ACOUSTIC SCATTERING FROM SURFACE SHIP WAKES

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1. INTRODUCTION

The passage of a surface ship introduces air bubbles into the water where they remain until they eventually dissolve or rise to the surface. The bubbles form an acoustic wake which is able to both scatter and absorb incident sound. This paper describes example results from a trials programme which had the aim of collecting scattering data from surface ship wakes.

2. MEASUREMENT PROCEDURE

2.1 Equipment

Three active sonars were mounted on a platform located on the sea bed in approximately 50 m of water and were used to view the wake from underneath. The platform included a pan and tilt mechanism to steer the sonar beams. An umbilical link, containing a power cable and an optical fibre link for acoustic data and sonar control transfer, connected the platform to the shore. The onshore facility housed the data recorder, the on-line analysis equipment and the PC used for sonar control.

2.2 Trials

During the trials, ships were instructed to maintain a steady speed along a straight course which passed directly over the sonar platform. Once a ship had completed its run it was instructed to clear the area until all remnants of the acoustic wake had disappeared from the sonar screen before commencing another run.

2.3 Sonars

The sonars used to insonify the ship wakes had transmit and receive arrays which were line arrays placed at right angles to each other. Thus they formed pencil composite beams of a few degrees width. Transmissions were short pulse continuous wave at spot frequencies within the range 20 to 200 kHz.

Following transmission, echoes arriving at the receive hydrophones generated a voltage which was amplified and then complex heterodyned at the transmit frequency. A low pass filter then restricted the frequency content of the signal. The inphase and quadrature components (I&Q) were sampled and placed on the optical fibre link to be recorded onshore.

Data is presented in the form of A-scans which show echo level as a function of time after transmission. The echo level (EL) is given by $10\log_{10}(I^2+Q^2)$ expressed in units of dB re 1 bit of the A/D converter. Time into the ping also represents the distance from the sonar provided that the speed of sound in water is constant.

3. THE ACOUSTIC ENVIRONMENT

A considerable amount of active data was recorded before and after a trial in order to assess the background against which the wakes had to be detected. With the pencil beam orientated vertically the dominant feature in calm weather was the reflection from the sea surface. The initial return comes from the surface immediately above as seen in the main beam; at later times the sidelobe response is responsible for returns from the surface at some distance from overhead. The range at which the first return occurred was modulated by surface waves.

During rough weather the magnitude of the surface return was reduced and scattering from the natural bubble layer was detected beneath the sea surface. The bubbles are introduced into the ocean by breaking surface waves and on occasion were observed to be carried to depths of up to 10 m. They provided significant scattering at all frequencies of interest and at times gave so much absorption that the echo from the sea surface was no longer detected. Good descriptions of the natural bubble layer are provided by Thorpe [1] and Crawford & Farmer [2].

4. SHIP WAKES

4.1 The Acoustic Wake

The passage of a surface displacement ship through a body of water produces a foamy white-water wake. The sources of the air bubbles are as follows:

a) The breaking of the bow wave and the waves of the Kelvin wake.
b) Entrainment of air along the ship's waterline into the hull turbulent boundary layer.
c) Propeller rotation drawing in air from the surface and propeller cavitation.

The evolution of the white-water wake viewed from above in aerial photographs is discussed by Peltzer [3]. Beneath the surface the air bubbles form an acoustic wake. In this paper it will be assumed that acoustic returns from the ship wakes are due to scattering from the air bubbles in the wake. It will also be assumed that the bubbles absorb a significant proportion of the incident sound energy. A considerable amount of information on the acoustic properties of surface ship wakes was gathered during World War II and reported by the National Defense Research Committee (NDRC) [4]. They are important to sonar operation since scattering from the wakes can generate false contacts, while wake absorption can lead to genuine contacts being hidden behind them. These effects are long lasting, and remnants of the acoustic wake can be detected up to half an hour after the vessel has passed by.

