Bistatic Reverberation from the Sea Surface

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William I.Roderick

Naval Underwater Systems Centre

and

University of Birmingham

Introduction

The bistatic backscattering of underwater acoustic signals from the sea surface has been investigated in a shallow water environment. A parametric source projected a narrow beam of acoustic energy at the sea surface and insonified on the surface a well defined scattering area of limited extent. The surface generated reverberation was received on eight, closely spaced, hydrophones of a vertical array. The restricted surface area and hydrophone-to-surface distances confined the received scattered energy to small solid angles. To generate reverberation signals that were statistically stationary, waveforms of sufficient pulse length were transmitted. By utilising the broadband capabilities of the parametric source, the reverberation was measured as a function of the transmitted frequency. Since the source was electromechanically controlled in angle of elevation, the reverberation was also measured with respect to the angle of incidence of the source to the surface. In concert with the reverberation experiment, the directional characteristics of the sea surface were measured with an array of five wave height sensors. The sensors simultaneously measured the time varying wave height at five discrete points on the sea surface.

A time period of approximately eight hours was required to obtain a complete oceanographic-acoustic data set. Of course, this necessitated that the sea surface remain statistically stationary during the measurements. After many days of false starts - due to either equipment failures or nonstationary sea conditions, a complete data set was obtained. During the measurements, acoustic propagation was under isovelocity conditions and there was no evidence of a near surface bubble layer.

The power spectral density of the instantaneous reverberation - the Doppler spectrum - was of primary interest in the analysis of the reverberation data. In order to compare (at a future date) the measured reverberation properties to theoretically generated predictions, the directional wave spectrum of the sea surface was estimated from the wave height sensing data. A brief overview is given here of the experimental design, the transmitting and receiving systems, the wave height sensing system, and the acoustic-oceanographic data processing techniques. As a conclusion, typical reverberation Doppler-spectra and sea directional wave spectra are presented and discussed.

Experimental Design

The experiments were conducted off the north-eastern coast of the United States in the Block Island Sound shallow water range. A barge, submerged in a water depth of 30m, supports a tower to which a vertical array of hydrophones is attached (Fig.1). Eight of the linearly-spaced hydrophones - with 1m spacing - were used to receive the reverberation. The parametric source was secured to the top of the barge, and displaced 14m from the hydrophone array. The sea wave measuring system consisted of five ultrasonic inverted fathometers, which were mounted to the tower 3m below the surface.

The experimental procedures were as follows : First, the wave heights were measured simultaneously and continuously for one hour and recorded on magnetic tape. For the next seven hours, the reverberation data were obtained. The parametric source was projected at normal incidence to the surface and four difference frequencies were sequentially transmitted (ie: generated by the non-linear interaction of two primary frequencies in the water) - 9.0, 7.0, 5.0 and 3.5 kHz. The instantaneous reverberation signals received on each of the eight hydrophones were recorded on magnetic tape. At each of the transmitted frequencies, three waveforms were sent - 25 msec pulsed CW, 1000 msec pulsed CW, and 500 msec pulsed LFM with a 100 Hz bandwidth. A large number of pulses were transmitted at each waveform to achieve statistical confidence in the estimates of the reverberation properties. The angle of incidence of the parametric source was then changed from normal incidence to an incident angle of 20 degrees and the same waveforms were transmitted at each of the four difference frequencies. The same procedures were followed for incident angles of 40 and 60 degrees. Wind speed, as a secondary indicator of sea surface stationarity, was recorded continuously throughout the eight hour measurement period and the wind direction was monitored.

Transmitting and Receiving Systems

It is well known that multipath propagation in shallow water can be quite restrictive in isolating a particular phenomenon for investigation. The parametric source has besides its broadband capabilities, the advantages of narrow beamwidth and virtually no sidelobes and therefore would be ideal in minimising multipath interference. Furthermore, the insonified surface would be confined to a known and controllable region.

The parametric source consisted of a 25 cm diameter piston transducer operating at a mean primary frequency of 263kHz and having a nominal primary beamwidth of 1.5 degrees. A double sideband suppressed carrier signal was power amplified to drive the parametric source over a coaxial cable length of 1.5 Km. A high pass filter coupled the power amplifier to the cable to eliminate driving the source directly by spuriously generated difference frequencies. Typical far field source levels were 175 dB re 1 μ Pa.m at a difference frequency of 9 kHz and a level of 158 dB re 1 μ Pa.m at 3.5 kHz. The source levels could easily be monitored - although in the interaction region - by projecting the maximum response axis of the source directly at a hydrophone. The difference frequency beamwidth, at the half-power levels, varied negligibly with difference frequency and were approximately 4 degrees.

