment.

The simulated spectra follow the shift in energy levels of the experimental spectra for all but the most inshore segment. The total energy levels of the simulated spectra lie within 20 percent of the measured levels but the shift in frequency of peak spectral density is not predicted by the simulated spectra.

For this set of experimental data, the theoretical techniques adequately simulate the changes in spectral shape and energy levels that occur due to shoaling and refraction effects to within 5 nmi of the shoreline. Shoreward of this region, the standard simulation technique fails to match the energy distribution of the experimental spectrum. Using an alternate method improves the comparison between the simulated and experimental spectra for this shoreward most segment. Further investigations in this research area will be required to make an adequate definition of the experimental spectra at low frequencies for subsequent comparison with theoretical calculations. The simulation model may also need to include the effects of shore reflection, bottom dissipation, and nonlinear wave-wave interactions.

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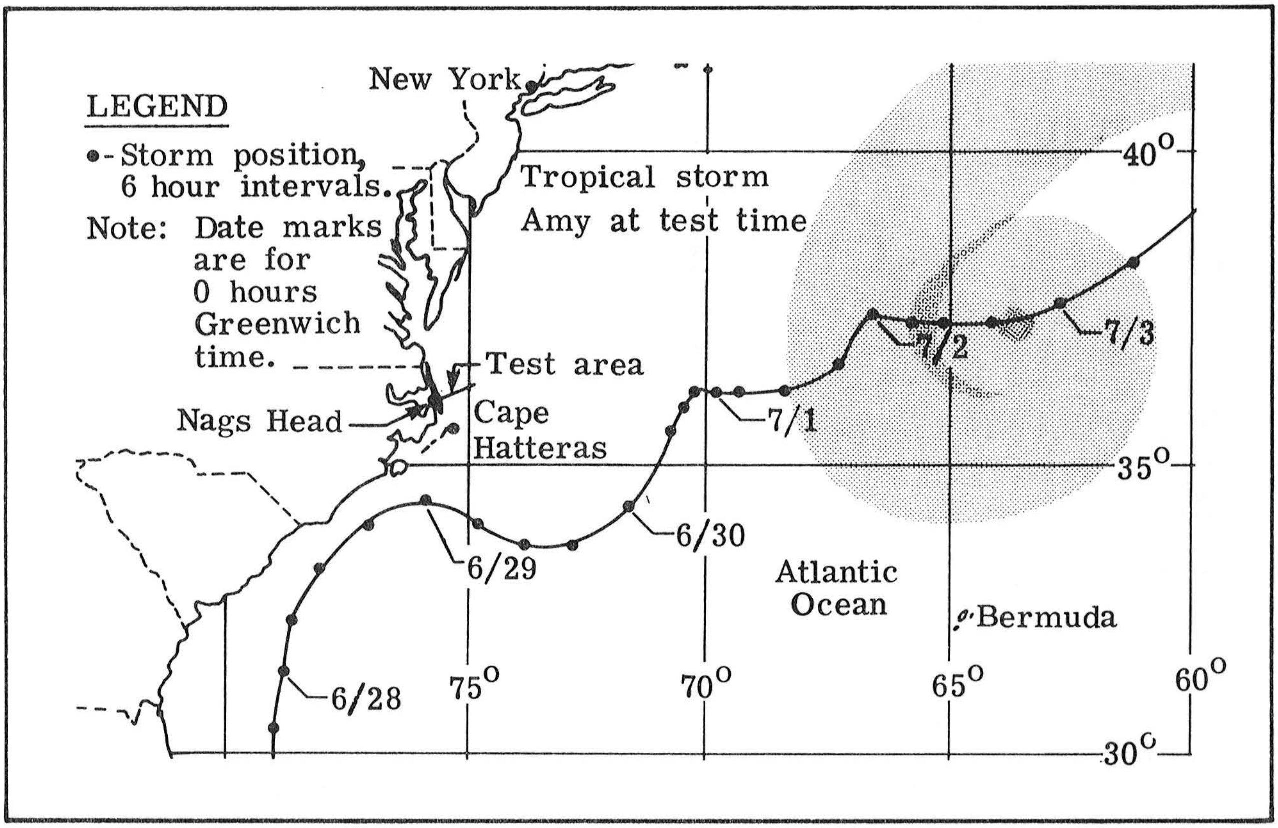

Figure 1.- Ground track of tropical storm Amy.

