Session 7: Target-strength measurement – techniques and results

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Target tracking with a split-beam echo sounder

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The split-beam technique makes it possible to determine the precise location of a fish in the acoustic beam. This is a very useful feature, as it permits behavioural observations to be conducted without disturbing the fish. A split-beam echo sounder (Simrad ES400) interfaced with a computer has been used to track fish swimming through the acoustic beam. Tracks of reference targets guided through the beams of split-beam transducers on three research vessels and the transducer used for fish-behaviour experiments are presented with associated beam patterns. A "best-fit" equation was used to represent the beam pattern measured in the tracking experiment. This was used to correct signal amplitudes for transducer directivity. *In situ* target-strength functions, representing the fish directivity pattern in the dorsal aspect, and three-dimensional plots of fish movement through the acoustic beam, are presented for three different gadoids.

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Introduction

The first commercially available echo sounder giving real-time information on fish size distributions was the split-beam echo sounder Simrad ES380, introduced in 1984. The scientific version of the sounder, the Simrad ES400 at 38 kHz and the ES470 at 70 kHz, have, since they were introduced in 1985, been used for *in situ* target-strength measurements and for analyses of the size distribution of surveyed fish. Some results obtained by the application of these split-beam echo sounders have already been presented and discussed (Foote *et al.*, 1984, 1986).

The split-beam principle was originally described and discussed by Ehrenberg (1979, 1983). Its realization in hardware and software in the Simrad split-beam echo sounders has been explained in detail (Foote *et al.*, 1984).

The purpose of the described experiments is to demonstrate the possibility of tracking targets through the sound beam. It is also the aim to show how fish target strength and directivity can be measured as a function of position in the beam.

Materials and methods

1. Collection of data

To demonstrate the quality of the target tracking and to check the beam pattern of hull-mounted transducers, a 60-mm copper reference target was guided through the sound beam using the standard sphere calibration rig (Foote *et al.*, 1986). Data are presented for three vessels, and also for the transducer used in the fish-tracking experiment.

The tracking experiments took place at a large, anchored aquaculture farm at Skogsvaagen, west of Bergen. The basic instrumentation and computer were installed in one of the accommodation rooms on the large, 100 m^2 raft carrying the automatic feeding systems and storeroom for the plant. The split-beam transducer was fixed between and below the salmon holding pens at a depth of 4 m to observe the free-swimming fish below the pens.

Most of the fish feeding on surplus salmon food, sinking through the bottom of the pens, were 40–60 cm saithe. During the measurements, however, both cod (*Gadus morhua*) of 45–60 cm and haddock (*Melanogrammus aeglefinus*) of 45 and 47 cm were caught on hooks at the tracking depth, 20–30 m.

For data-logging, the real-time parallel data output of the ES400 was fed to an IBM-AT computer. These contained depth, uncompensated signal amplitude, and longitudinal and transverse angle, totaling 6 bytes for each 10-cm depth. The signal amplitudes were logged in numbers from 0 to 4095, corresponding to the output from the 12-bit analogue-to-digital converter working on signals from 0 to 10 V. The angles were logged in numbers from −38 to +38 with an angular resolution of 0.13 degrees (Table 1).

For each reference target track or fish target track, data from 99 successive soundings over a specified depth interval were logged. The particular data-logging software was later improved for continuous storage of 15 kbytes/s, which is necessary for full monitoring of the split-beam parallel data.

The ES400 was set to a pulse duration of 1 ms and a bandwidth of 3.5 kHz. The display range used was 50 m with 140 soundings per minute.

2. Data processing

In the simple registration regime described, a window covering only one target trace was first opened.

Table 1. ES400 parallel output data from a depth layer, 17–20 m, containing one well-defined pulse from the calibration sphere. Framed area: CU-sphere echo as selected with threshold set to 50.

Depth	Amplitude	Y-angle	X-angle
170	0	−028	10
171	0	−026	−001
172	5	−030	−014
173	11	−024	−017
174	17	−030	−025
175	19	−006	−005
176	20	−012	−022
177	17	−032	−049
178	12	18	29
179	7	18	24
180	5	3	48
181	5	−011	−003
182	85	−015	−014
183	431	−016	−016
184	799	−016	−016
185	1 023	−017	−016
186	1 119	−017	−016
187	1 151	−017	−016
188	1 167	−016	−016
189	1 164	−018	−018
190	984	−024	−025
191	592	48	−022
192	308	39	−014
193	150	−018	1
194	75	−022	12
195	67	−028	14
196	74	−024	15
197	78	−022	11
198	85	−017	9
199	99	−020	15

To track the target in successive soundings a program routine was written which searched downwards inside the depth window until a sample with signal amplitude above a chosen threshold was found. The pair of angles corresponding to this depth sample plus the following six samples of angles along the pulse were processed as follows:

The three highest and the three lowest values of x- and y-angles were omitted. The remaining value for x- and y-angle gives the coordinate of the target in that particular sounding. This particular routine is felt to be less sensitive to erroneous "spikes" in the angle data than is a clean averaging process. The logged depth of the target corresponds to the first sample above the chosen threshold, and the echo amplitude is the maximum amplitude sampled within the pulse.

