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Comparison of airborne lidar with echosounders: a case study in the coastal Atlantic waters of southern Europe

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The feasibility of using airborne lidar (Light Detection and Ranging) was studied to assess the early juvenile fractions of the main pelagic fish species of the coastal Atlantic waters of southern Europe (anchovy, sardine, mackerel, and horse mackerel). Field comparisons with more established echosounder methods were undertaken in the summers of 1998 and 1999 during the recruitment period of sardine and anchovy in the selected areas, in the presence of a variety of oceanographic and environmental conditions. Backscattered energies as well as the types of target recorded by both devices were compared. The distributions of energies and the shape of the targets were generally similar for both techniques, with moderate numerical correlation between sensors, demonstrating the potential of lidar for assessment of anchovy, sardine, and juvenile mackerel. However, differences in received backscattering energy were found, especially in the presence of certain plankton assemblages (to which lidar is more sensitive) and isolated schools with large vertical dimensions (for which shadowing is more significant for light than sound). Experimental *ad hoc* optical reflectivity measurements of fish and plankton are proposed to discriminate these two types of targets. In addition, an improvement on lidar implementation and data processing is suggested to achieve fish abundance estimates.

Keywords: airborne lidar, anchovy, Bay of Biscay, echosounder, recruitment, sardine, West Iberian Peninsula.

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Introduction

One of the most important components of fishery management is the assessment of the strength of the year classes before they enter a fishery. Good survival of larvae produces strong year classes (Smith, 1985; Houde, 1996). It seems, therefore, that the strength of the recruitment of many species is already established five or six months after spawning, once the fish are already juveniles. This has been demonstrated for many populations all over the world, including California rockfish (*Sebastes* spp.; Ralston and Howard, 1995), walleye pollock (*Theragra chalcogramma*; Bailey and Spring, 1992), and several pelagic populations such as herring (*Clupea harengus*; Leblanc *et al.*, 1998) and northern anchovy (*Engraulis mordax*; Smith, 1985). Hence, when early juveniles can be assessed, the estimates can be used to predict the relative strength of the future recruitment to the fisheries. This strategy is of special interest to manage the fisheries for short-lived species because of the short time between spawning and the exploitation of subsequent emerging recruits, as in the South African anchovy fishery (*Engraulis encrasicholus*, formerly *E. capensis*; Hampton, 1992; Butterworth and Bergh, 1993) and Icelandic capelin (*Mallotus villosus*; ICES, 2000a).

Echosounder methods have traditionally been applied to obtain recruitment estimates (Dragesund and Olsen, 1965). However, the assessment of early juveniles may be difficult, because many juveniles display epipelagic phases, when they remain in the upper layers of the water column. Also, they are often found in coastal areas or, in some cases or phases, even in shallow water (Mays, 1974; Alshuth, 1988; Dias *et al.*, 1988, 1989; Lockwood, 1988; Boyd *et al.*, 1997; Villamor *et al.*, 1997; Leblanc *et al.*, 1998). Such behaviour would set juveniles outside the vessel range and/or the effective observational range of an echosounder transducer (MacLennan and Simmonds, 1992). Besides, echosounders may underestimate schools if they are actively avoiding the ship (Fréon and Misund, 1999). All these potential problems suggest a need for improved echosounder methods and/or complementary techniques for detecting juvenile fish.

In the Atlantic waters of the Iberian Peninsula and in the Bay of Biscay, sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicholus*) support important fisheries of Portugal, Spain, and France (Uriarte *et al.*, 1996; ICES, 2000a, b; Carrera and Porteiro, 2003). Off the Iberian Peninsula, the recruitment of sardine at age 0 is mainly in the northern and central parts of Portugal between summer and winter (ICES, 1982; Porteiro *et al.*, 1986, 1993; Dias *et al.*, 1988, 1989, 1993; Pestana, 1989). In the Bay of Biscay, the major nursery areas for anchovy are located in the southern part (Prouzet *et al.*, 1994; Uriarte *et al.*, 1996).