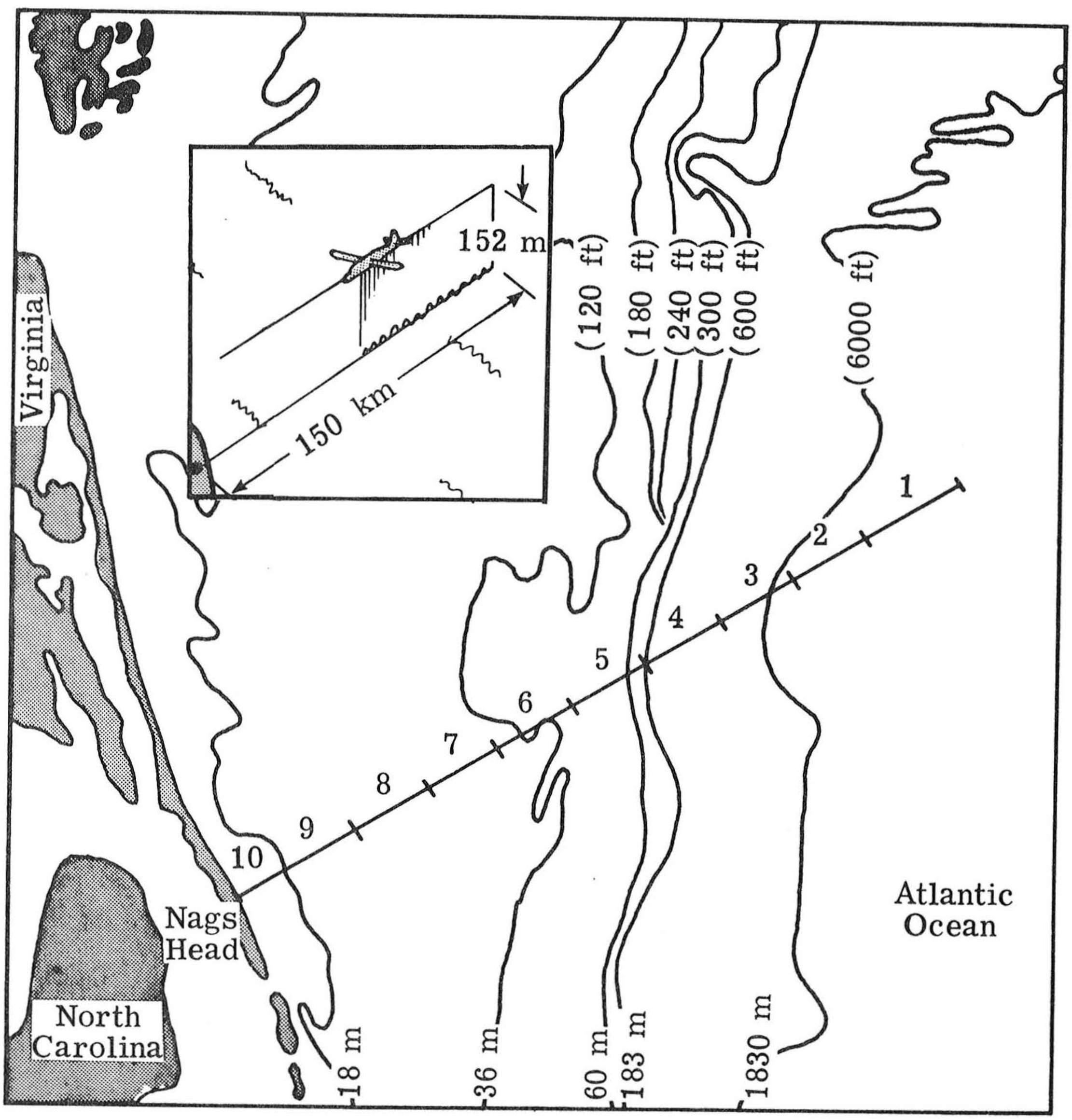

Figure 2.- Numbered spatial segments along the flight line. Contour depths in meters (feet).

