ARCHIVES OF ACOUSTICS
18, 1, 83–104 (1993)

ASSESSMENT OF THE PELAGIC FISH RESOURCES IN THE SOUTHERN BLACK SEA USING ECHO INTEGRATION AND DUAL-BEAM PROCESSING

A. STEPNOWSKI*, A. CEMAL GÜCÜ and F. BINGEL

Institute of Marine Sciences, Middle East Technical University,
(33731 Erdemli — Icel, Turkey)

The paper synthesizes the results of two hydroacoustic surveys on the pelagic fish stocks off the southern (Turkish) Black Sea coast, carried out during the winter seasons '89 and '90. The acoustic data acquisition and processing for estimating surveyed fish populations have been performed using real-time data analysis system, employing an echo integration and "in situ" target strength estimation by dual-beam processing. The results of the surveys are presented in the form of fish density and biomass distribution charts, 3D target strength histograms and reports. These findings provide quantitative measures of fish abundance together with their statistical characteristics and distribution patterns of the surveyed pelagic fish populations.

1. Introduction

During the last two decades acoustical methods of fish stock assessment have gained preference over conventional trawl catch methods like the Catch Curve Method (CCM) [5] or other methods of biostatistics, such as Virtual Population Analysis (VPA) [12], [14], and Length based Fish Stock Assessment (LFSA) techniques [12], [14], [22]. Moreover, the acoustical methods are in no danger of being displaced by satellite remote sensing methods, such as the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA series [3] or the Coastal Zone Colour Scanner (CZCS) sensors on NIMBUS [4], to estimate the range of fishery resources, to identify ocean fronts and to study surface circulation patterns — which determine the fate of fish eggs and larvae [17].

The biostatistical methods, despite many advantages, have at least three important limitations, namely: the long time required for acquiring the data and producing the results, the high costs and limited capabilities of automatization. While the satellite remote sensing methods, although possessing such advantages as: rapid large area coverage, long term monitoring and nodisturbance to the medium, they are confined to surface phenomena, are inaccurate, limited in resolution and needing calibration.

The attractions of acoustic methods in fishery research, and particularly in fish stock assessment are many, with the most important being [10], [11]:

*On leave from the Technical University of Gdańsk, Departament of Electronics, 80-952 Gdańsk, Poland

1. They offer a means of acquiring timely and synoptic information about the state of a number of fish stocks with:
— relatively large area coverage,
— relatively high accuracy and reliability,
— rapidity of data collection and data processing,
— flexibility and high degree of automatization.

2. They allow estimation of the abundance of a stock without recourse being made to other sources.

3. They may allow some features of fish biology to be measured which are otherwise less accessible (e.g. orientation distribution of fish under survey).

4. When used together with other environmental sampling techniques, acoustic methods may also contribute to the solution of some basic problems in marine biology (e.g. that of relating fish behaviour, such as aggregation and migration, to hydrography and the occurrence of prey).

Since the late 60's the abundance of exploited and unexploited fish stock has been acoustically estimated mainly by an **echo integration**. The principle which governs the generation of integrator-abundance estimates is that the **energy of echo signal**, scattered by the fishes is **proportional to the density of scatterers** [7], [11], [18]. This assessment technique, due to its versatility, accuracy and reliability has become the routine or standard method [2], [11], [16]. It has also shown promise in establishing indices of fish abundance, especially for the situations, which are difficult for other methods i.e. [10]:
— a temporarily closed fishery, resulting in a lack of catch and effort data,
— when catch and effort data are misreported,
— where is a need of rapid assessment of a widely distributed stock (e.g. for evaluation of the investment criteria)
— for a stock which becomes suddenly available for assessment within a few hours or days (e.g. spawning stock)
— for fish species with a short life span, where series of catch and effort data are hard to obtain for VPA.

The basic prerequisities for an acoustic survey are: a hydroacoustic transducer that is usually mounted in a towed body, an echosounder for acoustic signal transmission and reception of fish echoes, signal processing equipment for real-time (preferable) and post processing of acoustic data, plus some navigational aids (usually Sat. Nav. or Global Positioning System receiver) for vessel navigation and mappings of acquired and processed data. In addition, the hydroacoustic data are frequently "truthed" by fishing trawls and also compared with data from sonars.

The essential stages of an acoustic survey are the following:

1. The acoustically calibrated transducer is towed along the search track (trancsects) over the area of interest.

2. The echo signals acquired from successive transmissions are usually recorded on digital magnetic tape and simultaneously displayed as an echogram.

3. The processing of the echo signals consists of **echo integrating** the whole echo signal from single and multiple fish targets, over selected depth intervals, or in **echo counting** single-fish echoes if resolvable. Additionally, "*in situ*" **target strength estimation** may be performed to convert echo integrator readings into absolute fish den-

sity estimates. In complementary surveying by sonar, fish schools may be counted and mapped.

4. The outputs from the echo integration are classified into the groups of presumed fish species and extraneous scatterers (plankton, jelly fish, etc.).

5. Results of the classification process are expressed as "one-dimensional" fish densities along the transects, in depth strata.

6. These data are extrapolated to the "two-dimensional" density estimates over the entire area of interest and the total abundance or biomass of the surveyed scatterer classes is computed.

2. The material and method

2.1. Acoustic surveys

The primary objectives of the hydroacoustic surveys, carried out on November 1989 and December 1990 on board R/V "Bilim", were to estimate the absolute abundance of anchovy and other pelagic fish species of major commercial interest in the southern Black Sea [1]. The secondary objective was to obtain complementary data on behaviour and the migratory patterns of the surveyed populations, particularly the anchovy stock.

The "zig-zag" track pattern was used in surveying the apparent fish distribution. The transects were confined to water depths exceeding 15 meters, for safety reasons, particularly because of the uncertainty of the bathymetric charts and the presence of small fishing boats and fixed nets in the inshore waters. Offshore the surveys were limited to the 200 meters isobath, i.e. the continental shelf edge. The acoustic surveys were carried out at an average vessel speed of 8 knots, which was a reasonable compromise between the operational requirements and stability of the towed body and the noise level [1]. The sample track pattern from the second cruise is presented in Fig. 1.

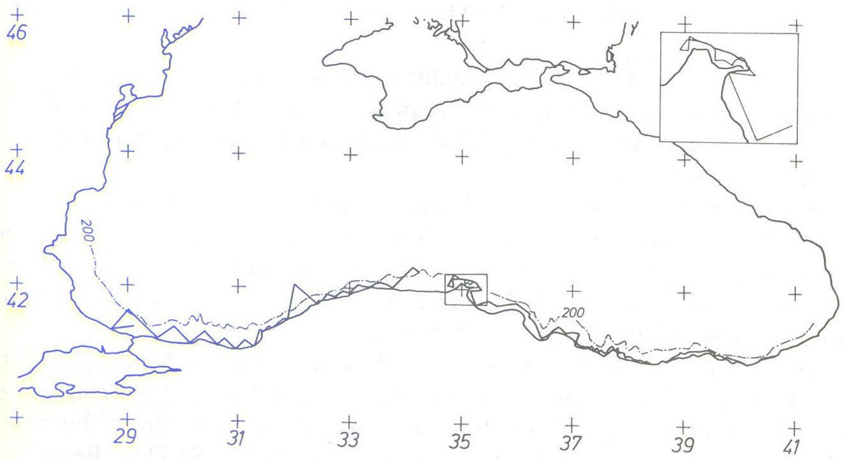

FIG. 1. The sample track pattern of R/V "Bilim", from the second Black Sea acoustic cruise (December 1990).

