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THE 1988 RWB STEPHENS LECTURE: SONAR ICHTHYOLOGY

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ABSTRACT

Sonar ichthyology refers to the interaction of underwater acoustics and fish, described here for audio frequencies and for clupeoid fish in the Bristol Channel. A quantitative review is given covering three sets of phenomena. First we have the long-distance attenuation due to dispersed fish, possible because of the high absorption and scattering losses associated with their swim bladders. The main evidence comes from the differences between daytime with aggregated fish and night with dispersed fish, but there are several other manifestations. Second there is an acoustic propagation fluctuation with period about one minute, due to individual fish. Third as our main subject we have sonar records showing fish, sometimes shoaled and sometimes dispersed, out to ranges of many tens of km. Besides the diurnal variations our observations include tidal, Doppler, modal interference and storm effects. There are major differences between pilchard and sprat as regards behaviour and the consequent pictorial records.

INTRODUCTION

I am delighted and honoured to be giving this R W B Stephens Lecture, first because I was a student of Ray Stephens at Imperial College many years ago, and second because I had a hand in setting up the Lecture Series. I admit that my subject is not really one at the centre of Ray Stephen's interests, but I hope the material is worthy of the occasion and anyway the first rule of the Series says there aren't any rules.

My title is a little fancy but is intended to reflect Eric Eastwood's studies and book on Radar Ornithology (ref 1). There are many close parallels between radar displays of bird behaviour and the pictures from fish in long-range sonar which I come to later in this talk. But I wish to start by describing observations on attenuation and related effects due to fish, which help to complete the story. The whole comprises a review of the interaction of sound with the clupeoid fish, such as sardine and sprat, living in the Bristol Channel (see figure 1).

Basically I will be presenting data taken some 20 years ago, but with a few new points. I would like at this stage to acknowledge the major contributions of many colleagues at the Admiralty Research Laboratory, MAFF Fisheries Laboratory and elsewhere, concerning the equipment and the experiments, and note that some of their names appear in the references.

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FISH ATTENUATION

Diurnal Changes

When operating an echosounder in shallow water it is not uncommon for the bottom return to be obscured as the ship passes over a shoal of fish. This is a high-frequency short-range effect due to the scattering and absorption by the high concentration of fish within the shoal. My subject is a little different: the low-frequency long-range effect due to dispersed fish.

The experiments were part of a study of the fluctuation of sound as it was transmitted from a fixed source, such as that in figure 2, to a fixed receiver. Figure 3 shows excerpts from an early record. The top trace shows signal level dropping some 30 dB about 40 minutes after sunset, to the consternation of everyone present. Fortunately it returned the next morning, but the whole process repeated on the following night. Note that the sunrise plots have a reversed time scale, so that the abscissa really represents light intensity.

It was eventually realised that the culprits were pelagic fish, in particular the sardine or Cornish pilchard, and in further particular the swimbladders of these fish. The swimbladder is an air-filled sac which helps control the buoyancy of fish, and which can resonate at a surprisingly low frequency. At frequencies close to resonance it is an extremely effective scatterer and absorber of sound, and will be shown to play an extremely important role in the general acoustics of shallow water. In view of this it is curious that another name for it is the "sound", with a derivation owing nothing to acoustics!

During the night the fish are dispersed - perhaps because it is too dark to stay close to their neighbours - and in view of their large numbers can produce the attenuation displayed in figure 3. During the day most of the fish congregate into shoals: those fish in the back row are ineffective scatterers and even those in the front row cannot pull their full weight because of mutual scattering or interaction. Roughly speaking we cannot lose more energy than is incident on the projected area of the shoal. There is an analogy with the poor visibility in mist and the relatively good visibility in rain.

Jumping over a very large number of observations, most taken in multi-frequency experiments, we come to the summary in figure 4. Three main groups may be picked out from this, as presented in table 1. Attention is drawn to the high values of the quoted attenuations, close to the maximum measured, and which can correspond to 37 dB over the 23 km path. The size and the population figures are realistic for the fish concerned. The identification experiments will be discussed later, but note now that in the last column "young" refers to the larval or post-larval stages of the other fish and is only a guess.

The work on diurnal changes has been fully published, see especially ref 2, and the numbers all agree so well with expectation that there is no doubt on the basic interpretation. Nevertheless after all these years we are still out on a limb since reports of the effect elsewhere are still uncertain or sparse.

TABLE 1 FISH POPULATIONS

Season	Late Summer	Mid Summer	February
Peak frequency kHz	0.7	1.4	3.5
Calculated fish length cm	24	12	5
Attenuation dB/km	1.6	1.6	1.1
Calculated concentration per m^3	3×10^{-3}	1.3×10^{-2}	5×10^{-2}
Identification	Sardine	Sprat	Young

Five Further Effects

I have evidence from six different aspects of fish attenuation: the diurnal effect just described plus five further effects which I will be able to do little more than list.

The range-dependence of signal level in shallow water is controlled by bottom and surface losses as modified by the sound-velocity profile in the water, but sometimes there are large discrepancies explained by the presence of fish.

Even the daytime levels show a large drop during the summer (figure 5), partly due to profile changes and partly to changes in the population of fish that do not shoal.

When the wind blows hard there is an increase in the shallow water transmission loss due to rough-surface scattering, possibly augmented by the entrainment of air bubbles. But we see additional effects around both 0.7kHz and 3.5kHz due to the turbulence breaking up the fish shoals.

Comparison of 7.5 kHz and 3.25 kHz propagation in the surface duct of the deep ocean clearly shows additional attenuation effects at the latter frequency, attributable to fish.

Figure 6 shows fluctuations due to modal interference and to surface waves. There is also a fluctuation (strictly not an attenuation) of period about one minute, present only during daylight hours, due to the excited movement of fish round the hydrophone (ref 3).

Reporting has been patchy on these latter five effects and there are further publications to come.