4.2 The Kelvin Wake

The surface wave train generated by a ship is known as the Kelvin wake. This wake comprises side arms with a half angle of $19\frac{1}{2}$°, generated from the bow and stern, and a series of transverse waves. A theoretical description of the Kelvin wake is given by Lighthill [5] while measurements of a surface ship wake are provided by Hughes [6]; this latter document also discusses the generation of internal wave wakes. Since the Kelvin wake keeps station with the ship the transverse waves travel at the ship speed. From consideration of the dispersion relation for deep water gravity waves it can be shown that both the wavelength and the period increase with increase in ship speed. Furthermore it may be shown that the faster the ship the greater the depth of water disturbed by the surface waves.

4.3 The Thermal Wake
The thermal wake is the disturbance of the temperature distribution in the top layer of the ocean caused by the passage of the ship. It can persist up to half an hour after the ship has passed by. Images of the thermal wake taken from an aircraft are provided by Peltzer et al. [7].

4.4 The Turbulent Wake
The turbulent wake is the body of water behind the ship which has been set into turbulent motion. Turbulence is introduced both by the passage of the hull through the water and also by the propellers. It is shown in the NDRC report that acoustic scattering and absorption from both the velocity and the temperature structure is negligible in comparison to the scattering from the air bubbles. The importance of the thermal and turbulent wakes lies in their rôle in the transport of the air bubbles, leading to persistence of the acoustic wake for longer than simple consideration of bubble rise times and dissolution times would predict. A model of the evolution and transport of bubbles in the turbulent wake is described in Miner et al. [8].

5. ACOUSTIC WAKE MEASUREMENTS

5.1 Experimental Procedure
In the work presented in this paper the sonar pencil beam was directed upwards so that the ship's run gave a vertical section through the wake. The angle and location of the section was dependent on the ship's speed and track relative to the sonar and the rate and direction of the tidal flow which carried the wake through the sonar beam. All runs were recorded in calm weather with the ships travelling at 12 knots. Pulse lengths were of 0.2 ms duration giving 15 cm resolution of detail in the wakes.

5.2 Example Measurements
The first measurements presented are those from the Clovelly class fleet tender Headcorn; this vessel weighs 143 tons full load and has dimensions 21.4x6.4x2 m. The insonifying frequency was towards the lower end of the frequency range stated in paragraph 2.3.

Averaged A-scans recorded during the run are shown in Figure 1; each is obtained by summing 10 consecutive A-scans together. The graphs are labelled by the ping (or entry numbers) which are counted from the start of the recording; the pulse repetition frequency was 5/s. The first averaged A-scan was recorded before the ship arrived overhead and clearly shows the surface return at 68 ms into ping; the floor to this graph is provided by the ambient noise. The other averaged A-scans were recorded after the ship had passed and show echoes from the acoustic wake beneath the sea surface. The reflection from the sea surface is attenuated by the wake, sometimes by as much as 40 dB.

The A-scan information can also be presented as echo level modulating intensity on axes of time into ping (or range from the sonar) and ping number (or time of transmission). Figure 2 shows the result of plotting all pings in this way. As before the surface return forms the dominant feature before the ship arrives. When the ship is overhead returns from the keel are seen as well as from bubbles which have been entrained along the ship's waterline into the turbulent boundary layer. These bubbles descend past the keel and then rise with the flow to approach the surface near the stern; the flow pattern is independent of ship speed and therefore is not related to the surface waves generated by the ship. Once the ship has passed overhead, the bubbles, together with those introduced at the transom, form the passage wake of the ship. Beneath the passage wake is the propeller wake which contains air which has become entrained in the propeller vortex and also bubbles from propeller cavitation. The air bubbles from all these sources mix to form the region of acoustic scatterers seen on the display; the attenuation created is sufficient to completely remove the reflection from the sea surface above. The wake descends to a depth of 3 m and tidal flow takes it out of the sonar beam after 2 minutes.