Free-flooded ceramic ring transducers, having omnidirectional beampatterns in the horizontal and "doughnut-shaped" in the vertical, were used as hydrophones to receive the reverberated signals. The effects of the vertical beampatterns restricted measurement of the absolute reverberation levels to angles near the horizontal. The hydrophone outputs were individually cabled to a shore facility over a multiconductor cable and then the signals were identically conditioned. The instantaneous reverberated signals - for all frequencies - were bandshifted to a common lower frequency (220 Hz). The bandshifted signals were FM recorded on a 14 channel Honeywell 5600 magnetic tape recorder. Bandshifted replicas of the transmitted difference frequencies were also recorded to serve as reference signals. A servo control signal was recorded to provide play-back speed accuracies to within 0.1 percent.

Wave Height Sensing System

Five upward-looking transducers (inverted fathometers) measured the sea surface wave height simultaneously, at five discrete points. The transition region from the near to far field characteristics of the transducers were used to insonify spot sizes on the surface which have cross sectional diameters smaller than the 4cm diameters of the circular piston transducers. The transducers were orientated in a horizontal line array positioned at a depth of 3m below the mean low tide surface elevation. The transducer spacing in the array was not linear, but was chosen such that there would be a maximum number of contiguous spacings between all combinations of sensor pairs. A minimum spacing of 30cm was chosen between the two closest transducers. Discrete spacings, at multiples of 30cm, were obtained from the array configuration, to a maximum spacing of 270cm. A priori information was required with the line array to determine from which side of the array the surface waves were propagating. Visual observations of the sea surface and wind direction measurements were used to resolve the front-to-back ambiguity of the array.

Each transducer of the wave sensing system was individually and sequentially pulsed with 16μsec, 450 kHz, pulses over separate coaxial cables. The first transducer was pulsed, switched to a receive mode, and the surface reflected signal was received. After a delay of 7 msec from the initial transmission, the next transducer was pulsed and the surface reflected signal was received. This procedure continued for each transducer such that the surface was "sampled" at a period of 35 msec above each of the five transducers. A bistable device was set on each transmitted pulse and reset by the initial reflection from the sea surface. The bistable output pulse length was modulated by the changing wave height above the transducer. The wave height variations were extracted from the pulse length modulation by a low pass filter having a cut-off frequency of 4Hz. Each of the five low pass filter outputs was FM recorded on the Honeywell type recorder.

Reverberation Data Processing

For all three transmitted waveforms, the bandshifted reverberation signals were analogue-to-digital converted at a rate of 1024 samples/sec and the sampled data were processed on a Univac 1108 computer. The Doppler spectrum of the reverberation was computed from the 1000 msec pulsed CW using Fast Fourier Transform (FFT) techniques. Approximately 90 msec after transmission of a pulse, a reverberation record of 900 msec duration was processed from each hydrophone. The data samples were Hanning weighted to reduce frequency leakage and "zeros" were added to the sampled data to give spectral estimates at frequency spacings of 0.57 Hz. Overall spectral resolution of the weighted data was 1.64 Hz between the half-power points. The discrete Fourier transform was evaluated via Singleton's FFT algorithm. The magnitude squares of the discrete Fourier transforms were ensemble averaged over thirty four transmissions to obtain spectral stability in the Doppler spectra estimates.

The reverberation signals from the 25 msec transmitted waveforms were processed by ensemble averaging squared samples over sixty consecutive transmissions. Ensemble averaging was performed at selected times following each transmitted pulse. Every fifth sample, (ie: samples separated by about 5 msec) from the onset of transmission to 200 msec following, were squared and averaged over the sixty pulses. This resulted in forty ensemble averages for each hydrophone output at each frequency and angle of incidence.

The processing of the reverberation signals from the LFM transmissions has not been completed at this time.