The samples within the frame in Table 1 represent the echo as selected by the program with threshold set to 50 mV. In this case, the logged depth would be 182 dm, the echo amplitude 1167 mV, and logged angles $y = -16$ and $x = -16$ ($= -2.08$ and -2.08 degrees).

Plotting of the different reference target tracks through the sound beams, together with the amplitudes giving the transducer beam patterns in the corresponding cross-sections, was caried out manually (Figs. 1–4).

The beam pattern of the transducer used in the fish-tracking experiment was established. The actual rather than the nominal beam pattern was represented by a mathematical expression and used for compensation of the fish echo amplitudes.

With *in situ* measurements of transducer directivity in two directions, it was possible to make a fairly simple tuning of the beam correction factors through the equation:

$$B(X,Y) = 7.72 \times 10^{-3} \times X^{2.3} + 7.72 \times 10^{-3} \times Y^{2.3}. \quad (1)$$

The data were further transferred to a general statistical/graphical program for analysis and graphical presentation of the results.

3. Calibration

3.1. *Checking of beam patterns of hull-mounted transducers*

Tracking of a 60-mm copper reference target was carried out on board the vessels RV "Simrad", RV "G. O. Sars", and RV "Eldjarn". The sphere was pulled through the beam in several different cross-sections. The uncompensated echo signal levels plotted against the target positions give the beam pattern of the transducer. Typical lobe diagrams (beam patterns) are shown for the three vessels in Figures 1–3.

3.2. *Measuring the lobe diagram of the transducer used at Skogsvaagen during the fish-tracking experiment*

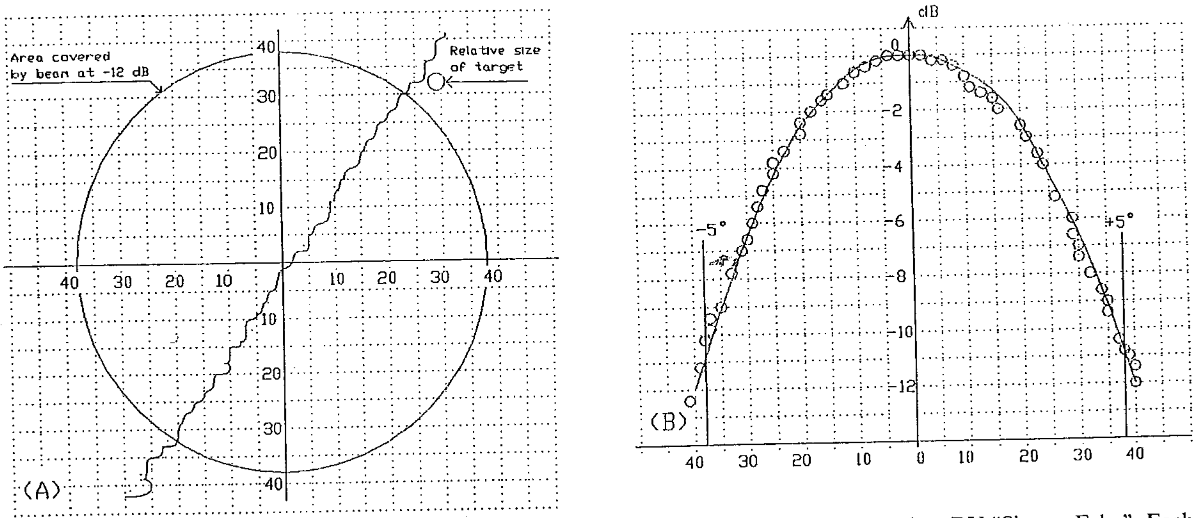

Figure 1. (A) Passage of the sphere target through the beam at 10-m depth: Transducer mounted on RV "Simson Echo". Each step corresponds to 0.13 degrees. (B) Beam pattern obtained from track A, with the nominal curve indicated. As a spherical target is used, B represents the product of the transmit and receiving beam patterns of the transducer.

The reference target was pulled through the transducer beam at a range of 18 m from the transducer. Data from successive soundings are shown in Table 2 and Figure 4, where the curve of the "best-fit" equation, representing the measured beam pattern, is also shown.

The plotted sphere track shows a small deviation between the acoustic beam axis and the ES400 angular axis of one step in the x-direction and two steps in the y-direction. This offset was compensated for in the program by adding one step (0.13 deg) to the measured x-direction and two steps to the measured y-direction.