Direct estimation of the recruitment at age 1 for both species by echo integration is routinely done in spring at the time of spawning (Massé *et al.*, 1992; Porteiro *et al.*, 1993, 1996; Scalabrin and Massé, 1993; Massé, 1996). Although an echosounder survey is conducted in November off Portugal to estimate the recruitment of sardine aged 0 (Dias *et al.*, 1996, Porteiro *et al.*, 1996), a systematic study of juvenile age-0 anchovy and sardine off southern Europe had never been performed. Among other reasons, juvenile shoals of both fish species have an epipelagic distribution and, in the case of sardine, a shallow water one too (Cort *et al.*, 1976; Martín, 1989; Soares, 1995). This could make it difficult to estimate fish biomass with echosounders with any accuracy.

In the 1990s, research began into the development of airborne lidar (Light Detection and Ranging) surveys for detecting fish schools (Hunter and Churnside, 1995; Gauldie *et al.*, 1996), based on earlier feasibility studies (Fredriksson *et al.*, 1978; Squire and Krumboltz, 1981). Over its operational range (about 30−40-m depth) lidar was tested as a technique to detect tuna (*Thunnus* spp.) in the Pacific (Oliver *et al.*, 1994), and pelagic species such as sardine (Churnside *et al.*, 1997), capelin (Brown *et al.*, 2002), mullet (Mugilidae; Churnside *et al.*, 2003), and even zooplankton (Churnside and Thorne, 2005). According to these experiments, lidar was a potentially useful tool to map the distribution of schools of juveniles close to the surface. As it can be operated from a small aircraft, it is an accessible tool to survey shallow coastal waters. Processing the lidar signal to obtain quantities proportional to the number of fish within the operational depth range has been demonstrated, although conversion into biomass requires species identification and experimental knowledge of fish reflectivity and size (Churnside and McGillivray, 1991; Krekova *et al.*, 1994; Churnside and Hunter, 1996; Churnside *et al.*, 1997).

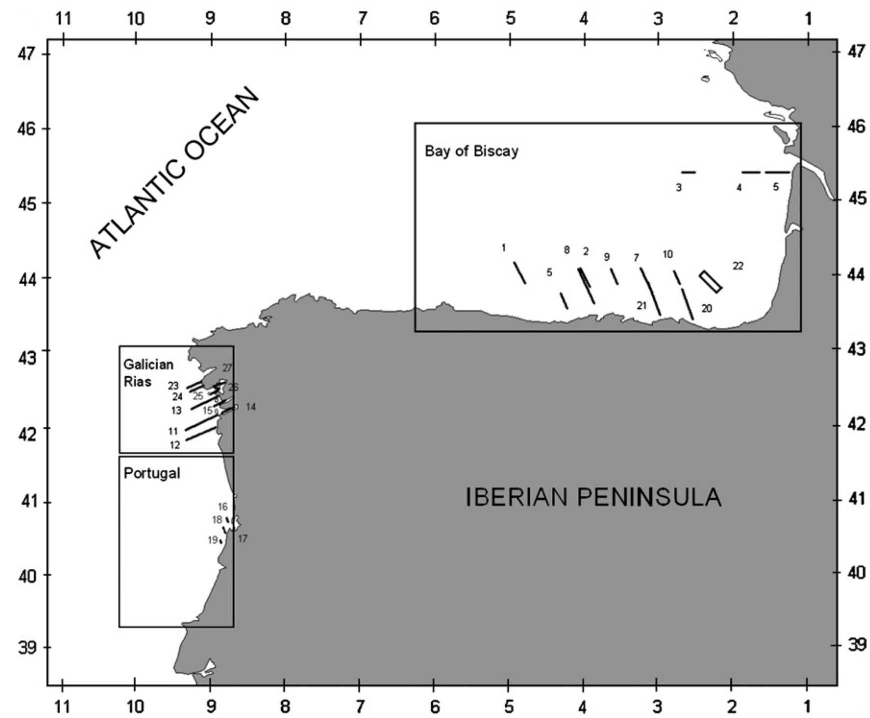

Figure 1. Survey areas and position of the HAGCs.

In this context, to improve estimation of recruitment at age 0 of the pelagic resources in the Atlantic waters of the Iberian Peninsula and the Bay of Biscay, a research project named "Experimental Surveys for the Assessment of Juveniles" (JUVESU-FAIR CT97-3374) was developed. The major goal of the project was to evaluate airborne lidar systems for surveying the distribution and relative abundance of early juvenile sardine and anchovy,

Table 1. Details of and equipment used during the cruises.