2.2. *The echo integration/dual-beam processing system*

2.2.1. *System block diagram*

The echo-integration/dual-beam processing system, which was installed on board R/V "Bilim" for surveying the pelagic fish resources over the Southern Black Sea, is capable of **real-time fish density and target strength output from acoustic data**. The entire signal processing in the system is completely configured and controlled by the PC host computer, using Microsoft Windows operational environment, which provide series of menus, windows and data editors for system setup data entry and output [6], [20]. The system consists of the following units [1] — see Fig. 2:

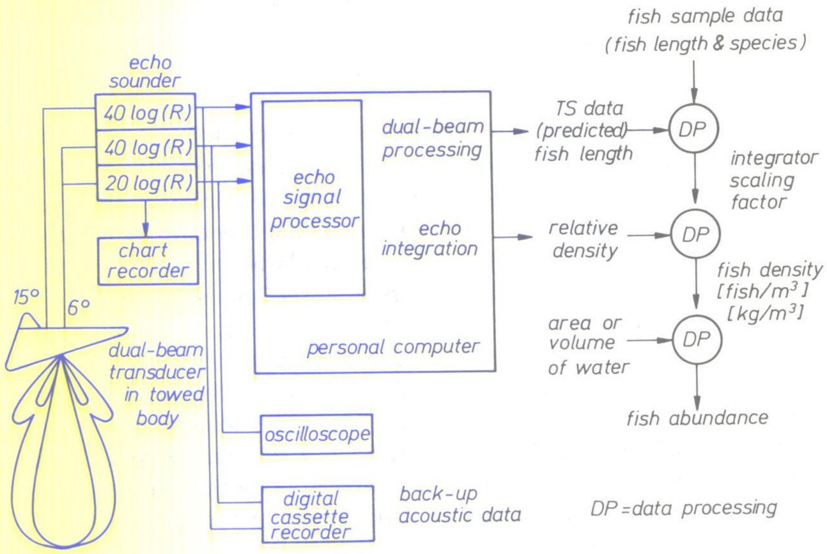

FIG. 2. The Echo-Integration/Dual-Beam Processing System block diagram.

1. The Biosonics Model 102 Echo Sounder configured for a dual-frequency operation and for a dual-beam/single-beam application, providing simultaneous data collection with "$40\log R/20\log R$" Time Varied Gain (TVG) function for target strength estimation and echo integration respectively.

2. Three dual-beam transducers for 200 kHz, 120 kHz and 38 kHz, installed in a towed body (4-foot V-fin). Simultaneous use of 200/120 kHz was found to be the optimum combination for surveying the Black Sea pelagic fish populations, as these frequencies were "low enough" for effective fish detection down to 200 meters, and "high enough" to be less affected by interferences and vessel noise.

3. The Biosonics Echo Signal Processor (ESP) comprising the Model 221 Echo Integrator and Model 281 Dual-Beam Processor [6], [21]. The Model 221 Echo Integrator is a programmable signal processor, which allows estimates to be made of the relative and absolute fish densities, in up to 100 depth layers. The Model 281 Dual-Beam Processor identifies and measures single and multiple target echoes at the echo sounder output, giving "*in situ*" target strentgh estimation [8], [15].

4. A Compaq III host computer for system control.
5. Two Thermal Chart Recorders which produce the echograms using the detected output signal of the echo sounder.
6. Two Sony Digital Audio Tape (DAT) Recorders as the recording/playback system for post-processing the acoustic data ashore.
7. A Satellite Navigation Receiver for mapping the survey data.

2.2.2. System operation

The echo sounder's trigger interval was set at 0.5 s and therefore, due to multiplexing between two frequencies, each transducer transmitted one pulse per second. The detected outputs of the echo sounder were directed to the chart recorders and to the ESP for either real time echo integration or dual-beam processing. A parallel data stream was sent to the DAT recorders. All sounding pulses were transmitted on the narrow beam elements of the transducers. For echo integration, echoes were received on the narrow beam elements only, whereas for dual-beam processing both the narrow and wide beam elements were used to receive the echoes.

Echo integration

The signals received for echo integration were amplified in the echo sounder receiver set at 20log(R) TVG and recorded continuously throughout the survey. The gain-corrected signals were then band-shifted to a 10 kHz intermediate frequency for data recording and display. The detected outputs of the echo sounder, constituting a full-wave rectified, filtered version of the 10 kHz outputs, were squared and transferred to the echo integrator. The integrator averaged echo returns in 2-min intervals — so called Time Between Reports TBR. The integrated outputs were converted to absolute fish densities and recorded [1], [6].

Dual-Beam Processing

While signals amplified for echo integration were recorded continuously, the dual–beam recording system was on stand by until well defined single echoes from individual fish were encountered. When the echograms indicated such dispersed fish configurations in the water column, then dual-beam data processing was initiated. The echoes received on both wide- and narrow-beam transducer elements were amplified at 40log(R) TVG, then band-shifted and envelope-detected. The detected outputs of the related channels of the echo sounder were transferred to the dual-beam processor where they were translated into mean target strength TS and backscattering cross section σ_{bs} estimates [1], [6].

3. Hydroacoustic data logging and processing

The acoustic data acquisition was carried out as shown in Fig. 2, using an echo integration technique. The detected echo sounder output voltages V_e were sampled and squared in depth strata, and then averaged over TBR intervals. By these means, so called "relative densities" RD_i were obtained in real-time at the integrator output, according to the algorithm [1], [21]:

$$RD_i = \frac{\left(\sum_{i=1}^{n} V_e^2\right)_i \cdot MULT_i}{(PP \cdot N_i) - MS_i} \qquad (1)$$

where $(\sum V_e^2)_i$ sum of sampled squared voltages in "i" depth stratum, $MULT_i$ multiplier correcting for non ideal TVG function, PP number of processed pings during TBR, N_i number of samples in range interval "i", MS_i number of missing samples in interval "i" during TBR.

The component parameters of the RD_i are written to files, and stored as echo integration data files for post-processing. Simultaneously, the raw data (echo envelope at the sounder output) were recordered on the digital magnetic tape recorder (DAT) along the ship's track, as a standard data acquisition procedure throughout the cruise.

