1.5

The Depth and Species Dependence of the Target Strength of Gadoids

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1. Introduction

In recent years the assessment of fish stocks by acoustic surveying has become a widely accepted technique. The quantitative acoustic information so obtained provides, in the first instance, a relative measure of fish abundance. However, reliable interpretation of echo integration results in terms of absolute fish densities depends on accurate values being available for the target strength per unit weight of fish.

Measurements on single fish, for example those reported by Nakken and Olsen (1977) and Goddard and Welsby (1977), have often been used in the derivation of the target strength per unit weight of gadoids. Unfortunately, a number of factors limit the confidence with which the values so obtained can be applied to acoustic survey results. These include the limited knowledge of the orientational frequency distribution of fish in the wild, the limited amount of data on live fish, and the fact that experiments have generally been conducted under hydrostatic pressures considerably lower than those normally encountered by fish in the wild.

Preliminary experiments to determine the target strength per unit weight of gadoids, using moderately large numbers of caged fish, were carried out by the Marine Laboratory at Loch Etive in 1975 and reported by Edwards (1975). Useful information was obtained on the practical problems involved in conducting such experiments. Subsequently, a full scale series of experiments was embarked upon to determine the dependence of the target strength of gadoids on depth, species and fish length.

This paper deals with the results of the 1976 and 1977 experiments on depth and species dependence. These were carried out at Loch Hourn and Loch Duich respectively. The results of the 1978 experiments to determine dependence on fish length will be reported later.

2. Measurement Facilities

2.1 Underwater Equipment

This is shown in Figure 1. The fish were contained in an octagonal cross section cage, constructed from polythene garden netting and suspended between two 3 metre diameter tubular steel rings. A guard net of 12 mm knotless purse seine netting was rigged over the steel rings to prevent predators and other interfering organisms from entering the acoustic beam in the vicinity of the fish cage.

A Hydro Products low light television camera was mounted in the centre of the bottom panel of the guard net so as to provide a ventral aspect view of the fish in the experimental cage. The complete assembly was suspended from a square wooden frame, on which was mounted a Simrad EK38 transducer. A reference target in the form of a brass sphere was suspended on the acoustic axis to provide continuous monitoring of the system sensitivity throughout the experiments.

The complete underwater rig was suspended from a raft moored in 100 metres of water. The transducer and television camera were connected to the shore laboratory by two 1000 metre long cables.

2.2 Measurement System

The electronic equipment was installed in a mobile laboratory stationed on shore and connected to the public electricity supply.

The data acquisition and logging system is shown in Figure 2. It was based on a Computer Automation LSI 2/20 computer, which performed a useful amount of real time analysis. The transmitter generated a 38 kHz pulse of 500 microseconds duration with a repetition period of 300 milliseconds. Echo signals from the transducer were amplified and demodulated in the fixed gain receiver before being sampled and digitised. For each transmission the computer accepted 100 samples at 100 microsecond intervals. The computer then applied a 20 log R correction to the sample amplitudes and squared the result to convert to intensity. Values corresponding to the fish and reference echoes were accumulated for 1000 transmissions. Simultaneously, an overall depth profile of echo intensity was generated by adding the corresponding values from each transmission. After each 1000 transmissions the accumulated data was output to a Perifile digital cartridge tape recorder for subsequent laboratory analysis. The mean fish and reference integrals and their standard deviations were output to a line printer for immediate use. A complete set of data was generated every 6 minutes. In addition to enabling preliminary analysis of results on site, this provided a useful means of detecting faults in the measuring system. Sufficient data was stored on tape to allow each experiment to be regenerated in detail at a later date.

In the original system, as operated in 1976, three optional outputs were available on the line printer after each complete page of data. Examples of these are shown in Figures 3, 4 and 5. Figure 3 is a depth profile of echo intensity, accumulated over 1000 transmissions. Echoes due to the reference target, the upper supporting ring of the guard cage, the fish being measured and the television camera can be readily identified. This facilitated the choice of the most appropriate depth limits for the fish cage and reference integrals at the start of each experiment. Figure 4 is a typical histogram of single transmission fish echo integrals for 1000 consecutive transmissions, classified in fifty amplitude bands. Figure 5 is an equivalent histogram of single transmission reference integrals.

Additional refinements were incorporated in the measurement system for the 1977 experiments. The most significant of these was the use of a graphics terminal to provide a pictorial summary of each group of 1000 transmissions. Permanent copies could be obtained as required. An example is given in Figure 6.

2.3 Calibration

Calibration of the system was performed by positioning a standard table tennis ball on the acoustic axis and comparing the maximum echo intensity produced by the reference target with the corresponding maximum from the table tennis ball. The method used to calculate the fish target strength values from the experimental data has been described in detail by Forbes (1977).

The reference target echo integral was used to monitor the system sensitivity continuously. Since the sensitivity of the magnetostrictive transducer used in 1976 was found to be significantly depth dependent, this was an essential feature of the measurement system. In 1977 a new Simrad ceramic transducer was used. This was found to have constant sensitivity over the required depth range. The positional stability of the reference target can be gauged by referring to the histograms of reference integrals in Figures 5 and 6. Typical standard deviations of 1% were observed for 1000 transmissions.

2.4 Television

The low light television system monitored and recorded the behaviour and spatial distribution of the fish during the course of each experiment. This was particularly important since the accuracy of the measurements depends on the fish distributing themselves, on average, randomly in the horizontal plane. In midsummer it was possible to view the fish by available light from about 3 am until 11 pm. No artifical illumination was used, in the interest of minimising disturbance of the fish.

3. Experiments

Fish availability was the main factor determining the experiments which were performed. The cod, haddock and whiting were hand lined in Broadford Bay and transported by road to the experimental station. The saithe were hand lined in Loch Duich. They were stored in keep cages at a depth of approximately 2 metres and fed regularly on squid. Mortality was negligible.

Preliminary measurements were carried out to determine the best timing for the main operation. It soon became clear that at least two weeks would be required even for an experiment involving only two depths.

The 1976 experiments were all of the same form. Fish were loaded into the experimental cage at the surface and the rig lowered to 20 metres. In all cases the echo intensity increased progressively after an initial settling period of a few hours. The fish were maintained at this depth until the echo intensity stabilised. The cage was then lowered to 70 metres. This caused a substantial drop in fish echo intensity. Subsequent recovery as the fish adapted to the new hydrostatic pressure was continuously monitored. When the echo intensity averaged over successive 24 hour periods had stabilised, the fish were raised by stages to 20 metres. After the echo intensity had stabilised once more, the fish were raised to the surface by stages, measured, weighed and dissected to check swimbladder integrity.

In 1977, two experiments similar to the 1976 series were performed. The remainder of the experiments were carried out at the single depth of 17.5 metres. This was the shallowest depth at which interference from back echoes from the sea surface could be avoided. In experiment 77/1, 30 haddock were allowed to acclimatise for 13 days, in order to check the long term consistency of the mean target strength for successive 24 hour periods. In experiments 77/3 and 77/4, a wide range of numbers of saithe were measured in order to test for any bias which might have been caused by the relatively high packing density used in the experiments.

4. Results

4.1 Consistency of measurements

Figure 7 shows the progress of an experiment in which thirty haddock were kept at a depth of 17.5 metres for thirteen days. The two hour running mean target strength is plotted with respect to time. Even when averaged on this time scale, extreme fluctuations of up to 4 dB are observed. These are attributed to variations in the spatial distribution of the fish within the cage.

Television observations indicated that the fish could be regarded as redistributing themselves on two widely differing time scales. In the short term, the mobility of the fish with respect to each other was sufficient to give rise to substantial variations in echo intensity from one transmission to the next. Standard deviations of the order of 80% were typical for 1000 consecutive transmissions (Figures 4 and 6). Viewed overall, the fish spent a substantial part of each day distributed more or less uniformly over the acoustic beam. At other times they moved as a group, occupying only part of the cage but exhibiting no detectable preference for any particular part of it. The time scale of these group movements was of the order of several hours.

The 24 hour running mean target strength is plotted in Figure 8, for the same experiment as in Figure 7. The maximum range of target strength values, after the initial acclimatisation period, is about 0.6 dB. This consistency is taken as confirmation that 24 hours is a sufficient time interval to ensure that the fish are, on average, randomly distributed over the acoustic beam.