Area	Dates	Echosounder settings	Lidar settings
Bay of Biscay	04/09/98–18/09/98	RV "Gwen Drez", echosounder and pelagic trawl FV "Beti Euskalherria", purse-seine hauls OSSIAN1500 (38 kHz, single beam, hull mounted) Echogram: digital post-processing: Movies+ Calibration: copper sphere	Aircraft: CASA 212–200 Transmitter: Laser CFR200 doubled Nd:YAG Wave length 532 nm Pulse length 12 ns Pulse energy 100 mJ Pulse repetition rate 30 Hz
Galicia	20/08/98–28/08/98	RV "José María Navaz", echosounder FV "M. Presas", purse-seine hauls SIMRAD EY500 (38 kHz, single beam, towed body) Echogram: digital Post-processing: Echoview Calibration: copper sphere	Beam divergence, day: 17 mrad Beam divergence, night: 65 mrad Receiver: Detector R6915U PMT Aperture diameter 17 cm Field of view: 17–65 mrad (day and night) Operational bandwidth 10 nm Electronic bandwidth 300 MHz
Portugal	26/08/98–03/09/98	RV "Noruega", echosounder, pelagic and bottom trawl SIMRAD EK500 (38 kHz, single beam, hull mounted) Echogram: digital Post-processing: Echoview Calibration: copper sphere	Sample rate 1G Hz Digitizer STR81G
Bay of Biscay	01/09/99–19/09/99	RV "Gwen Drez", echosounder and pelagic trawl l FV "Divino Jesús de Praga", purse-seine hauls OSSIAN1500 (38 kHz, single beam, hull mounted) Echogram: digital post-processing: Movies+ Calibration: copper sphere	Aircraft: CASA 212 Transmitter: Laser CFR200 doubled Nd:YAG Wave length 532 nm Pulse length 12 ns Pulse energy 100 mJ Pulse repetition rate 20 Hz
Galicia	25/08/99–03/09/99	RV "José María Navaz", echosounder FV "Praia de Portonovo", purse-seiner SIMRAD EY500 (38 kHz, single beam, hull mounted) Echogram: digital Post-processing: Echoview Calibration: copper sphere	Beam divergence, day: 17 mrad Beam divergence, night: 65 mrad Receiver: detector R6915U PMT Aperture diameter 17 cm Field of view: 17–65 mrad (day and night) Operational bandwidth 10 nm Electronic bandwidth 300 MHz
Portugal	24/08/98–30/08/98	RV "Capricornio", echosounder and pelagic trawl RV "Mestre Costeiro", bottom trawl SIMRAD EK500 (38 kHz, split beam, hull mounted) Echogram: digital Post-processing: Movies+ Calibration: copper sphere	Sample rate 1 GHz Digitizer STR81G

and comparing the results with those from the traditional shipborne echosounder systems. The experimental surveys were made in 1998 and 1999 around the western Iberian Peninsula, and in the southern part of the Bay of Biscay (Figure 1). These areas represent remarkable oceanographic differences and contain nurseries of several pelagic species of major interest for various European fisheries (mainly sardine and anchovy, and secondarily mackerel, *Scomber scombrus*, and horse mackerel, *Trachurus trachurus*).

This manuscript describes the results of the analysis of the relative performance of the lidar and echosounder systems for detecting juveniles of the main pelagic species arising from these experimental surveys. In addition, direct analysis between sensors was made in discrete areas with particularly homogenous distribution of juvenile school type. Finally, we discuss the potential of lidar technology for future assessment of pelagic fish juveniles in the study areas.