Measurements from the Tornado class torpedo recovery vessel Tormentor and the Sal class mooring and salvage vessel Salmaid are shown in Figures 3 and 4 respectively. Tormentor weighs 698 tons full load and has dimensions 40.0x9.2x3.3 m while Salmaid weighs 2500 tons full load and has dimensions 77.0x14.8x3 m.

The Tormentor data was recorded at the same acoustic frequency and pulse repetition frequency as that of Headcorn and the wake shows similar features. The formation of the propeller wake is not visible on the display as the ship passed uptide of the sonar, although scattering from air bubbles which have been transported by the propeller to a depth of 6 m is observed as the wake drifts overhead.

The Salmaid data was recorded at an acoustic frequency in the middle of the band of interest with a pulse repetition frequency of 2/s. Again the keel of the ship is visible and this time passive noise from the ship can be seen breaking through on the active display; the noise is received at all times into the ping and peaks when the propeller is overhead. After the ship has passed by, the wake is seen descending to 12 m and eventually drifts out of the sonar beam after 6 minutes.

6. WAKE VOLUME SCATTERING STRENGTH

Measurements of the volume scattering strength were made using the sonar equation as specified in Urick [9]. He makes the following assumptions about volume reverberation:

a) Sound propagates in straight lines, and sources of attenuation other than spherical spreading and sea water absorption are neglected.
b) A random homogeneous distribution of scatterers exists throughout the insonified volume.
c) A large number of scatterers exist in the insonified volume.
c) The pulse is short enough for attenuation over its length to be negligible.
d) Multiple scattering, that is reverberation produced by reverberation, is negligible.

It should be recognised that measurements made under these assumptions ignore the absorption in the wake ie true readings of scattering strength per unit volume are only obtained close to the wake edge where absorption is low.

The sonar equation for the reverberation level received by the hydrophone is:

$$RL_v = SL - 2\,TL + S_v + 10 \log_{10} V ,$$

where: RL_v = reverberation level (dB re 1 μPa),
S_v = scattering strength per unit volume (dB/m^3 @ 1m),
SL = source level (dB re 1 μPa @ 1m),
TL = one way transmission loss (dB re 1m),
V = insonified volume (m^3).

The transmission loss is assumed to be spherical spreading plus sea water absorption: $TL = 20 \log_{10} r + \alpha r$, where r is the range in metres to the reverberating volume and α is the sea water absorption at the transmit frequency as given by Schulkin & Marsh [10]. The insonified volume is:

$$V = c\tau r^2 \Theta / 2,$$

where: c = speed of sound in sea water (m/s),
τ = pulse length (s),
Θ = equivalent composite beamwidth (steradians).

Thus the measured volume scattering strength of the data may be obtained from the A-scans using the above equations and knowledge of the sonar parameters, namely source level, receiver calibration, pulse length and beamwidth. Typical averaged A-scans which have been recalibrated to volume scattering strength are shown in Figure 5. These have been derived from the Headcorn run of Figures 1 & 2 and show volume scattering strengths in the wake of the order of -20 dB/m^3 @ 1m. Note that data at times greater than 68 ms into ping includes the surface reflection and should be ignored. Futhermore the floor of the A-scan is due to ambient noise and its scattering strength measurement should also be ignored.

7. CONCLUSIONS

An active sonar with a pencil composite beam has been used to view the acoustic wakes of surface ships from below. The results presented show the passage of the ship overhead and the formation of the wake as air bubbles enter the water. In addition to the acoustic scattering, the bubbles are seen to absorb sound and reduce the intensity of the sea surface reflection.