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FISH SONAR PICTURES

General

The sonar experiments to be described here were initially carried out at 1 kHz, changing over at the end of 1965 to a 2 kHz system. The sonar pulses were radiated from a powerful trainable projector, laid on the sea-bed; that for 2 kHz has already been shown as figure 1. The echoes were received on a fixed horizontal hydrophone array of length 60 feet (18m), and this implies a beam-width of 4° at 1 kHz and 2° at 2 kHz. Most of the remaining figures show a history of the happenings in such a narrow beam, as a function of time and range.

Performance was improved by correlation processing. In this technique the pulse is long and of broad bandwidth, typically with a linear frequency modulation lasting 4s and covering 100 Hz, and at our shore station the returning waveform was continuously compared with a replica of that transmitted. The outcome was a nominal time resolution equal to the reciprocal bandwidth or 10ms, equivalent to a nominal range resolution of 8m and a practical resolution of at least the same order.

Figure 7 shows an early record (ref 4), note that the darker regions correspond to the stronger returns. It is a montage since we were using recorder displays that could show range elements of only about 2 miles. So as in figure 8 we eventually changed over to a drum recorder that lasted for approximately one day, showing all ranges in the chosen beam out to 40 nautical miles (100s return travel time). Note that this is just about the distance from London to Cambridge!

Figures 7 and 8 show the main features that we became accustomed to in the succeeding years. We have the wrigglers or pilchard shoal echoes, with sinusoidal tracks due to their passage on the tidal stream, and usually with a few added wriggles of their own. These tracks disappear when the shoals break up at night. We have the diffuse interference patterns, with a commentary later. We have fixed bottom echoes due to bottom roughnesses, note especially the strong returns at 10 miles which correspond to an underwater extension of Trevose Head.

Figure 9 shows the somewhat different appearance at 2 kHz, with part of this record enlarged to form figure 10. The estimated (guessed) target strength for the typical shoal is + 5dB (re $1m^2$), with dimensions perhaps 13m across by 3m deep. From the known packing density this would contain the order of 30,000 sardines.

In the course of the decade 1960-1970 a very large number of records were accumulated, and it is possible here to pick out only a few special aspects.

Identification

In 1964 a major experiment was mounted to identify the scatterers and tie down their characteristics. The long-range sonar was operated continuously for 23 days (ref 5), and although the records cannot conveniently be reproduced here it was possible to monitor the changes both in fish behaviour and in the environment. For example storms were seen on several occasions to spoil the propagation and reduce the effective range of the displays. Figure 11 shows one special item when an artificial target, with about 30 0.2m diameter floats arranged in a vertical array, was streamed from a buoy. Just like the fish it paints a sinusoidal track following the tidal stream; note that the broken-up appearance comes from the necessity to switch beams in order to follow it.

The experiment was actually a cooperative venture with the long-range sonar; long-range attenuation measurements; ARL sector-scanning sonar operated from PAS GOSSAMER: echo-sounding and fish catching from RV CLIONE and RV PLATESSA (MAFF Lowestoft); tidal stream measurements from HMS EGERIA and others; and boomer measurements from CLIONE (NIO Wormley). It was highly successful and for the first time we became sure that it really was sardines that were producing our sonar traces. The one thing missing was getting everyone looking at the same shoal at the same time, in effect we had to wait till 1967 to achieve this.

In 1967 a diffuse target about a mile across was found on the long-range sonar, at a range of about 35 miles or 65 km. The RV CORELLA (MAFF) was directed to this target and as a result of her echo sounding and fish catching it was identified as a group of relatively small shoals of sprat. The correlation between the two sets of acoustic observations is shown in figure 12. This patch of sprats was tracked on the long-range sonar for six days, and at the same time the water movement was measured using a drogue suspended from a buoy. The movements of the sprat and of the water were virtually identical, as regards both the tidal stream and the residual current.

Other Aspects

Diffuse patterns have already been remarked on, and a good 1 kHz example appears in figure 13. It is clearest at night, but may also be seen modulating the shoal returns in the daytime. It arises because of the wave-guide or modal nature of the shallow-water acoustic propagation, the first two modes having slightly different phase velocities and beating together in space to produce the regular interference pattern of figure 13. The positions of the intensity peaks agree well with calculation. The whole pattern scale varies with the tidal changes in water depth, and this also agrees with theory. Patterns are not always so simple, for many reasons. For example at close ranges there are extra modes participating, even at 1 kHz, and this is so for all ranges at 2 kHz (compare figure 9).

The timing of shoal disappearance and appearance is usually close to civil twilight, approximately 40 minutes after sunset or before sunrise - compare figure 3 on attenuation. But the manner of the change-over varies in an erratic way, eg we have sharp changes, diffuse changes, a tramlines effect due to a temporary rise in attenuation, and even the presence of tracks throughout the night. This variability mirrors that observed in the diurnal attenuation effect and is partly caused by it. Figure 14 summarises the timing information, with a plot similar to those from radar ornithology. Of course there are departures from the twilight rule, note for example the relatively late rising of the fish at midsummer.

By counting the tracks we can estimate the number of shoals, demonstrate the peak for sardines in the late summer, and note the variation from year to year. In a typical year the mean summertime figure is about 3 per nautical mile, and the maximum about 5. The latter corresponds to 10 shoals per square mile, 3×10^5 fish per square mile or fish concentration 2.5×10^{-3} m^{-3}. These day-time shoal figures agree quite well with the night attenuation figures in table 1.

The Doppler of the returns can be measured if we project pure tone pulses. Selecting ranges where there are fish, at 2 kHz the daytime spread between quarter power points is 3.4 Hz, corresponding to 1.38 m/s. At night the fish are quiescent and the spread drops to 2.1 Hz. But at twilight we get maximum activity (it is a good time for feeding) and a maximum in the spread at 3.8 Hz.

The studies on fish echoes have only been published in part, with refs 4 and 5 as the most accessible, and there is more to come. I am unaware of any similar records elsewhere which fit the conditions of long range and having a fixed installation.