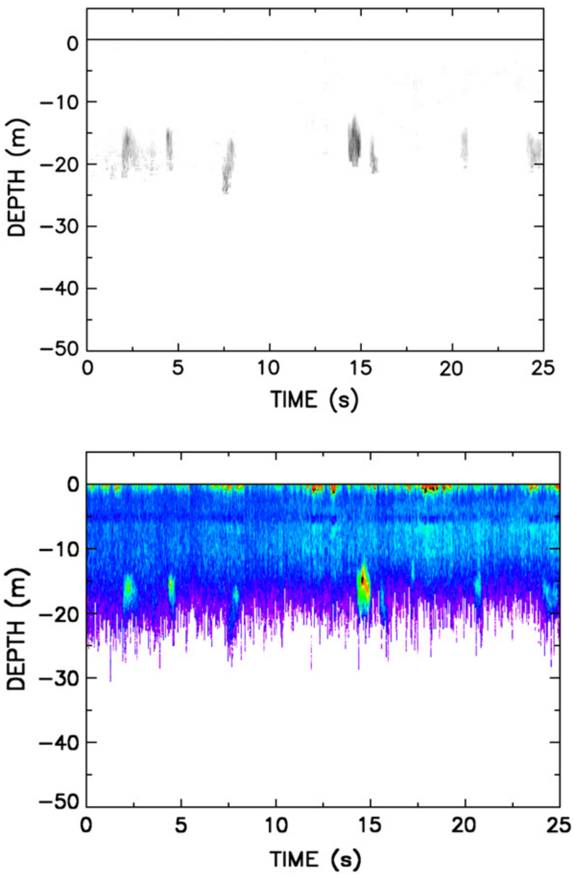

Figure 2. Comparison of the results of school processing (top panel) and echo-integration processing (bottom panel) for a period of 25 s (about 1 nautical mile) on the Galician shelf (around 42°N, 9°10′W) on the morning of 31 August 1999. Several large, dense schools can be seen below a diffuse plankton layer in a zone where the echosounder made no detections.

Material and methods

Two experimental surveys were performed, in August/September of 1998 and 1999, to test the performance of lidar and echosounder systems in detecting fish, primarily juveniles. These study areas, shown in Figure 1, were the southeastern Bay of Biscay (43°N–46°N, 1°W–5°W), the Galician Rías and the shelf off the northwest Iberian Peninsula (41.8°N–43°N, 8.7°W–9.4°W), and the northern central shelf off Portugal (39.5°N–41.8°N, 8.6°W–10.2°W). These are areas where juvenile anchovy, sardine, mackerel, and horse mackerel historically occur.

Fish distribution mapping and species identification were carried out by shipborne echosounder and fishing surveys, coupled with airborne lidar surveys. Echosounder surveys of each area were accomplished with various research vessels. Fishing to provide ground truth (McClatchie *et al.*, 2000) was performed by the same vessels (pelagic and bottom trawl), and by chartered commercial vessels (purse-seine). Table 1 presents sampling details by year and region.

Surveys were conducted in two phases: (i) an extensive coverage of the target area; and (ii) an intensive coverage of a selected portion of the area. The ship and aircraft surveyed common transect lines at speeds between 7 and 10 knots and ∼140 knots, respectively. An Elementary Distance Sampling Unit (EDSU) was set at 1 nautical mile (hereafter referred to as mile). The extensive area was covered only during daylight. The intensive legs were located in those areas of high juvenile abundance, where repeated passes were made at different periods of the day. The main goal of this second phase was to characterize pelagic fish aggregations in space and time. For the analysis presented here, both the extensive data and the day and evening intensive data were used. The extensive data were used to compare backscatter intensities, and both extensive and intensive data were used to perform echo trace analyses.

The lidar system is the NOAA radiometric lidar described by Churnside *et al.* (2001). With a mean altitude of 300 m, the lidar beam diameter was 5 m at the sea surface. Depth penetration varied by area and year, depending on water clarity, light level, and laser power, but was 25–30 m. In 1998, the lidar was installed in a twin-engine Casa aircraft operated by the Instituto Nacional de Tecnica Aeroespacial (INTA). In 1999, the Spanish Air Force supplied a similar aircraft. However, the electrical power system had to be augmented with dry batteries to accommodate the lidar laser power, so lidar performance was reduced to extend survey time (i.e. a lesser repetition rate).

Data analysis

The primary lidar data-processing method, henceforth referred to as school processing, involves a threshold that removed the noise from each shot. The threshold was approximately the median backscatter intensities from all shots over ∼1 mile. School processing was applied to the entire extensive coverage. Because school processing rejected extensive juvenile layers, another method was developed, denoted "echo-integration" for its similarity to the echosounder processing method (see Figure 2 for an illustration of each). Similarly, echosounder data with a −60-dB threshold were integrated over 5-m depth layers from the transducer depth (3−5-m depth) to the bottom. Several school size and descriptors were extracted from the echosounder and lidar data but biomass estimations were not attempted.

For comparison, it was assumed that the sound echo-integration method provided an accurate fish echo trace characterization and biomass estimate. Bias attributable to fish avoidance was assumed to be negligible (Fernandes *et al.*, 2000a, b), but fish responses were expected, specially diving reactions (Blaxter *et al.*, 1981; Schwarz and Greer, 1984).