8. ACKNOWLEDGMENTS

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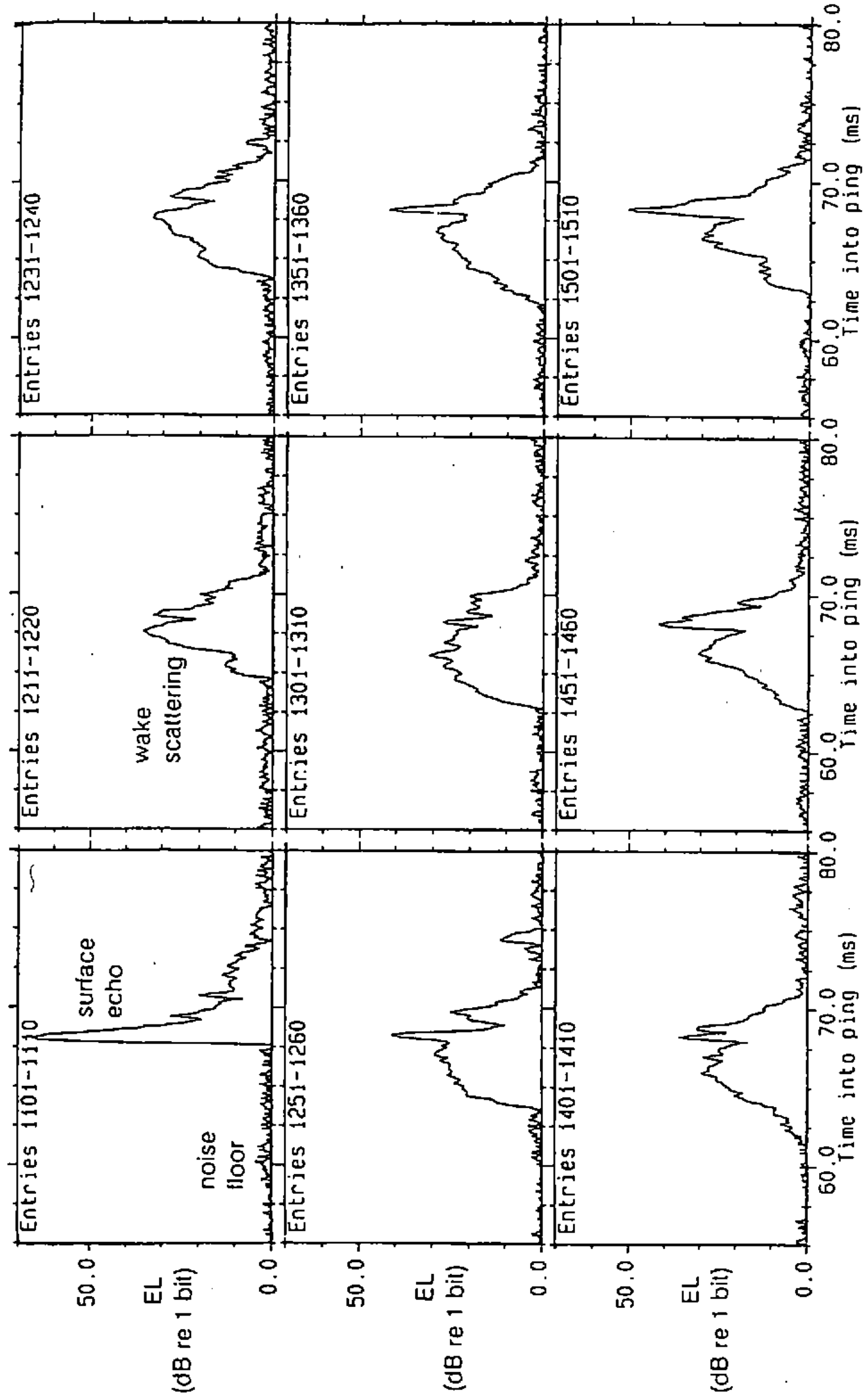

