A PRELIMINARY ANALYSIS OF THE VARIATION IN TARGET STRENGTH OF MULTIPLE FISH TARGETS AT VARIOUS DEPTHS. LOCH ETIVE 1975.

by J. I. Edwards *

1. SUMMARY

The variations in the target strength of Gadoid fish with depth are an important factor in the calculation of fish stocks. The experiments described were designed to investigate this phenomenon. Multiple targets (Cod and Saithe) were contained within the acoustic beam and raised and lowered in the water column. The large variation in target strength observed confirms the importance of this type of measurement, but the analysis so far has failed to quantify the two components associated with the reduction in target strength, i.e. the angle of tilt and the effect of change in hydrostatic pressure on the swimbladder.

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2. CONTENTS

3. INTRODUCTION

The application of acoustic methods to fish stock assessment problems is, at first glance simple. One finds an equation which relates returned echo intensity to fish mass. Viz

$$\text{Fish Mass} \propto \text{Echo Intensity}$$

Unfortunately, closer examination soon reveals difficulties in this simple equation. Returned echo intensity is dependent not only on fish mass, but also on other physical parameters, notably frequency, hydrostatic pressure, fish length and on behavioural parameters which are perhaps more difficult to monitor, eg., the attitude of the fish, the degree of acclimatisation and the psychological state, i.e. whether the fish is frightened or not.

The experiment reported here was designed to explore the effects of varying the hydrostatic pressure upon the target strength of the Gadoids, Haddock, Cod and Saithe in dorsal aspect, although in general the author recognises that it is impossible to isolate the effects of hydrostatic pressure from those due to the other factors mentioned, except frequency.

4. DESCRIPTION OF EXPERIMENT

(a) The Cage

The experimental cage consisted of a 1 m cube constructed from welded monofilament nylon, 30 mm stretched, of a type sold as "strawberry netting". All seams and suspensions were made using 30 lb monofilament fishing line. The experimental cage was suspended between two tubular steel rings 3 m in diameter and spaced 4 m apart (Figure 1). The rig was then covered by a guard cage, cylindrical in shape, 3 m in diameter, 4 m in length and made from 12 mm stretched, knotless purse seine netting. The guard net was designed to prevent other organisms entering the acoustic beam at the range of interest.

The experimental cage proved to have a target strength which was too small to be detected on the highest gain setting used, and thus, in effect, was acoustically invisible.

The complete experimental rig as described above and illustrated in Figure 1 was suspended from a "U-shaped" raft by a single 4 mm galvanised steel wire. The experimental rig could be placed anywhere in the water column between 8 m and 100 m by hauling or paying-out the 4 mm wire. Electrical connection from the raft to the rig was made with 100 m of twin-core screened cable which remained in circuit regardless of the depth of the rig.

The raft was moored in the centre of Loch Etive in approximately 120 m of water. Typical hydrographic conditions were:

Salinity 24 ppm
Temperature 10°C
Oxygen saturated to 85 m

(b) Electronics

Electrical connection between raft and shore was made with 1 km of 13 core, plus one co-axial netsounder cable. The cable was terminated with correct capacitive loading at the output of the transmitter to enable the transmitter to work into a resistive load.

All the electronic equipment was housed in a mobile laboratory and powered by a 4 kVA (220 volt) diesel generator, the laboratory being located in a disused quarry near Craig Cottage, on the North bank of Loch Etive.

The principal instrument was a multi-channel echo integrator based on a Simrad EK38 and Laben Pulse Height Analyser, as described by Forbes and Dunn[73]. A Simrad M69 (13° x 7°) rectangular transducer was used for all measurements. The instrument was adapted for the experiment viz: The sampling rate was increased, one sample being taken every 0.1 msec or every 0.075 m. The sampling signal was random with respect to the transmitter pulse within 0.1 msec. A block diagram of the system is given in Figure 2. Unfortunately the system used precludes real-time analysis.

(c) Fish

The Cod and Saithe used in the experiment were hand-line caught within Loch Etive from a depth not greater than 5 m. The haddock were caught off the Isle of Skye and transported in an oxygenated container by road to Loch Etive. The fish were stored in keep-cages 2 m x 1 m x 1.5 m at a depth of approximately 3 m for a minimum of one week and a maximum of 3 weeks before use in the experiment.

At least 12 hours before the first data set was taken, the fish were transported by small boat and plastic bin to the experimental cage and lowered to a depth of 8 m. (The minimum distance from the surface consistent with the transducer near-field effects).

Data were then taken in blocks of 10 minutes (approximately 1000 transmissions) throughout the rest of the experiment.

$$\text{i.e. Output} = \sum_{0}^{1000} \int_{R=5.5\text{ m}}^{R=7.5\text{ m}} V^2 \, dR$$

where V^2 = the square of the calibrated output voltage

and R is the range in metres.

(d) Calibration

All the target strength measurements quoted were made by comparison with a table tennis ball which has been assumed to have a value of -42dB at 38kHz. To enable calibrations to be carried out at depth, substandards were measured in a series of calibration experiments. The substandard chosen was a brass sphere of 7 cm radius with a 1/32" hole through the centre. The substandard had a measured target strength of -33.34dB ±0.87dB compared with a table tennis ball, at 38kHz, and at a hydrostatic pressure of 1.8 atmospheres.

The equipment was calibrated by direct substitution of the substandard within the experimental cage. The on-axis sensitivity of the equipment was checked at the various depths of operation. The resultant curve is presented in Figure 3. The observations noted are the normalised means of two sets of integrations, one taken on descent, the other on ascent.

Long-term changes in equipment constants were monitored by substitution of the standard target at various times throughout the experiment.

As will be seen from the theory, the exact form of the TVG is important when calibrating with a standard target. Thus the TVG of the Simrad EK38 was measured on many occasions, and between 6 msec and 26 msec it was calculated to be:

$$15.71\log R \pm 0.2\text{dB}$$

Although the gain sweep is incorrect (it should be 20 logR) it remained stable over the three month period. The gain sweep between 5.5 and 6.5 m should be 1.45 dB. With a 15.70dB TVG the gain sweep is 1.13dB, a difference of 0.31dB which has been assumed to be insignificant. Since the calibrations were performed at the same range as the experiments with fish, no corrections are required when calculating the value of area scattering coefficient.