We first compared the extensive coverage of the three areas surveyed, assuming a stationary distribution and either single species or uniform mix of species. The mean backscattered energies over the surveyed area from the echosounders and lidar were compared with the expectation that they should be similar. Echosounder data to depths up to 30 m were used to correspond to mean lidar depth penetration. Each data set was log-transformed, then put in relative units by normalizing each observation by its maximum. For each data set, the spatial distribution was studied by means of geostatistic tools (Matheron, 1971; Petitgas, 1991, 1993). The analysis was Estimation Variance Analysis (EVA; Petitgas and Prampart, 1993) using a SURFER v7.0 (Golden Software) package. Kriged contour maps were constructed and compared using variogram models with the same map grid for both echosounder and lidar data. Wilcoxon paired-sample tests were performed on results obtained after the kriging process.

A second comparison was made over segments that satisfied the following constraint criteria: (i) similarity on echo traces recorded by both devices; and (ii) elapsed time between ship and aircraft coverage less than two days. These segments were called Homogeneous Areas for Geographic Comparison (HAGC). Figure 1 shows the location of selected HAGCs. Both lidar-processing methods were compared with the echosounder results for the HAGCs. The quantitative and ordinal (Pearson and Spearman) correlations between the average echo-integrated sound and light energies across HAGCs were calculated. Lidar and echo-integration energies were normalized by the average value for each area and year, and were log-transformed, i.e. for every HAGC i, the energy E_i was substituted by the result of the following expression:

$$\log E_i - \log\langle E\rangle_{\text{area,year}},$$

where $\langle E\rangle_{\text{area,year}}$ corresponds to the average value of the energy from a given sensor obtained for the corresponding year and area (Bay of Biscay, Galician, or Portuguese surveys). Correlations were made for these transformed energies. Also, acoustic echo traces were classified according to their shape in four categories (schools, pelagic layers, bottom layers, and scattered echo traces).

Results

In Portugal in 1998, most fish schools were near the shore. The main species were juvenile and adult sardine, but there was no clear horizontal separation of the two life stages. A greater proportion of juveniles was found close to the shore from Aveiro to Figueira da Foz, so this area was selected for the intensive survey. Both the echosounder and lidar data showed the same general patterns in the coastal area (see sample echograms in Figure 3). Exceptions included: (i) plankton layers detected by lidar but not by echosounder

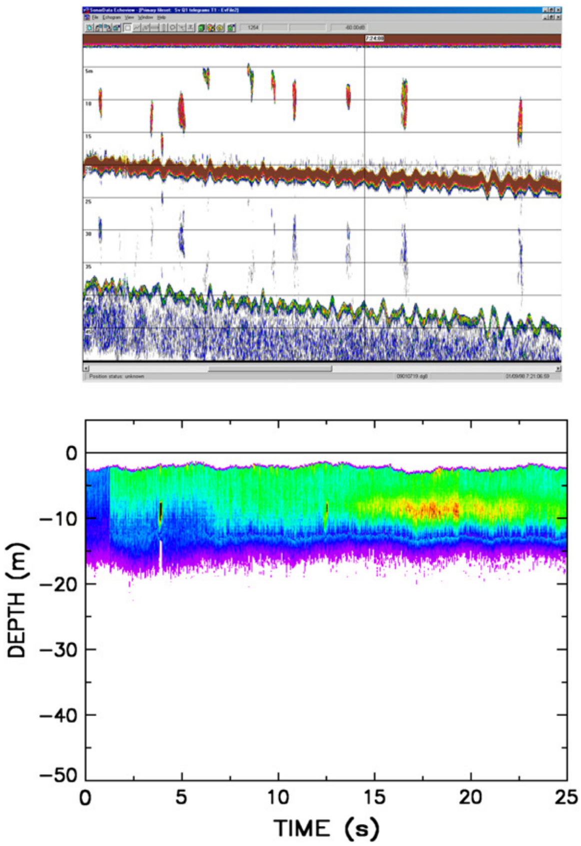

Figure 3. A fragment of HAGC 17. (top panel) Echogram of a Portuguese shallow area (1 nautical mile) with many dense fish schools (juvenile and adult sardine) in the middle of the water column at about 40°34′N, 8°50′W covered during the morning of 1 September 1998. (bottom panel) Lidargram of about 1 nautical mile over a nearby area on the morning of the following day, showing distinct schools and thick layers of fish and/or plankton.

using the −60-dB threshold; (ii) consistently greater light backscatter offshore; and (iii) some large schools detected by echosounders, but not by lidar.

