Fol. 41 B

"This paper not to be cited without prior reference to the author"

International Council for the
Exploration of the Sea

C.M. 1984/B:21
Fish Capture Committee

TRIAL OF A NEW, SPLIT-BEAM ECHO SOUNDER

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ABSTRACT

The first at-sea trial of a new, split-beam echo sounder, the SIMRAD ES380 system, is described following a review of the split-beam principle, outline of its realization in hardware and software, and description of adaptation of the commercial model for research purposes. Actual uses of the system during a cruise about Lofoten in March 1984 are described. These include direct *in situ* measurement of single-fish target strengths for several species, and investigation of avoidance reactions of fish under observation. Some planned features of the system are listed.

RESUME: ESSAIS D'UN NOUVEAU SONDEUR À FAISCEAU SCINDÉ

Les premiers essais d'un nouveau sondeur à faisceau scindé, SIMRAD ES380, sont décrits dans cette note. Après un rappel des principes du faisceau scindé, sont exposées les grandes lignes du système en ce qui concerne le hard et le soft ware et l'adaptation du modèle commercial pour la recherche. Le système actuel a été essayé au cours d'une campagne autour des Lofoten en mars 84. Des mesures directes in-situ d'index de réflexion des poissons de différentes espèces y ont été effectuées ainsi que des observations sur les réactions d'évitement des poissons. On donne la liste des caractéristiques prévues pour la première version du système adaptée pour la recherche.

INTRODUCTION

Development of a split-beam echo sounder has been long-awaited by the Institute of Marine Research. With the introduction of the SIMRAD ES380 split-beam echo sounder, such an instrument is now available. Although developed specifically for use by fishermen, to indicate both abundance and sizes of fish, the instrument also has enormous potential as a research tool.

It is the present aim to introduce the new echo sounder to the scientific community. In order to show its need and likely, immediate applications in fisheries research, the well-reviewed subject of fish target strength measurement (Ehrenberg 1983, Midttun 1984) is reviewed again, in brief. The underlying principle of the echo sounder is described. Its realization in hardware and software is outlined, as is adaptation of the commercial model for trial use on a research cruise. Numbers of collected data and some of the kinds of studies conducted during the cruise are summarized. Experience with the echo sounder and planned additional features of its research version are discussed.

BRIEF REVIEW OF FISH TARGET STRENGTH MEASUREMENT

The echo integration method of assessing fish abundance is known to depend critically on the backscattering cross section or target strength of observed fish. Midttun (1984), in his 1982 review of fish target strength, described a range of methods which have been used to determine the elusive quantity. These have included theoretical computations, controlled measurements on immobilized, tethered fish and on encaged, swimming fish, and a variety of in situ measurement techniques. This last group has been further subdivided and extended by Ehrenberg (1983), who categorizes the methods as being indirect or direct.

Indirect in situ methods remove the influence of transducer beam pattern on the observations by purely numerical means. Resultant solutions are often unstable, however, for they are by their nature extremely sensitive to noise and sample size, including ordinary statistical fluctuations in numbers of resolved single-fish echoes along the survey track. A prominent exception to this comment is due to Lindem (1983), who has applied the method of Craig and Forbes (1969) successfully in freshwater surveys, undoubtedly under very fine conditions, which are often denied the marine scientist.

Direct in situ methods determine fish target strength by removing the beam pattern effect through a combination of physical and electronic means for each individually resolved echo. The first of the methods, that of dual beams (Ehrenberg 1974), involves transmitting in a broad beam, and receiving the echo on two coaxial beams of different but precisely known widths and other directional characteristics. By comparing the echo strengths on the two receivers, the beam pattern at the detection angle can be found, hence removed directly from the echo.

The second in situ method, that of split beams, whose realization in an echo sounder is the subject of this paper, requires separation of the transducer under reception into at least three segments. For present purposes, it is conveniently divided into four quadrants. Half beams are formed in each of the two planes, allowing measurement of phase differences, hence of the direction of the echo source. Removal of the beam pattern is then immediate.

A particular advantage of the method of split beams over that of dual beams is precise localization of scatterers in the beam. Reactions of fish to the passage of the acoustic surveying vessel (Olsen 1979) can then be determined by mapping individual fish tracks through the echo sounder beam. Other advantages of the split-beam method are its superior performance in a noisy environment and in the presence of interfering targets (Ehrenberg 1979).

Clearly, to win the named advantages as a research tool, and also to serve fishermen by indicating both quantities and sizes of aggregating fish in a practical device, the split-beam echo sounder must be able to manipulate four receive signals and perform a number of operations in real time. This is fait accompli in the Simrad ES380 echo sounder.

SPLIT-BEAM PRINCIPLE

The split-beam principle has a long history of application in direction-finding both in radio and in sonar. Some of its history over the last 40 years is illustrated through U.S. patents numbered 2524180, 2666192, 2702379, 2943297, 2982941, 3290646, 3618013, 3729703, 3732535, and 4119942.