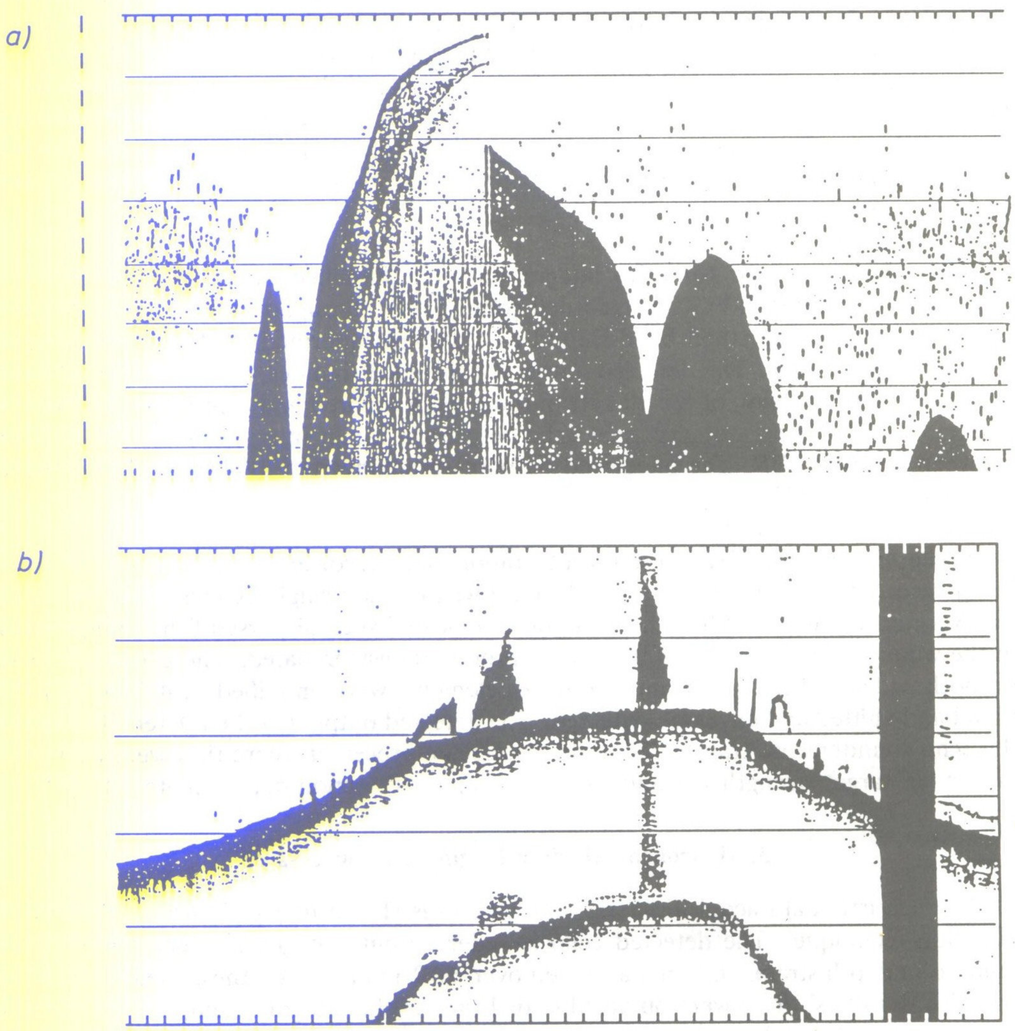

FIG. 3. The echograms of the surveyed pelagic fish populations: (a) Dispersed schools of anchovy mixed with jelly fish, (b) Dense schools of anchovy: corresponding target strength histogram (see Fig. 5)

distribution. Additionally, during the first cruise these two regions were further divided into the thirteen subregions due to some requirements of data processing[1].

Concurrent fishing activities were performed during the acoustic surveys with the standard pelagic trawl, employing 7 mm stretched mesh size. The fish sample data from control trawl catches were used for determining the species composition and length and weight distributions of the surveyed fish populations. The relationship between the weight and length data for anchovy and sprat is shown in Fig. 4, together with their best fit curves. The corresponding fish length histograms are also presented. The length data were in turn converted to the equivalent target strength distribution estimates according to Love's formula [13]:

$$TS = 19.1 \log L - 0.9 \log f - 62, \text{ dB} \tag{2}$$

where L length of fish [cm], f operating frequency [kHz].

The estimates of mean TS and σ_{bs} derived from these data were subsequently used for scaling of the echo integration readings (relative densities RD_i) obtained from the first cruise. This combined method of echo integration scaling was applied due to some difficulties found in extracting the single fish echoes — necessary for the dual-beam "*in situ*" TS estimation. These difficulties were overcome and during the second cruise the acoustic estimates of the surveyed fish target strength — obtained from the Model 281 Dual-Beam Processor — were used for the echo integrator scaling.

4. Acoustic calibration of the system

The acoustic calibration of the system consists of the measurement of the expected target strength from the reference target (calibration sphere), and determining the correction factor of the combined parameter $(SL + SR)$ [9]. The calibration was performed by means of a dual-beam processing of echoes received from the reference target. Two reference standard targets (tungsten spheres), having calibrated target strengths for each of the echosounder operating frequency were used, viz.:

$$TS_{200\text{kHz}} = -39.5\text{dB} \quad \text{and} \quad TS_{120\text{kHz}} = -40.8\text{dB}$$

Having the echo sounder TVG function set to $(40 \log R + 2\alpha R)$, the expected output voltage level VL of the standard target can be expressed as:

$$VL = SL + SR + RG + TS - 2B \tag{3}$$

where SL — Source Level, [dB//1μ Pa], SR — Receiveier Sensitivity, [dB//V/μ Pa ref. 1m], RG — Receiver Gain, [dB], TS — Target strength, [dB], $2B$ — Beam Pattern Factor, [dB] ($B = 0$ for on axis target).

The source level and the receiver sensitivity, which form the combined parameter $(SL + SR)$ are known from the primary tank calibration of the system (221.9 dB and -179.9 dB for 200 kHz). If the receiver gain is also known (or set to 0 dB), if the target is on axis and if the TVG exactly compensates for range dependence of target echo (transmission loss), then the expected voltage level of the standard target can be calculated from equation (3).

[1] Stratification into subregions was done mainly due to limited number (20) of files which can be processed by post processing echo integration routines (ESP CRUNCH program) [21].

Taking the difference between this and the measured level gives the $(SL + SR)$ correction factor required for system's calibration.

The calibration procedure is simplified if the Dual-Beam Processor is used, as this allows direct measurement of target strength of the standard target. The speed of sound c required for the dual-beam processing was calculated using Wilson formula [19]:

$$c = 1445 + 4.66T - 0.055T^2 + 1.3(S - 35) \tag{4}$$

where T temperature [°C], S salinity [‰].

The dual-beam TS measurements performed on 200 kHz gave the measured $TS_m = -40.1$ dB. The difference between the expected and the measured values $\Delta TS = 0.6$ dB becomes the $(SL + SR)$ correction factor. If it is divided equally between both parameters, then the corrected values becomes: $SL = 221.6$ dB, $SR = -179.9$ dB. The sample target strength quasi 3D histogram obtained from the dual-beam TS measurement of standard target is shown in Fig. 5.