In Galicia in 1998, most fish were near the coast, especially within or at the mouth of the Rías, as observed by both sensors (Figure 4). Juvenile sardine were the most abundant fish species, but in low abundance from a historical perspective. In 1999, sardine abundance was even lower and more restricted to coastal waters. Outside the bays, the main species (although scarce) was mackerel. No fish were found in surface waters near the 200-m isobath. That year, relative to the echosounder, the lidar detected more scatterers in the outer part, and few dense schools in the inner part of the surveyed area.

In the Bay of Biscay in 1999, almost all fish caught were juvenile anchovy, found off the continental shelf. The comparison of the maps produced by each sensor did not show clear patterns such as those observed in the western Iberian Atlantic, except for some differences near the beginning or end of the tracks (Figure 5). Lidar estimates were slightly higher in the peripheral areas, and echosounder estimates were slightly bigger in the central part of the surveyed area. In the Garonne area, for the single track analysed, juveniles in weak densities occupied the midwestern part of the shelf, whereas in the coastal zone, larger concentrations of adults of different species were found. Along the track, there were two gaps in the acoustic echosounder data that were not seen in the lidar data.

Extensive area comparison

Summary statistics for each data set (area, year) are shown in Table 2. Neither fish nor thick plankton layers were observed in the uppermost layers in some parts of the western areas, but no empty EDSU were seen in the Bay of Biscay. Raw data were in general skewed, with a few high values dominating both the arithmetic mean and the standard deviation. The weighted and log-transformed data were more

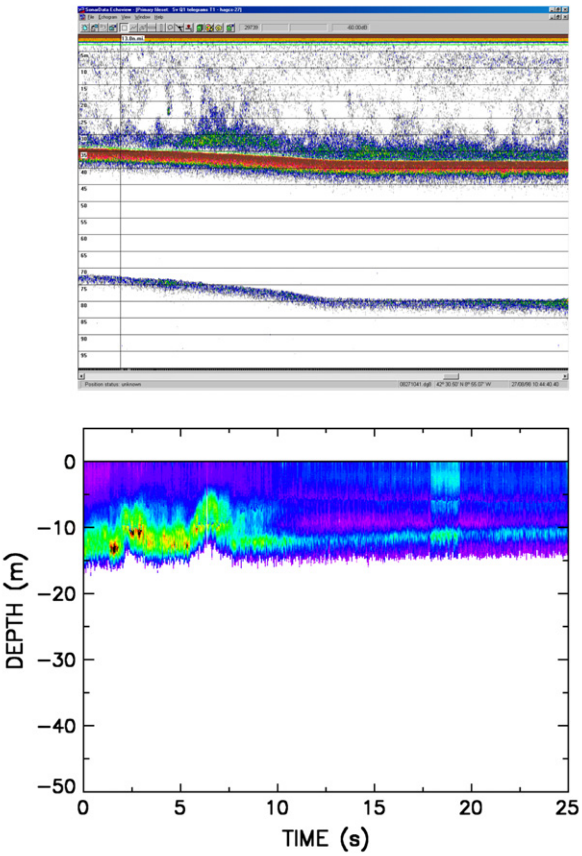

Figure 4. A fragment of HAGC 27. (top panel) Echogram of a transect line over the central part of the Galician Ría de Arousa (0.5 nautical miles) with a thick plankton layer close to the seabed. (bottom panel) Lidargram of about 1 nautical mile over the inner part of the area covered during the morning of the same day, showing fish and/or plankton aggregations over the seabed.