Similar results were obtained in experiments on cod and whiting. However, considerable difficulty was experienced in conducting reliable experiments on saithe, as they were much less amenable to caging than the other species. Except when very large numbers of fish were used, they did not readily distribute themselves randomly throughout the cage. As a result, the target strength values obtained for saithe are subject to wider confidence limits than those for cod, haddock and whiting.

During the course of each experiment, 24 hour running means of echo intensity were plotted to ensure that ample time was allowed for the fish to acclimatise after depth changes. Where possible, the fish were not moved until the 24 hour mean had remained stable for at least three days. Acclimatised target strength values were derived by averaging all of the data collected after the point at which a stable value was first reached.

4.2 Acclimatisation

Variations in target strength resulting from enforced depth changes are shown in Figures 9 and 10. It is probable that in the whiting experiment (Figure 9) the decrease in target strength on lowering to 70 metres was masked to some extent as a result of the time taken to lower the fish. No substantial change in measured target strength occurred when the whiting were raised to 20 metres, after being allowed to acclimatise at 70 metres. The reason for this is not clear. In most of the experiments an increase in target strength was observed in similar circumstances. When such an increase was observed, as in Figure 10, full recovery to the original shallow depth acclimatised value did not usually occur within the period of the experiment.

Acclimatisation times were estimated by extrapolating the rising portion of the target strength versus time curve, following each enforced depth increase, to the eventual mean value of the target strength at the new depth. The results are summarised in Table 1. For cod, haddock and whiting about one day was required for acclimatisation following a drop from the surface to about 20 metres. This is in agreement with the results of buoyancy adaptation measurements on cod and saithe reported by Tytler and Blaxter (1973).

In contrast, the saithe of experiment 77/4 required about 2.5 days to acclimatise under similar conditions. The lower reliability of the saithe measurements has already been mentioned. However, this alone does not satisfactorily explain the large difference in acclimatisation time.

An approximately linear dependence of acclimatisation time on the corresponding absolute pressure increase is suggested by Figure 11, which is derived from the results of Table 1 for cod, haddock and whiting.

4.3 Target Strength per Kilogram of Acclimatised Fish

Table 2 shows values of target strength per kilogram for fish acclimatised at various depths. For all species the values for fish acclimatised at about 20 metres lie in the range -28.7 to -30.5 dB/kg. No significant species dependence is apparent.

In the saithe experiments, increasing the total weight of fish in the cage from 1.49 kg to 20.2 kg resulted in a decrease in measured target strength of 1.8 dB for fish of similar length. However, a further increase in total weight to 38.43 kg resulted in an increase of 0.4 dB. These results suggest that the differences in the measured target strength of saithe are due to random scatter in the measurements, rather than a systematic dependence on the packing density of fish in the experimental cage. This conclusion is supported by the results for cod, in which no systematic dependence on packing density is evident.

Taken as a group, the results for cod, haddock and whiting acclimatised at about 20 metres fall within a 1.3 dB range. The lowest values tend to correspond to the largest fish, which is in accordance with previous findings. However, for the range of fish lengths used in the experiments, differences in target strength are so small that any length dependence which may exist is masked by random scatter in the measurements.

In all cases, when the depth of the fish was increased, a reduction in acclimatised target strength resulted. In the 1976 experiments an average reduction of 1.3 dB was observed for a pressure ratio of 2.67. The 1977 measurements suggest a smaller depth dependence, of the order of 0.8 dB for a similar pressure ratio. This difference may partly be accounted for by the improved stability of the sensitivity of the transducer used in 1977. The reduction in target strength cannot be explained by differences in the randomness of the spatial distribution of the fish at the two depths. In all cases, the maximum short term average echo intensities measured at the deeper station were lower than the maximum values at the shallower depth. The minimum short term average echo intensities were also lower at the deeper station.

The reduction could be explained if the fish were to adopt different average tilt angles when acclimatised at different depths. An alternative, and possibly related, explanation might be that the preferred buoyancy adopted by the fish is dependent on depth. Were either explanation to be correct, there is no evidence to show that similar behaviour does not occur in the wild. Consequently, though the effect is small, it is believed that the existence of a genuine dependence of acclimatised target strength on depth cannot be ruled out.

4.4 Target Strength of Unacclimatised Fish

Values of the initial reduction in target strength following enforced depth increases are given in Table 3. For the purpose of estimating the reduction when fish were lowered from the surface, the acclimatised target strength at 20 or 17.5 metres was taken as a good approximation to the unknown value at the surface. Reductions of between 4 dB and 6 dB were typically observed for cod, haddock and whiting. The larger reduction exhibited by the saithe was almost certainly due to their tendency to swim around the outside edge of the cage for some time after being lowered. If the saithe results are ignored, the values in Table 3 suggest that the initial reduction in target strength is dependent on the pressure increase ratio, rather than the absolute increase in pressure. This is consistent with the swimbladder volume changing in accordance with Boyle's Law, as suggested by Alexander (1966).

These results clearly demonstrate the importance of taking into account the state of pressure adaptation of the fish when interpreting the results of target strength measurements.

4.5 Second Order Effects

In the experiments on whiting and saithe a diurnal variation in fish echo intensity was observed. An example can be seen in Figure 9, in which both 12 hour and 24 hour running means are plotted. The 24 hour running mean effectively eliminates the pronounced variation which is clearly evident in the 12 hour running mean.

In a few experiments there was evidence of a cyclic variation in echo intensity with a period of 12.5 hours, suggesting correlation with tidal flow.

Figures 12 and 13 show acoustically derived evidence of the vertical distribution of the fish in the cage throughout the course of two experiments. In each case, the depth of the peak of the fish echo, relative to the bottom of the cage, is plotted. The depth range between -3 dB points on the echo intensity depth profile is also plotted.

After lowering from the surface to 20 metres the whiting (Figure 12) maintain a constant position relative to the bottom of the cage. On lowering to 70 metres there is an initial drop in mean depth, and almost immediately a marked tendency to disperse vertically at night is evident. As the fish adapt to the new pressure, the night time dispersal diminishes. Instead, the fish tend to migrate collectively upwards during darkness. Raising the fish to 20 metres results in regeneration of the night dispersal effect and the disappearance of collective migration.

When the cod (Figure 13) were lowered from the surface to 20 metres, and from 20 metres to 70 metres, they tended to occupy the lowest part of the cage. This was confirmed by television observations, which showed some of the cod resting on the bottom of the cage for part of the acclimatisation period. As the cod acclimatised they moved higher in the cage (Figure 13). On raising the fish to 20 metres, the fish moved towards the bottom of the cage. A gradual movement to higher levels in the cage then took place over a period of about two days. A tendency to disperse vertically at night was detectable throughout the experiment.

5. Conclusions

The time taken by gadoids of the order of 30 cm in length to acclimatise after an enforced pressure increase is dependent on the absolute change in pressure, and is measurable in units of days rather than hours. This determines the time scale required for any target strength measurements of fish which have swimbladders.

The target strength per kilogram for gadoids of about 30 cm in length is -29.5 dB/kg. Differences in target strength for the four species measured are insignificant.

The target strength per kilogram for fully acclimatised gadoids is dependent on the depth to which the fish are acclimatised. The target strength decreases sufficiently with depth to suggest that caution should be exercised in applying results of shallow water measurements directly to deep living fish such as blue whiting.

The target strength of unacclimatised fish may easily be as much as 6 dB less than the fully acclimatised value. Since the state of acclimatisation of fish in the wild is not known, particularly in the case of species which perform substantial diurnal migrations, there is likely to be a high degree of uncertainty regarding the most appropriate target strength value for any given occasion.

6. Acknowledgements

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7. References

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Goddard, G.C. and Welsby, V.G., 1977. Statistical measurements of the acoustic target strength of live fish. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 170: 70–73.

Nakken, O. and Olsen, K., 1977. Target strength measurements of fish. Rapp. P.-v. Réun. Cons. int. Explor. Mer, 170: 52–69.

Tytler, P. and Blaxter, J.H.S., 1973. Adaptation by cod and saithe to pressure changes. Netherlands J. Sea Research. 7: 31–45.