FIG 1 AVERAGED A-SCANS FROM THE WAKE OF HEADCORN

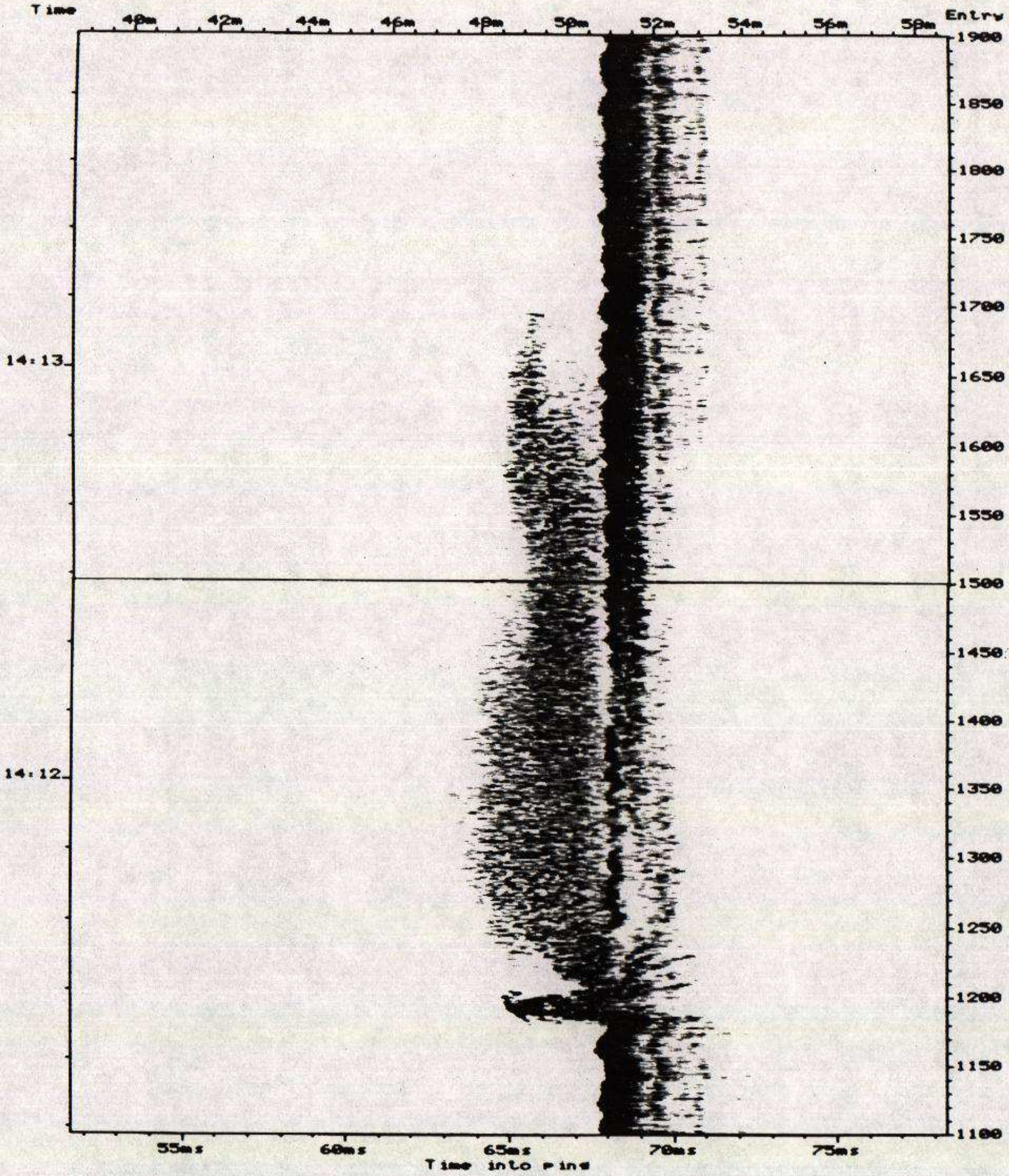

FIG 2 ACOUSTIC RETURNS