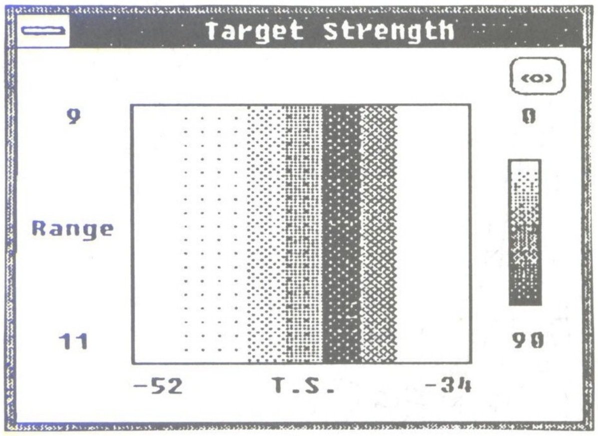

FIG. 5. Quasi 3D Target Strength histogram of standard target (36 mm tungsten carbide sphere) at 200 kHz.

5. Fish target strength estimates

5.1. Target strength estimates from TS-Length regression

The average values of the target strength $\overline{TS}$, the backscattering cross section $\overline{\sigma}_{bs}$ and backscattering cross section per unit weight $\overline{\sigma}_{(1kg)}$, obtained from TS/L regression Love formula applied to the fish sample caught on the first cruise, are presented in Table 1. In addition, the average length $\overline{L}$ and weight $\overline{w}$ of the four major fish species surveyed, are also given.

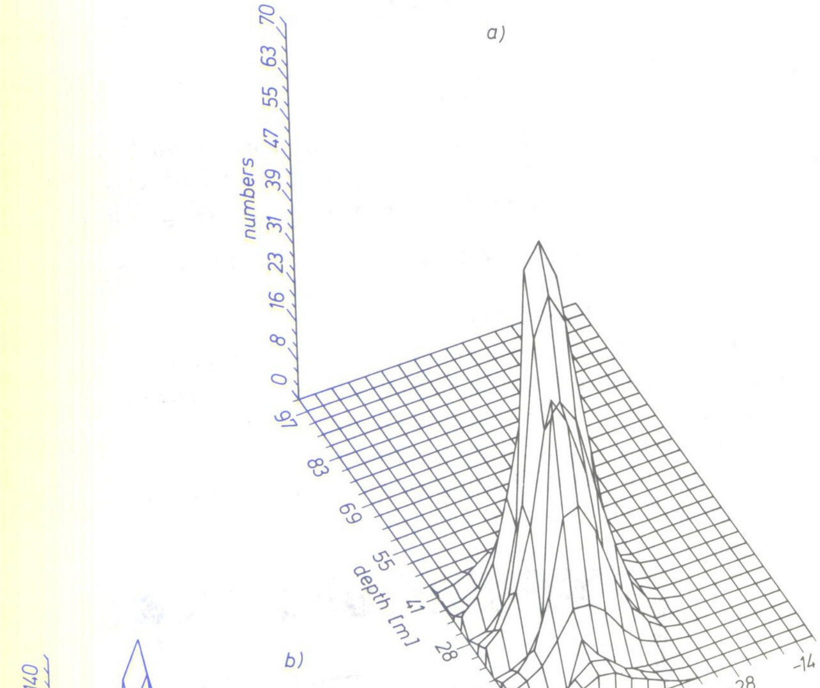

FIG. 6. 3 D Target Strength histograms for anchovy (a) and sprat (b) obtained from a dual-beam processing.

Table 1.

Fish species	Length	Weight	TS	σ_{bs}	$\sigma_{(1kg)}$
	average				
	cm	g	dB	m^2	m^2/kg
Anchovy	8.23	4.93	-46.59	2.19E-5	0.00444
Horse mackerel (west)	9.60	8.91	-45.31	2.94E-5	0.00333
Horse mackerel (east)	13.23	19.67	-42.65	5.43E-5	0.00276
Whiting	10.82	14.74	-44.32	3.70E-5	0.00251
Whiting+Sprat (west)	9.42	6.62	-45.47	2.84E-5	0.00429
Whiting+Sprat (east)	9.86	13.04	-45.09	3.10E-5	0.00237

5.2. Fish target strength estimates from dual-beam processing

The dual-beam processing for target strength estimation was applied in between the echo integration runs — usually simultaneously with the fishing operations. The dispersed populations giving resolvable single fish echoes were selected wherever possible. The examples of 3D target strength histograms of surveyed fish populations, obtained from the ESPTS post-processing program of the dual-beam data are shown in Fig. 6. The average TS and σ_{bs} values for two major species of interest are as follows:

$$\textit{Anchovy}\ TS = -51.2\text{dB}, \quad \sigma_{bs} = 0.19910^{-4},$$

$$\textit{Sprat}\ TS = -52.4\text{dB}, \quad \sigma_{bs} = 0.72610^{-5}.$$

The estimates of the average TS_i and σ_{bsi} in selected 10 depth strata (10 meters intervals) covering the integrated depth layer $\Delta R = (2\text{m}, 102\text{m})$ were calculated by the ESPDB program in each TBR. These data were averaged over the region and stored for further use in the echo integration scaling by the ESPCRUNCH program [21].

6. Results of acoustic estimation of fish density and biomass

The fish abundance estimates were obtained from the echo integration data in depth strata. The echo integrator "relative densities" (RD_i) were converted to the absolute fish density estimates (AD_i) by ESPCRUNCH post processing program, using the integrator scaling factor C, incorporating the system parameters obtained during acoustic calibration and the mean backscattering cross section obtained from the dual-beam processing [16], [21]:

$$AD_i = C \cdot RD_i \qquad (5)$$

where AD the estimate of absolute density of fish, [fish/m^3], RD the estimate of the relative density of fish, [V^2], (integrator output),

$$C = [\pi c \tau p_0^2 s_x^2 \mathrm{E}\{b^2(\theta,\phi)\}\mathrm{E}\{\sigma_{bs}\}]^{-1} \qquad (6)$$

τ = transmit pulse width [s], c = speed of sound [m/s], p_0 = rms transmitted pressure measured at one meter from the transducer on its acoustical axis [µPa], $p_0 = 10^{0.05SL}$, s_x = system through sensitivity (including receiver fixed gain g_s and transducer sensitivity

s_i, $s_x = s_i g_s$) [V/µPa], $\mathsf{E}\{b(\theta,\phi)\} = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{\theta_{\max}} b^2(\theta,\phi)\sin\theta d\theta d\phi$ average beam pattern factor, $\mathsf{E}\{\sigma_{bs}\} \equiv \overline{\sigma}_{bs}$ average backscattering cross section [m^2/fish].

There have been two different methodologies applied for extrapolating the absolute fish densities AD obtained from echo integration along ship's transects, to the total area density or biomass over the regions of interest. For the first cruise only the data acquired over the extent of existing fish concentrations along the transects were integrated, so measured integrator outputs (RD) were extrapolated to the entire region areas. During the second cruise all integrated data from the transects were written to ESP EI files. These allow the full and direct utilization of the ESPCRUNCH program outputs [1], [21].

However, although there have not been any fish echoes on some certain transects, the echo integrator program output some values due to noise, bottom intrusions and interferences from porpoises. Therefore, files from the transects in which no fish echoes were detected (which was determined by comparative analysis of the corresponding echograms), were replaced by artificially produced dummy files. Dummy files contained exactly the same auxiliary parameter as original files, i.e. number of sequences TBR's, processed pings PP's and missing samples MS's, but their integrator outputs RD's were replaced by zeros. The sample ESPCRUNCH program printout for dummy files with zero padded integrator outputs is shown in Table 4. Because of this difference the results are divided into two groups. The first group refers to the November '89 cruise, while the second refers to the December '90 cruise.