Results

1. Measurements on the three vessels

The tracking of a 60-mm copper sphere through the beams in various cross-sections shows that the precision of tracking corresponds to the angular resolution of 0.13 degrees of the ES400 measuring system. At a depth of 18 m, the horizontal position of the sphere is measured with a precision of 4.1 cm. This precision is maintained within, and also to a certain extent outside of, the −12 dB limit (corresponding to a 10 deg circular beam)

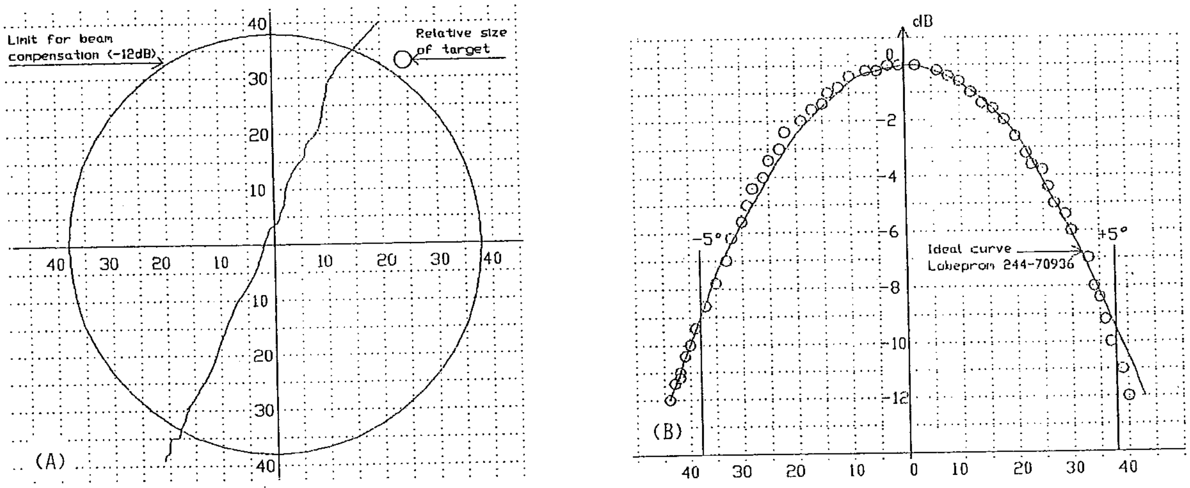

Figure 2. (A) Passage of the spherical target through the beam of the hull-mounted ES400 transducer on RV "G. O. Sars", with (B) corresponding two-way beam pattern.

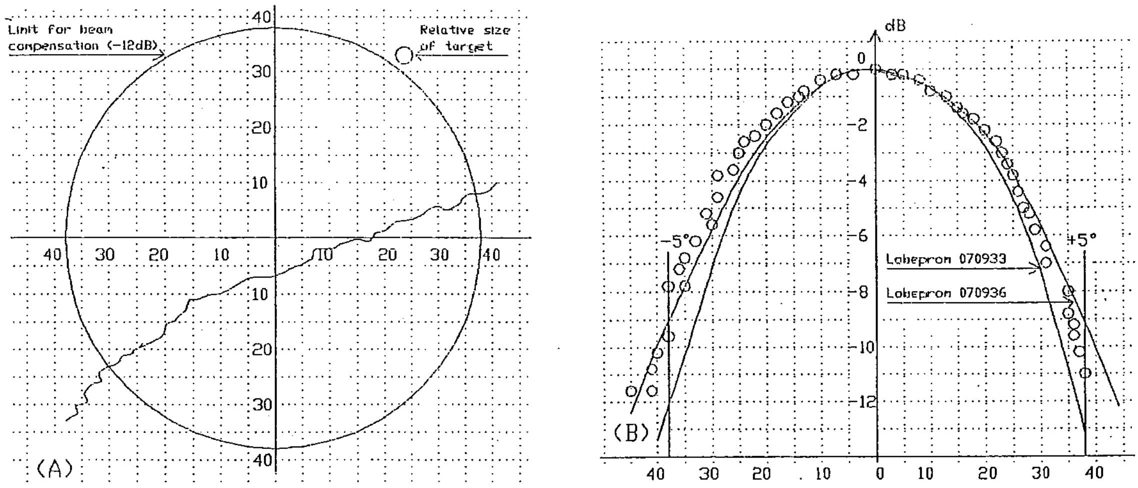

Figure 3. (A) Passage of the sphere through the beam of the hull-mounted transducer on RV "Eldjarn", with (B) corresponding two-way beam pattern and two versions of nominal, internal compensation proms.

for the ES400 measurements. The sphere tracks together with corresponding sphere echo-amplitude tracks for the three vessels are shown in Figures 1–3. The lobe diagrams obtained in this way show that they are well within the manufacturer's specification of ±1 dB one-way.

Excellent target strengths are obtained when these target measurements (Figs. 1–3) and the correction algorithms are applied. When on-line TS measurements are required, a "custom" PROM describing the actual pattern, rather than the nominal specification, can be used. Later measurements, with exact mapping of the beam of the ES400, have shown that an accuracy of ±0.1 dB within the −3 dB points, one-way, can be achieved (Degnbol, 1988; Degnbol and Lewy, 1990). A three-dimensional fitting of the measured surface is then needed for beam compensation. In our case, only two tracks through the beam have been used to establish the compensation factors.