Reverberation Data Analysis

Analyses of the ensemble averages resulting from the 25 msec pulsed CW data revealed that the reverberation signals could be contaminated with interference from multipath arrivals. Direct path radiation and surface reflected-bottom scattered arrivals were the major interferences; however, in-laboratory electrical pickup could also be a source of interference. The 25 msec pulses were of short enough duration to resolve the multipath structure. The multipath interference was dependent on transmitted frequency and angle of incidence - normal incidence and 20 degree incident angle data were the least contaminated. Theoretical and experimental studies have shown that the bandwidth of the interference arrivals (direct path and surface reflected-bottom scattered) are narrower than the reverberation bandwidth. Also, the reverberation spectral content is Doppler shifted from the transmitted spectrum; whereas, the interference spectra are symmetrical about the transmitted spectrum.

A replica of each transmitted difference frequency was recorded on magnetic tape along with the reverberation data. The replica signal was conditioned through the same receiving system and was processed in the same manner as the reverberation signals to verify recording procedures and processing techniques. As an example, the power spectral density of a 7 kHz transmitted difference frequency is shown in Fig.2. The Hanning weighting slightly increases the half-power bandwidth (in comparison to uniform weighting), but the first sidelobes are reduced and are approximately 32 dB down from the peak energy. Note that the difference frequency has been referenced to a frequency of zero Hertz.

A reverberation Doppler spectrum, resulting from a transmitted frequency of 9 kHz at an incident angle of 20 degrees, shows considerable spectral broadening (Fig.3). For this spectrum the scattering angle was 27 degrees, and the spectrum is indicative of the spectra obtained at other scattering angles. The spectrum bandwidth is approximately 15 Hz with the centre of the spectrum displaced from zero in an up-Doppler direction. The ensemble averaged spectrum appears continuous without any predominant spectral peaks at this transmitted frequency and angle of incidence. Also, for the same angle of incidence, the spectra at the other transmitted frequencies show the same characteristic of exhibiting an up-Doppler and spectral broadening. However, the bandwidth of the reverberation decreases with decreasing frequency. As an example, the bandwidth of the 3.5 kHz transmitted frequency was approximately 5 Hz. An up-Doppler was characteristic at every incident angle. It will be seen shortly that an up-Doppler would be expected since the bearing of the acoustic projector was heading almost directly into the direction of propagation of the surface waves (wind). The wind speed was averaging 4.6 m/sec and the mean square wave height was 75 cm^2.

The Doppler spectrum shown in Fig.4 was obtained at a transmitted difference frequency of 5 kHz and at an incident angle of 60 degrees. The spectral peak at zero Hertz is due primarily to direct path radiation and a surface reflected-bottom scattered arrival. The spectral broadening at an up-Doppler of 3 Hz from the transmitted frequency is due to surface reverberation. Likewise, the spectral peak at 10 Hz from the transmitted frequency is also due to reverberation. First order resonance scattering would predict a 3 Hz Doppler shift. The direction of the Doppler shift would depend on the directional wave spectrum of the sea surface waves; and the displacement would be a function of acoustic frequency, angle of incidence, and angle of scatter. The 10 Hz shift observed at the 60 degree incident angle was also observed on other hydrophones as well as on other frequencies. Although the spectrum is contaminated with the spectra from multipath arrivals, it is evident that the bandwidth is greater than 10 Hz and less than 15 Hz wide. The detailed reverberation spectra is masked by the interference spectra, except for the dominant spectral peak at 10 Hz.

<u>Wave Height Data Processing</u>

The time varying wave heights were analogue-to-digital converted at a rate of 16 samples/sec and the sampled data were processed on the Univac 1108 Computer. As in the reverberation signal processing, the wave height data were processed using FFT techniques. A total record length of 30 minutes was divided into

30 second segments on each channel. Prior to FFT processing, the mean value was removed from each segment and Hanning weights were applied to the data samples.

The sea surface was assumed to consist of a superposition of uncorrelated plane waves propagating from various directions. The two dimensional wave spectrum of the surface waves could be estimated from the second order statistical relationships between the outputs of the wave height sensor pairs. It can be shown that a spatial Fourier transform relates the directional wave spectrum of the surface waves to the cross spectral density between sensor pairs.

The cross spectral densities were computed via FFT processing of overlapped segments of the weighted data. Overlaps of 50 percent were used to obtain statistical stability in the spectral estimates. A spectral resolution of .048 Hz was obtained from the 30 second weighted data. Directional wave spectra were computed using two conventional and a high resolution technique. The high resolution technique, based on a maximum likelihood criterion, was the most successful.