6.1. The fish biomass abundance estimates obtained from the first acoustic survey

Table 2 summarizes the acoustical estimation of fish biomass in the Southern Black Sea. It consists of two parts. The upper part gives the partial biomass estimates for four major fish species measured along the transects in all 13 subregions, together with the sums of these estimates over the regions and species and the overall sum — labelled as a Quantity Measured in kilograms. Additionally, it gives the areas of the transects surveyed in each subregion, as well the total areas of the subregions as their sum are also given. In the lower part, the biomass estimates extrapolated for the area of subregions are presented, and the total biomass extrapolated for the entire surveyed area of the Southern Black Sea, labelled as a Total Quantity in tons, is also given. The table was produced as a spread-sheet using the EXCEL 3.0 program.

The partial biomass estimates in subregions (Quantity Measured — q_k) have been calculated from the integrator outputs (RD) measured over the extent of existing fish concentration along transect. The RD values were first converted to the corresponding volume biomass densities (d_k) and then multiplied by the adequate surveyed volumes (V_k), for each stratum i.e.:

$$q_k = d_k V_k = (C\overline{\sigma}_{(1\mathrm{kg})})^{-1} RD_k V_k \qquad (7)$$

where $C_e = C/\overline{\sigma}_{(1\mathrm{kg})}$ sounder constant — see equation (6), $\overline{\sigma}_{(1\mathrm{kg})} = \overline{\sigma}_{bs}/\overline{w}$ mean backscattering cross section per unit weight, $\overline{w}$ average weight of surveyed fish.

These measured biomass estimates have been extrapolated to the entire area of subregion to give the total biomass (Total Quantity — Q) by multiplying by the volume ratio [1]:

Table 2. Acoustic estimates of fish biomass („Quantity") in the southern Black Sea for four major pelagic species — November 1989 cruise echo integration data

Sub-region	Reg. #	H. mack. (kg)	Anchovy (kg)	Whiting (kg)	Whit+Sprat (kg)	All (kg)	Trans. area km^2	Total area km^2
Igne Ada - Ist. Bog.	I	294.5			1555.225	1849.725	0.86561866	4338.452
Istanbul - Kefken	II	1412	14.91			1426.91	0.41808	2345.45
Kefken-Eregli	III	737.1				737.1	0.41141	1590.45
Eregli - Amasra	IV		3.09	430.569		433.659	0.1978	329.8
Amasra - Inebolu	V		141.76		306.4972	448.2572	0.43234	10.47.87
Ineblu - Inceburun	VI	II	94.99			105.99	0.3858	2481.22
Inceburun - Bafra	VII	754.38	26.43	11.8746		792.6846	0.50829	2065.161
Bafra - Civa brn.	VIII	436.4	273.68			710.08	0.559882	1077.77
Civa brn. - Tasun	IX	488.3	61.41	1.973222		551.68322	0.348778	1354.903
Yasun - Tirebolu	X	48.7	154.79			203.49	0.399734	787.87
Tirebolu - Trabzon	XI	66.5	601.41			667.91	0.210789	394.516
Trabzon - Pazar	XII	93.1	282.85			375.95	0.48297	228.515
Pazar - Batumi	XIII	1121	196.27			1317.47	0.487716	305.58
QUANTITY MEASURED (kg)		5463.18	1851.59	444.4168	1861.7222	9620.909	5.70920766	18347.557
Sub region	**Reg #**	**H. mack. (tons)**	**Anchovy (tons)**	**Whiting (tons)**	**Whit+Sprat (tons**	**All (tons)**		
Igne Ada - Ist. Bog.	I	1476.0242	0	0	7794.7361	9270.7603		
Istanbul - Kefken	II	7921.3916	83.645856	0	0	8005.0375		
Kefken - Eregli	III	2849.5192	0	0	0	2849.5192		
Eregli - Amasra	IV	0	5.1520829	717.9052	0	723.05732		
Amasra - Inebolu	V	0	343.58618	0	742.86261	1086.4488		
Ineblu - Inceburun	VI	70.744997	610.91521	0	0	681.66021		
Inceburun - Bafra	VII	3065.0144	107.38398	48.246	0	3220.6444		
Bafra - Civa brn.	VIII	840.06778	526.83261	0	0	1366.9004		
Civa brn. - Yasun	IX	1896.9062	238.56033	7.665404	0	2143.1319		
Yasun - Tirebolu	X	95.987004	305.08888	0	0	401.07588		
Tirebolu - Trabzon	XI	124.46244	1125.6084	0	0	1250.0708		
Trabzon - Pazar	XII	44.04983	133..82916	0	0	177.87899		
Pazar - Batumi	XIII	702.4914	122.97359	0	0	825.46499		
Western Black Sea	I–VI	12317.68	1043.2993	717.9052	8537.5987	22616.483		
Eastern Black Sea	VII–XI	6768-979	2560.2769	55.91141	0	9385.1673		
TOTAL QUANTITY (Tons)		19086.659	3603.5763	773.8166	8537.5987	32001.651		

$$\widehat{Q}_k = q_k \frac{A_{Tk}\overline{R}_{Tk}}{\sum\limits_{t=1}^{m} A_t \overline{R}_{trn}} \qquad (8)$$

where

A_{Tk} total area of subregion "k",

A_t transect area,

R_{Tk} average depth over the total area of subregion "k",

R_{trn} average depth over the sum of transects area.

Assuming that survey pattern was designed so that the difference between the average depth of the entire area under examination and the average depth of the transect area is negligible, equation (8) can be rewritten as follows:

$$Q_k = q_k \frac{A_{Tk}}{\sum_{t=1}^{m} A_t} \tag{9}$$

6.2. The fish biomass abundance estimates obtained from the second acoustic cruise

The results of the second acoustic survey are presented in Fig. 7 and in the Tables 3 and 4. Fig. 7 shows the vertical (depthwise) distribution of the total biomass estimates of pelagic fish populations (without differentiating into species) in the Eastern and Western regions of the Southern Black Sea Coast.

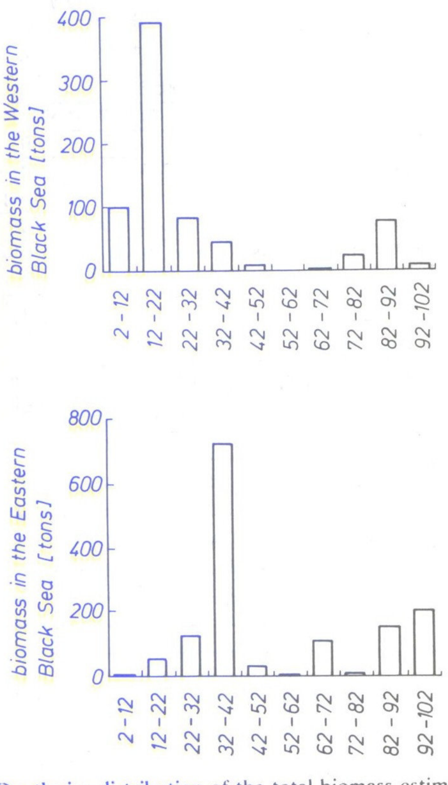

FIG. 7. Depthwise distribution of the total biomass estimates of surveyed pelagic fish populations in the Black Sea.