TABLE 1. Acclimatisation time (in hours) following enforced depth increase.

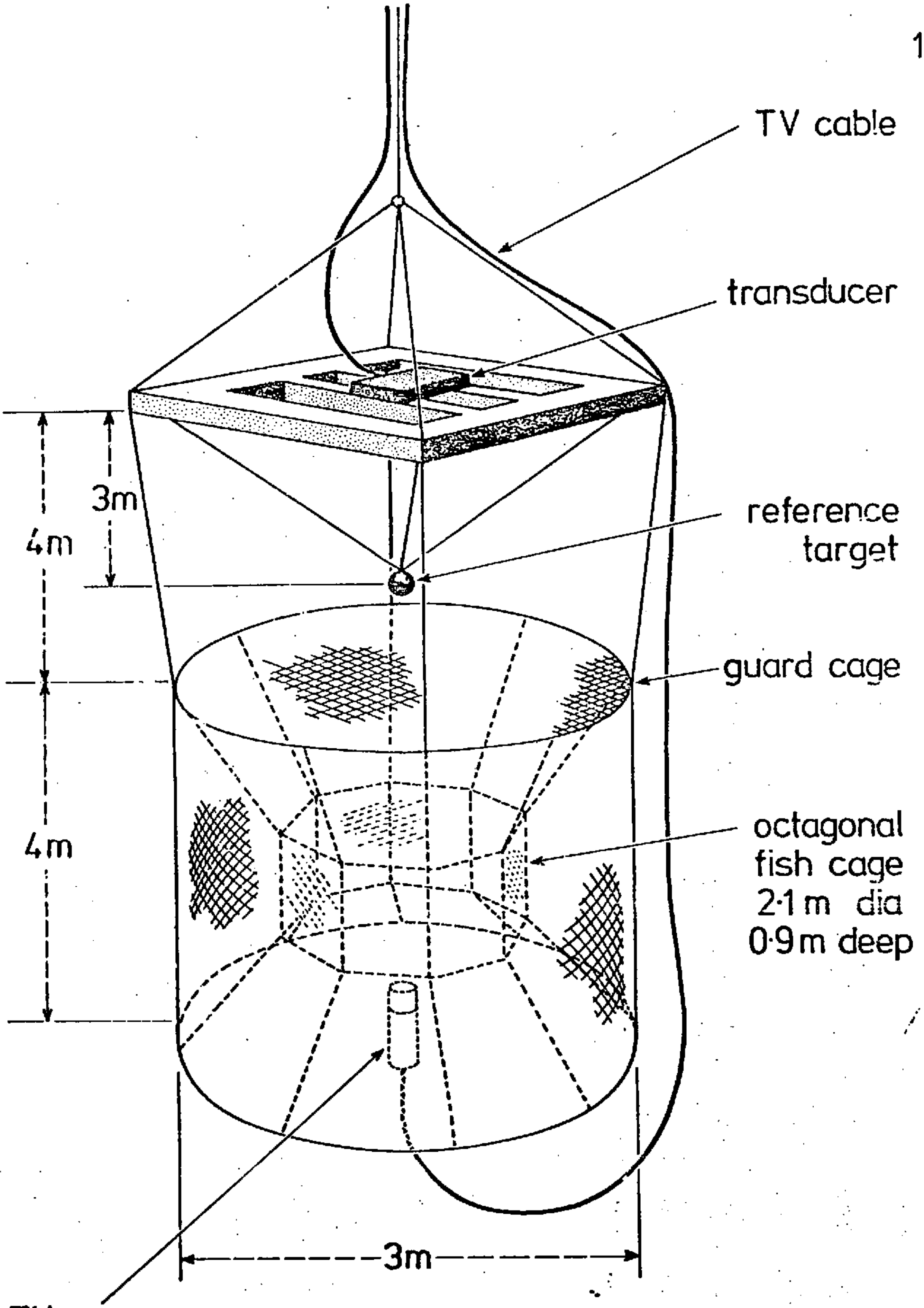
		Column	1	2	3	4	5
		Absolute Pressure Increase (Atmospheres)	2.0	1.75	5.0	2.45	4.45
		Pressure Ratio (Final/Initial)	3.0	2.75	2.67	1.89	2.62
Experiment	**Species**	**Mean Length (cm)**					
76/19	Cod	35.9	28		86		
76/20	Whiting	23.3	19		45		
76/21	Cod	34.4	27		101		
77/1	Haddock	28.4		24			
77/2	Haddock	29.2		21		40	
77/4(a)	Saithe	25.5		60			
77/4(b)	Saithe	26.0		65			
77/5	Cod	28.7		33			66

TABLE 2. Target strength per kilogram for acclimatised fish at various depths.

Expt No	Species	Mean Length (cm)	Total Weight (kg)	No of Fish	Depth				
					20 m	17.5m	70 m	42 m	62 m
76/18	Cod	35.3	6.05	18	-29.4				
76/19	Cod	35.9	7.80	19	-29.5		-30.2		
76/20	Whiting	23.3	4.48	45	-28.9		-31.3		
76/21	Cod	34.4	9.15	26	-30.2		-32.1		
77/1	Haddock	28.4	5.61	30		-29.8			
77/2	Haddock	29.2	3.63	15		-29.6		-30.5	
77/3(a)	Saithe	25.7	8.79	56		-29.7			
77/3(b)	Saithe	25.1	3.81	28		-28.9			
77/3(c)	Saithe	24.0	1.49	14		-28.7			
77/4(a)	Saithe	25.5	38.43	216		-30.1			
77/4(b)	Saithe	26.0	20.2	111		-30.5			
77/5	Cod	28.7	12.98	54		-29.1			-29.8

TABLE 3. Initial reduction (in decibels) of target strength per kilogram due to enforced pressure increase.

Expt. No.	Species	Mean Length (cm)					
		Pressure Increase (Atm)	2.0	1.75	5.0	2.45	4.45
		Pressure Ratio (Final / Initial)	3.0	2.75	2.67	1.89	2.62
76/18	Cod	35.3	6.0				
76/19	Cod	35.9	6.0		6.0		
76/20	Whiting	23.3	5.0		5.0		
76/21	Cod	34.4	6.0		6.0		
77/1	Haddock	28.4		4.3			
77/2	Haddock	29.2		4.0		3.6	
77/4(a)	Saithe	25.5		10.5			
77/4(b)	Saithe	26.0		8.0			
77/5	Cod	28.7		5.0			7.7