FROM THE WAKE OF HEADCORN

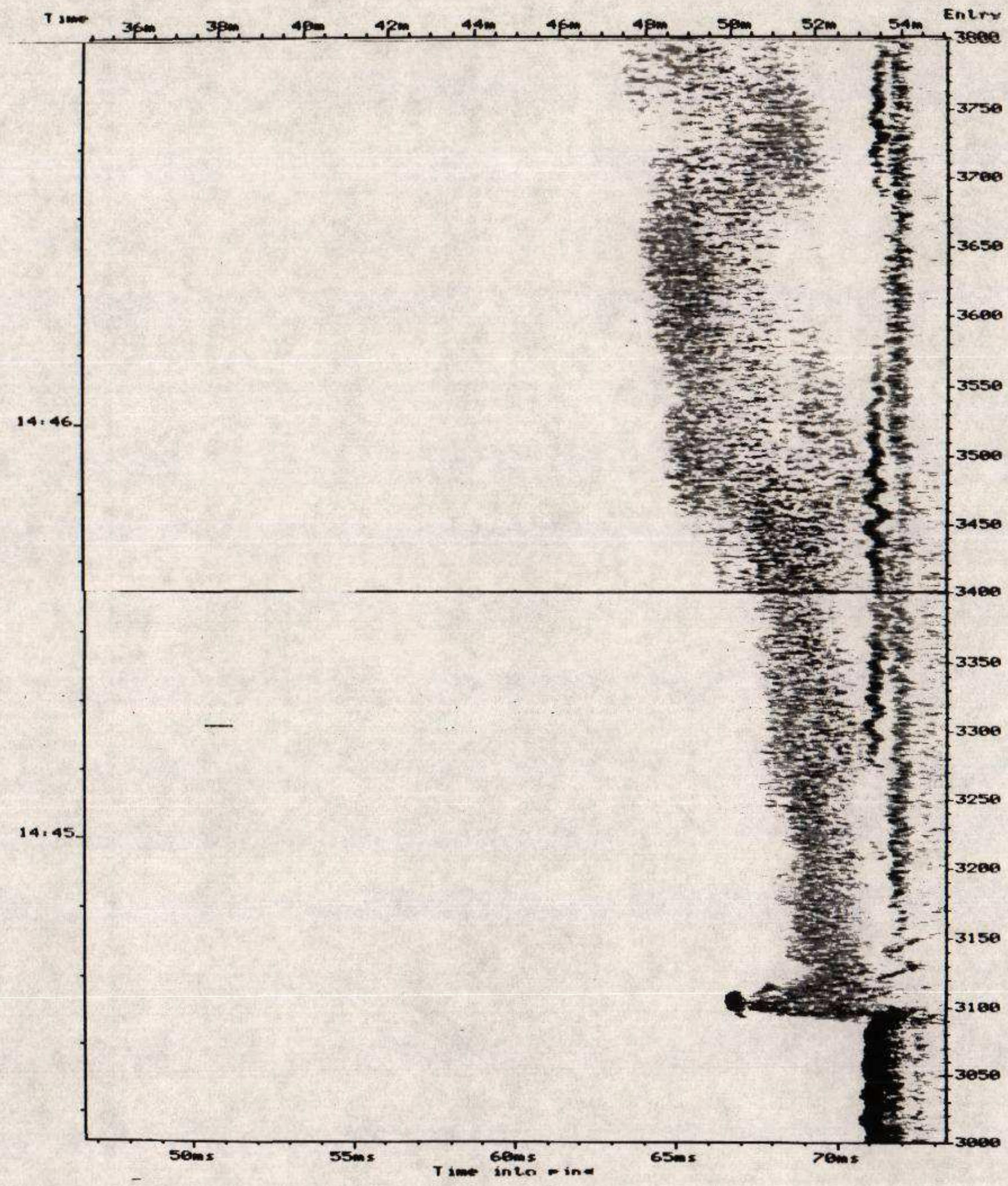

FIG 3 ACOUSTIC RETURNS FROM THE WAKE OF TORMENTOR