CONCLUSION

I hope I have demonstrated the complementary nature of the attenuation and echo data. They also have a dual importance:

a. underwater acoustics is a powerful tool in the study of fish and environmental features.

b. underwater acoustic mysteries may often be traced back to fish.

REFERENCES

1. E Eastwood 1967 Radar Ornithology Methuen London.

2. P A Ching and D E Weston 1971 J Sound Vib 18,499-510. Wideband studies of shallow-water acoustic attenuation due to fish.

3. P A Ching and D E Weston 1975 J Sound Vib 39,287-292. Fast acoustic fluctuations caused by fish.

4. D E Weston and J Revie 1971 J Sound Vib 17,105-112. Fish echoes on a long-range sonar display.

5. J Revie, G Wearden, P D Hocking and D E Weston J Cons int Explor Mer 36, 82-86. A twenty-three day twenty-mile echo record of fish behaviour.

THE 1988 RWB STEPHENS LECTURE: SONAR ICHTHYOLOGY

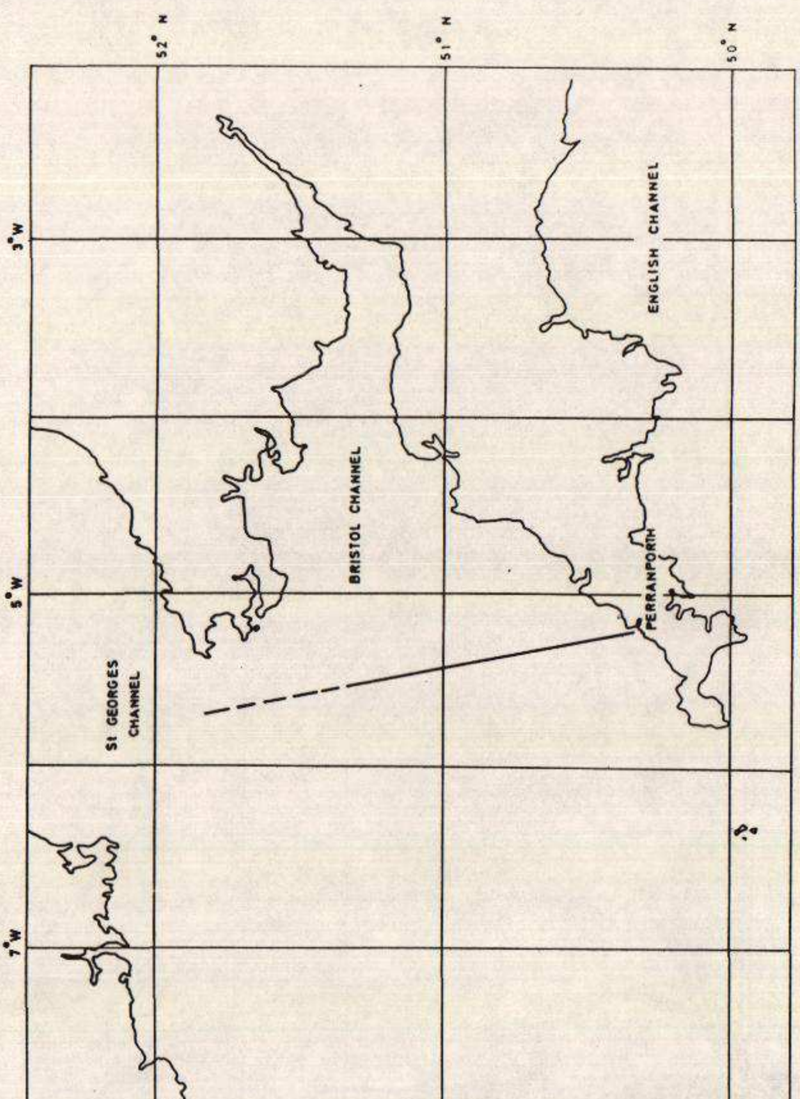

Fig 1 Trials Area in the Bristol Channel

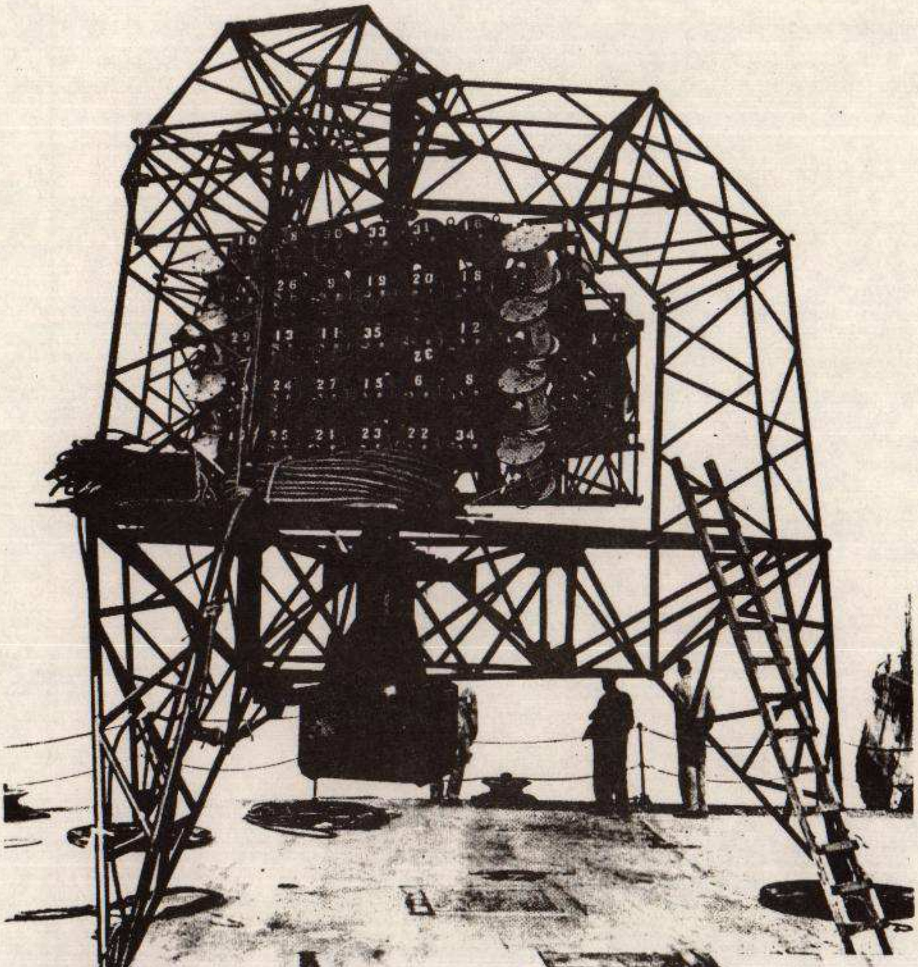

Fig 2 Projector Array for 2 kHz

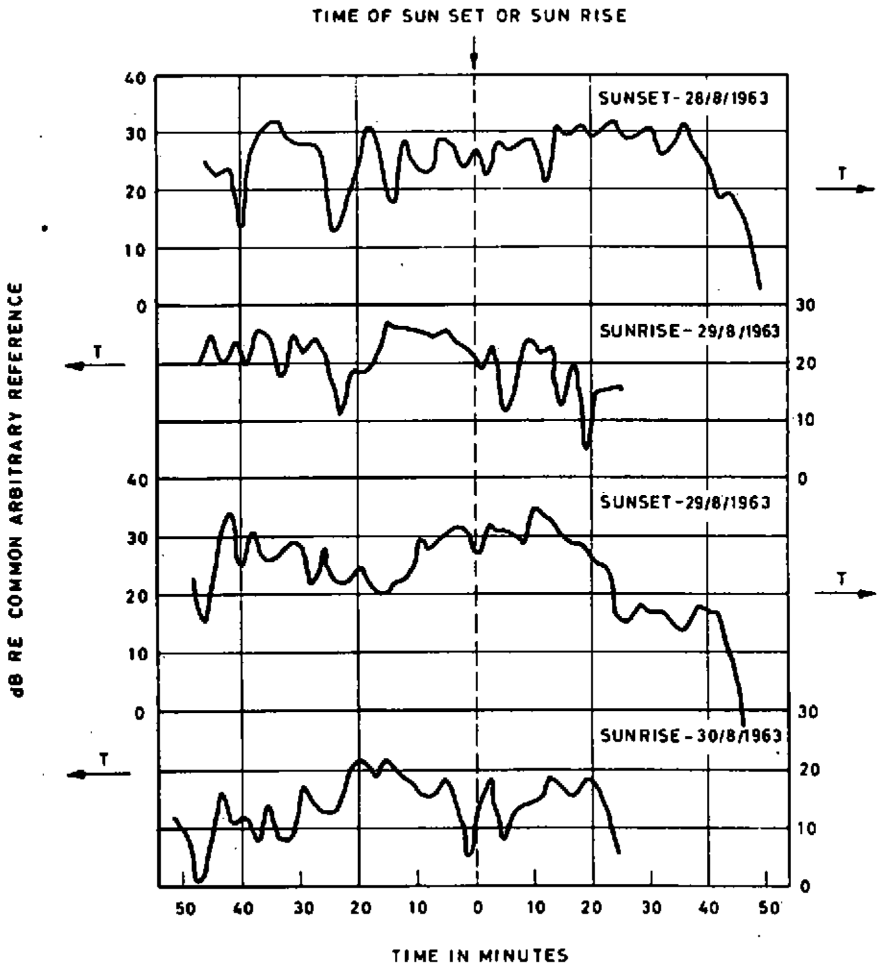

Fig 3 First Evidence for Fish Attenuation: 1042 Hz Signal Level Received from a Source 137 km Distant.