EXPERIMENTAL RIG

FIGURE 1

DATA ACQUISITION and LOGGING SYSTEM

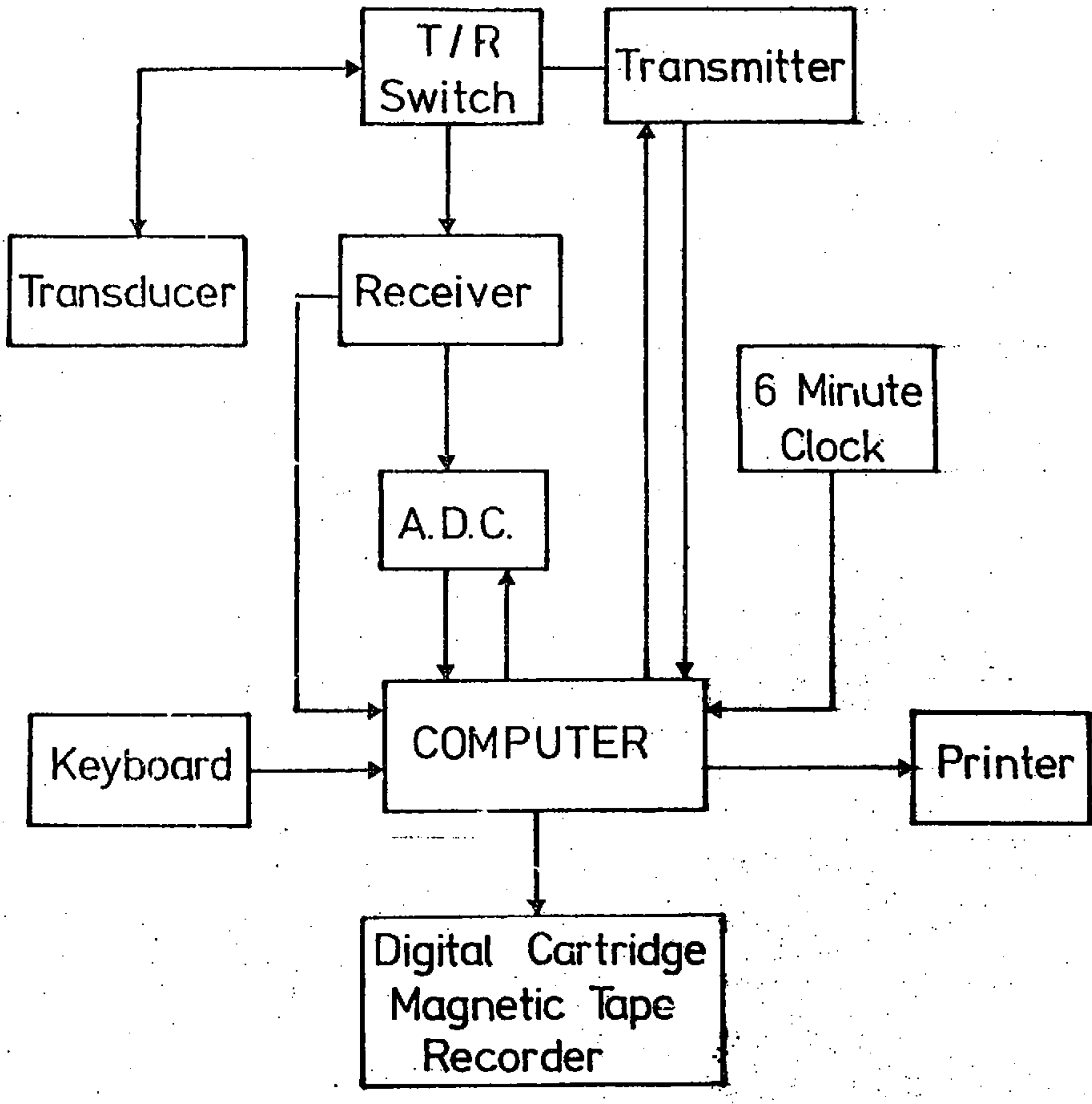


FIGURE 2

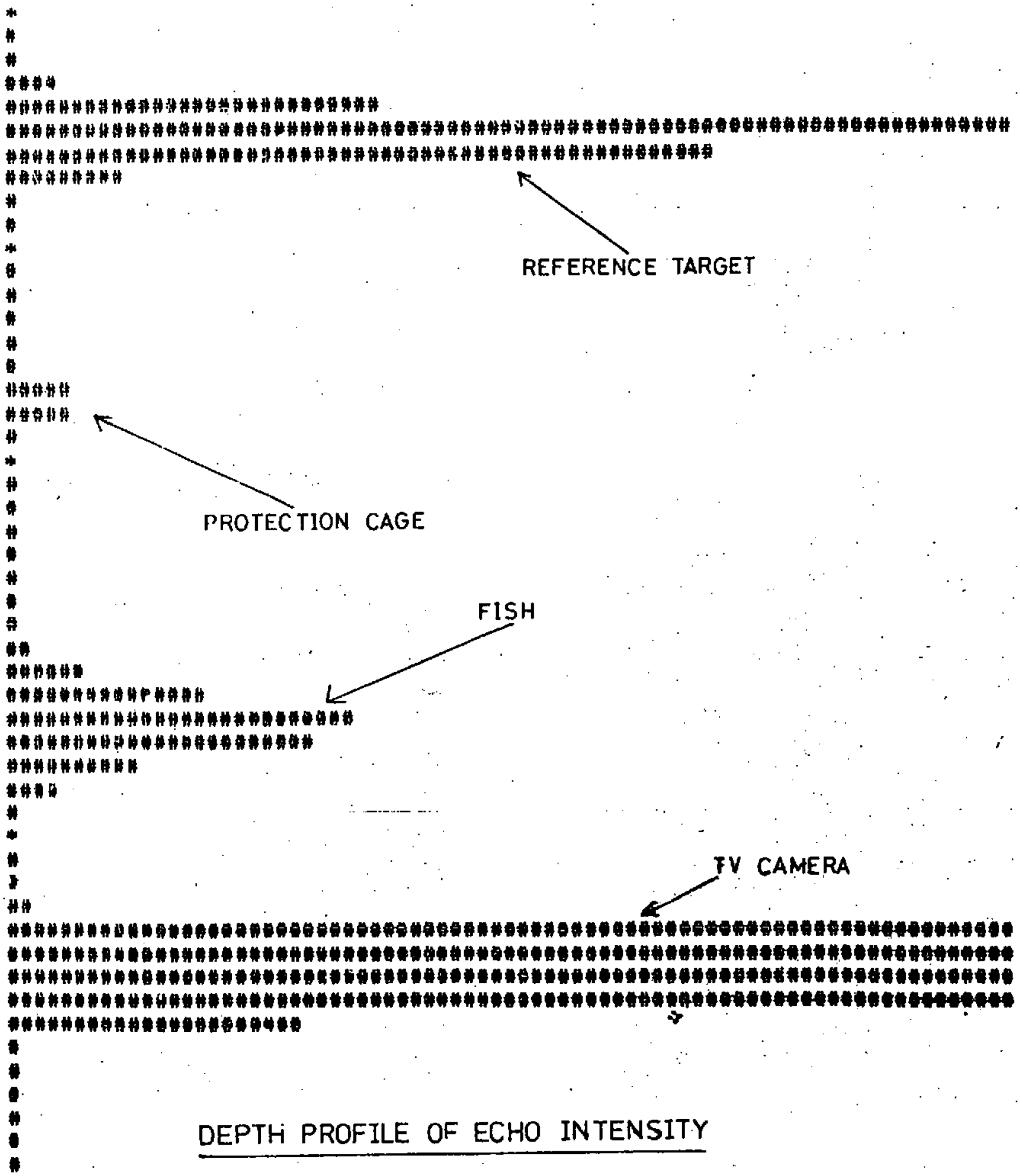
PAGE 032 EXPERIMENT 021

T 1000 S 100 P 035 R 3000 TC 072 BC 104 TT 035 BT 055 RX TX PL 06A5

S. D. (C)	C	S. D. (T)	T	C/T(DB)	C/T

12/03/76. 09:30. +3.116788E+10 +5.802148E+10 +5.371783E-01
06A5 +2.671210E+10 +4.864005E+08 -2.698814E+00

DEPTH PROFILE MAX VALUE +2.539137E+13



DEPTH PROFILE OF ECHO INTENSITY

FIGURE 3

```
T 1000 S 100 P 035 R 3000 TC 072 BC 104 TT 035 BT 055  RX TX PL 06A5

                S.D.(C)       C       S.D.(T)       T       C/T(DB)      C/T

25/08/76. 01:00.        +5.569607E+09         +4.947684E+10         +1.125700E-01
   06A5      +3.966216E+09        +2.221187E+08        -9.485772E+00

     HISTOGRAM OF CAGE INTEGRALS

+0.0000