Wave Height Data Analysis

The power spectral density of the surface waves, measured from one sensor output, is shown in figure 5. The sea wave spectrum is peaked from .233 Hz to .267 Hz. There also appears to be swell wave present, although at a much lower energy level, in the vicinity of .10 Hz. It can be seen that the sea wave spectra does not fall off with increasing frequency at a constant rate. The power spectra measured from each of the five wave height sensors were practically identical.

The directional wave spectrum, as a function of the azimuthal angle, is shown in figure 6 for a frequency of .267 Hz. The wavelength for this frequency can be obtained from the dispersion equation for gravity wave and is 2194 cm. This is approximately eight times longer than the length of the array. It should be mentioned that the conventional techniques could not resolve the directionality for this wave length-to-array length ratio. The energy is predominantly in a direction that makes an angle of 55 degrees with the array, or 313 degrees from magnetic north. The surface waves, for this frequency were propagating at an angle of 35 degrees from the bearing of the acoustic projector.

Conclusions

A sea surface reverberation experiment conducted in shallow-water, has been briefly described. Unique to the experiments were the use of a parametric source as an acoustic projector and an array of wave height sensors to measure the directional characteristics of the sea surface. Fast Fourier Transform techniques were used in the processing of both the reverberation and the wave height data to compute the reverberation Doppler spectrum and the directional wave spectrum. Analyses of the reverberation data revealed considerable spectral broadening in the up-Doppler direction. This direction of Doppler shift was in agreement with the direction of propagation of the sea surface waves. Bandwidth of 15 Hz were observed for a transmitted frequency of 9 kHz and the bandwidth was seen to decrease with decreasing transmitted frequency. Analyses of the LFM data are underway and other properties of the reverberation field are being investigated.

EXPERIMENTAL DESIGN

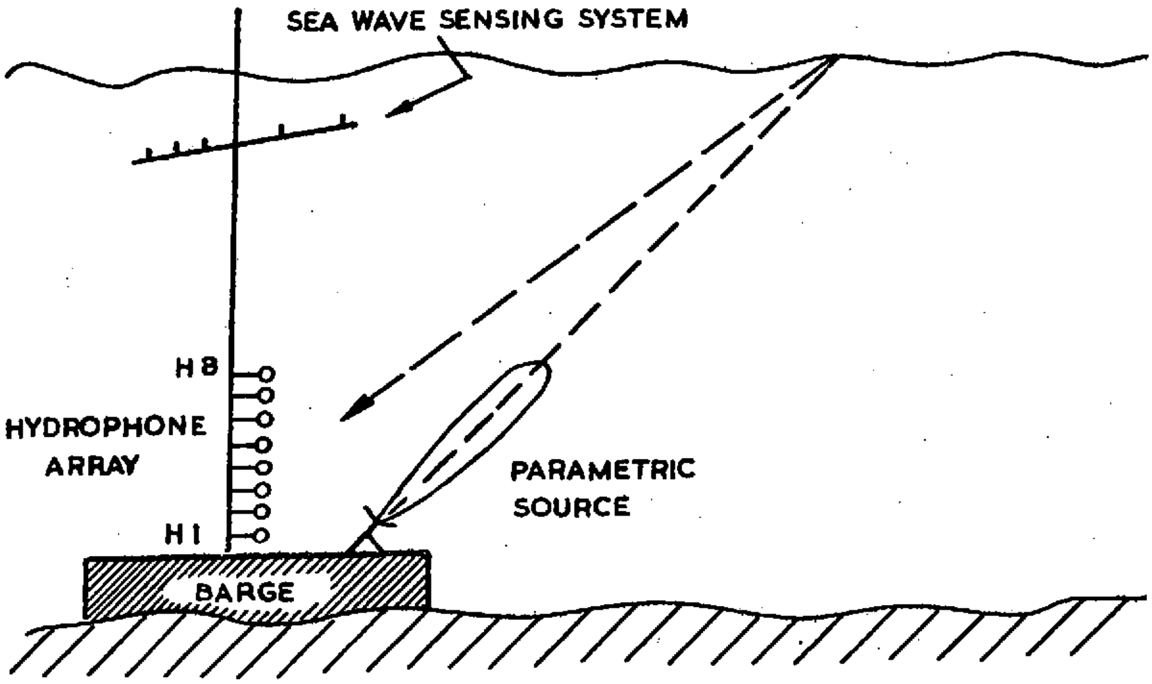

FIGURE (1)