THE 1988 RWB STEPHENS LECTURE: SONAR ICHTHYOLOGY

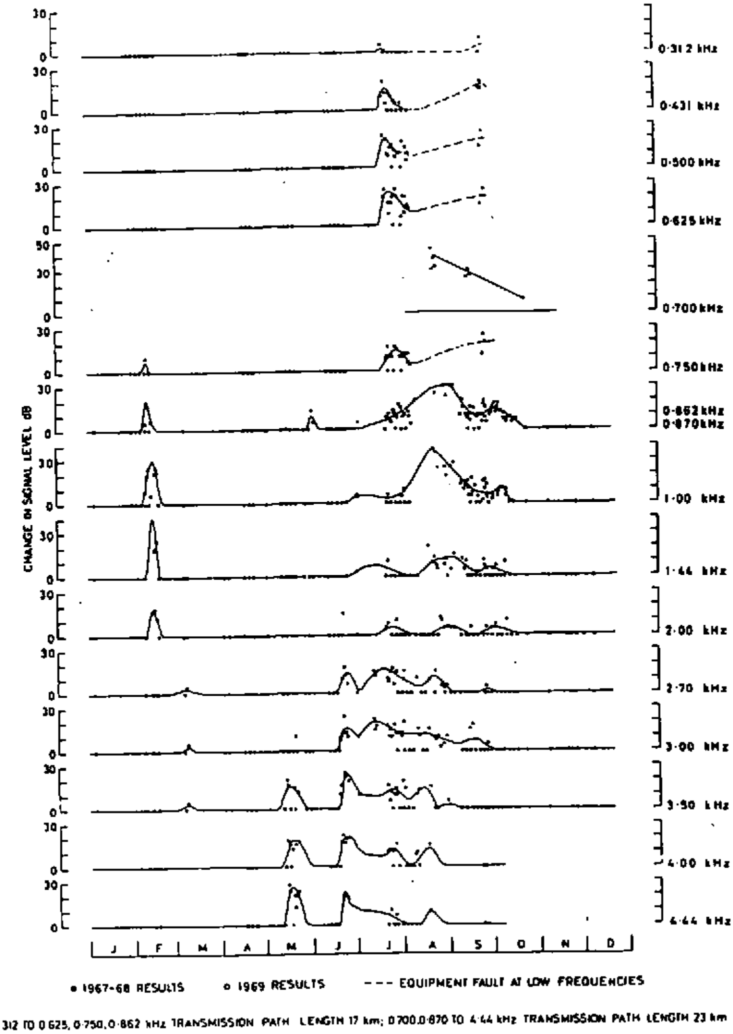

Fig 4 Seasonal Dependence of Short-Range Diurnal Level Changes 1967-69

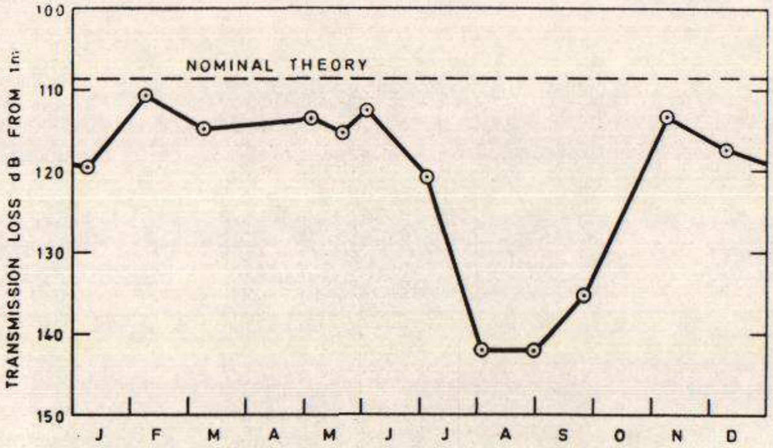

Fig 5 Example of Seasonal Change in Transmission Loss, 137 km Path, 870 Hz, Maximum Daytime Levels

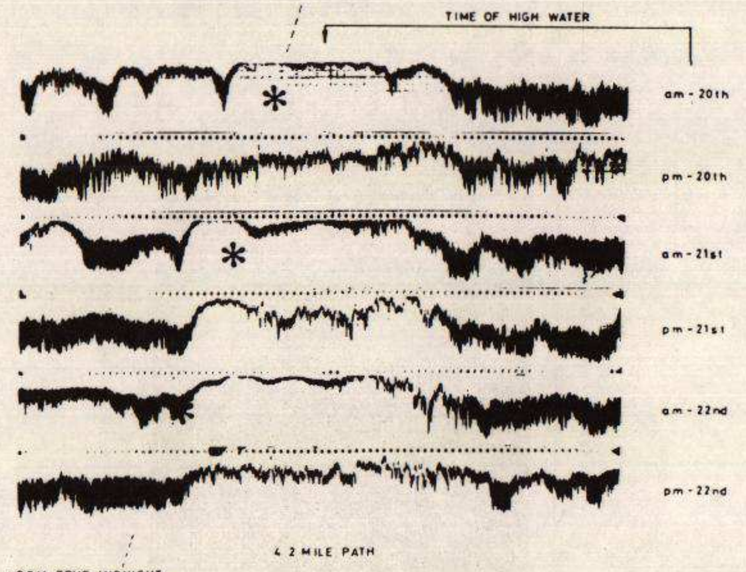

Fig 6 Fast Fluctuation due to Fish Seen over 7.8 km path, 2083 Hz, June 1964, with Consecutive 12½ Hour Records