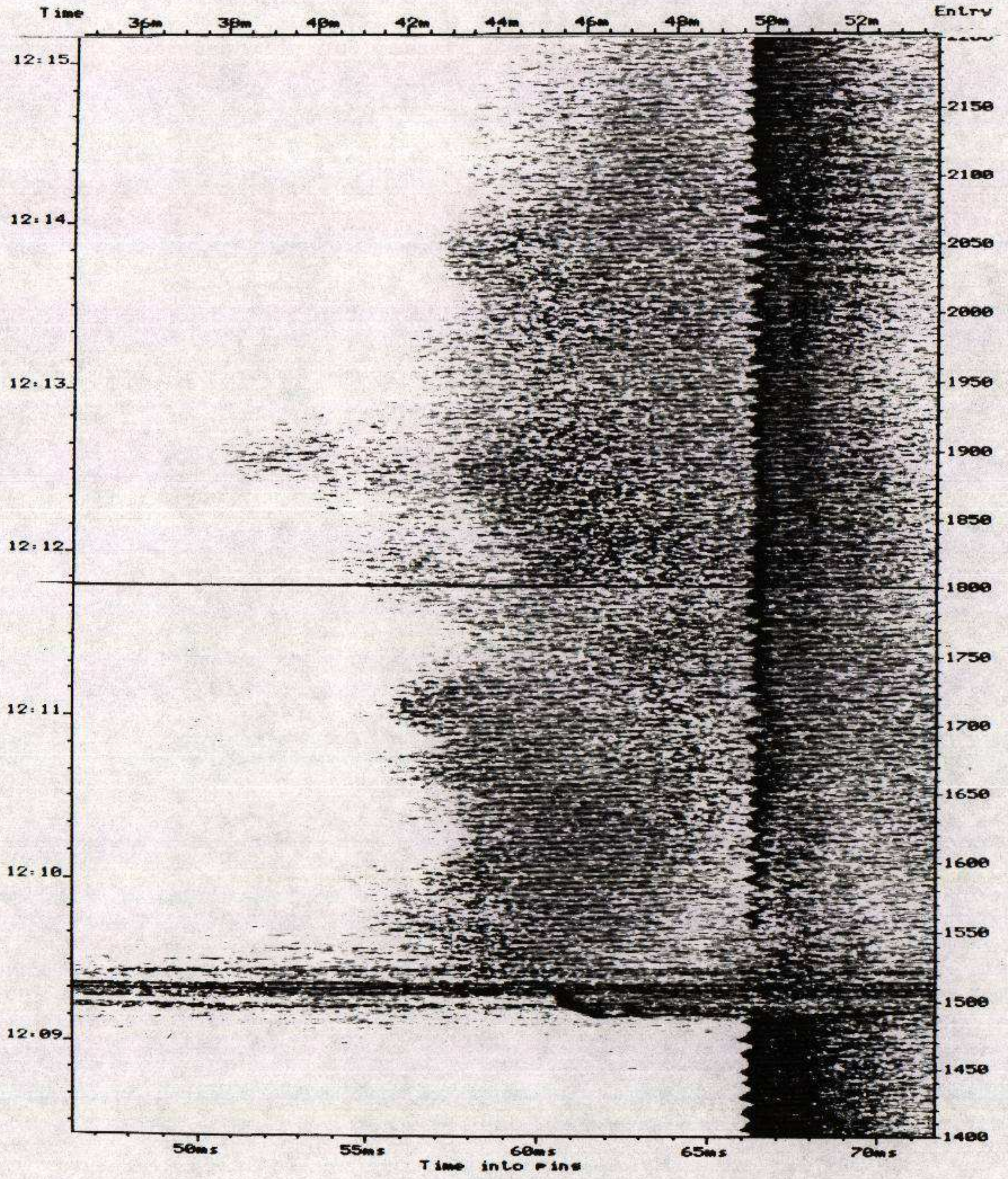

FIG 4 ACOUSTIC RETURNS FROM THE WAKE OF SALMAID