2. Measurements at Skogsvaagen

2.1. Tracking of the reference target

After having measured the transducer lobe diagram on site, the formula compensating for the beam pattern was established. The sphere was pulled through the beam twice diagonally, once along the x-axis, and once with the transducer rotated (uncontrolled) to simulate a circular sphere track.

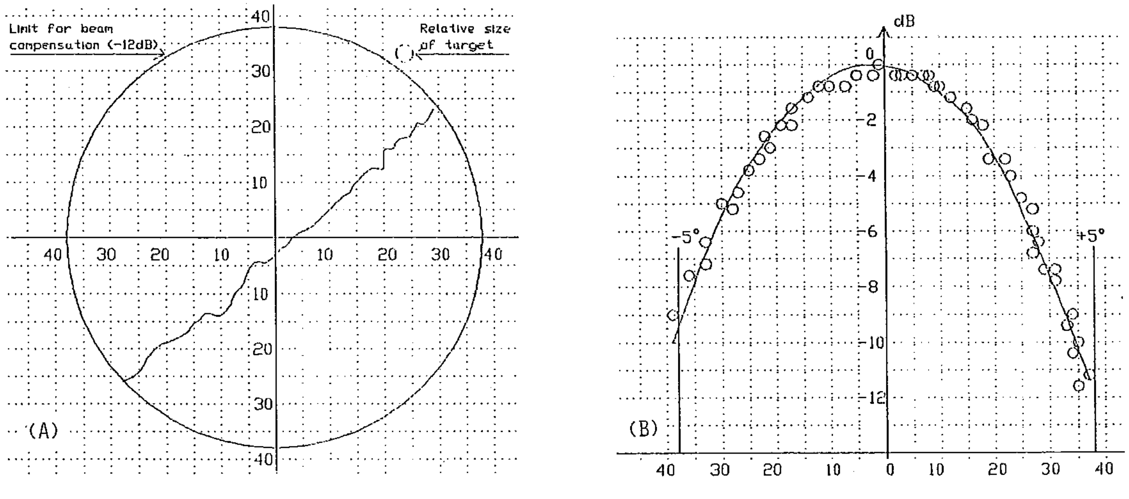

Figure 4. (A) Passage of the spherical target through the beam of the transducer used in the fish-tracking experiment, with (B) corresponding two-way beam pattern and fitted-function compensation.

Table 2. Extract of data collected when guiding the sphere through the transducer beam used during fish tracking.

Sounding	Depth	Amplitude	Y-angle	X-angle
22	184	−33.699 11	−15	−15
23	184	−34.469 03	−11	−13
24	184	−34.039 94	−13	−13
25	183	−33.636 3	−14	−11
26	183	−33.911	−12	−10
27	183	−33.794 86	−12	−7
28	183	−33.718 42	−10	−7
29	183	−33.761 48	−9	−6
30	183	−33.988 66	−5	−5
31	182	−33.767 49	−5	−3
32	182	−33.810 38	−5	−2
33	182	−33.728 66	−3	0
34	182	−33.565 73	−2	1
35	182	−33.682 16	−1	3
36	181	−33.597 72	0	4
37	181	−33.504 25	1	5
38	181	−33.475 76	2	7
39	181	−33.273 62	3	8
40	181	−33.655 02	4	8
41	181	−33.558 43	4	9
42	180	−33.605 96	5	10
43	180	−33.552 08	6	11
44	180	−33.213 99	8	13
45	179	−33.181 74	8	14
46	179	−33.554 81	9	14
47	179	−33.312 47	10	15
48	179	−33.711 31	11	16
49	178	−33.050 1	13	18

The plots of sphere target strength vs x−y positions are shown in Figure 5. We have also included points, well outside the −3 dB points, one-way.

If the equation compensating for the beam pattern was absolutely correct for all angles, the measured TS of the reference target should always be −33.7 dB. As shown in Figure 4 this is not the case, and the variations in the measured TS for the sphere are in accordance with the deviation of the "best-fit" curve from the measured beam pattern. A higher-order polynomial would have to be fitted to include the smaller deviations.

The x−y plots of the different sphere tracks are shown in Figure 6. The angular resolution of 0.13 degrees causes the small random variation along the tracks.

2.2. *Tracking of free-swimming fish*

All together, six successful fish tracks were obtained where the fish moved through most of the beam. The start of a fish track had to be initiated manually; one waited until a fish echo appeared on the ES400 screen within the pre-chosen depth layer, and the data from the following 99 soundings were collected.

Graphical plots of horizontal movement (Figs. 7, 8, and 9A), target strength vs sounding number (Figs. 7, 8, and 9B), vertical vs horizontal movement (Figs. 7, 8, and 9C), and target strength vs horizontal movement (Figs. 7, 8, and 9D), are shown for three different fish.