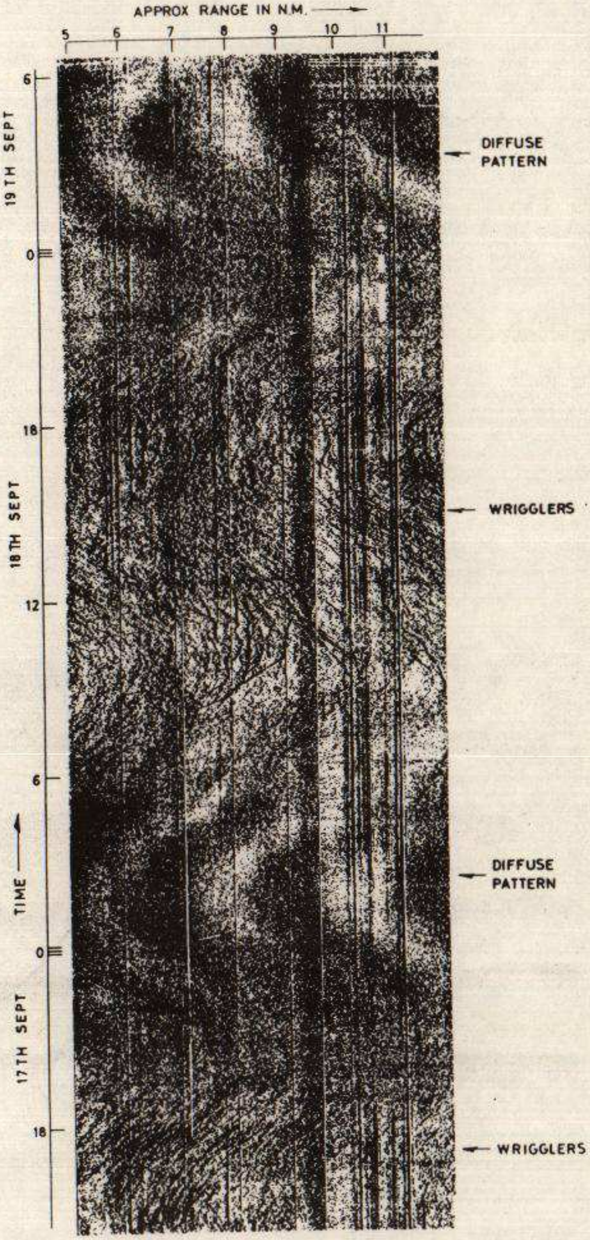

Fig 7 Echoes from Fish at 1 kHz, 17-19 Sept 1962

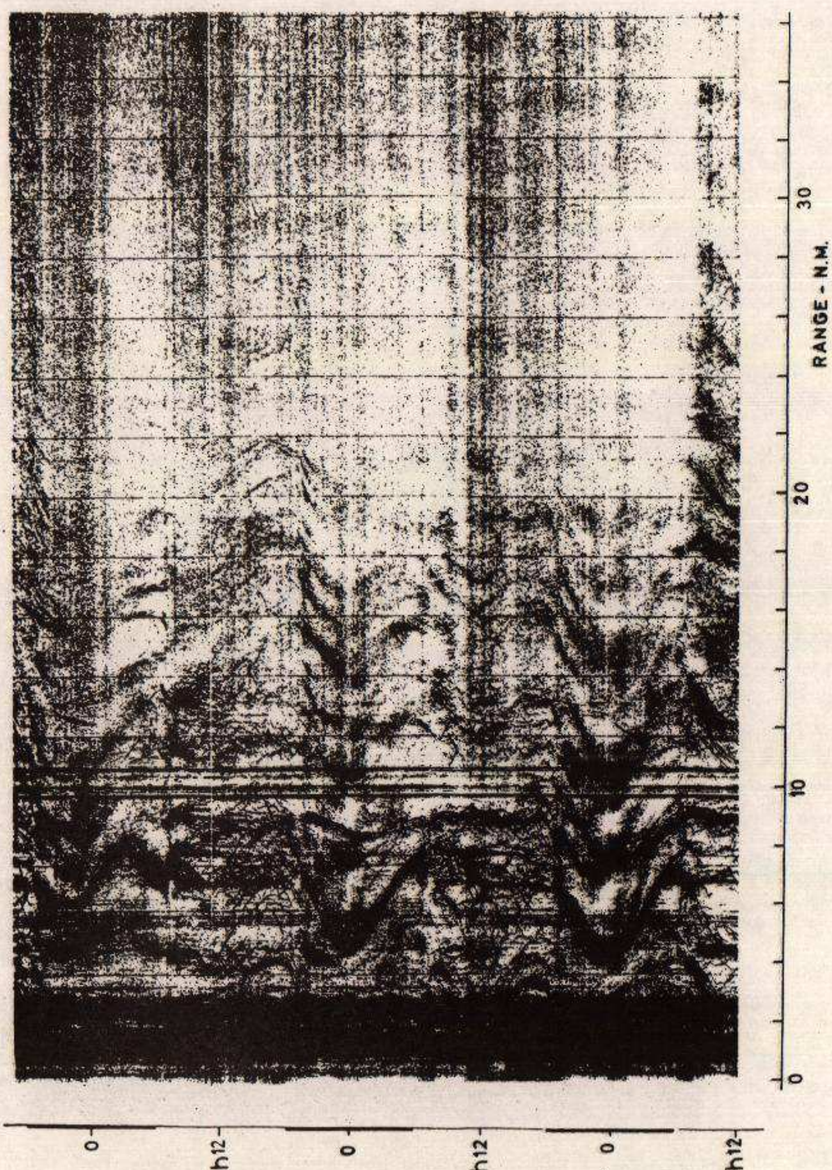

Fig 8 Echoes from Fish at 1 kHz, 11-14 Oct 1963

THE 1988 RWB STEPHENS LECTURE: SONAR ICHTHYOLOGY

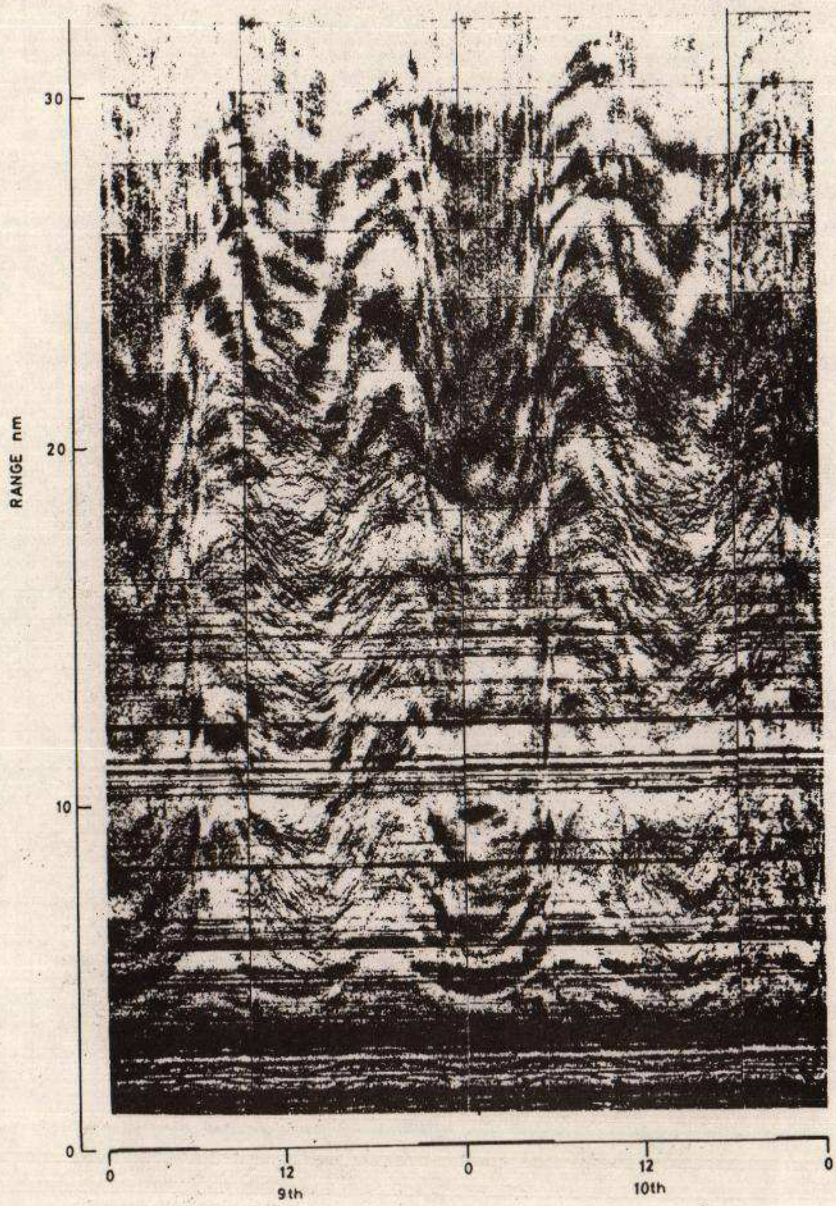

Fig 9 Echoes from Fish at 2 kHz, 9-10 May 1967