Despite a diversity in application, the underlying physics is the same. Radiation emanating from a body by direct emission or scattering is received by at least three non-collinear elements, the time or phase difference is sensed in at least two non-parallel planes, and the source direction is determined by considerations of geometry.

Figure 1 illustrates direction-finding in a single plane for a distant point source and receiver consisting of two point-elements separated by the distance d, which is assumed for convenience to be less than the acoustic wavelength. As the wave passes over the elements, the time difference T between passings of the same wave feature, e.g., trough or crest, is measured. The source direction ϕ is then given by the equation

$$\phi = \begin{cases} \sin^{-1}(cT/d) \\ \pi - \sin^{-1}(cT/d) \end{cases} , \qquad (1)$$

where c is the propagation speed in the medium. Thus each of two source directions can produce the same positive time difference T in the present idealized case. In practice, one of the directions would often be

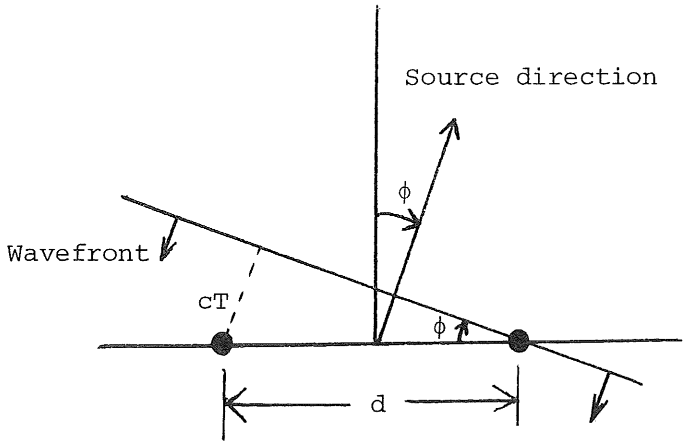

Fig. 1. Direction-finding in a plane with an idealized two-point receiver.

excluded because of the presence of physical boundaries or other obstacles, e.g., baffles on the underside of the finite-size receiving elements.

If the present model of a two-element receiver were to be used as a direction finder in three dimensions, then the source direction could only be specified as a cone of vertex angle $\pi - 2\sin^{-1}(cT/d)$. It is not hard to imagine that with the addition of a second pair of receiving elements, oriented at a non-zero angle with respect to the first pair, the precise source direction can be found. Knowing the source direction, compensation for the directivity factor or beam pattern loss can be applied, thus removing the influence of directional reception on the incident pressure field.

HARDWARE

The hardware, exclusive of the transducer and its mechanical couplings, is contained in two cabinets, which fulfill the display/control and transceiver functions. The display/control cabinet contains the raster scan color display and the joystick control. The transceiver cabinet contains a power supply unit and the five printed circuit boards that constitute the actual echo sounder electronics. These boards include the transmitter, receiver, interfacing, computer, and display controller.

The heart of the ES380 echo sounder is the transducer. This is represented in side view in Fig. 2 to illustrate the sensing of phase differences by elements of finite size, and the performance of the measurement in the electrical domain.

The actual transducer is divided into four quadrants, denoted by their fore and aft and port and starboard locations referred to the ship, as shown in Fig. 3. In the transmission mode, the four quadrant elements are excited simultaneously by high-voltage pulses of identical amplitude and phase. These are delivered by the transmitter, which is a bridge-type circuit driving separate transmit/receive transformers in a series