00*********************
01****************************************************
02********************************************************************
03************************************************
04*****************************************************************
05*************************************************************************
06******************************************************
07***********************************************************
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+3.191882E+10
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HISTOGRAM OF FISH ECHO INTEGRALS

FIGURE 4

PAGE 056 EXPERIMENT 020 1.5

T 1000 S 100 P 035 R 3000 TC 072 BC 104 TT 035 BT 055 RX TX PL 06A5

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              S.D.(C)      C       S.D.(T)      T      C/T(DB)      C/T

26/03/76. 01:00.      +7.851846E+09       +5.245892E+10       +8.149676E+00
   06A5      +6.082502E+09       +2.390120E+08       -8.248476E+08

      HISTOGRAM OF TARGET INTEGRALS

+0.0000
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30
31
32
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41
42
43
44
45
46
47
48*
49******************************************************************************
+5.302584E+10
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HISTOGRAM OF REFERENCE INTEGRALS

FIGURE 5

EXPERIMENT 001 24/06/77 11:42 00FF

C= 2.462E+10 SD(C)= 8.1E+01 T= 5.619E+10 SD(T)= 9.3E-01

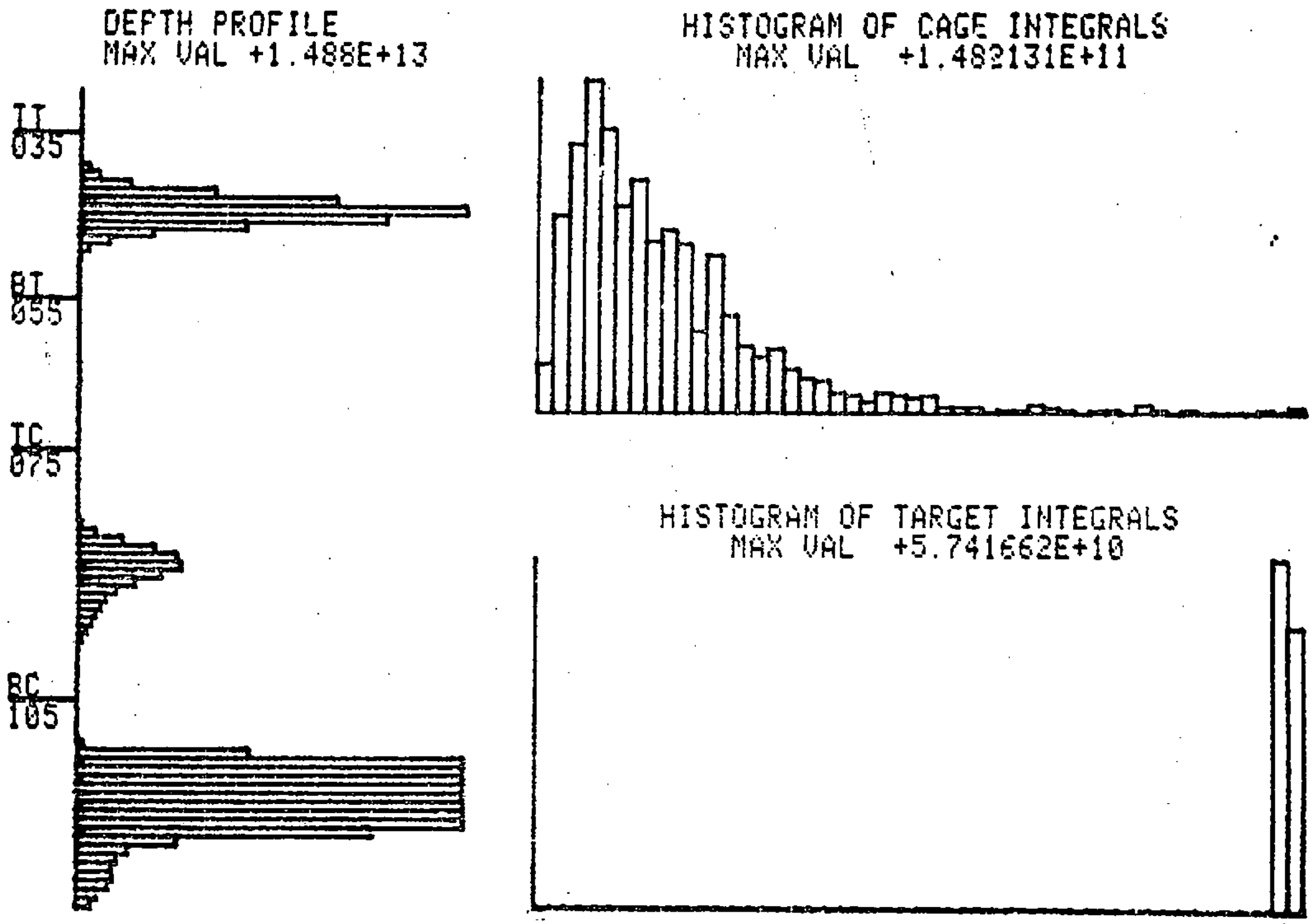


FIGURE 6. SUMMARY OF 1000 TRANSMISSIONS

FIGURE 7

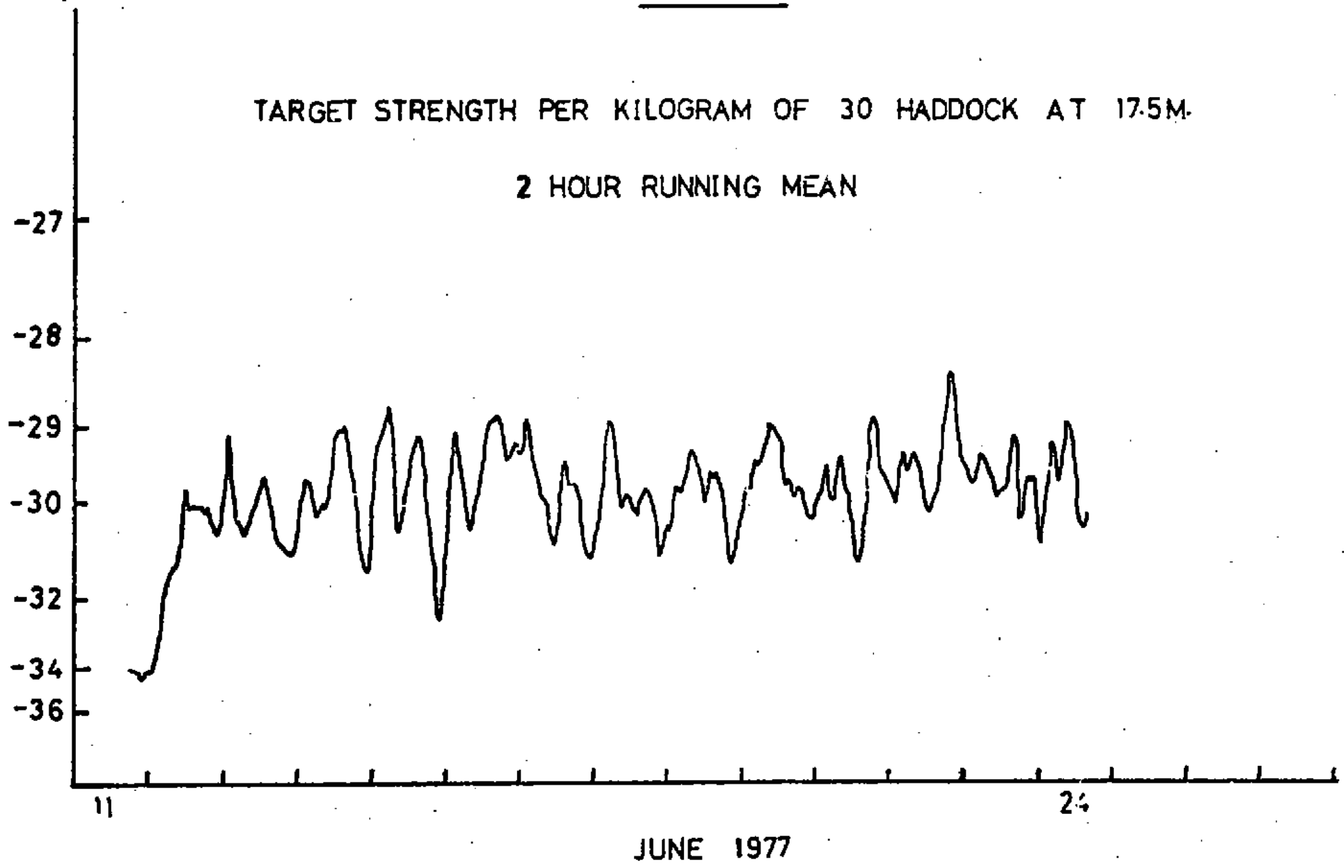
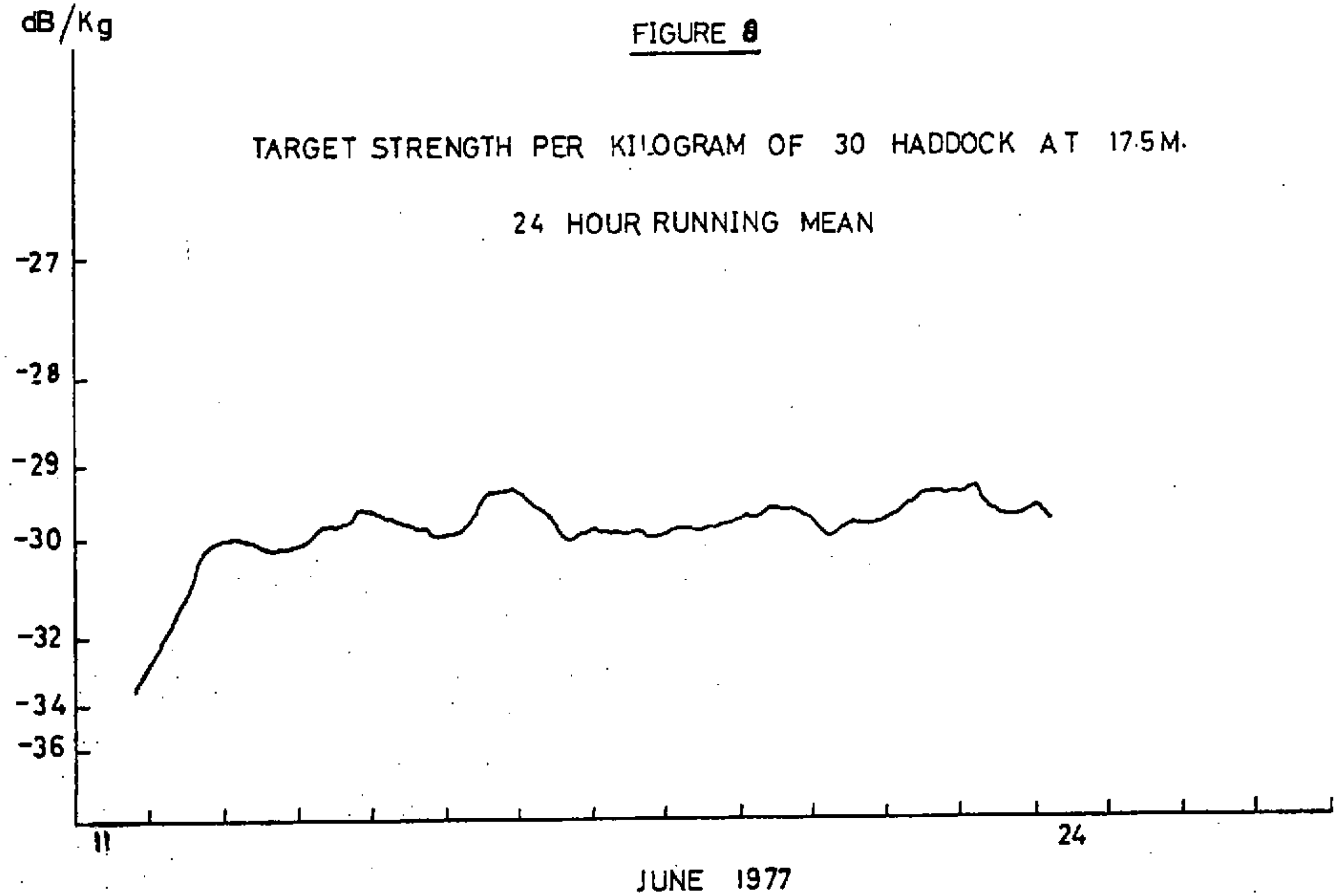
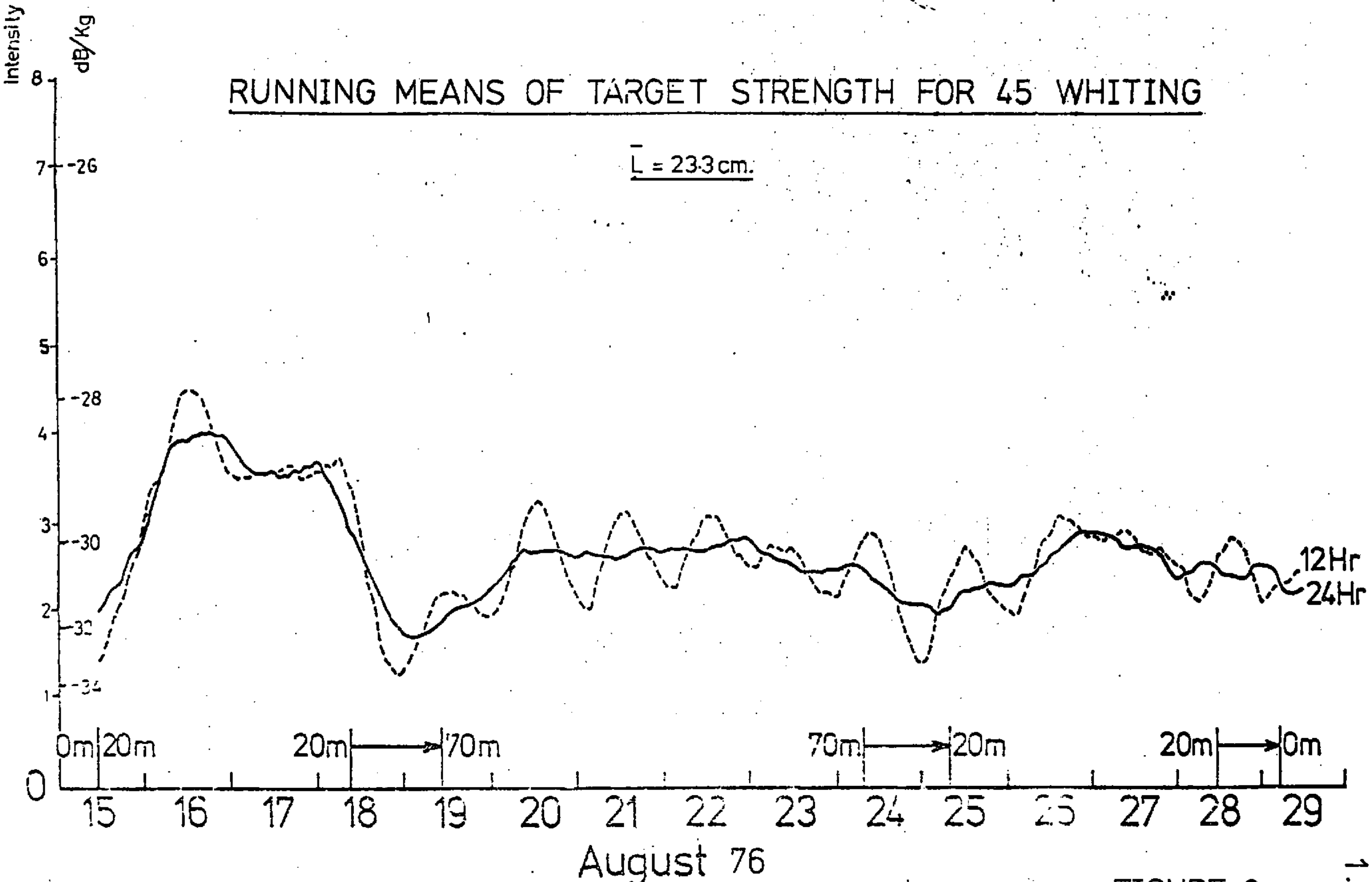