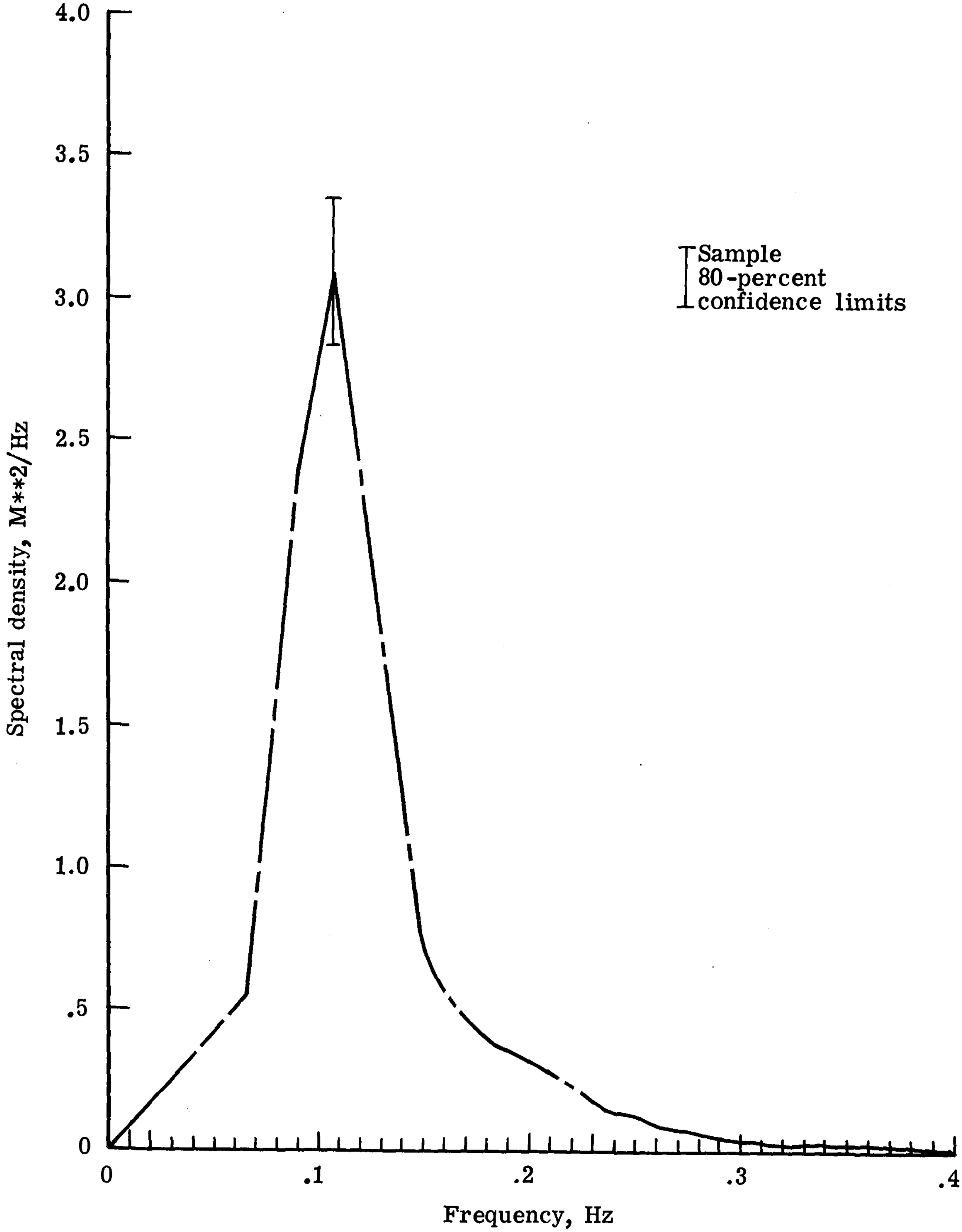

Figure 3.- Deepwater reference spectrum. (Represents average of deepwater segments 1, 2, 3 and 4.)