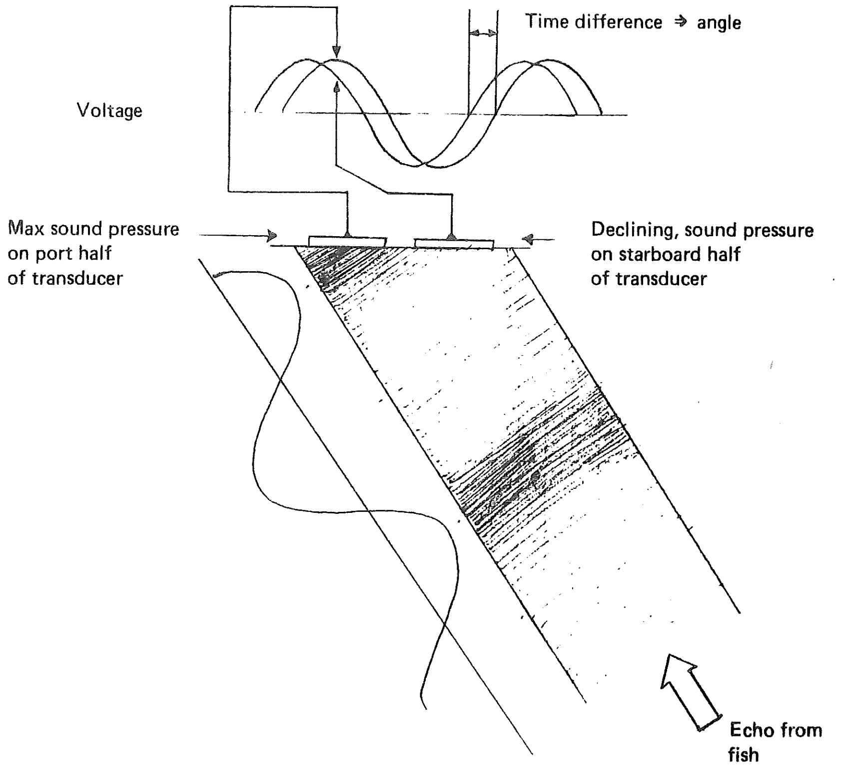

Fig. 2. Split-beam principle in the ES380 echo sounder.

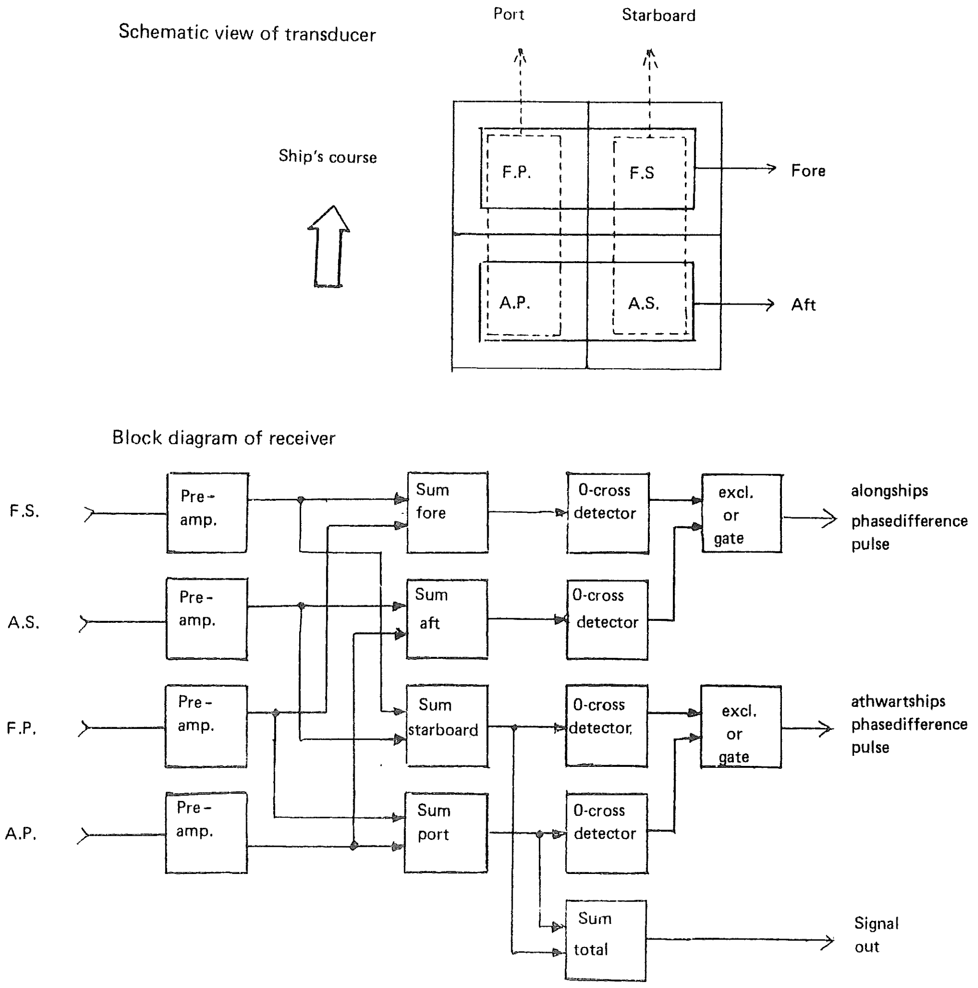

Fig. 3. Quadrant-beam summation in the ES380 receiver.

connection, with back-to-back separator diodes to isolate each output transformer when in the receive mode.

During reception, each quadrant signal is separately amplified according to the same time-varied-gain (TVG) function, with 79 dB at expiration. The TVG consists in continual upward adjustments of a -40 to 0 dB attenuator in steps of 0.375 dB, followed by switching to a 40 dB gain and repetition of the stepwise adjustment. Depths from 9 to 500 m are thus compensated with "40 log r" TVG with ±0.2 dB accuracy. To cover depths from 500 to 750 m, an additional 12 dB TVG sequence is applied, with compensation in the dc gain.