TARGET STRENGTH PER KILOGRAM OF 30 HADDOCK AT 17.5M.
2 HOUR RUNNING MEAN
dB/Kg
-27
-28
-29
-30
-32
-34
-36
11
24
JUNE 1977

FIGURE 8


dB/Kg
TARGET STRENGTH PER KILOGRAM OF 30 HADDOCK AT 17.5M.
24 HOUR RUNNING MEAN
-27
-28
-29
-30
-32
-34
-36
11
24
JUNE 1977


RUNNING MEANS OF TARGET STRENGTH FOR 45 WHITING
$\bar{L}$ = 23·3 cm.
Intensity
dB/kg
8
7
6
5
4
3
2
1
0
-26
-28
-30
-32
-34
12Hr
24Hr
0m
20m
20m
70m
70m
20m
20m
0m
15
16
17
18
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20
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23
24
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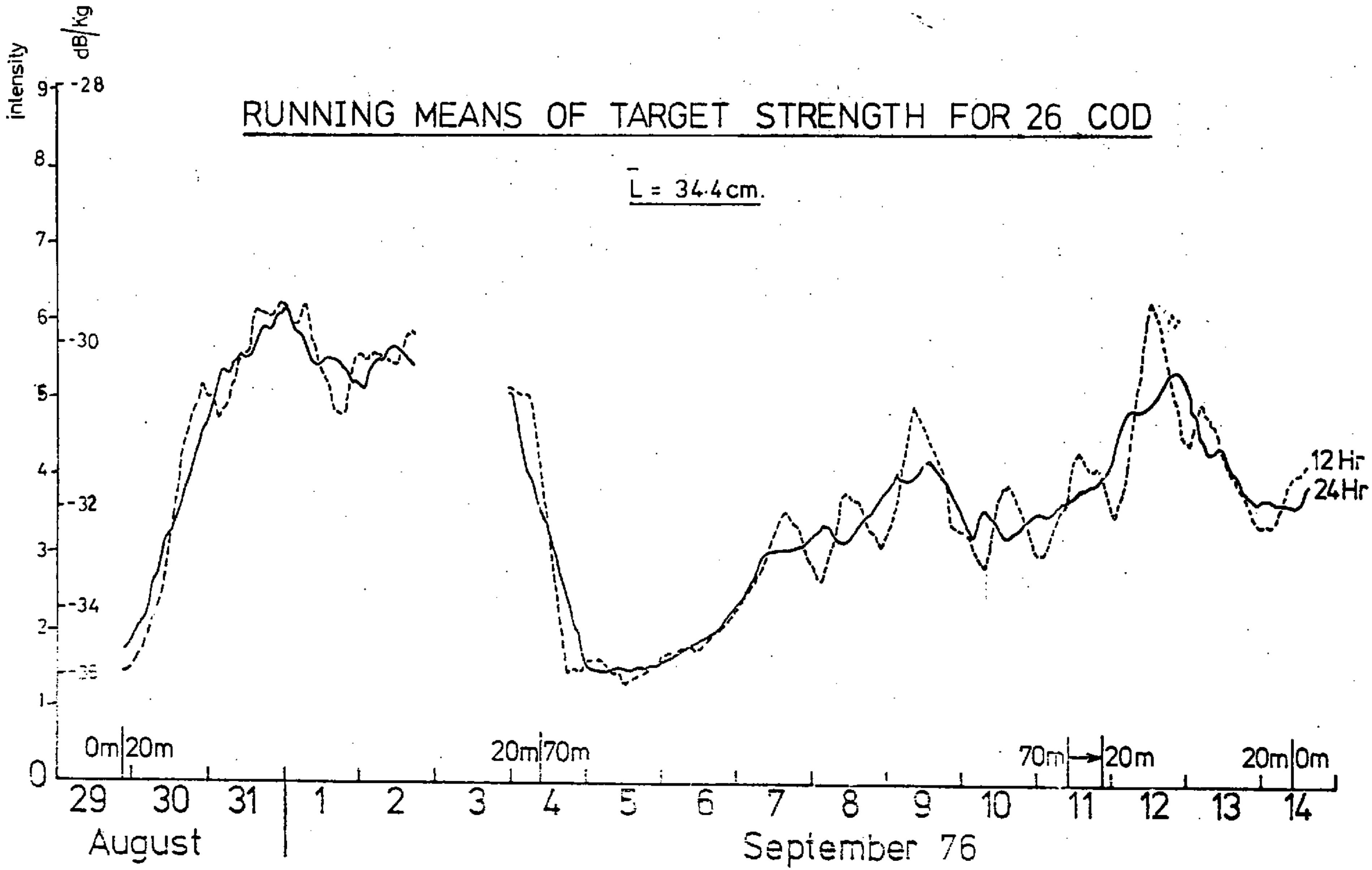
28
29
August 76

FIGURE 9


RUNNING MEANS OF TARGET STRENGTH FOR 26 COD
L̄ = 34·4 cm.
intensity
dB/kg
9
8
7
6
5
4
3
2
1
0
-28
-30
-32
-34
-36
12 Hr
24 Hr
0m
20m
20m
70m
70m
20m