The tracked fish swam at depths between 19 and 25 m and similar ranges from the transducer. At 19 m the 10 deg beam covers a circular area with a 3.3-m diameter; at 25 m the diameter is 4.4 m.

As the observed fish were probably more or less stationary at the site of the aquaculture plant, the observed swimming speeds were very low. The "fastest" fish was the first one tracked, while the slowest was the fourth. The first fish swam a distance of 4.5 m, while the fourth moved only 1.5 m during the tracking period of 45 s.

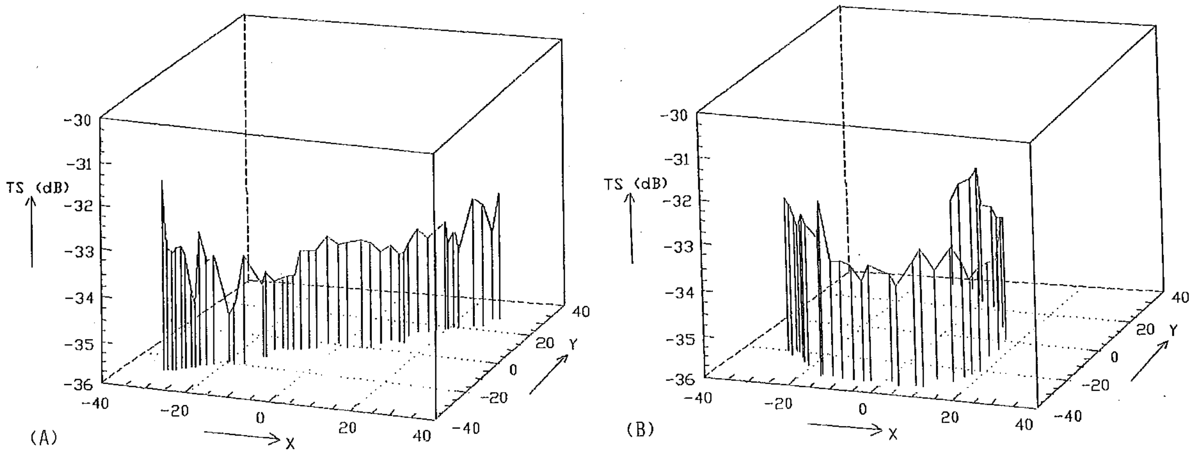

Figure 5. Different tracks of the sphere through the beam of the transducer used during the fish-tracking experiment. Compensated values are shown on the z-axis as target strength. The most accurate compensation with the established function seems to be within the −3 dB angle, one-way, corresponding to an angle of ±28 steps in both directions. (A) Track of sphere moved through beam of fixed transducer, (B) uncontrolled rotation of the transducer with fixed sphere.

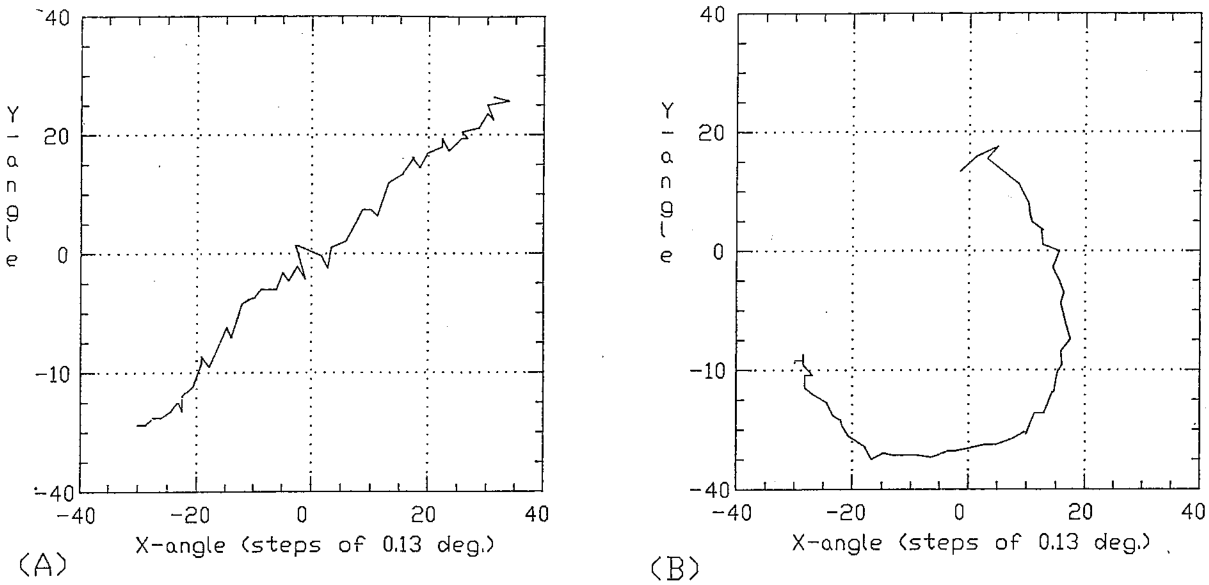

Figure 6. Two different tracks of the sphere through the beam of the transducer used for fish tracking. Angular resolution in steps of 0.13 degrees. See Figure 5.