TRANSMITTED POWER SPECTRAL DENSITY

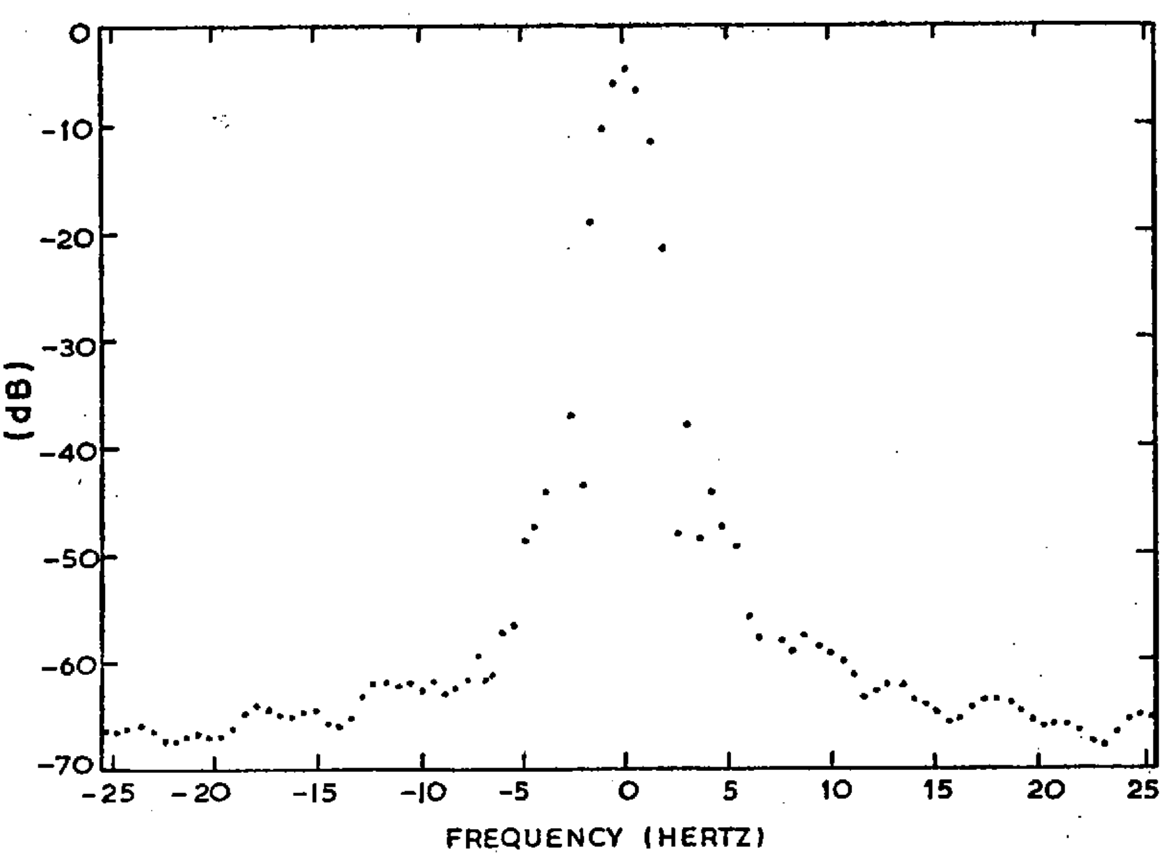

FIGURE (2)