20m
0m
29
30
31
1
2
3
4
5
6
7
8
9
10
11
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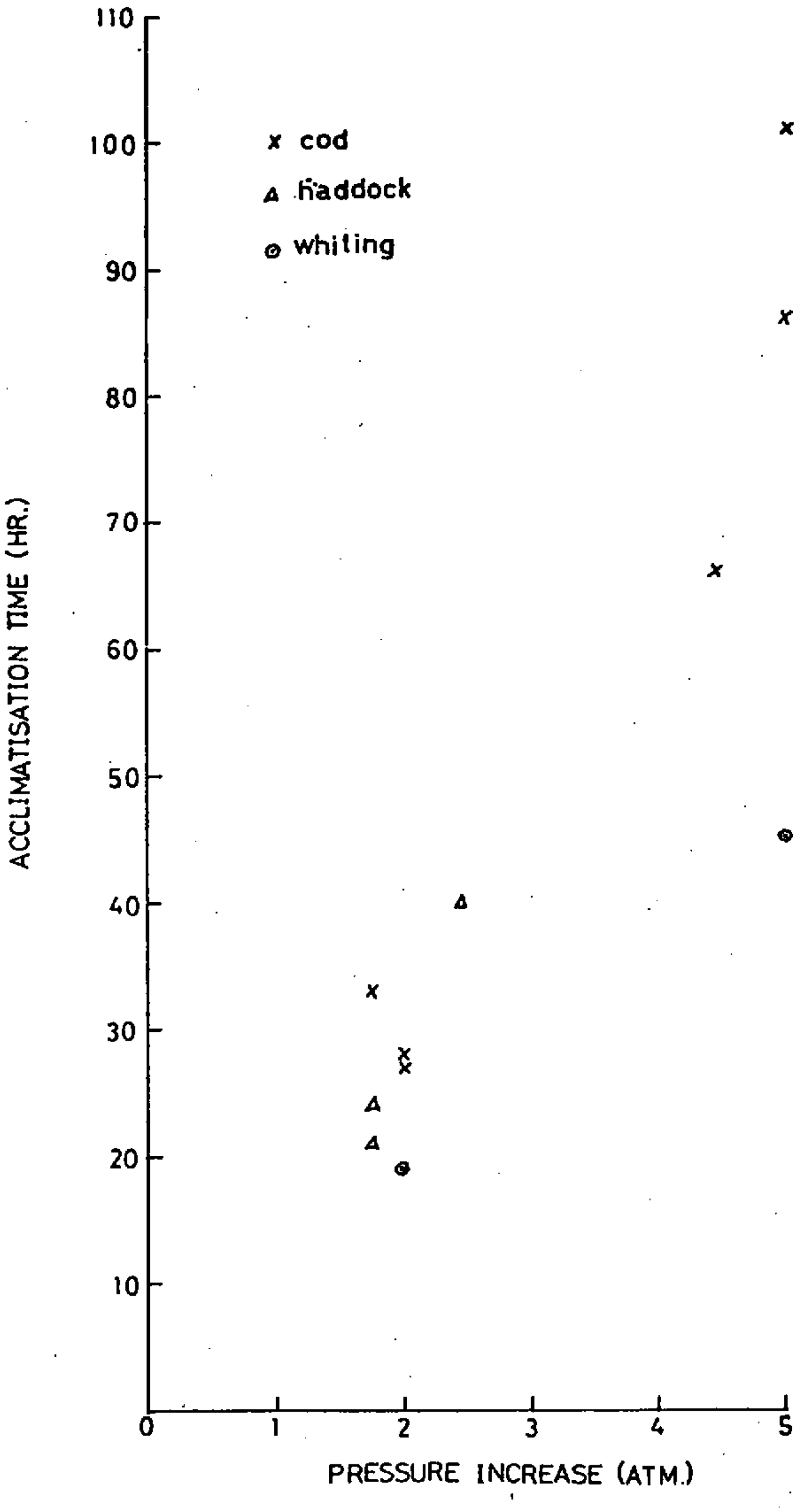
14
August
September 76

FIGURE 10



ACCLIMATISATION TIME FOLLOWING ENFORCED DEPTH INCREASE

FIGURE 11

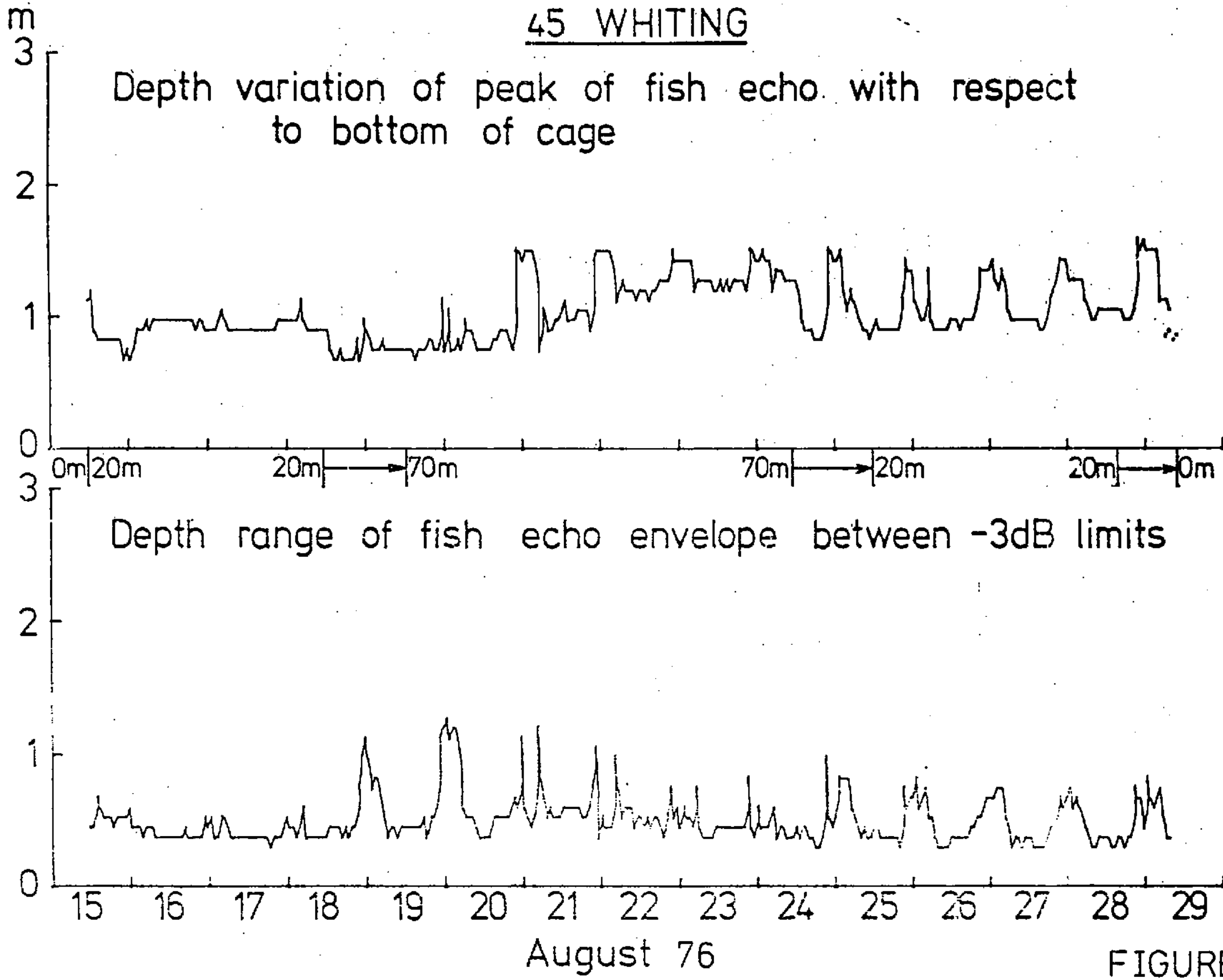

m
45 WHITING
Depth variation of peak of fish echo with respect to bottom of cage
3
2
1
0
0m 20m
20m → 70m
70m → 20m
20m → 0m
Depth range of fish echo envelope between -3dB limits
3
2
1
0
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
August 76

FIGURE 12

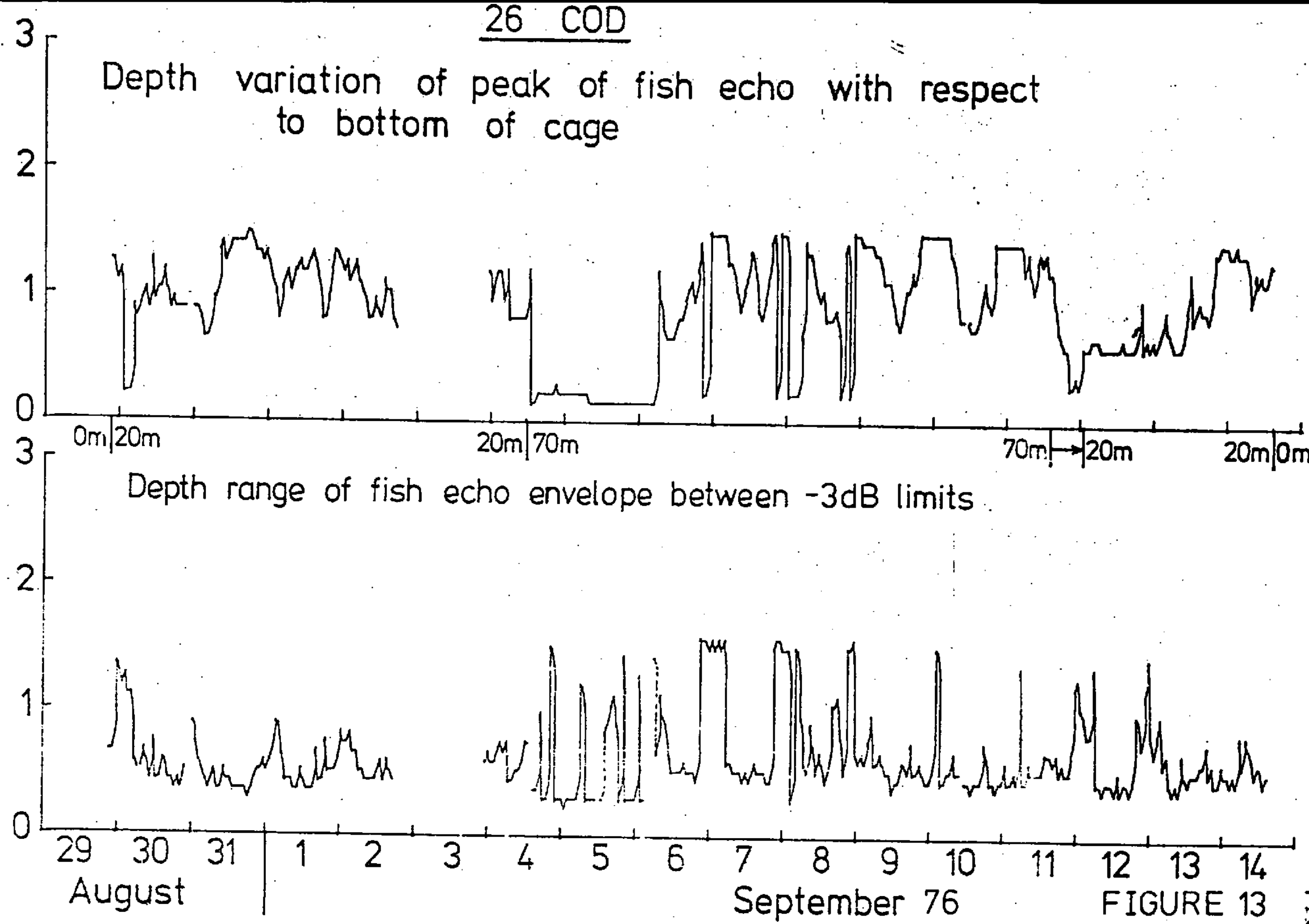

26 COD
Depth variation of peak of fish echo with respect to bottom of cage
3
2
1
0
0m
20m
20m
70m
70m
20m
20m
0m
Depth range of fish echo envelope between -3dB limits
3
2
1
0
29
30
31
1
2
3
4
5
6
7
8
9
10
11
12
13
14
August
September 76

FIGURE 13