After TVG regulation, the two starboard channels, the two port channels, the two fore channels, and the two aft channels are summed separately, thus forming four half beams. A zero-crossing detector is applied to each half-beam signal, producing a pulse chain bearing the phase information. The fore and aft half-beam signals are then gated, as are the port and starboard half-beam signals. This results in two pulsed outputs, one containing the fore-aft phase difference, and the other, the port-starboard phase difference, represented by the respective output duty cycle. At the same time, the signals from the port and starboard summing amplifiers are summed, producing a total signal output. The total gain as measured from one quadrant input to the calibrated output is thus 91 dB.

A high-frequency clock signal is gated with each of the pulsed phase difference signals, as indicated in Fig. 4. By means of counters, two six-bit words are generated, one word for the fore-aft angle and the other for the athwartships angle. These encompass the range in spatial angles from 0 deg, on the acoustic axis, to 4.94 deg, where the combined transmit and receive beam pattern loss is 12 dB. Division of the angle range is accomplished in equal increments, with an angular resolution of 0.13 deg. Angle values from 0 to 37 are thus valid for compensation.

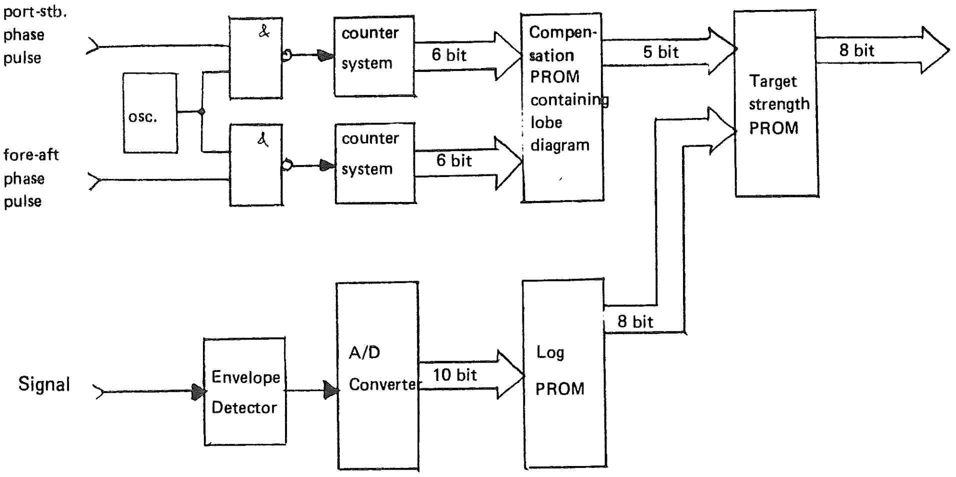

Fig. 4. Detail from the ES380 interface board.

The two words are used as the address in a programmable read-only memory (PROM) where beam pattern information is stored. Upon receipt of the address, the PROM retrieves the desired compensation value for angle values less than 38. The compensation value and the logarithm of the detected and digitized total signal output form a set of addresses for a target strength (TS) PROM. This provides the sought TS value, in coded form, for further manipulation by software. For angle values greater than or equal to 38 the compensation PROM provides a value which, when used in addressing the TS PROM, generates a null output signal.

For reference, the data rate is a constant one sample per decimeter, and the shortest pulse length in water is 0.35 m.

SOFTWARE

The computer in the ES380 echo sounder runs a program for monitoring the hardware and the operator system, cf. Fig. 5. The program uses the input/output system to trigger the transmitter, and to read target strength data at each decimeter until a proper stop condition is detected. The data, stored in memory, are processed and presented on a display before the next ping is initiated. Interleaved with the collection and refinement processes are the operator handling and other background processes.

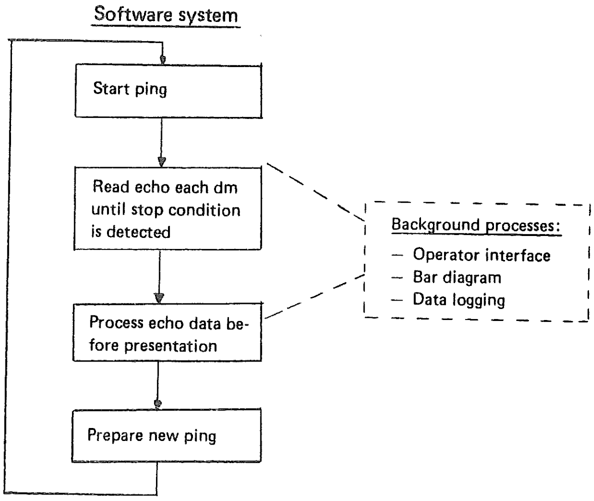

Fig. 5. Schematic diagram of the ES380 software system.

Operator interface

The joystick and display are the hardware elements for the operator interface. Together with a command-driven menu, the system is designed to be as operator-friendly as possible. The joystick has four control positions: center or neutral, up, down, and side or enter. Echo sounder settings may be readily changed by means of the joystick. Striking the enter position puts the main command menu on the left part of the screen, and shows the active menu line or cursor in inverted video. The cursor may be moved up and down using the joystick until the desired menu line is reached. Entering this parameter setting results in replacement of the command menu by a sub-menu. This enables the operator to change the parameter by moving the cursor to the desired position, and entering this by the joystick. The menu is now erased, ending the parameter-change procedure. The operator system is now ready for a new parameter change using the joystick/cursor system. All parameters are stored in backup memory and are not destroyed by power off.