POWER SPECTRAL DENSITY

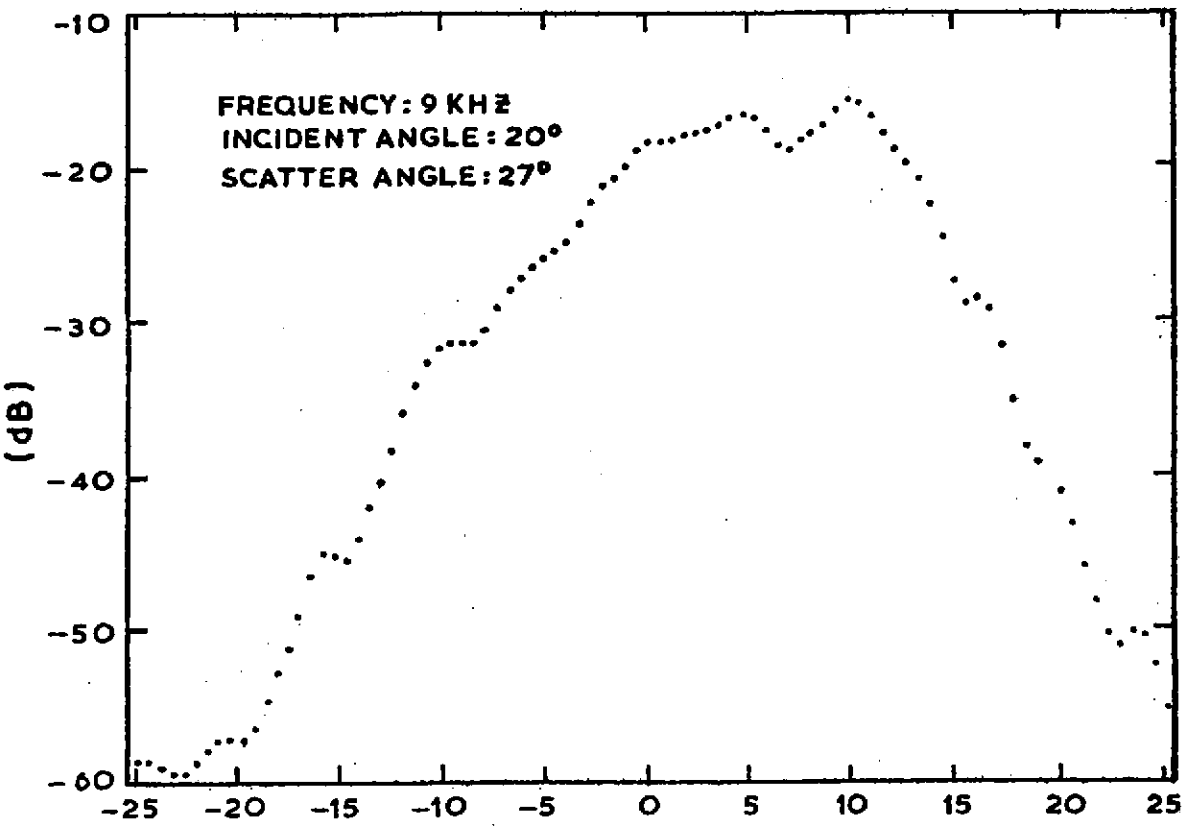

FIGURE (3)