(e) Behavioural Monitoring

The reaction of the fish to changes in depth is difficult to monitor. A stereo camera was used in an attempt to provide some information. The camera system consisted of two Nikon F1's with motor drives (Reference 2) synchronised with two electronic flash units. The cameras have an automatic triggering mechanism which was adjusted so that one stereo-pair was exposed every 35 minutes. The photographs were later printed and then encoded on a plotting table. The data thus encoded was used as an input to a programme developed by J. Britton and L. Featherstone, which computes the co-ordinates (x,y,z) of the head of the fish and the three directional cosines (α, β, γ) of the major axes of the fish.

Unfortunately, it proved extremely difficult to obtain satisfactory photographs near the surface during the hours of sunlight. Best results were obtained when either the sun fell below the critical angle for water or when the cage was lowered below 30 m. The fish were then illuminated by the flash against the dark background.

The stereo-photographs enable the distribution of the fish within the cage to be measured, i.e. giving a measure of the randomness of the distribution in space and enabling the calculation of the mean attitude of the fish as a first step to understanding the reaction of caged fish to enforced changes in depth.

5. BIOLOGICAL SAMPLING

A careful check was kept on the condition of the fish, particular attention being paid to fish which showed typical signs of swimbladder damage. Several fish were dissected under water and all had their swimbladders intact. The experiments using Haddock have been discarded because the condition of the fish deteriorated, the flesh becoming soft, perhaps because of the low salinity (24 ppm). Three experiments on Saithe have also been discarded, the Saithe were very difficult to handle and made desperate attempts to escape, which inevitably ended in either exhaustion of the fish or the fish being gilled in the experimental cage.

6. THEORY

The area scattering coefficient for the fish in the cage was calculated from the following basic relationship:

$$S_a = 10 \log \frac{Es}{Et} + T - A - 20 \log R_T$$

which assumes a 20 log R time-varied gain, where:

E_r = Integrator output voltage from 1000 Transmissions using the standard target.

E_S = Integrator output voltage for 1000 transmissions using the fish.

T = The target level of the standard target in dB net 4 m dia sphere.

S_a = Area scattering coefficient of caged fish.

A = Equivalent beam angle for integration.

$= 10 \log \frac{\lambda^2}{4\ ab} + 7.4$ dB = -18.64 dB for the transducer used in these experiments (Baragos, P. A. 1964)

R_T = Range of standard target

The target strength per kilogram was calculated from the measured value of S_a using the following equation:

$$T_K = S_a - 10 \log {}^{W}/_{\delta}$$

where T_K = the target level of the fish per kilogram

W = weight of fish measured in kg

δ = horizontal area of the cage in m^2

7. ANALYSIS

Initial data reduction was performed using the Marine Laboratory's 905 computer. Data sets were transformed into graphs of returned power versus 0.075m depth intervals (Figure 4). Each data set was then checked by hand and the returned power extracted, correction being made for changes in instrument gain and the variation in axial sensitivity of the transducer with depth (calculated from standard target calibration). The returned powers were then transformed into target levels compared with a table tennis ball (-42dB at 38kHz, reference Welsby and Hudson[72]) using the theory described in Section 6.

The analysis assumes that the fish are evenly distributed within the experimental cage and that the area of the cage is greater than the cross section of the beam at that range. The stereo photographs analysed tend to indicate that the first assumption is correct. However, for practical reasons the cage was only $1m^3$, a little on the small size for a range of 6m. The error this incurred is expected to be small and the result is undoubtedly a slight under-estimate of the target level.

To obtain the target level per kilogram the fish were weighed at the end of each experiment, the cross-sectional area of the experimental cage was measured and hence the area density of fish was calculated. The area density was then compared with the area scattering coefficient and the target level per kilogram calculated.

The data was then re-punched as a time sequence and used as input to a programme which calculates and plots a 5-point moving average. (Figures 5,6,7,8 and 8. Note that the vertical lines mark a discontinuity in time and that the gap in Fig. 5 is due to the incorrect setting of the analog to digital convertor).

8. RESULTS

All the experiments performed were vetted to ensure that the results were reliable, i.e. that the fish were in good condition and that no fish escaped during the acoustic measurements. Figures 5 to 9 present the results of the most reliable experiments.

The results are very difficult to describe. A cursory glance reveals a similarity in general form:

- The initial target strength for the cod is in close agreement with previous work.

- An increase in hydrostatic pressure produces a dramatic change in target strength.

- The target strength subsequently increases slowly with time.

- Further increases in hydrostatic pressure produce decreases in target strength.

Decreases in hydrostatic pressure have a less predictable effect, generally giving rise to a much more gradual change in target strength, but occasionally causing a decrease in target strength for a decrease in pressure - an unexpected result.

The target strength never rises above the initial target strength and the Saithe react more rapidly than Cod to changes in pressure.

Table 1 summarizes the results giving the rates of change in target strength. No consistency is revealed in the rates of change with pressure and time, rates vary from zero to 2.66dB/hr. and are typically 0.3dB/hr.

The analysis of stereo photographs using the techniques currently available within the Marine Laboratory is a very slow process, and accordingly of the 2,000 pairs exposed only 7 have been analysed to date. These indicate that the fish are randomly distributed within the experimental cage and that on average they adopt a nose-down attitude, making an angle of approximately 20° with the horizontal. Table 2 summarizes the results of this analysis.

9. DISCUSSION OF RESULTS

The relationship between the wave length of sound transmitted by practical echo sounders and the typical dimensions of fish, places fish in the 'middle zone', midway between Geometric Scattering and Rayleigh Scattering. Simple mathematical predictions of target strengths are not possible within the Middle Zone. In order to obtain some 'feel' for the situation the expected changes in target strengths with depth have been calculated assuming (a) Geometric Scattering, and (b) Rayleigh Scattering. In both cases it is assumed that the swimbladder is the major cause of the reflections.

(a) Calculation of variation in target strength due to changes in volume assuming Geometric Scattering

Assume the swimbladder to be ellipsoidal:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

Where 2a = length of swimbladder and is assumed to be constant

2b = width of swimbladder and is assumed to be a function of c

2c = depth of swimbladder and is allowed to vary without restriction

Thus one would expect a 1dB change in crossectional area for every 3dB change in volume: $^V/v$ (Table 3). Clearly changes in crossectional area do not account for the changes in target level observed.