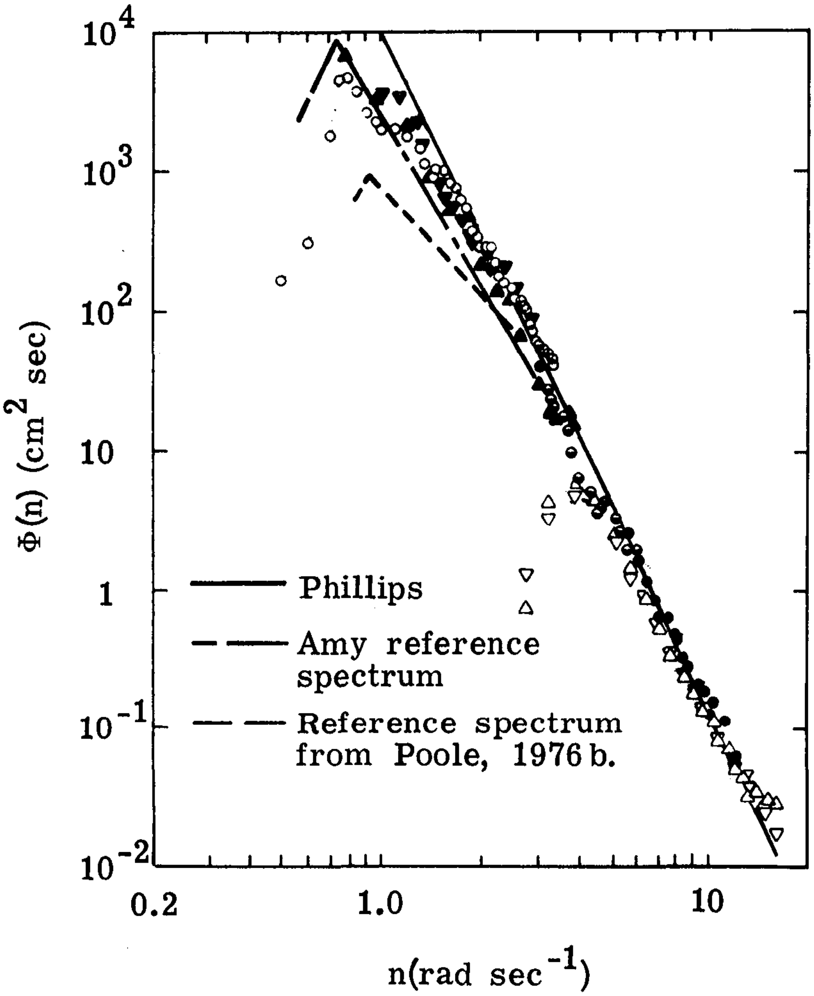

Figure 4.- Deepwater reference spectra from the current study and from Poole (1976 b.) superimposed onto the chart from Phillips (1977, page 146, figure 4.8), showing the frequency spectra of wind generated waves in the equilibrium range (solid line).

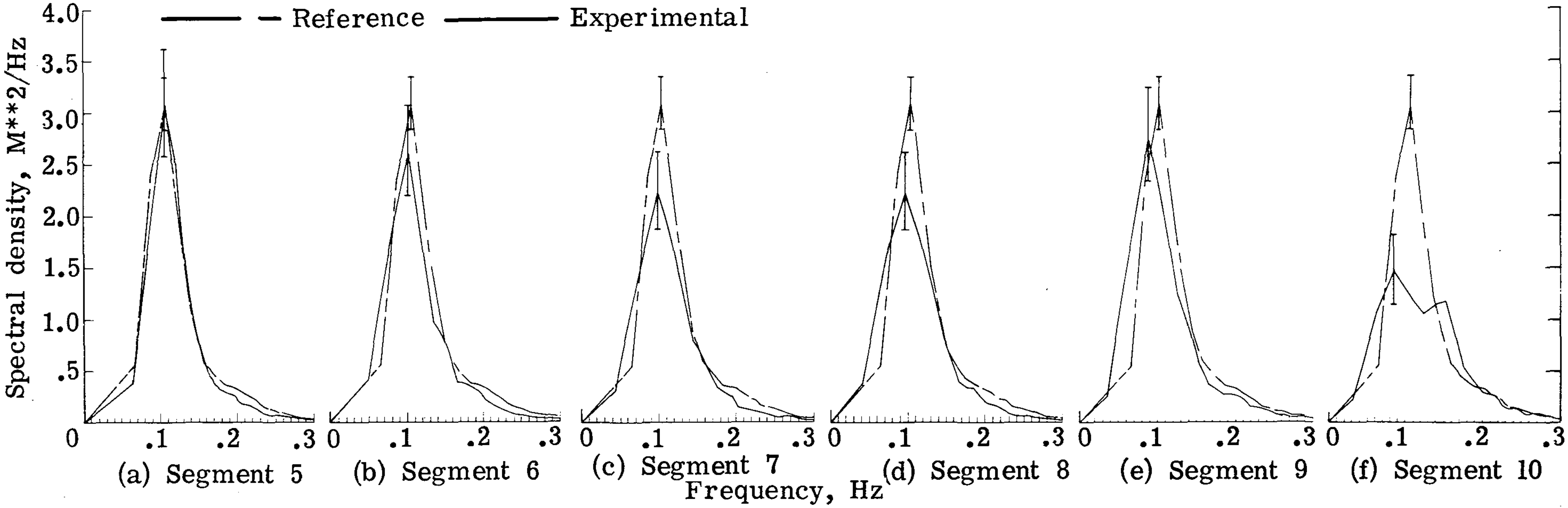

Figure 5.- Comparison of experimental wave spectra with the reference spectrum for each spatial segment.