Table 3 constitutes the report printout from the echo integration post-processing program ESPCRUNCH and summarizes the acoustical estimates of the surveyed fish biomass in the Southern Black Sea. Similarly to the Table 2, it consists of two parts. The upper half presents the data on biomass estimates — labelled as Quantity (in kg) — for the Western Region, and the lower half presents the data from the Eastern Region. Along with the biomass estimates the corresponding estimates of absolute density (AD's) — labelled as Density of Fish (in fish/km^2), are given as well as the Integrator Output (RD's) data. All data were calculated in ten meters depth strata — covering the range interval (2m,102m). The average $\overline{\sigma}_{bs}$ values, calculated by the ESPDB and ESPTS programs for all these depth strata are also included in the table. In addition, the statistics of fish biomass estimates — i.e. Fish Quantity Variance and its Confidence Limits calculated by ESPCRUNCH program are also presented in two last columns of the table. Both parts of the table are complemented by two associated sets of the calibration data for two regions, comprising also the surface area of the regions.

The biomass estimate of surveyed fish populations in each depth stratum (Q_i's), as well as of the total biomass (Q) in the entire water column sampled (ΔR = 100 m), were calculated for both regions from the relative (RD_i's) or absolute density estimates (AD's) according to the formula [1]:

$$\widehat{Q}_i = (C\overline{\sigma}_{i(1\mathrm{kg})})^{-1} RD_i V_i = C_{i(w)} AD_i V_i \tag{10}$$

where

$\overline{\sigma}_{i(1\mathrm{kg})} = \overline{\sigma}_{\mathrm{ibs}}/\overline{w}$ mean backscattering cross section of fish per unit weight in i-th depth stratum,

$\overline{w}$ average weight of fish in i-th depth stratum,

$\overline{\sigma}_{bs(i)}$ mean fish backscattering cross section in i-th stratum,

V_i volume sampled in the i-th depth stratum,

$C_{i(w)} = C_i/\overline{w}$ integrator scaling constant per unit weight

and

$$\widehat{Q} = \sum_{i=1}^{10} \widehat{Q}_i \tag{11}$$

The strata population (biomass) totals ($\widehat{Q}$'s) are the products of two random components $\sigma_{bs(i)}$ or $\sigma_{(1\mathrm{kg})i}$ and RD_i. Therefore, the normalized variance of Q_i is calculated as a sum of the component variances, assuming their statistical independence:

$$\mathrm{Var}\,\widehat{Q}_i = \widehat{Q}_i^2[\mathrm{Var}(\overline{RD}_i)/(\overline{RD}_i^2) + \mathrm{Var}(\overline{\sigma}_{i(1\mathrm{kg})})/(\overline{\sigma}^2_{i(1\mathrm{kg})})] \tag{12}$$

where

Var ($\overline{RD}_i$) is the integrator output variance of the mean,

Var ($\overline{\sigma}_{i(1\mathrm{kg})}$) is the variance of backscattering cross section per unit weight mean.

The confidence limits (CL_i's) of the strata population (biomass) totals Q_i's, at the 95% level of significance were calculated for i-th stratum as follows:

$$CL_i = \widehat{Q}_i \pm 1.96[\mathrm{Var}(\widehat{Q}_i)]^{1/2} \tag{13}$$

Table 3. Echo integration post-processing report printout:

Acoustic estimates of biomass and density of pelagic fish populations in the Southern Black Sea — December 1990 cruise data.

DEPTH STRATUM	STRATUM VOLUME	MEAN SIGMA	# FISH USED	STD DEV SIGMA	A CONSTANT	INTEGRATOR OUTPUT	# OF SEQUENCES	VARIANCE OF INTEG MEAN	DENSITY OF FISH	QUANTITY KILOGRAMS	FISH QUANTITY VARIANCE	CONFIDENCE LIMITS(95%)
2.0– 12.0	1208D+12	.680BE–01	900	.2225E–04	.1048E–02	.8102E–03	↑↑↑↑	.17570–06	.8193E–06	.10262E+06	.2817E+10	.1041E+06
12.0– 22.0	.1197D+12	.6704E–01	3535	.5467E–04	.1064E–02	.3081E–02	↑↑↑↑	.1504 05	.3780E–05	.39371E+06	.2450E+11	.3068E+06
22.0– 37.0	.1148D+12	.6468E–01	13022	.2300E–04	.1103E–02	.6776E–03	↑↑↑↑	.1012D–06	.7478E–06	.86087E+05	.1624E+10	.7900E+05
32.0– 42.0	.1102D+12	.3366E–01	6002	.2272E–04	.2120E–02	.2017E–03	↑↑↑↑	.1307D–08	.4277E–06	.47350E+05	.7178E+08	.1663E+05
42.0– 52.0	1014D+12	1035E+00	765	.2292E–03	.6871E–03	.1711E–03	↑↑↑↑	.3108D–08	.1179E–06	.11953E+05	.1518E+08	.7635E+04
57.0– 62.0	.9224D+11	.8796E–01	1658	.1035E–03	.8113E–03	.4776E–04	↑↑↑↑	.6576D–10	.4053E–07	.37388E+04	.3655E+06	.1185E+04
62.0– 72.0	.8062D+11	.8052E–01	2366	.7648E–04	.8863E–03	.7173E–04	↑↑↑↑	.2346D–07	.6375E–07	.51395E+04	.1198E+07	.2145E+04
72.0– 82.0	.6686D+11	.5056E–01	3310	.3499E–04	.1411E–02	.2666E–03	905.	.8060D–08	.3762E–06	.25155E+05	.2891E+08	.1741E+05
82.0– 92.0	.5495D+11	.4076E–01	2260	.2573E–04	.1751E–02	.8324E–03	778.	.3434D–06	.1457E–05	.80077E+05	.3178E+10	.1105E+06
92.0–102.0	.4470D+11	.3888E–01	837	.1087E–04	1835E-02	.1504E–03	644.	.1377D–08	.2760E–06	.12336E+05	.9269E+07	.5967E+04
	.9070D+12								.76766E+06	+ OR –	.3522E+06	

CALIBRATION DATA

SURFACE AREA IN METERS SQUARED =	.12133E+11
PULSE WIDTH IN MILLISECONDS =	.400
VELOCITY OF SOUND, METERS//SECOND, =	1474.4
SQUARED BEAM PATTERN FACTOR =	.51370E 03
SOURCE LEVEL IN dB =	.2220E+03
RECEIVING SENSITIVITY AT 1 METER, 20LOGR, =	–.15028E+03
RECEIVER GAIN DURING DATA ACQUISITION =	.00

Western Black Sea Region

Table 3. [cont.]