(b) Calculation of Variation of Target Strength due to changes in volume assuming a Rayleigh Scattering

If one assumes Rayleigh Scattering then the angle the fish present to the incident beam is unimportant and the target strength varies as the volume squared. Thus one would expect a -6dB change in target strength for a doubling in pressure and a -12dB change if the pressure is quadrupled.

Reference to Table 1 and Figures 6, 7, 8 and 9 (experiments on Cod) shows good agreement between the Rayleigh Scattering predictions and changes in depth from 8 m to 26 m (Figure 6) and 8 m to 36 m (Figure 7). However changes in depth from 8 m to 56 m produce decreases in target strength which are significantly greater than those attributable to either prediction.

The difference between the mathematical predictions based on swimbladder volume and experimental results may lie in the tilt angle of the fishes. Previous work (Nakken and Olsen 1973) has demonstrated that fish of the size and type used in this experiment have complex polar diagrams, and that at 38kHz the tilt angle has a dramatic effect on target strength, a 10° tilt producing a 6 dB decrease in target strength and a 20° tilt a 10dB decrease. Nakken and Olsens' figures refer to one static fish while the experiments reported here measure many swimming fish. Thus the corresponding "average" polar diagram is likely to be smoother.

If one then considers the joint effect of reduction in swimbladder volume and angle of tilt it is possible to explain the initial reduction in target strength. An obvious further step in the analysis of these data is a comparison of tilt angle (as measured from the stereo photographs) with target strength. Such an analysis might well lead to a proportioning of the reduction due to change of tilt and change of swimbladder volume.

Figure 5 presents results from the only experiment reported on Saithe and has several interesting features. The reactions to changes in pressure are more dramatic than observed in Cod. This is not a surprising result if the behavioural patterns of the fish are considered. Further just before the final ascent (Expt 16 13.00 25 June 75) a spectacular decrease in target strength, was observed, and the author speculates that this is solely due to changes in tilt angle, caused by the approach of outboard powered dinghy and preparation on the raft to enable the cage to be raised. This observation is indicative of the saithes lively behaviour.

A comparison between the observed rates of increase in target strength, and the ability of the fish to secrete gas (as measured by Harden-Jones) indicate that the fish recover at a much slower rate than expected. Harden-Jones' measurements indicate that a Cod, 0.3 kg in weight with a swimbladder occupying 3.6% of its volume (from Sand and Hawkins 1974) can secrete enough gas at 10°C to refill its swimbladder to within 10% after a 18 m change in depth in approximately 20 hours. The Cod in the experiment did not regain their original target strength in twenty-four hours and the indications are that the target strength was still increasing. Whether this is a function of the constraining influence of the cage or not is a matter for future work.

A final point worthy of discussion is related to the fact that the maximum target strength measured was invariably the initial target strength (at 8 m). This observation suggests the following hypothesis:

It is commonly accepted that fish find it less difficult to dive than to ascend. Blaxter and Parrish (1953) reported the extent to which fish were willing to follow a lamp as it was raised and lowered in the water column, and concluded that fish would endure an increase in pressure of 400% and a decrease in pressure of only 50%. These facts tend to indicate that the acclimatised volume of a swimbladder is approximately half its maximum volume. If a fish migrates at a rate faster than the rate at which it can secrete gas to maintain its neutral buoyancy, it is likely to have a target strength which is considerably less than that at acclimatisation. If this conjecture is proven then care must be taken when extrapolating steady state target strength measurements to dynamic situations, in order to avoid significant under-estimates of fish stocks.

10. CONCLUSIONS

(a) The initial target strength of Cod as measured at a depth of 8 m is much the same as reported in previous work (approximately -33.25dB/kg).

(b) Forcing the fish to dive produces a dramatic decrease in target strength, greater than that to be expected from the forced contraction in volume of the swimbladder, probably due to a combination of tilt angle and the effect of pressure on the swimbladder.

(c) Acclimatisation times are significantly greater than one would expect from other observations.

(d) The target strength is never greater than the acclimatised target strength.

(e) Saithe have the ability to acclimatise faster than cod.

11. ACKNOWLEDGEMENTS

Thanks to Mr S J Feltham a student at Salford University for his hard work during the practical phase of the experiment and Mr W Hall of the Marine Laboratory for his invaluable help during the analysis.

12. REFERENCES

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Exp.		Initial T.S. dB/kgm	Change in T.S. dB/kgm	Rate of Recovery dB/hr	T.S. after 24 hours. dB/kgm	Change in T.S. on 2nd Change in Pressure dB/kgm	Rate of Recovery dB/hr	T.S. after 48 hours dB/kgm	Change in T.S. on 3rd. Change in Pressure. dB/kgm	Rate of Recovery dB/hr	T.S. after 72 hours dB/kgm	Change in T.S. on 4th Change in Pressure. dB/kgm	Final value of T.S. /kgm
Exp 16 Saithe	Variable Depth m	-30.4 8	-21.6 8-26	0.58 26	-37.5 26	-8.7 26-66	0.31 66	-58.6 66	+8.1 66-26	? 26	-34 26	-10 26-8	-35 8
Exp 26 Cod	Variable Depth m	-33 8	- 6.0 8-26	0.17 26	-34.8 26	-8.6 26-56	0.22 56	-39.1 56	? 56-26	0.0 26	-38.5 26	-3.8 26-8	-35 8
Exp 27 Cod	Variable Depth m	-34.2 8	-9.6 8-36	0.03 36	-44.5 36	+9.3 36-14	0.38 14	-34.1 14	? 14-8	0.0 8	-34.2 8		
Exp 28 Cod	Variable Depth m	-32.0 8	-20.4 8-56	0.53 56	-41.4 56	+5.20 56-26	0.15 26	-38.5 26	-5.2 26-8	0.82 8	-34.0 8		
Exp 30 Cod	Variable Depth m	-33.7 8	-14.7 8-56	2.66 56	-41.6 56	0 56-26	0.19 26	-36.6 26	? 26-8	0.0 8	-36.0 8		

TABLE 1.