The parameters in the command menu are as follows: Screen format: range, phase, screen speed, and bottom expansion; Echo presentation: presentation mode, pulse duration, gain, echo threshold, color set, and color threshold; Modes settings: layer limits, minimum depth, and depth marker; and Others: language, external recorder, standard settings, and data logging. These commands are described in detail in the ES380 User Manual.

Echo refinement process

This process involves reading a digital value for target strength every decimeter. The program puts the value into an array in memory until a legal stop condition is detected. The compensation mode is active from three-meters range to the bottom.

The array with echo samples is converted into a 500-pixel color array. If the range exceeds 50 m, multiple echo samples will occupy the same pixel. In this case, the maximum echo sample value determines the pixel color. The color scale consists of ten colors in 3 dB steps, spanning the absolute target strength range from -50 to -20 dB. Ranges of less than 50 m or use of the bottom expansion mode extends one-decimeter echo samples to multiple pixels with the same color.

After initial establishment of the pixel color array, another program identifies single-fish echoes as those fulfilling the criterion that echo lengths lie between 80 and 180% of the transmit pulse duration. In the compensation mode, the pixel color of any one selected echo is determined from the largest mean of each pair of adjacent amplitudes within the echo length. Before presentation of the pixel array on the screen, layer markers are added to the array as simple white pixels at the specified depths.

Sizing

In the compensation mode, the operator may select the bottom channel, with maximum thickness of 20 m, or define a pelagic layer for forming the size distribution. Each single-fish target strength value is entered into a 20-element array spanning the range from -50 to -20 dB in equal 1.5 dB steps. After the single-fish echoes from 100 successive pings are sorted, this array is combined with the sorted TS values from the four immediately preceding 100-ping sequences. The combined data are then deconvolved with a representative single-fish TS distribution. The resultant distribution of maximum single-fish target strengths TS_{max} is converted to relative biomass by means of the equations

$$TS_{max} = 20 \log \ell - 62 \quad , \qquad (2)$$

where ℓ is the fish length in centimeters, and

$$w = C\ell^3 \quad , \tag{3}$$

where w is the fish weight, and the condition factor C is assumed constant.

The percentage biomass distribution is displayed against fish length by means of a bar diagram positioned in the lower left-hand corner of the screen. The bars are color-coded in accordance with the underlying target strength class. Updating occurs automatically with each new 100-ping sequence.

ADAPTATION OF THE COMMERCIAL MODEL

The ES380 split-beam echo sounder is entirely self-contained. The operator may specify a number of parameters, as with other modern echo sounders, e.g., SIMRAD EK400 echo sounder, but the output format is confined to the color-screen display of echoes and regularly updated histogram presentation of relative biomass as a function of fish length. Thus, in order to begin exploiting the research potential of the tool, certain modifications were necessary.

For the first trial of the ES380, the modifications were effected entirely through the software. In particular, available microprocessor memory was configured as a special buffer to store the ping number, depth, and target strength of each resolved single-fish echo lying in the specified depth interval. After each accumulation of 200 such data triplets, the data were transferred over an RS232 serial line to an on-board NORD computer. With initiation of the transfer, various log information was attached to the 200-echo data set by the NORD computer, which stored all data directly on floppy disk. The log or heading information consisted of the date, time, longitude, latitude, ship's log and speed, and data set number.

New single-fish echoes resolved during the data transfer were processed and displayed as usual on the ES380 color screen, but were not stored in the buffer. Following completion of each data transfer, storage of single-fish echoes in the buffer was resumed.

DATA COLLECTION

Data were collected during a cruise of R/V G. O. SARS about Lofoten in March 1984. These were generally collected during trawling to ensure maximal knowledge of fish species and size distribution. The single exception was that of observation of spawning cod in an area of active fishing, where trawling would have interferred with fishermen's stationary gear. Biological data were derived in this case from measurements on fishermen's catches from the same area.

Numbers of resolved single-fish echoes, whose basic characteristics were stored on floppy disk, as mentioned, are presented in Table 1.

Table 1. Numbers of single-fish echoes resolved by the ES380 echo sounder and stored in permanent memory.