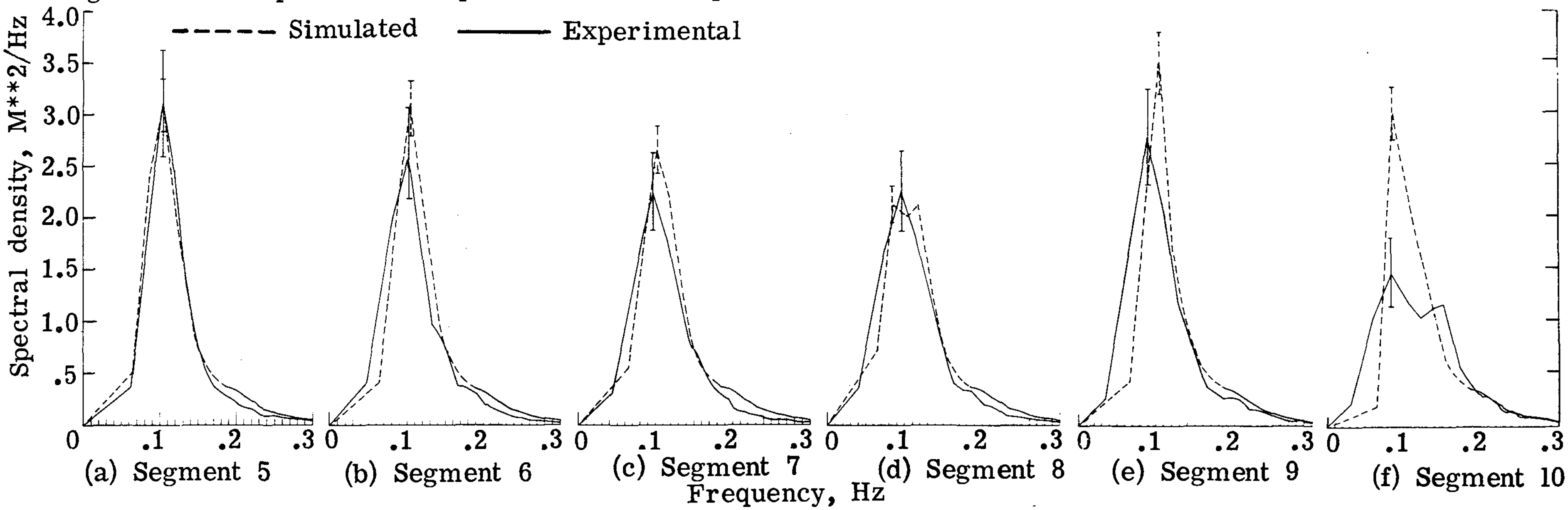

Figure 6.- Comparison of experimental and simulated wave spectra for each spatial segment.