SUMMARY OF RESULTS

TABLE 2. RESULTS OF ANALYSIS OF STEREO PHOTOGRAPHS

Time	Date	Expt.	Frame	$\overline{\cos^{-1}\gamma}$
12.45	8 July	27	39	69.14°
19.45	"	27	51	78.08°
07.45	9 July	27	71	80.99°
08.20	"	27	72	65.9°
17.20	30 June	26	40	70.44°
20.50	"	26	46	71.97°
01.30	31 June	26	54	69.005°

Where γ = angle between the axis of the fish and the Z or vertical axis.

TABLE 3. CALCULATED VARIATIONS IN TARGET STRENGTH OF SWIMBLADDER WITH $^V/_{V'}$ ASSUMING GEOMETRIC SCATTERING.

$^V/_{V'}$	$^V/_{V'}$ in dB's	Target Strength dB relative to V'
2	+3	+1
1	0	0
½	-3	-1
1/3	-4.771	-1.55
1/4	-6	-2
1/6	-7.781	-2.6
1/8	-9	-3

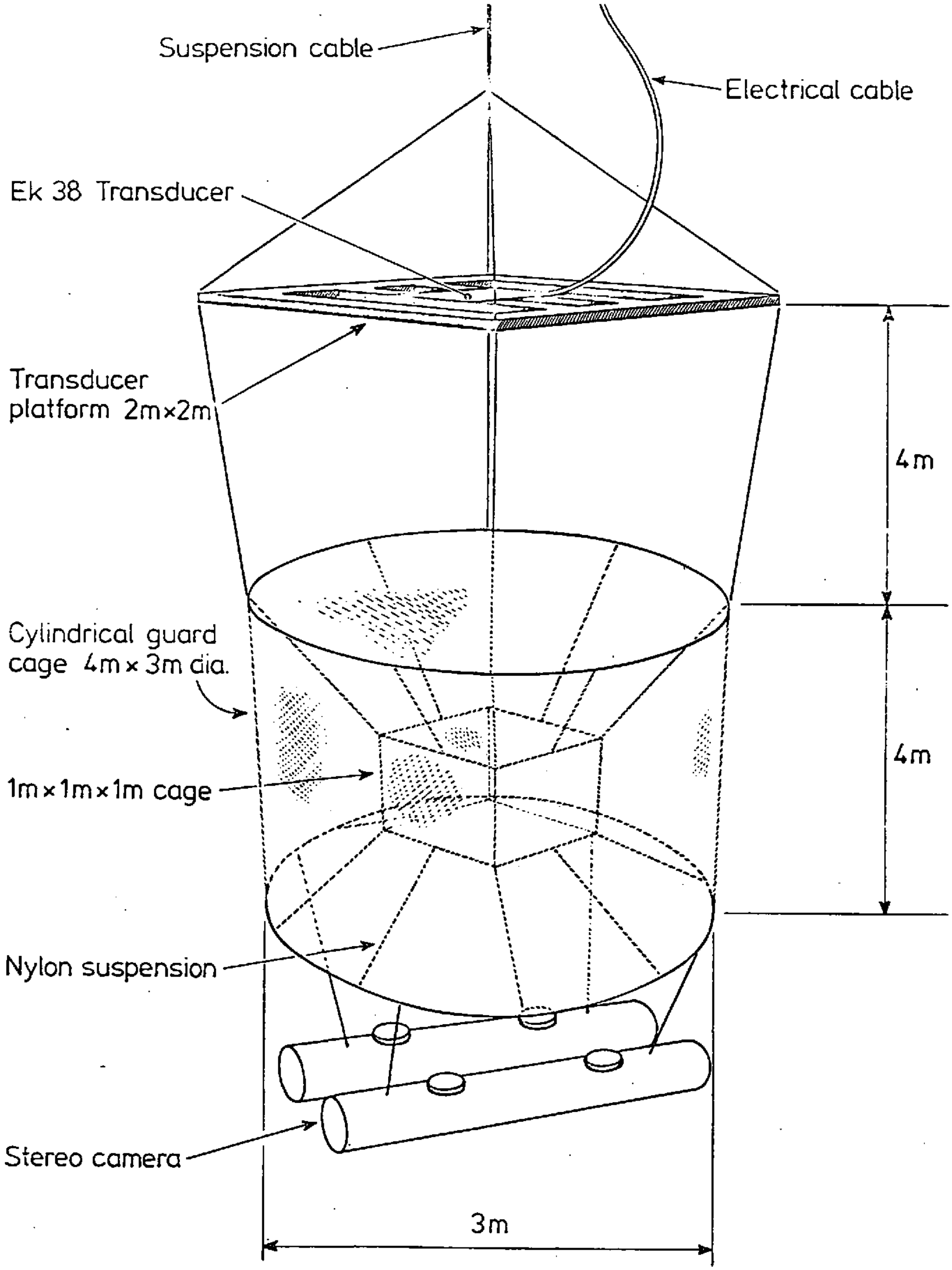

Fig 1 GENERAL VIEW OF EXPERIMENTAL RIG

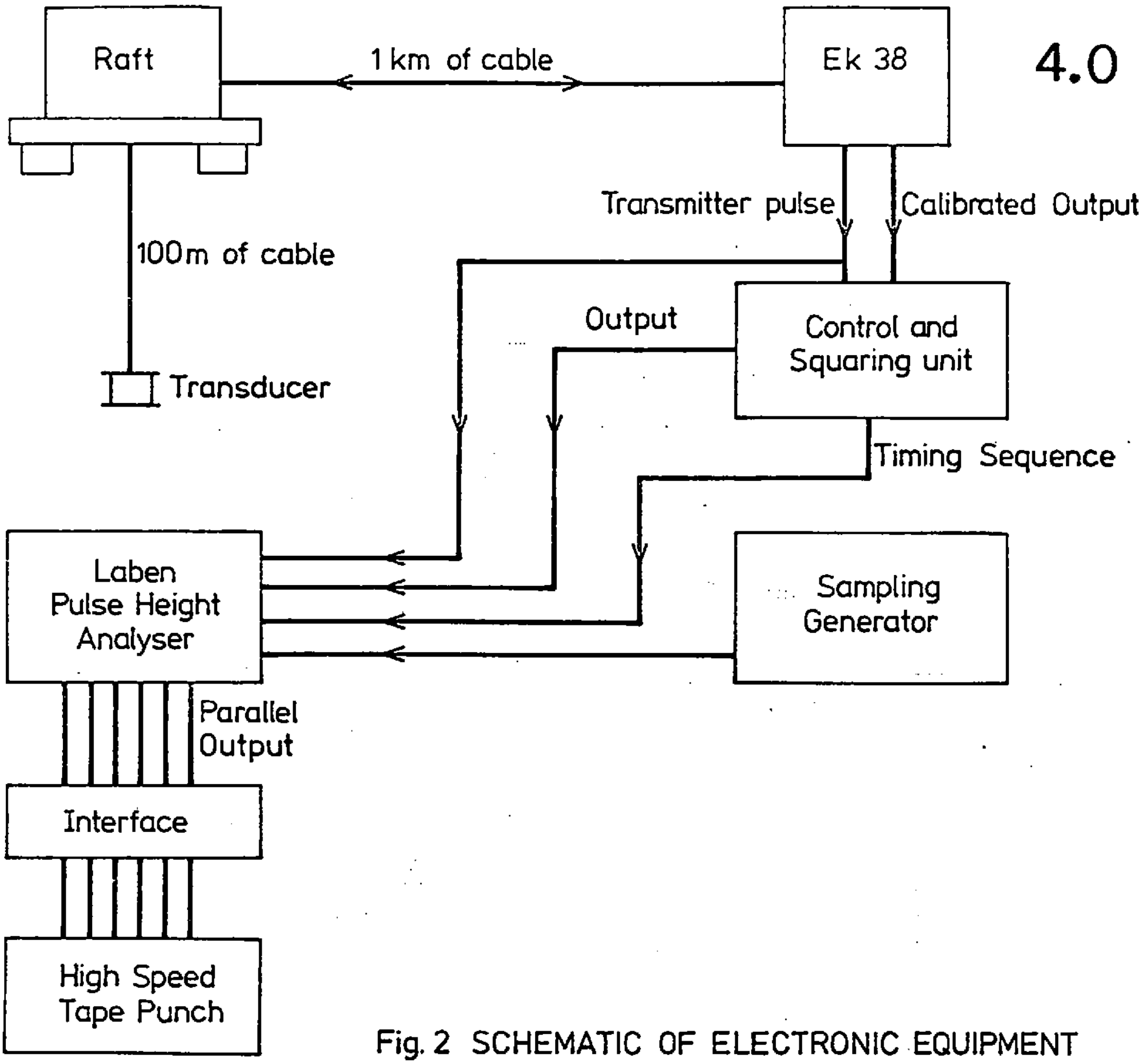

Fig. 2 SCHEMATIC OF ELECTRONIC EQUIPMENT

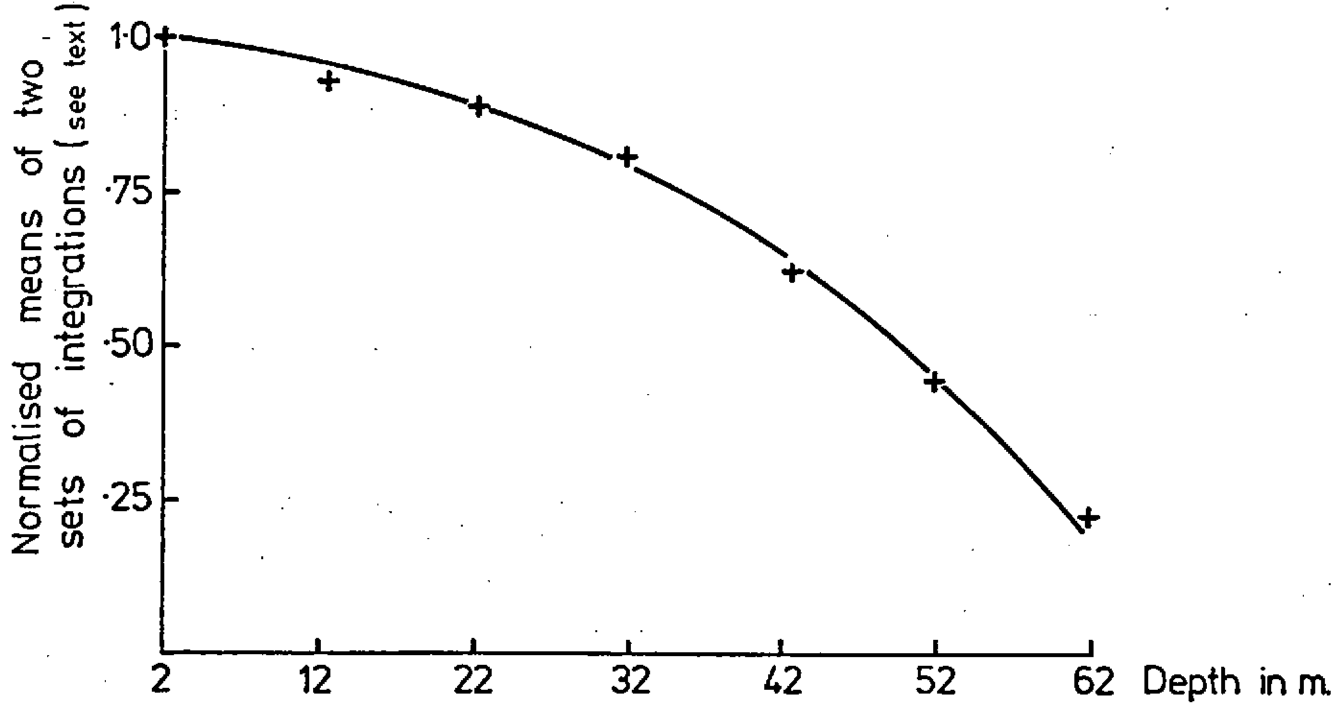