Data series	Day (March)	Collection time (minutes)	No. data sets	No. data	Depth range (m)
1	12	81	52	10400	100 - 235
2	13	23	17	3400	90 - 125
3	13	78	43	8600	160 - 220
4	14	44	32	6400	190 - 230
5	14	53	4	800	100 - 175
7	15	48	27	5400	65 - 160
8	15	47	39	7800	260 - 375
9	16	45	17	3400	200 - 240
10	17	31	22	4400	240 - 275
11	18	326	151	30200	80 - 155
12	20	54	50	10000	200 - 290

Data series 6 is omitted from the table as this was used for calibration data. The calibration showed, incidentally, the expected on-axis value, but under-compensation by about 1.5 dB at the edge of the beam, nearly 5 deg from the axis. Because the beam pattern was measured along just a single cut from the axis, the values in the compensation PROM were not changed. The correctness of this decision was proved by extensive measurement on a subsequent cruise, which revealed no discrepancy in the original compensation.

DATA ANALYSES

The fundamental quantities for analysis outside of the ES380 consisted of multiple sets of 200-echo data triplets. These were collected sequentially, although with generally rather short gaps between sets due to the method of data transfer. Each data triplet consisted of the ping number, depth to nearest decimeter, and target strength between -50 and -20 dB with 0.375 dB resolution.

Primary analyses performed on each 200-echo data set may be broadly divided into two groups. In the first, the data are assumed to be completely independent or uncorrelated, while in the second, multiple echoes from the same fish over a number of pings is allowed.

Uncorrelated-data analyses

These analyses were based solely on the depth and target strength of each resolved single-fish echo. The basic analyses consisted in sorting of data by depth and by target strength. The results were displayed in the form of histograms and averaged in situ target strengths. The sorted target strength data were alternatively displayed through histograms of the total backscattering cross section,

$$SBT = 4\pi\ 10^{TS/10}\ n(TS) \quad , \qquad (4)$$

and of the relative biomass,

$$BIO = 10^{3 \cdot TS/20}\ n(TS) \quad , \qquad (5)$$

where n(TS) is the number of observations of a particular target strength value in the resolved 200-echo sequence.

The basic data were also combined in summary fashion for larger data sets, according to time, location, boat's speed, and other parameters of interest. Examples of summary histograms for two complete data series are shown in Fig. 6. Part A shows the data from Series 1, whose trawl haul indicated a predominance of Norway pout (*Gadus esmarki*) with most lengths between 15 and 20 cm, with admixture of saithe (*Pollachius virens*) of lengths from 45 to 70 cm. The dominant fish in part B were large spawning cod (*Gadus morhua*) of lengths from 60 to over 105 cm.

Correlated-data analyses

Circumstances of data collection were often such that the same fish was observed more than once. To exploit the presence of correlations, echo traces were extracted according to an algorithm based on the connectedness of resolved single-fish echoes. In particular, an algorithm was established to select all echoes separated by less than a certain number of pings and occurring within a certain depth excursion of the immediately preceding echo in the trace.

The number of echo traces selected according to the criteria that echoes from the same fish lie in successive pings and be separated from neighboring echoes by no more than 0.4 m is shown for eight data series in Fig. 7. Distributions of echo trace lengths for the other data series are comparable.

The actual target strength values of individual echoes in each trace selected according to the particular criteria were arranged according to maximum target strength. The difference values $TS_{max} - TS$ were then computed for each echo in each trace, relative to the maximum target strength in that trace, and arranged in a histogram. This was used in a deconvolution of the target strength histogram. Comparison with the catch data for the largest fish resulted in the target strength-fish length relation given in Eq. (2). It is particularly noted that the relation pertains for the calibration and beam pattern compensation applicable during the trial.

Other echo trace analyses were performed, for example, of the types in Midttun and Nakken (1971) and Foote (1981), especially with reference to sizing and avoidance reactions. Results are, however, too preliminary to justify their presentation here.