POWER SPECTRAL DENSITY

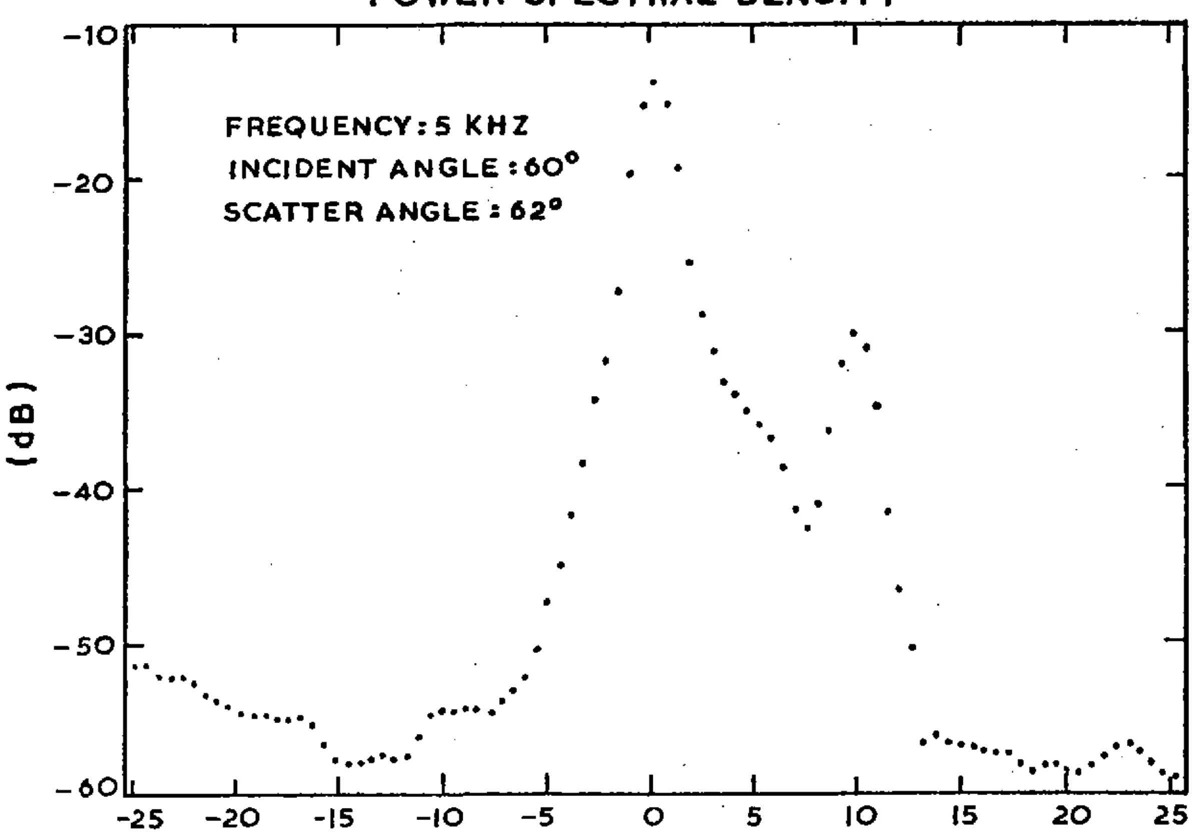

FIGURE (4)