STRATUM	MEAN	# FISH	STD DEV	A	INTEGRATOR	# OF	VARIANCE OF	DENSITY	QUANTITY	FISH QUANTITY	CONFIDENCE
						SEQUENCES	INTEG MEAN	OF FISH	KILOGRAMS	VARIANCE	LIMITS(95%)

Table 3. [cont.]

DEPTH STRATUM	STRATUM VOLUME	MEAN SIGMA	# FISH USED	STD DEV SIGMA	A CONSTANT	INTEGRATOR OUTPUT	# OF SEQUENCES	VARIANCE OF INTEG MEAN	DENSITY OF FISH	QUANTITY KILOGRAMS	FISH QUANTITY VARIANCE	CONFIDENCE LIMITS(95%)
2.0.– 12.0	.6174D+11	.6808E-01	900	.2225E-04	.1048E-02	.1609E-03	↑↑↑↑	.17670-08	.1686E-06	.10417E+05	.7410E+07	.5335E+04
17.0– 77.0	.5938D+11	.6704E-01	3535	.5467E-04	.1064E-02	.8617E-03	↑↑↑↑	.4837D-07	.9167E-06	.54433E+05	.1933E+09	.2725E+05
22.0– 32.0	.5485D+11	.6468E-01	13022	.2300E-04	.1103E-02	.2187E-02	↑↑↑↑	.2147D-06	.2413E-05	.13234E+06	.7870E+09	.5198E+05
32.0– 42.0	.4872D+11	.3366E-01	6002	.2272E-04	.2120E-02	.7081E-02	↑↑↑↑	.2836D-04	.1501E-04	.73134E+06	.3026E+12	.1078E+07
42.0– 57.0	.4143D+11	.1035E+00	765	.2297E-03	.6875E-03	.1186E-02	↑↑↑↑	.5074D-06	.8175E-06	.33868E+05	.4793E+09	.4271E+05
52.0– 62.0	.3339D+11	.8796E-01	1658	.1035E-03	.8113E-03	.4884E-03	↑↑↑↑	.1823D-07	.3962E-06	.13228E+05	.1338E+08	.7168E+04
62.0– 72.0	.2705D+11	.8052E-01	2366	.7618E-04	.7763E-03	.4863E-02	↑↑↑↑	.9642D-05	.4310E-05	11657E+06	.5539E+10	.1457E+06
77.0– 82.0	.1925D+11	.5056E-01	3310	.3499E-04	.1411E-02	.6916E-03	767.	.1007D-06	.9762E-06	.18791E+05	.7433E+08	.1670E+05
82.0– 92.0	.1407D+11	.4076E-01	2260	.2573E-04	.1751E-02	.6411E-02	601.	.3091D-04	.1129E-04	.15797E+06	.1876E+11	.2684E+06
92.0–102.0	.9555D+10	.3888E-01	837	.1087E-04	.1835E-02	.1203E-01	432.	.1179D-03	.2209E-04	.21104E+06	.3628E+11	.3733E+06
	.3674D+12								.14799E+07	+ OR –	.1184E+07	

CALIBRATION DATA

SURFACE AREA IN METERS SQUARED =	.67143E+10
PULSE WIDTH IN MILLISECONDS =	.400
VELOCITY OF SOUND, METERS//SECOND, =	1474.4
SQUARED BEAM PATTERN FACTOR =	.51370E-03
SOURCE LEVEL IN DB =	.2220E+03
RECEIVING SENSITIVITY AT 1 METER, 20LOGR. =	–.15028E+03
RECEIVER GAIN DURING DATA ACQUISITION =	.00

Eastern Black Sea Region

Table 4. Echo integration post-processing report printout for dummy files.

DATA FOR PRIMARY STRATA, MULTIPLEX CHANNEL 1

DEPTH STRATUM	STRATUM VOLUME	MEAN SIGMA	# FISH USED	STD DEV SIGMA	A CONSTANT	INTEGRATOR OUTPUT	NUMBER OF SEQUENCES	VARIANCE OF INTEG MEAN	DENSITY OF FISH	QUANTITY NUMBERS	FISH QUANTITY VARIANCE	CONFIDENCE LIMITS(95%)
2.0– 12.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+00	.0000E+00	300.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
12.0– 22.0	.0000D+00	.1000E+01	0	.0000E+01	.0000E+00	.0000E+00	295.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
22.0– 32.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	274.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
32.0– 42.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	254.	.000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
42.0– 52.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	220.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
52.0– 62.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	182.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
62.0– 72.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	151.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
72.0– 82.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	114.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
82.0– 92.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	88.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
92.0–102.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00	63.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
								.00000E+00	+ OR –	.0000E+00		
TOTAL:	.0000D+00											

SUMMARY OF DATA STARTING AT Wed May 15 14:38:18 1991
AND ENDING AT Fri May 17 13:59:41 1991

Table 4. [cont.]

DATA FOR PRIMARY STRATA, MULTIPLEX CHANNEL 2

INTEGRATOR	NUMBER OF	VARIANCE OF	DENSITY	QUANTITY	FISH QUANTITY	CONFIDENCE

Table 4. [cont.]

DATA FOR PRIMARY STRATA, MULTIPLEX CHANNEL 2

DEPTH STRATUM	STRATUM VOLUME	MEAN SIGMA	# FISH USED	STD DEV SIGMA	A CONSTANT	INTEGRATOR OUTPUT
2.0– 12.0	.0000D+00	.1000E+01	0	.0000E+00	.10000E+01	.0000E+00
12.0– 22.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
22.0– 32.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
32.0– 42.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
42.0– 52.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
52.0– 62.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
62.0– 72.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
72.0– 82.0	.0000D+00	.1000+01	0	.0000E+00	.1000E+01	.0000E+00
82.0– 92.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
92.0–102.0	.0000D+00	.1000E+01	0	.0000E+00	.1000E+01	.0000E+00
TOTAL:	.0000D+00					

DEPTH STRATUM	NUMBER OF SEQUENCES	VARIANCE OF INTEG MEAN	DENSITY OF FISH	QUANTITY NUMBERS	FISH QUANTITY VARIANCE	CONFIDENCE LIMITS(95%)
2.0– 12.0	300.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
12.0– 22.0	295.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
22.0– 32.0	274.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
32.0– 42.0	254.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
42.0– 52.0	220.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
52.0– 62.0	182.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
62.0– 72.0	151.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
72.0– 82.0	114.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
82.0– 92.0	88.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
92.0–102.0	63.	.0000D+00	.0000E+00	.00000E+00	.0000E+00	.0000E+00
TOTAL:		.00000E+00	+ OR –	.0000E+00		

LIST OF FILES PROCESSED:

a:dummy1.dat

and for the total population biomass in the entire water column:

$$CL = \sum_{i=1}^{10} \widehat{Q}_i \pm 1.96 \Big[\sum_{i=1}^{10} \mathrm{Var}(\widehat{Q}_i) \Big]^{1/2} \tag{14}$$

7. Conclusion

It is known from present and historical catch data that a rough estimate of the total abundance of pelagic fish in the Black Sea should be in the range of hundreds of thousands of tons [1]. The acoustic estimates in the present study — about 30 000 tons from the first survey and about 2200 tons from the second survey — are remarkably low. Despite the evident decrease of the pelagic fish stock reported throughout the last years, such a discrepancy between the acoustic and other data can not be explained by statistical underestimation. There are obviously some other reasons likely related to non-representativeness of the acoustic data.