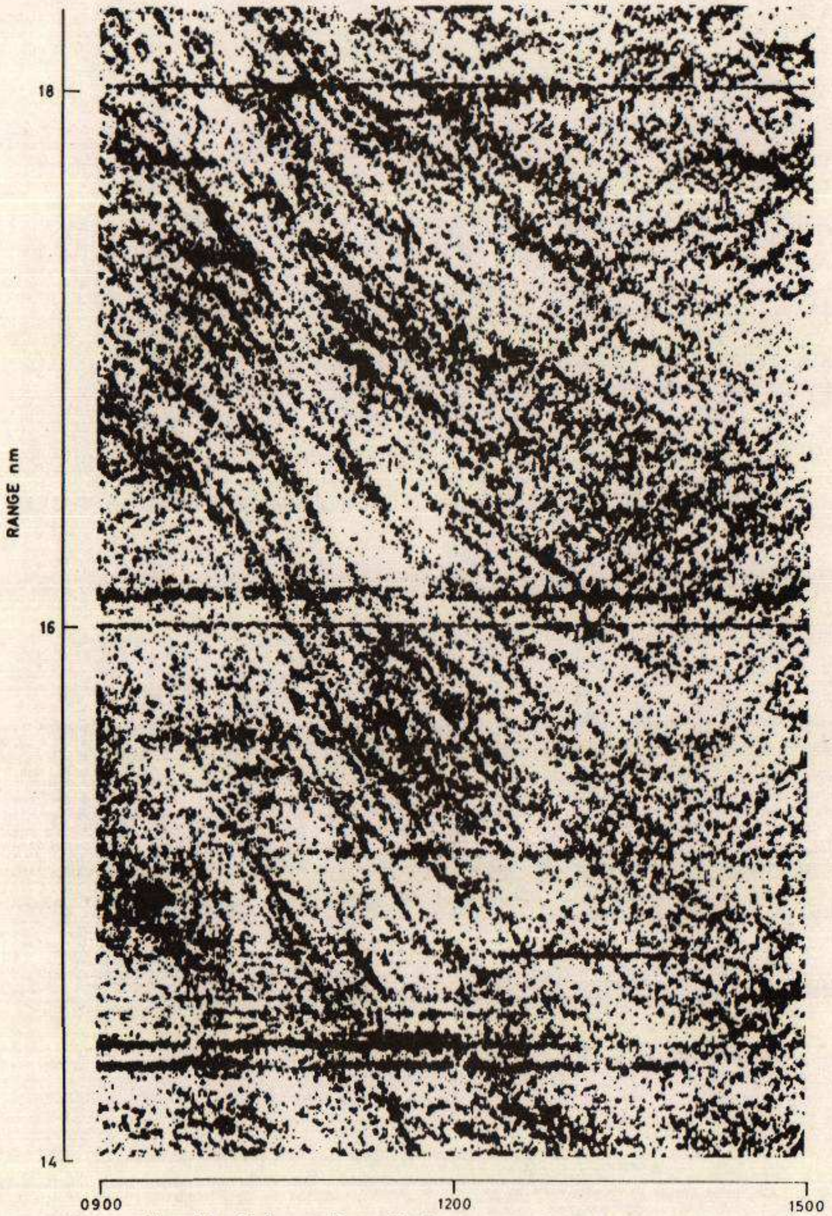

Fig 10 Echoes from Fish at 2 kHz, 10 May 1967

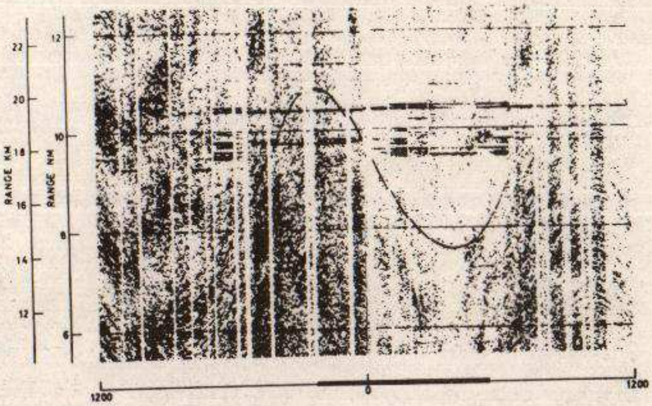

Fig 11 Echoes from Artificial Target at 1 kHz, 11-12 June 1964

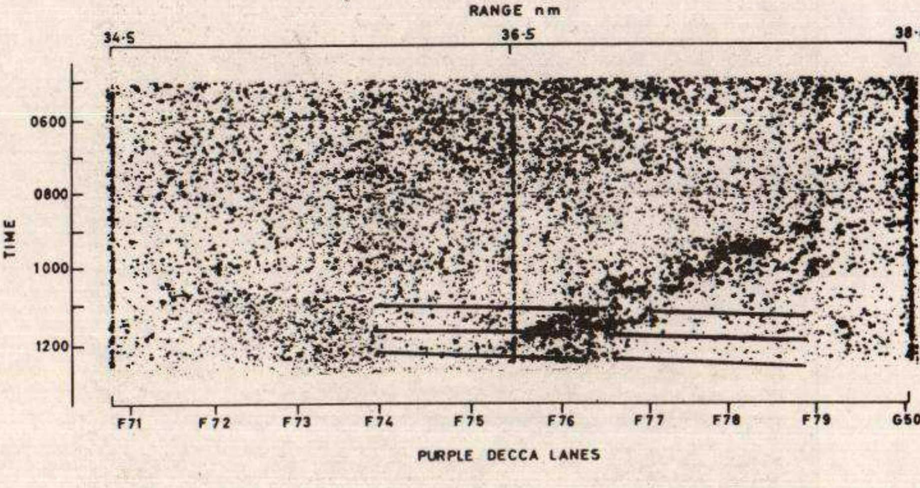