Discussion

The presented material shows that fish can be tracked through the ±5 degree beam of the ES400 transducer with high precision. If the offset in sound-beam axis and ES400 angular axis is compensated, the accuracy of the tracking relative to the sound-beam axis is equal to the angular resolution.

For accurate TS measurements as a function of target position in the beam, the beam pattern of the installed transducer should be measured by means of a reference target. A special PROM compensating for this beam pattern could then be produced, or the actual, measured pattern could be used for post-processing of data.

Five of the six fish tracks show great variations in target strength as the fish move through the sound beam. Fish number four, however, has a remarkably constant TS of approximately −32 dB at its various beam positions (Fig. 10). Although this fish did not pass through the whole beam, it is evident that its reflected sound is more omnidirectional than the sound reflected from the other five fish. Earlier work on fish directivity (Nakken and Olsen, 1977), shows large cod being almost omnidirectional over a limited range of angles in the dorsal plane. The more directional fishes, where a range of target strengths of more than 20 dB is observed, were probably saithe (*Pollachius virens*). The effect of the long and slender swimbladder of this species on fish directivity was recognized by Midttun and Hoff (1962).

From the positional data, two kinds of variation in angle can be observed. For target spheres, a fairly low ping-to-ping variation is evident. This is connected with the step-size in angle determination. For fish data, however, a cyclic, sinusoidal variation is superimposed on the random angular variation. This seems to be related to the tail-beat frequency of the fish, or to the transverse movement of the fish imposed by fin strokes. If this is the case, further FFT analysis of angular data may isolate this frequency.

Future development of programs for tracking fish by means of the presented method, together with better methods for the presentation of data, will surely tell us more about the reflecting properties of fish. The possibility of finding the speed and direction of fish migration is also obvious. This, in turn, may lead to more accurate fish-stock estimates by means of the acoustic method.

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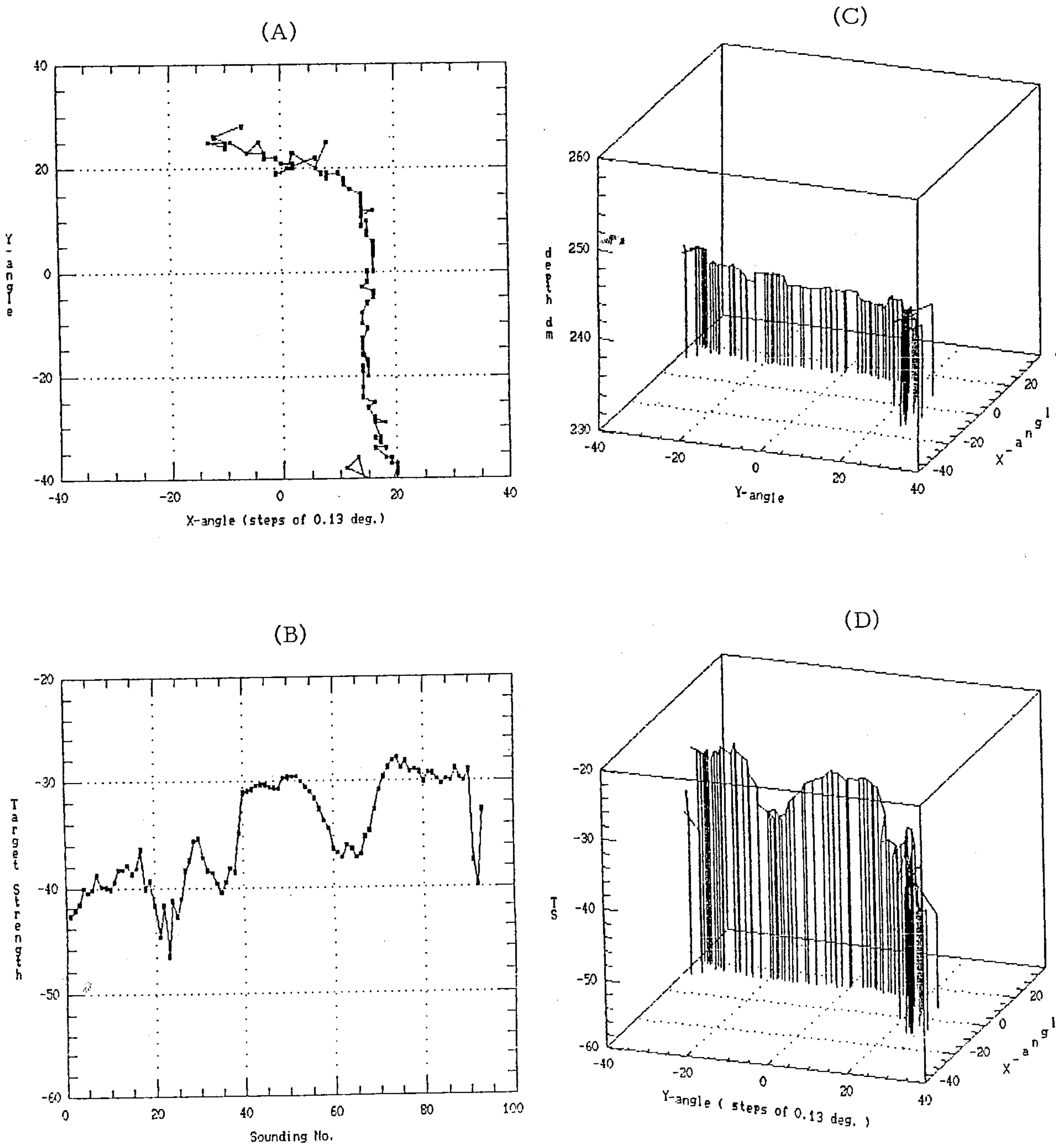