Fig. 3 AXIAL SENSITIVITY AS A FUNCTION OF DEPTH

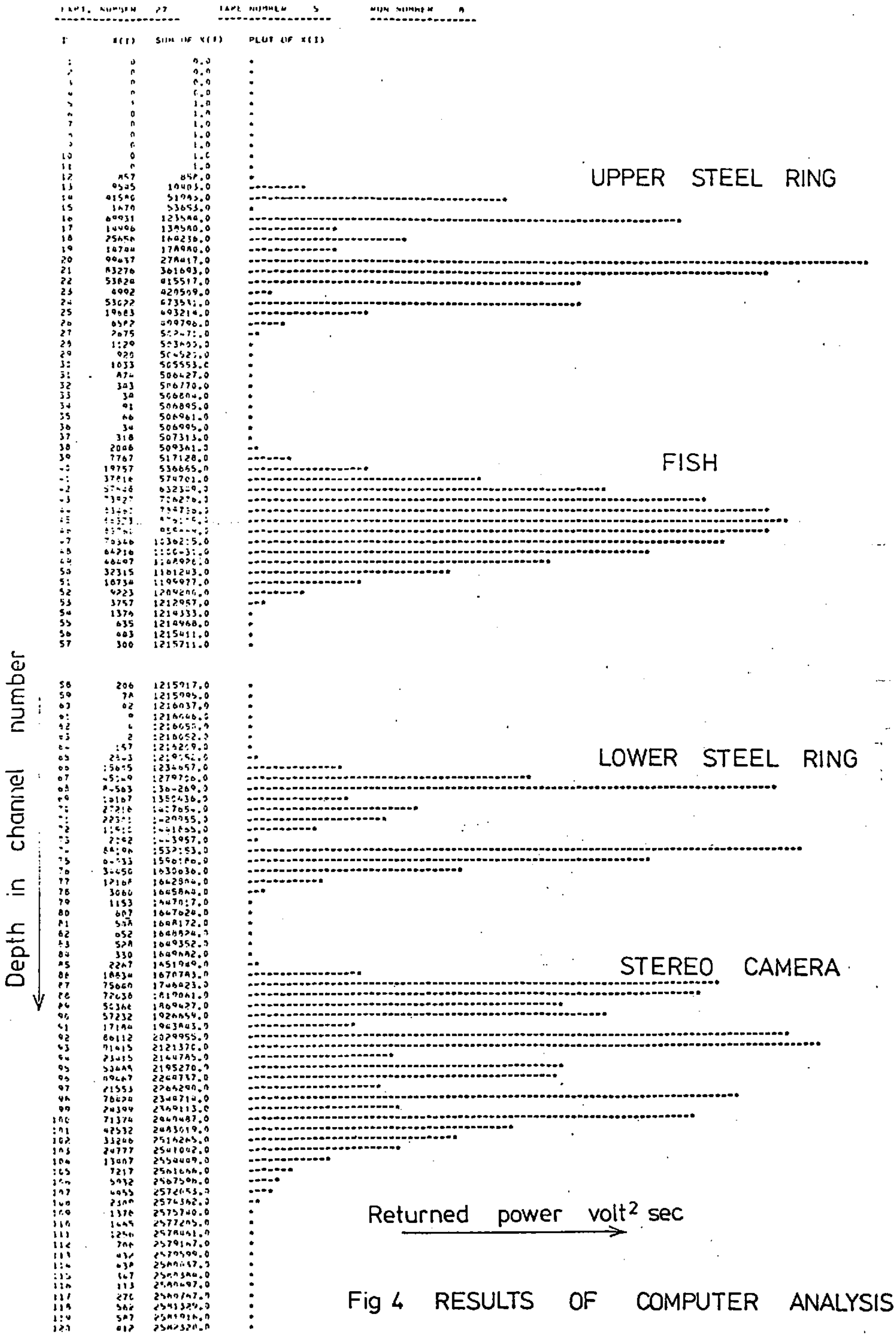

Fig 4 RESULTS OF COMPUTER ANALYSIS

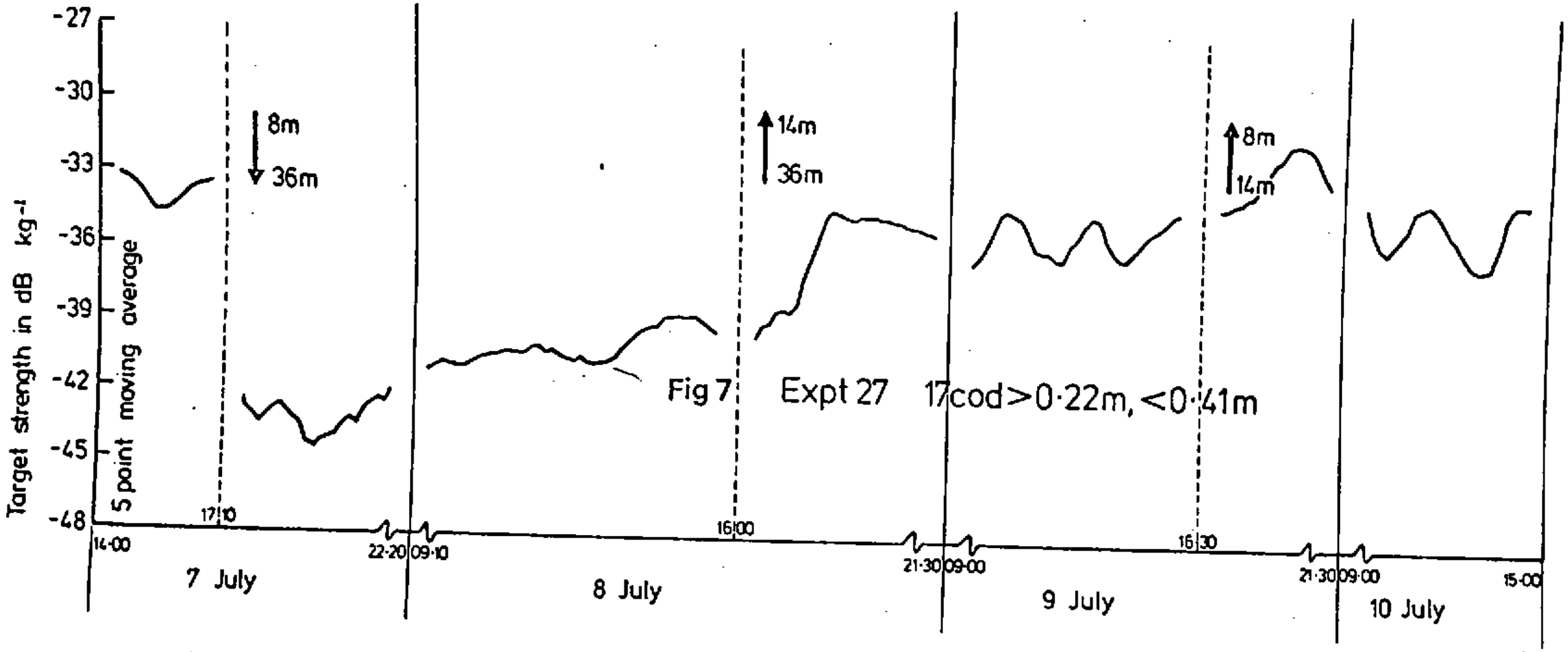

Fig 7 Expt 27 17cod >0·22m, <0·41m

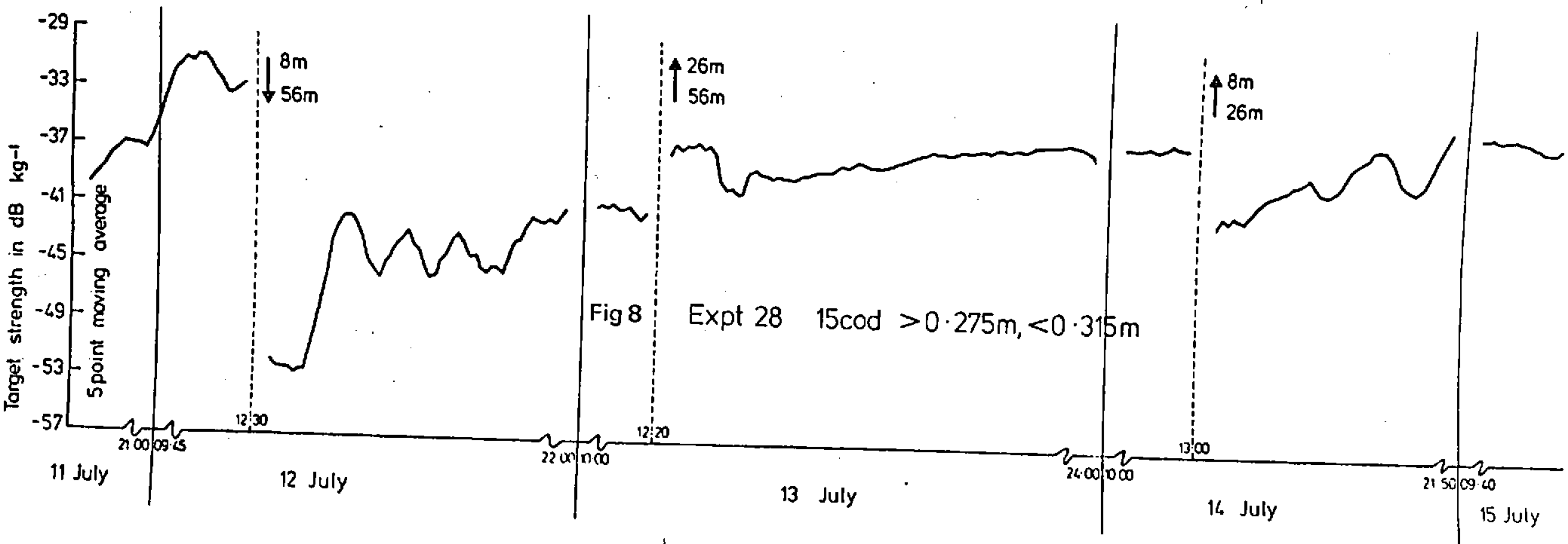