Fig 12 Echoes from Sprat Shoals at 2 kHz in Relation to Echo-Sounder Survey Tracks; Shoals on Echo-Sounder are Indicated by a Break in the Track.

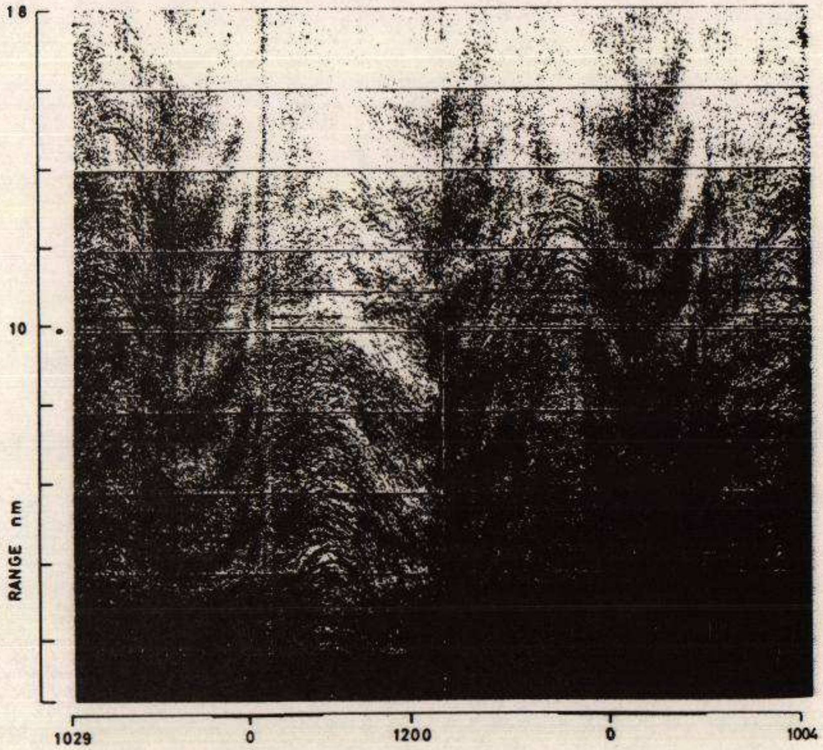

Fig 13 Modal Interference Patterns at 1 kHz, 23-25 May 1963

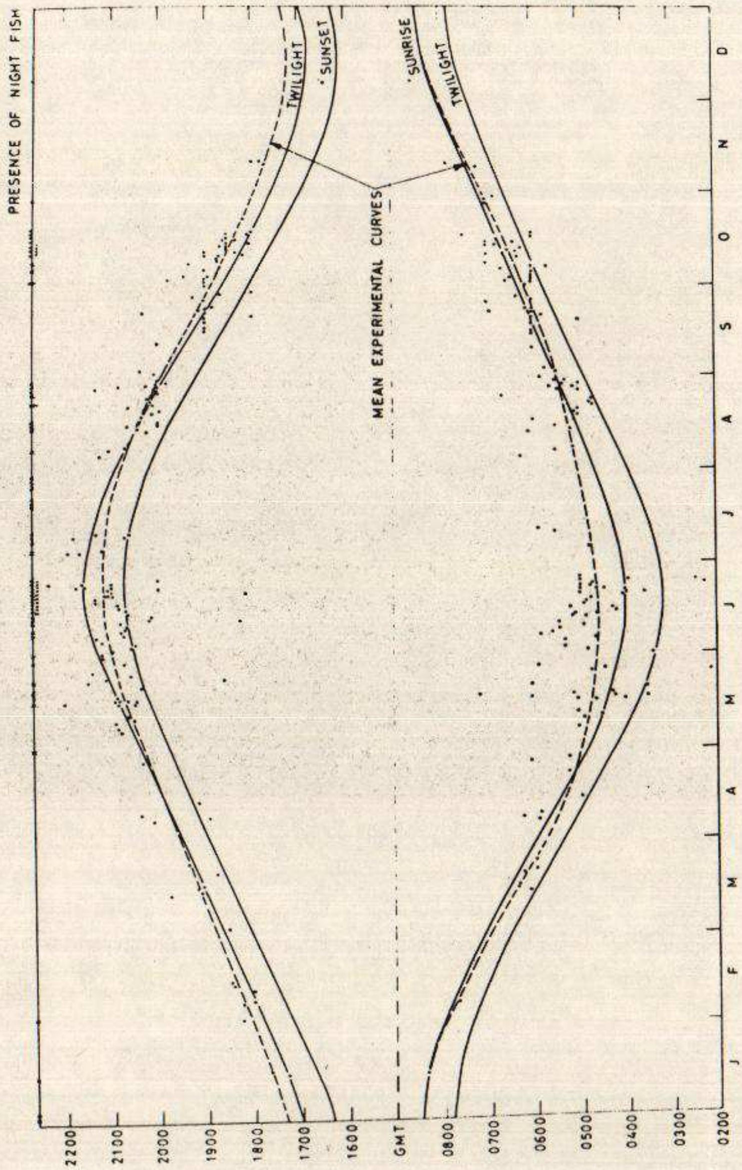

Fig 14 Seasonal Variation in Shoaling Times 1963-1968