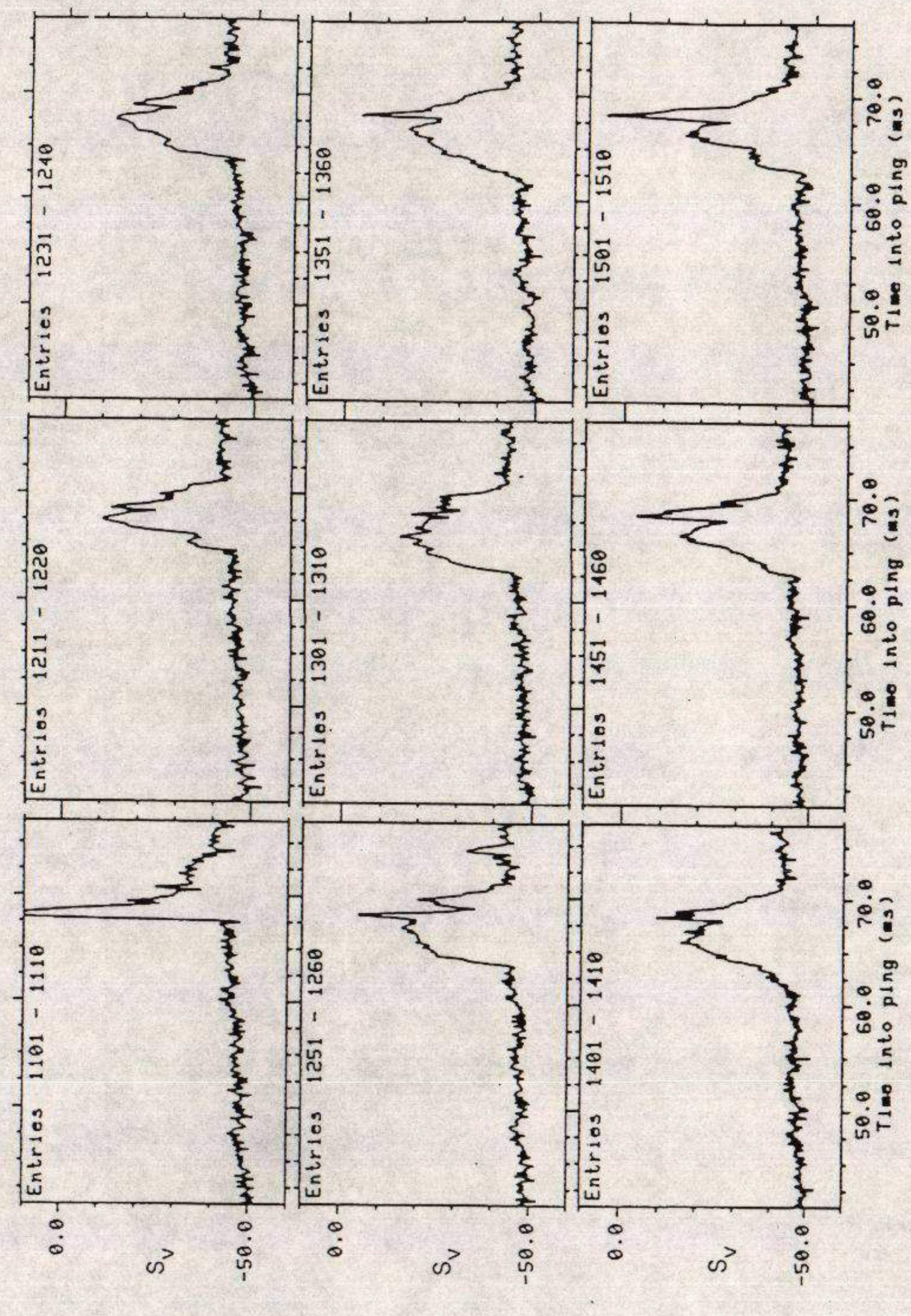

FIG 5 VOLUME SCATTERING STRENGTH (dB/m^3@1m) ESTIMATES FROM THE WAKE OF HEADCORN