Fig 8 Expt 28 15cod >0·275m, <0·315m

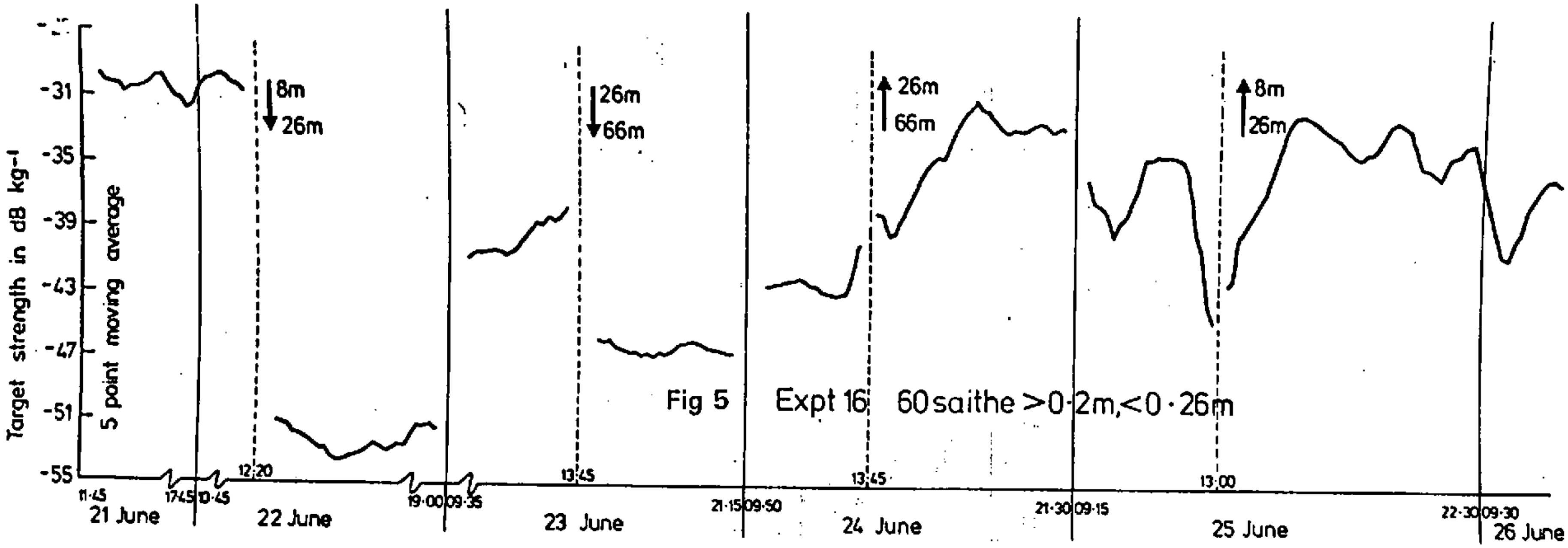

Fig 5 Expt 16 60 saithe >0·2m, <0·26m

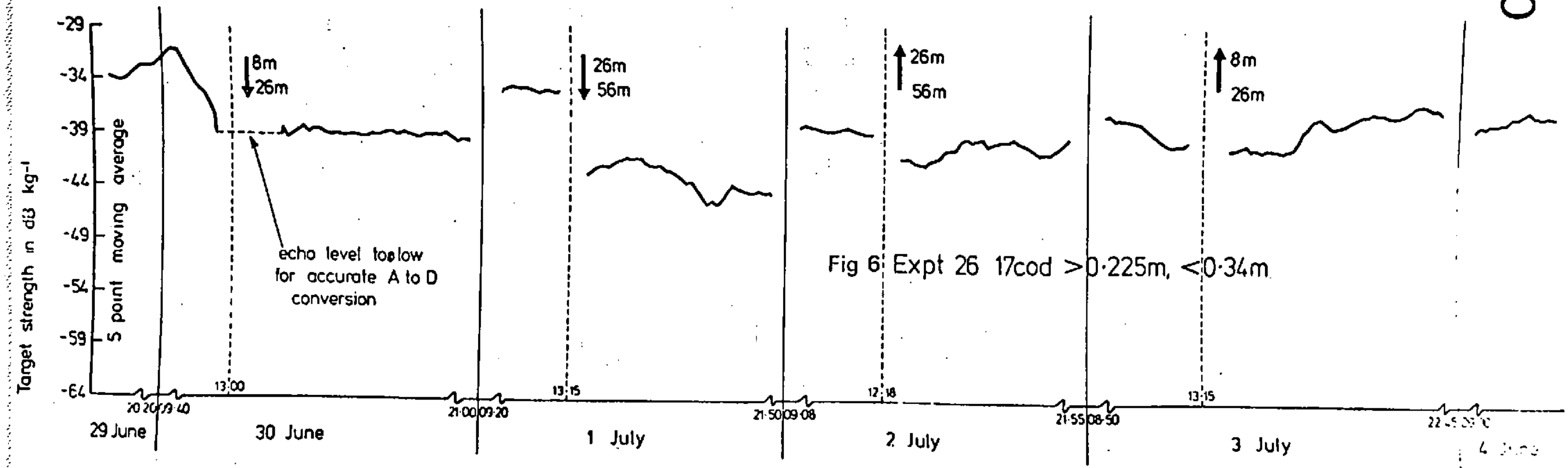

Fig 6 Expt 26 17 cod >0·225m, <0·34m

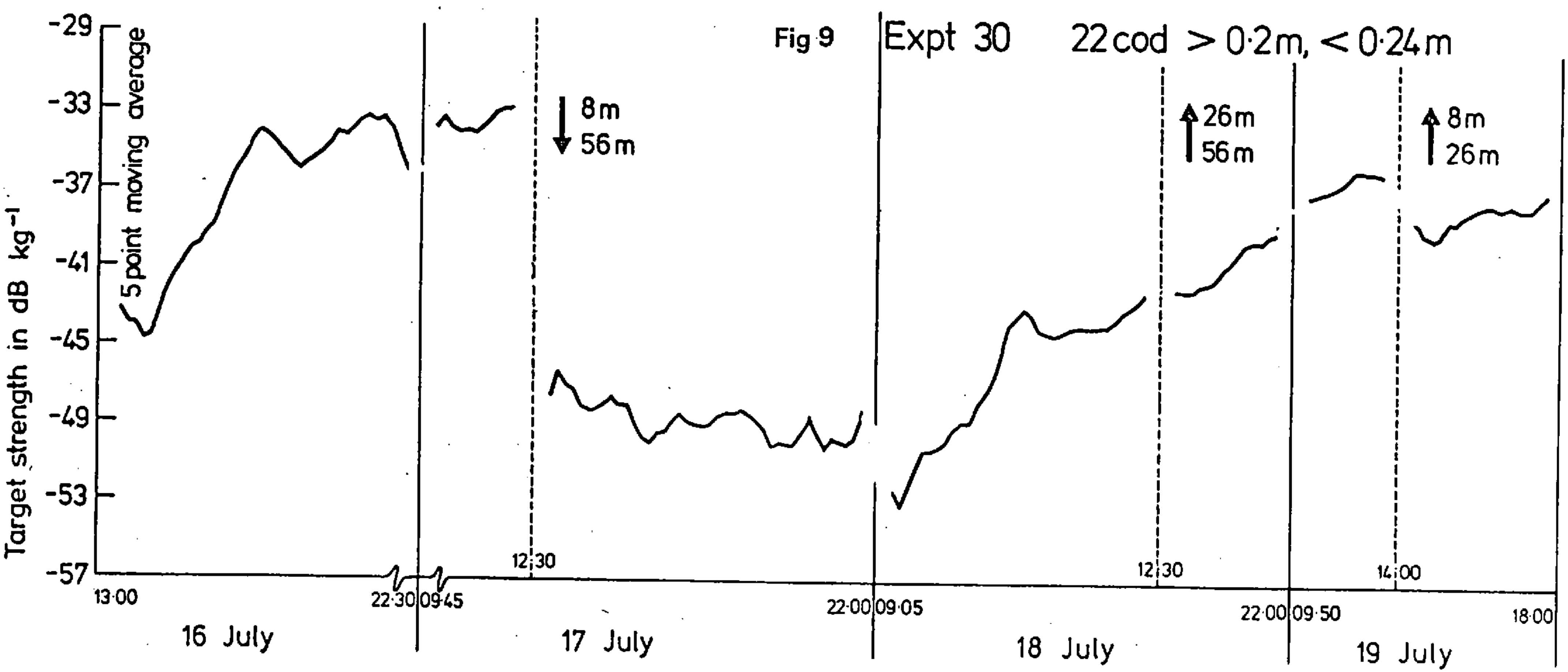

Fig 9 Expt 30 22 cod > 0·2m, < 0·24m

4.0