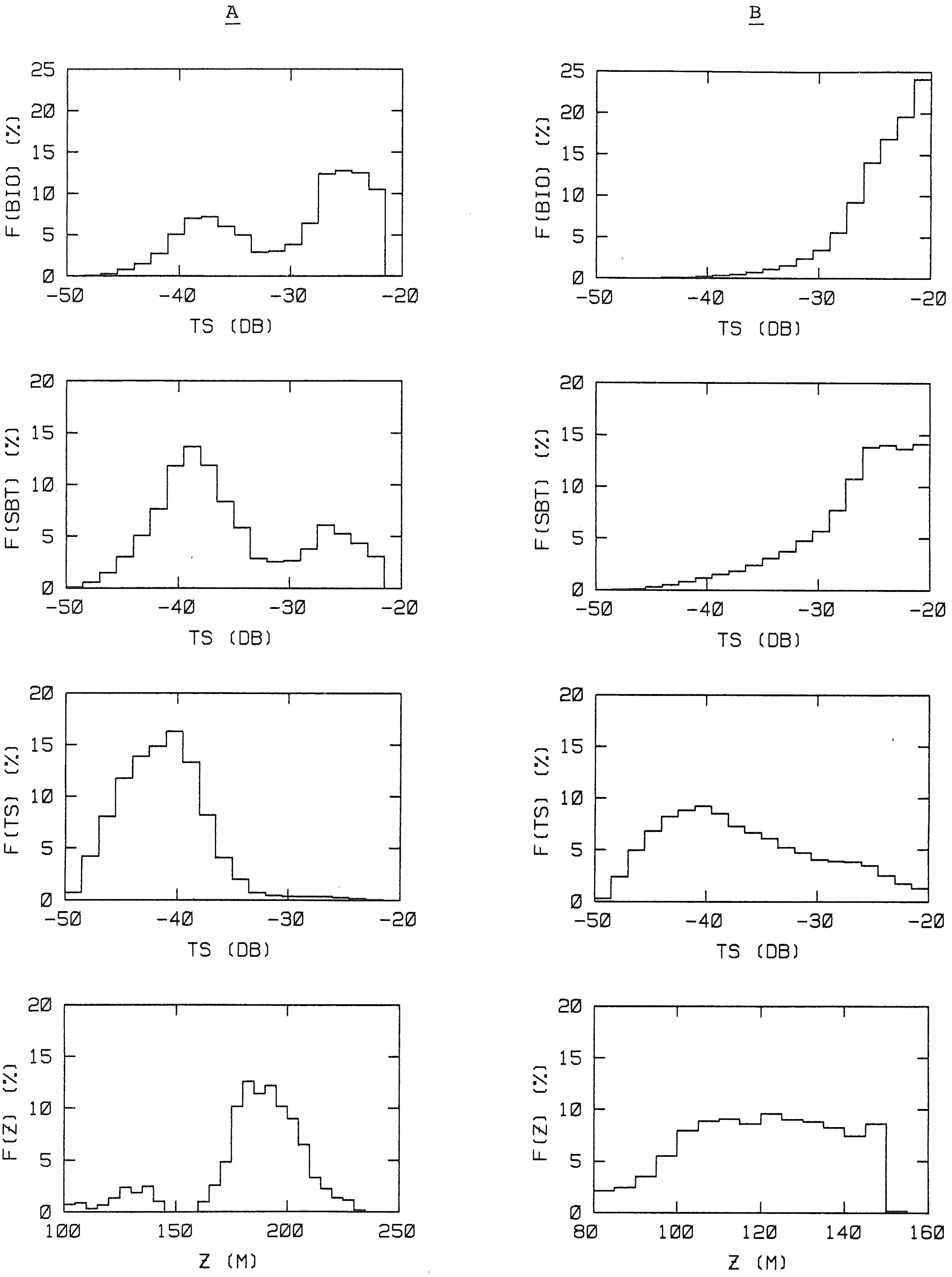

Fig. 6. Two examples of summary analyses of data assumed to be uncorrelated.