Figure 7. Tracking of fish no. 1 through the beam: (A) position of fish horizontally, (B) target strength or directivity pattern of the fish as a function of sounding number, (C) depth of fish as a function of position, and (D) target strength of fish as a function of position.

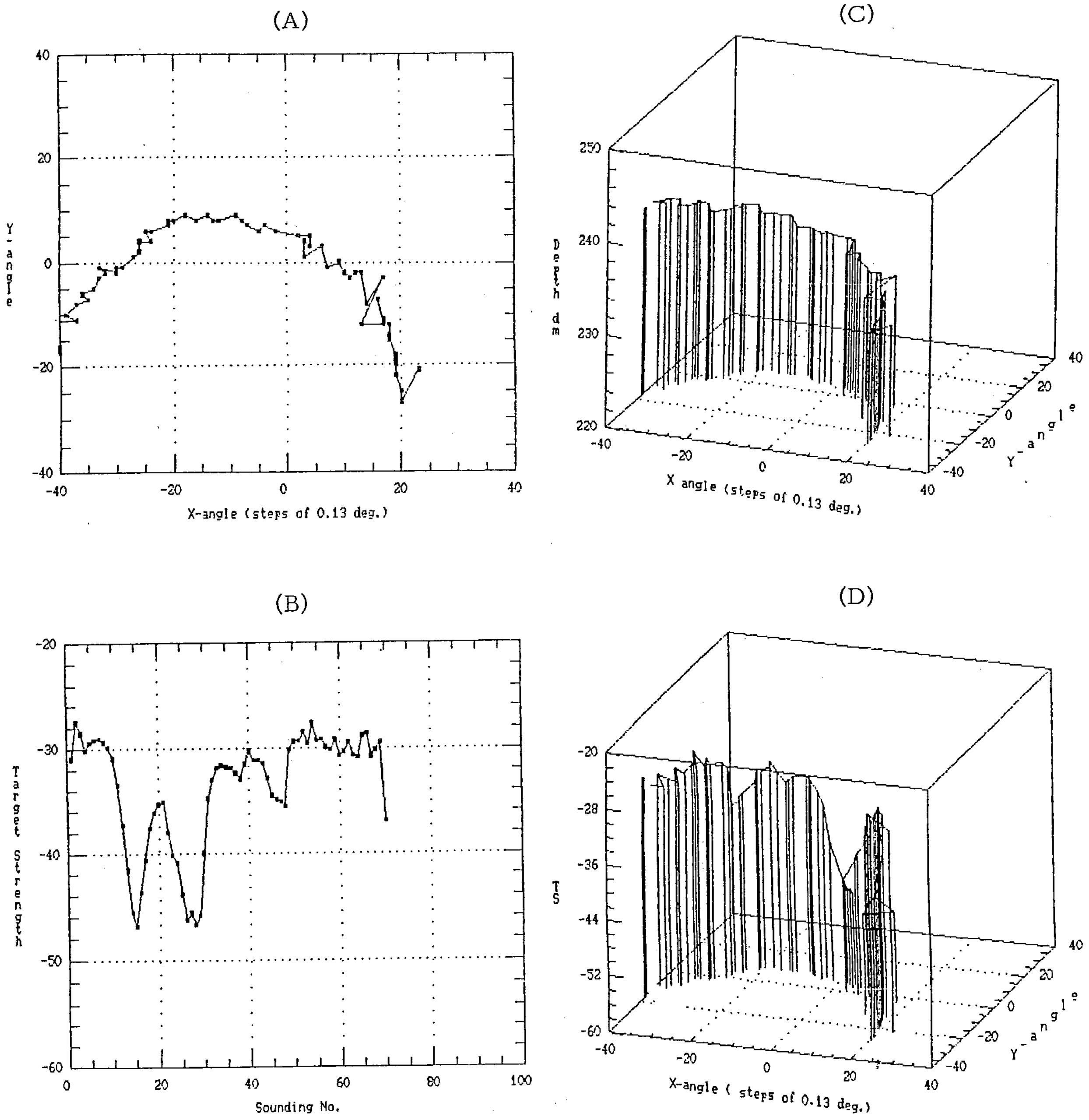

Figure 8. Tracking of fish no. 2 through the beam: (A) position of fish horizontally, (B) target strength or directivity pattern of the fish as a function of sounding