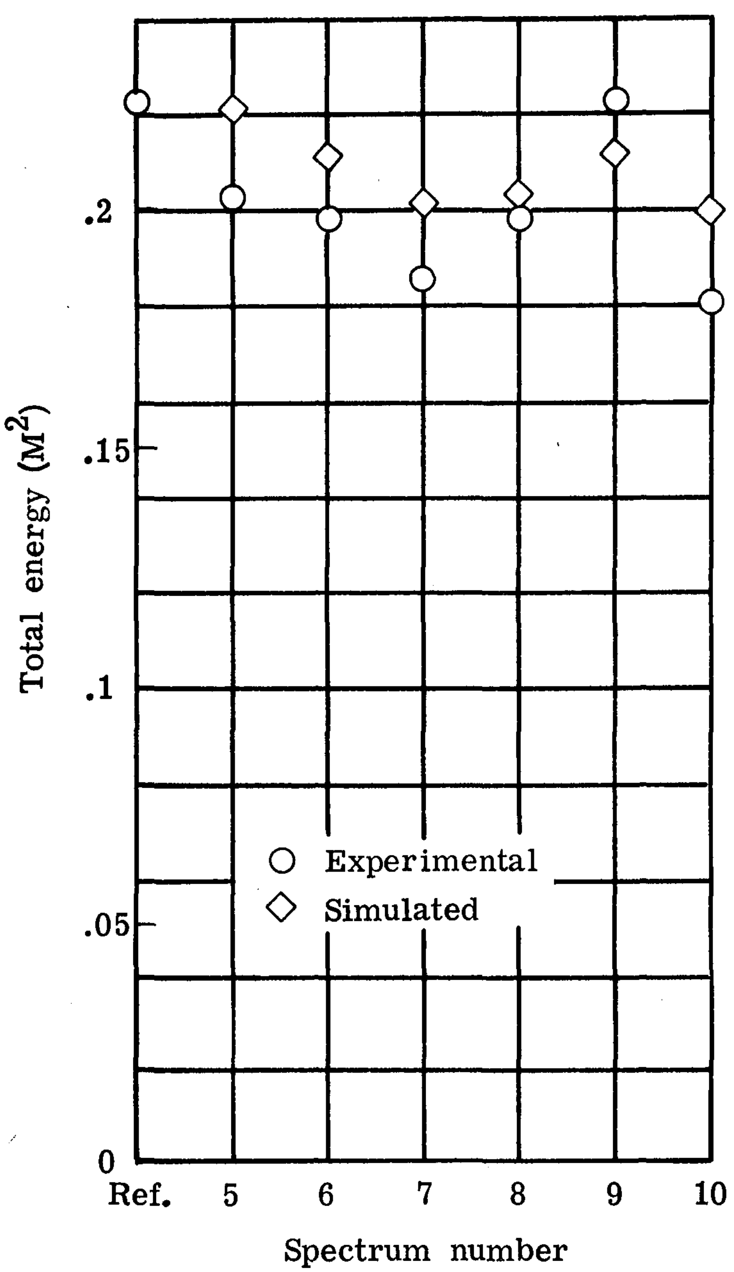

Figure 7.- Experimental and simulated total energy variation with data segment.

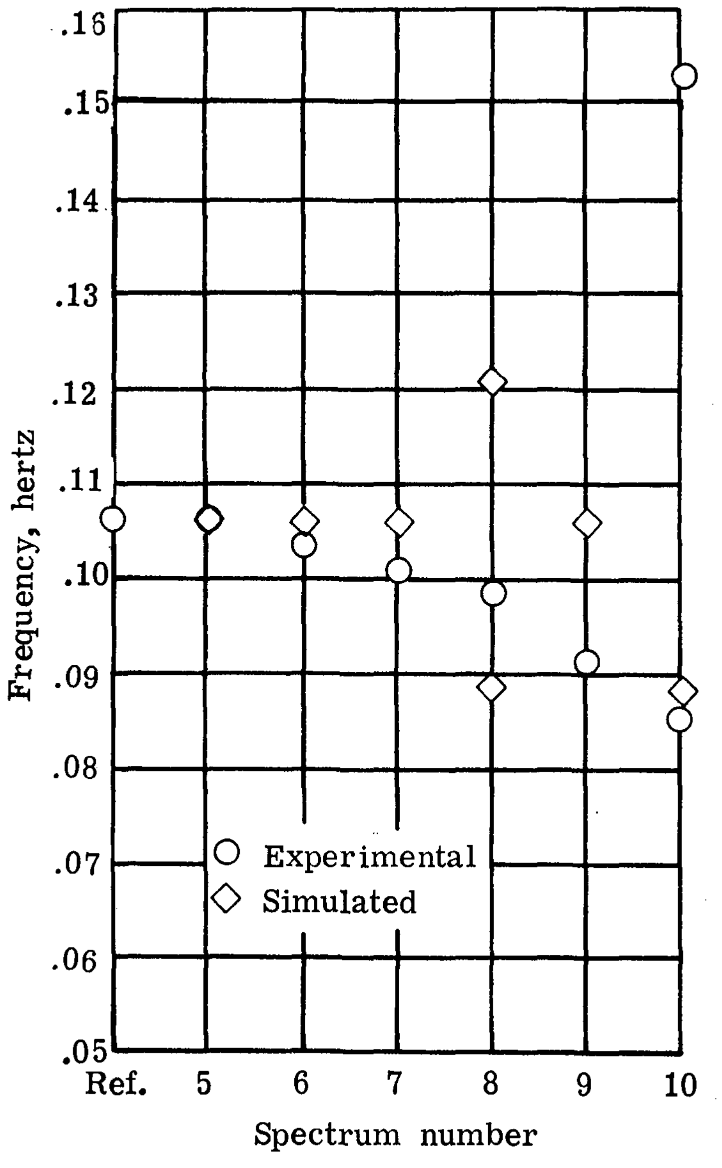

Figure 8.- Experimental and simulated frequency of peak spectral density variation with data segment.