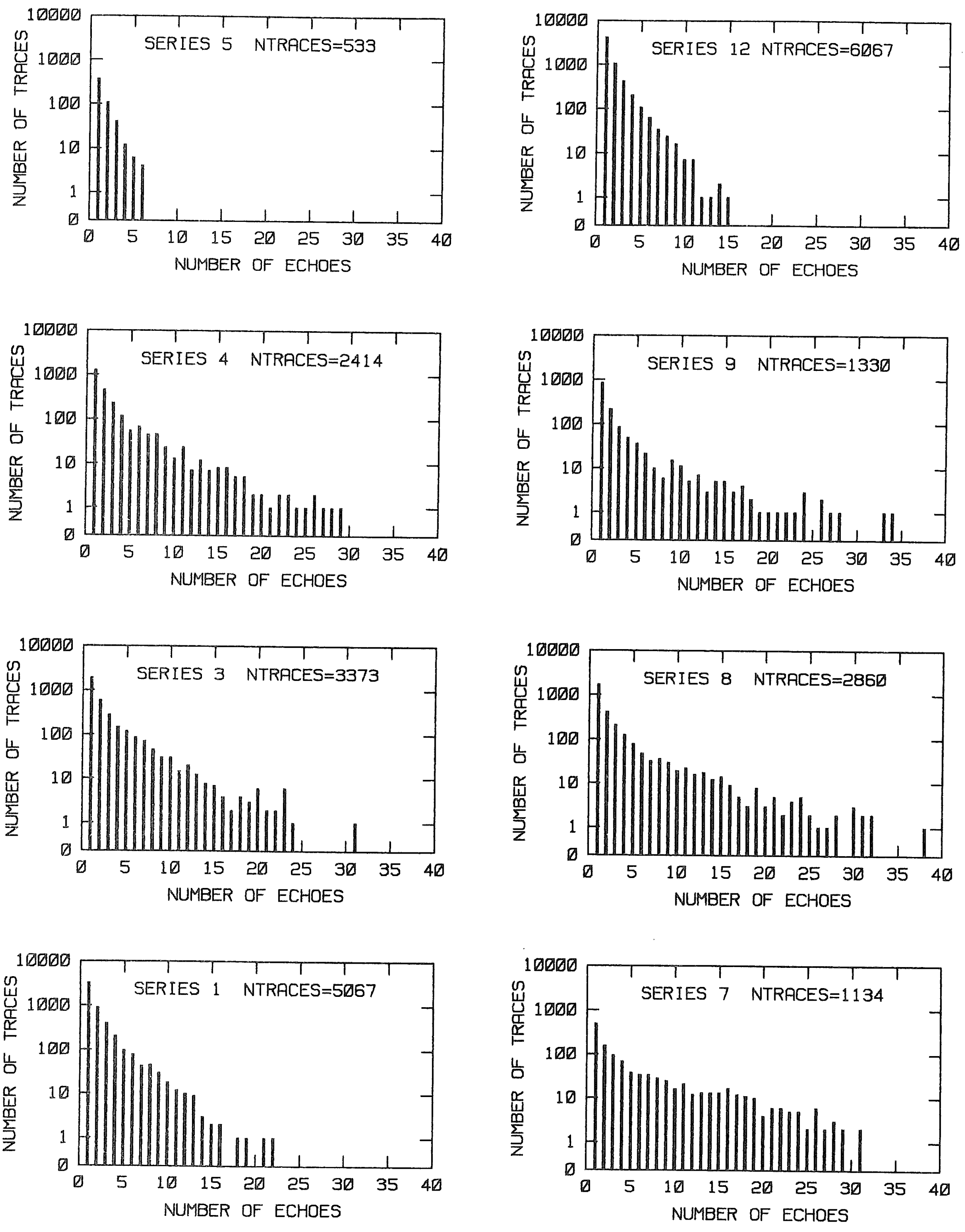

Fig. 7. Number distribution of echo trace lengths for eight data series.

DISCUSSION

What has not yet been described here is the actual performance of the new split-beam echo sounder in its maiden sea trial. In a word, it was flawless. Early suspicions of qualitative sizing by the color-coded echogram presentation alone were confirmed by each accompanying trawl. In particular, the presence of echo traces on the screen containing a broad spectrum of colors, say from the blue-green end, denoting rather weak target strengths, to the red-yellow end, denoting quite strong target strengths, was an invariable indicator of large fish. Similarly, the absence of a rich color spectrum generally indicated the absence of large fish. On those occasions of narrow-banded spectra in echo traces, the blue and green colors dominated, which was confirmed by the absence of large fish in the catch. Thus qualitative sizing was effectively accomplished by observation of the colored echogram.

Supplementary presentation of the automatically updated biomass distribution in the lower left-hand corner of the screen enabled quantitative measures of fish size to be made. As already noted, the target strength-to-length relation needed for this crucial conversion was established empirically during the cruise, with excellent user experiences on subsequent cruises.

Initial adaptation of the commercial model of the ES380 echo sounder was admittedly very limited, providing only ping number, depth, and target strength of each resolved single-fish echo. These data were quite useful, however, forming a sound data base for on-going investigations of *in situ* fish target strength, cf. Table 1 and Fig. 7, especially including avoidance reactions of surveyed fish. The summary histograms in Fig. 6, for example, after deconvolution, correlated well with the corresponding trawl hauls.

Development of the research version of the ES380 is underway. Some planned features include output of the entire digitized sum-beam echo signal and corresponding fore-and-aft and athwartships angles. Availability of the entire signal will facilitate special investigations of the echo integration process, for example, of the assessment of dense fish aggregations. Provision of the detection angles will be of the greatest value in assessing the possible reactions of fish to their surveying, for the tracks of individual fish through the echo sounder beam may be determined, and necessary compensations be applied to mean target strengths used in interpreting echo integrator values. Availability of angle information will also strengthen the echo selection process, especially in the case of rather dense fish aggregations, e.g., those of herring, for which acquisition of *in situ* data is often very difficult because of the phenomenon of schooling.

Another planned feature of the new split-beam echo sounder is its adaptation for simultaneous use with the EK400 echo sounder and integrator. The split-beam transducer may then be used as the primary transducer for both systems, allowing echo integrator values to be interpreted by *in situ* target strength data collected on the very fish in the very circumstances of the survey.

SUMMARY

The commercial model of the SIMRAD ES380 split-beam echo sounder has been used successfully as a research instrument during a cruise of R/V G. O. SARS about Lofoten in March 1984. Both the primary display of the commercial model and other data presentations derived from the *in situ* measurements have been useful in sizing surveyed fish aggregations. Development of the research version of the new echo sounder is underway.

ACKNOWLEDGMENTS

The authors wish to thank H. Bodholt, R. Brede, O. B. Gammelseter, T. Kortner, and O. Langeland, SIMRAD, for their participation in the development of the new echo sounder. They also wish to thank M. Aksland, P. Bangstad, O. Nakken, and I. Svellingen for assistance during the sounder's first sea trial. M. Diner is thanked for translating the abstract.

Sponsorship of the development by the Norwegian Council for Fisheries Research is gratefully acknowledged.

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