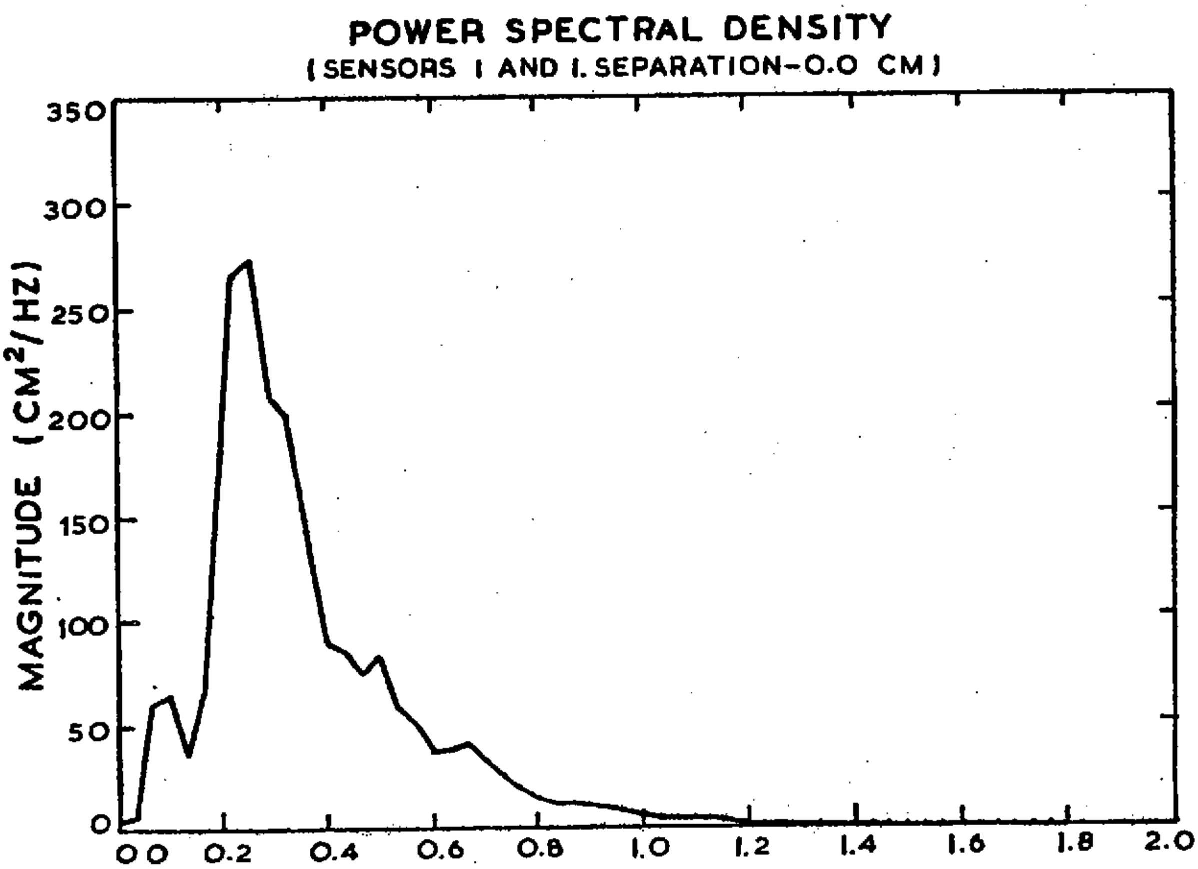

FIGURE (5)

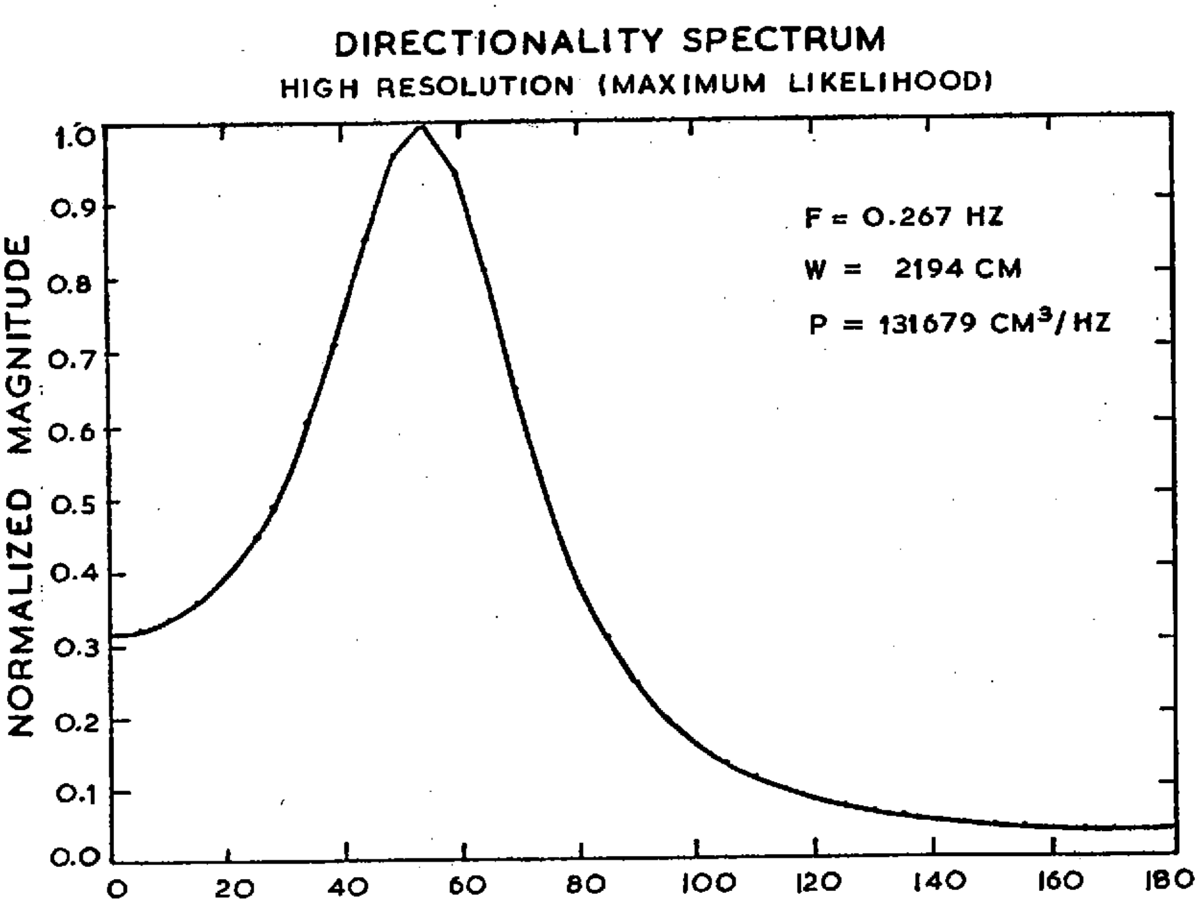

FIGURE (6)