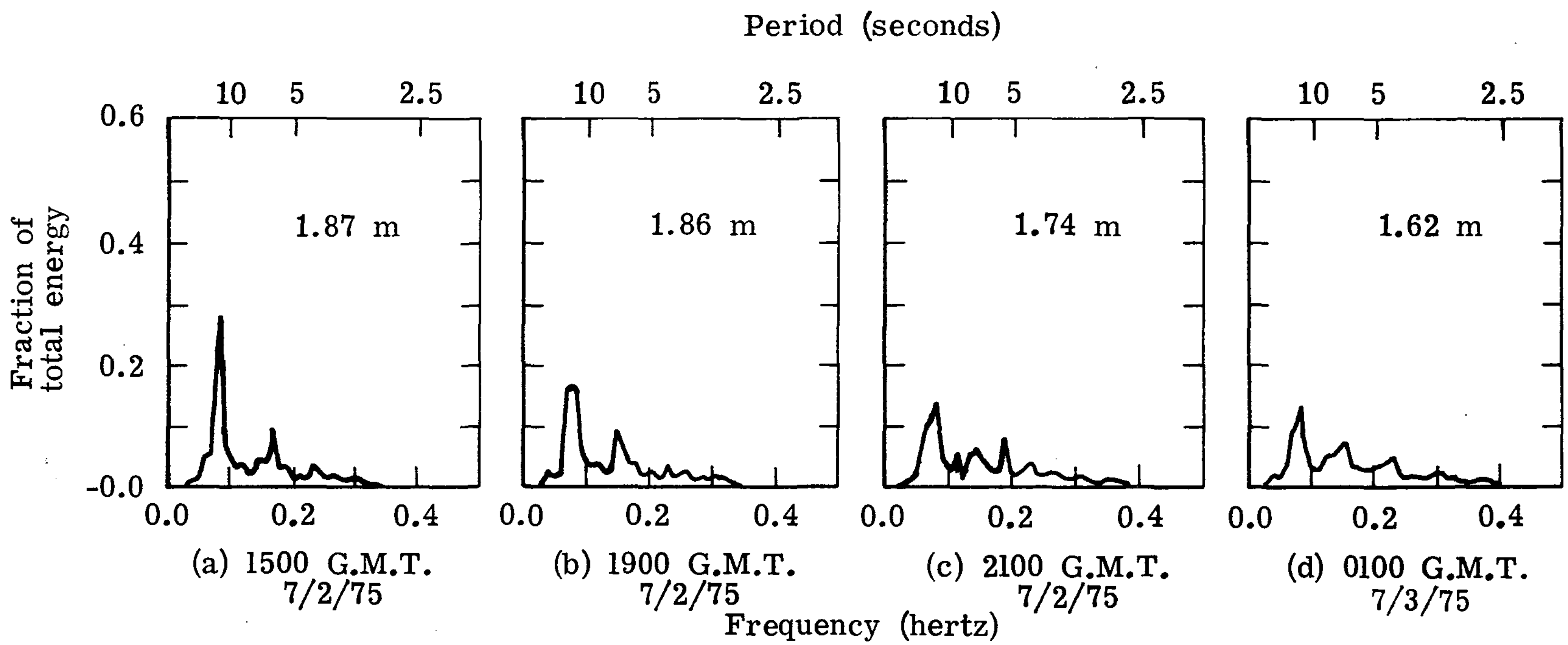

Figure 9.- Wave spectra computed from data obtained from the CERC shore gauge at Jennette's Pier, Nags Head, North Carolina (Harris, 1975). Significant wave heights are shown for each spectra.