number, (C) depth of fish as a function of position, and (D) target strength of fish as a function of position.

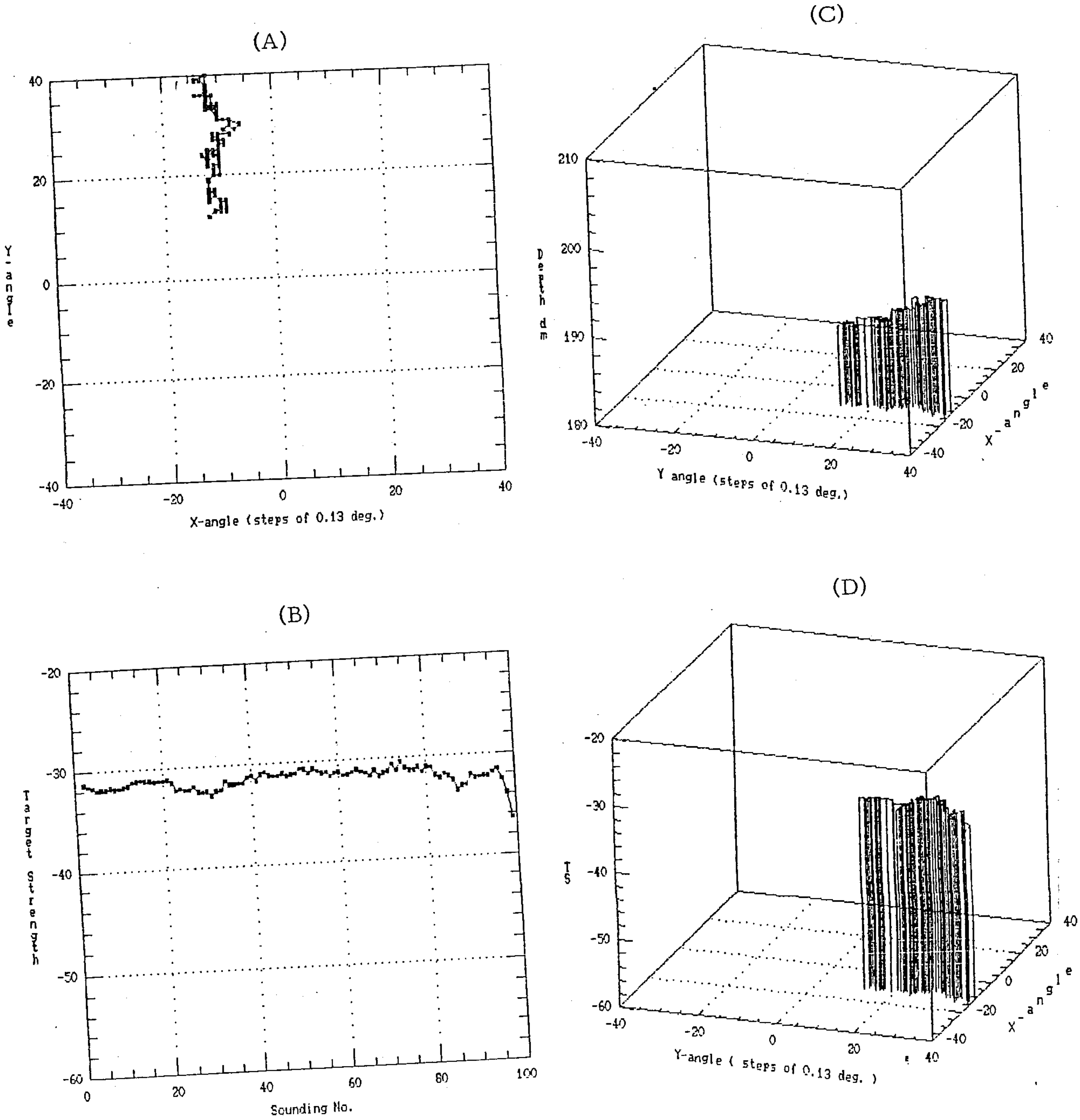

Figure 9. Tracking of fish no. 4 through the beam: (A) position of fish horizontally, (B) target strength or directivity pattern of the fish as a function of sounding number, (C) depth of fish as a function of position, and (D) target strength of fish as a function of position.

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