It is assumed that a reliable acoustic estimate of fish stock size can be achieved from the echo integration technique, provided following conditions are satisfied [10], [11]:

1. The fish stock is known to be available for acoustic measurement in the surveyed area.
2. The stock is not inextricably mixed with other populations.
3. The fish are neither too deep, nor too shallow to be detected by hydroacoustic system.
4. The distribution of fish over the area is sufficiently constant for extrapolations to be made from density measurement along widely-spaced survey transects.
5. The fish avoidance effect (reaction to vessel and system) is negligible.

For the Black Sea pelagic fish stocks, and especially anchovy stock, which can be considered as relatively small and dispersed, because of in general low productivity area (no patchiness and low degree of school activity) majority of the above requirements are not fulfilled. Practically, only the condition 1 and 5 could be considered as satisfied in full. The others are only partly fulfilled if there are at all. Therefore, the population estimates obtained from acoustic surveys are not necessary fully reliable, and particularly in the context of unknown degree of fulfillment of the conditions 2, 3 and 4, the surveyed stock seems to be underestimated by acoustic assessment.

There are at least two other factors which might be partly responsible for underestimating pelagic stocks. The first refers to the survey coverage and the second to the conceivable changes of the fish migratory space-time pattern. It was observed that most of the surveyed pelagic fish populations (particularly anchovy) exhibited an almost littoral distribution. This would require the survey vessel to run the transects into the shallows rather than staying seaward of a depth of 15 meters (see section 2). As a consequence, the survey coverage was incomplete as it was not feasible to carry out the sampling across the entire fish distribution area. This evidently decreases the final estimate of the fish biomass obtained from the acoustic data. However, the underestimation "factor" can not be determined easily, due to the lack of data on catches from the unsurveyed area.

The second factor is that commercial fishery observations of the anchovy stocks migratory patterns in the Black Sea suggest that they are most probably presente in the Southern part of the sea between November and February, [1]. For this reason, both acoustic surveys in successive years were undertaken in the Winter season. However, on these cruises the fish distribution was restricted to small areas in the East. Thus, there are basically two possible explanations of this fact. The first is the conceivable change in fish migratory seasonal habits. The second is the possible change of their distribution pattern, which can be in turn related to migration or not. In any case, the explanation of the obtained low estimates requires continuing of the acoustic surveys, complemented with the more frequent concurrent fishing operations, and extended if possible to the other seasons.

Acknowledgements

This study has been carried out within the framework of a Project sponsored by NATO Science for Stability Program, Turkish Scientific and Research Council (TUBITAK) and Turkish State Planning Office. We also extend our sincere thanks to Institute of Marine Science — Middle East Technical University (IMS–METU) Personnel who accompanied us in various ways.

References

[1] F. Bingel, A. Stepnowski, A. Gucu, *Hydroacoustic methods of fish stock assessment along the Turkish coast of the Black Sea*, Nato-TU Fisheries Report, NATO- Sciences for Stability Programme, Institute of Marine Sciences, Middle East Technical University, Erdemli 1991.

[2] J. Burczyński, A. Stepnowski, R. Salamon, *The hydroacoustic system on R/V "Professor Siedlecki" and its use in fish stock assessment by integration of thin depth layers*, Rapp. P.-V. Reun. CIEM, 170, 142–151 (1977).

[3] N. Castigne, L. E. Burgone, J. Le Vourch, J. P. Orly, *Operational measurements of sea surface temperatures at CMS Lannion from NOAA-7 AVHRR data*, Int. Journ. on Remote Sensing **7**, 8 (1986).

[4] D. K. Clark, *Phytoplankton pigments algorithm from the Nimbus-7 CZCS*, in Oceanography from space, J.F.R.Gower [Ed.], Plenum Press, New York 1981, 227–238.

[5] S. Clark, *Use of trawl data in assessment*, Can. Spec. Publ. Fish. Aquat. Sci., **58**, 82–92 (1981).

[6] J. J. Dawson, T. J. Brooks, E. S. Kuehl, *An innovative acoustic signal processor for fisheries science*, Proc. I.O.A. **11**, 8, 131–140 (1989).

[7] O. Dragesund, S. Olsen, *On the possibility of estimating year class strength by measuring echo abundance of O-group fish*. Fisk. Dir. Skr. Havunders **13**, 8, 47–71 (1965).

[8] J. E. Ehrenberg, *A review of in situ target strength estimation techniques*, ICES/FAO Symp. Bergen 1982, art. No. 104; also in: FAO Fish Rep., **300**, 85–90 (1982).

[9] K. G. Foote, P. H. Knudsen, G. Vestnes, *Standard calibration of echo-sounders and integrators with optimal cooper spheres*, ICES/FAO Symp. Bergen 1982, art. No. 40.

[10] K. G. Foote, *Fisheries acoustics diagnosis and prognosis*, Proc. I.O.A. vol. 11, Part 3, 1989.

[11] K. A. Johanesson, R. B. Mitson, *Fisheries acoustics*, A practical manual for acoustic biomass estimation, FAO Fisheries Technical Paper 240, FAO Rome 1983.

[12] R. Jones, *Assessing the effects of changes in exploitation pattern using length composition data with notes of VPA and cohort analysis*, FAO Fish. Techn. Paper. 256 (1984).

[13] R. H. Love, *Dorsal aspect target strength of an individual fish*, J. Acous. Soc. Am., **49**, 3, 816–823 (1971).

[14] P. Sparre, E. Ursin, S. Venema, *Introduction to tropical fish stock assessment*, Part 1. FAO Fish Techn. Paper No 306/1, FAO Rome 1989.

[15] A. Stepnowski, *Fish target strength estimation methods and techniques*, VIIIth Symposium on Hydroacoustics SHA'91 Gdańsk 1991.

[16] A. Stepnowski, R. S. Mitchell, *ECOLOG II — A real time acoustic signal processing system for fish stock assessment*, Ultrasonics **28**, 256–265 (1990).

[17] J. M. Streta, M. Petit, *Teledetection aero-spatiale et peche thoniere en Atlantique inter-tropical*. FAO Doc. Techn. sur les Pech. 302 J.Y. Le Gall ed FAO Rome 99–109 (1989).
[18] R. E. Thorne, *Investigations into the relation between integrated echo voltage and fish density*, J. Fish. Res. Board Can. **28**, 9, 1269–1273 (1971).
[19] R. J. Urick, *Principles of underwater sound*, 3 ed. McGraw Hill, New York 1983.
[20] Anon.1: Microsoft windows user's guide, Microsoft Co., Doc. 050050051-200-R01-0887, Redmont, USA 1987.
[21] Anon. 2: Echo signal processor manual with model 281 dual-beam processor and model 221 echo integrator software, Biosonics Inc. Seattle USA 1989.
[22] Anon. 4: Methods of collecting and analysing size and age data for fish stock assessment, FAO Fish. Circ. No. 736 FAO Rome 1981.

Received on December 10, 1991