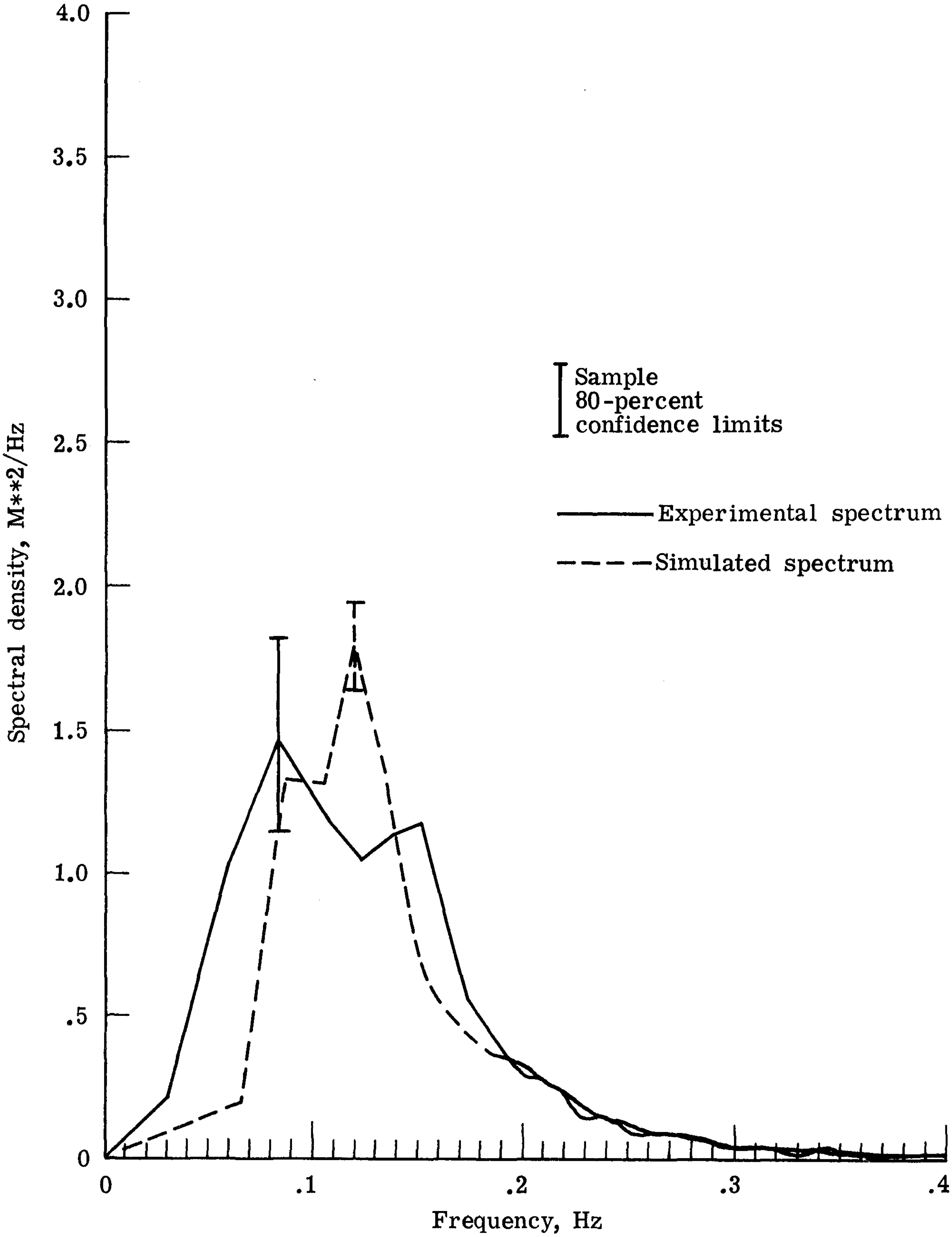

Figure 10.- Comparison of the experimental spectra of data segment 10 with the simulated spectra computed without energy from wave rays which formed "caustics".

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15. Supplementary Notes

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16. Abstract

Wave profile measurements made from an aircraft crossing the North Carolina continental shelf after passage of Tropical Storm Amy in 1975, are used to compute a series of wave energy spectra for comparison with simulated spectra. The results of these measurements indicate that, as it moves shoreward, the observed wave field experiences refraction and shoaling effects which cause statistically significant changes in the spectral density levels. Using a modeling technique, these changes in spectral density levels are successfully simulated in all but the most inshore of the six spatial regions that are compared. Total energy levels of the simulated spectra are within 20 percent of those of the observed wave field; however, the shift of the spectral density peak toward lower frequencies, seen as the wave field moves inshore, is not predicted by the simulated spectra. The results of the study represent the first successful attempt to theoretically simulate, at oceanic scales, the decay of a wave field which contains significant wave energies from deepwater through shoaling conditions. The comparison can also be used to establish a minimum level of spectral energy for which simulation would be expected to effectively predict the changing energy levels that occur as the wave field moves inshore. Problems in using this technique for simulation are discussed.

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