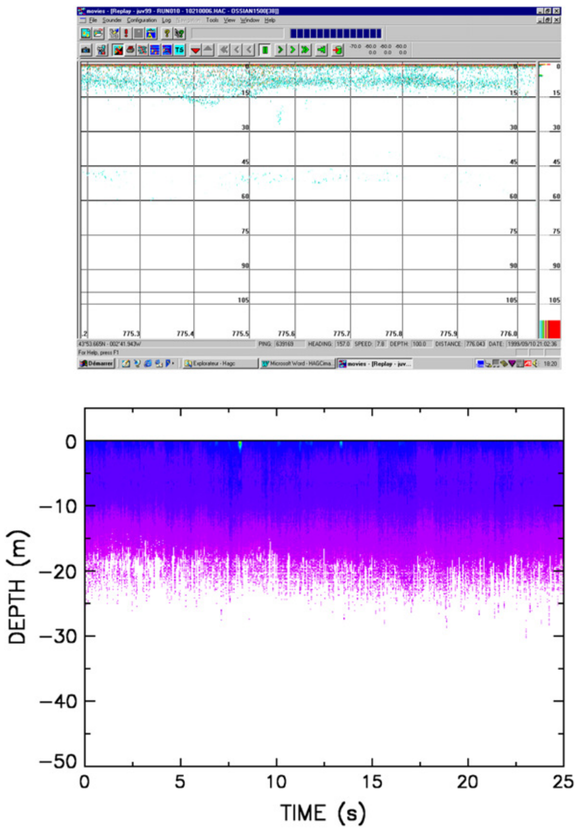

Figure 5. A fragment of HAGC 10. (top panel) Night-time echogram of almost 1 nautical mile over offshore waters of the southern Bay of Biscay, showing scattered anchovy juveniles close to the surface. (bottom panel) Lidargram of about 1 nautical mile, showing a homogeneous layer 0−12 m deep.

Table 2. Main statistics of the stationary comparison for each device and area.

			Echosounder		Lidar	
Year	Area	Statistics	Raw	Transformed	Raw	Transformed
1998	Portugal	Number of data	305		561	
		Sum	238 910.55	132.22	8.5651	405.26
		Maximum	24 047.00	1.00	0.2309	1.00
		Minimum	1.01	0.19	0.0000	0.16
		Arithmetic mean	783.31	0.43	0.0153	0.72
		Standard deviation	2 734.42	0.22	0.0268	0.14
		Median	12.00	0.39	0.0056	0.75
		Geometric mean	21.51	0.38	0.0040	0.71
1998	Galicia	Number of data	169		489	
		Sum	81 102.20	114.83	7.5681	353.27
		Maximum	6 326.51	1.00	0.3500	1.00
		Minimum	0.40	0.13	0.0000	0.15
		Arithmetic mean	479.89	0.68	0.0155	0.72
		Standard deviation	770.96	0.15	0.0281	0.12
		Median	215.00	0.69	0.0080	0.75
		Geometric mean	182.95	0.66	0.0053	0.71
1999	Galicia	Number of data	159		358	
		Sum	36 900.77	105.55	14.1459	252.74
		Maximum	4 636.02	1.00	0.9897	1.00
		Minimum	0.09	0.17	0.0000	0.22
		Arithmetic mean	232.08	0.66	0.0395	0.71
		Standard deviation	575.03	0.17	0.0840	0.10
		Median	118.08	0.72	0.0186	0.71
		Geometric mean	57.72	0.63	0.0171	0.70
1999	Bay of Biscay, inner part	Number of data	206		548	
		Sum	5 017 284.00	122.47	4.3345	363.08
		Maximum	871 882.00	1.00	0.0943	1.00
		Minimum	30.00	0.25	0.0002	0.32
		Arithmetic mean	24 355.75	0.59	0.0079	0.66
		Standard deviation	80 790.11	0.14	0.0111	0.12
		Median	2 946.50	0.58	0.0039	0.65
		Geometric mean	3 401.99	0.34	0.0043	0.65
1999	Bay of Biscay, Garonne	Number of data	46		56	
		Sum	304 210.00	36.28	0.2550	42.76
		Maximum	41 002.00	1.00	0.0124	1.00
		Minimum	486.00	0.58	0.0010	0.48
		Arithmetic mean	6 613.26	0.79	0.0046	0.76
		Standard deviation	8 156.88	0.08	0.0025	0.11
		Median	4 386.50	0.79	0.0036	0.75
		Geometric mean	4 341.73	0.78	0.0040	0.76

comparable; the maxima and minima for each device were similar for the same area and year.

There was spatial autocorrelation for each device, area, and year, as shown in Table 3. The range of this correlation was around 7 miles for the echosounder data. In comparison, the ranges of the lidar were 3 miles in 1998 and 6.5−11 miles in 1999. Empirical variograms were fitted according to the models shown in Table 3. These models were used to construct kriging surfaces over the same grid (Figures 6 and 7).

Wilcoxon signed-rank tests performed on the kriged values showed significant differences. In Galician and Portuguese waters, lidar values were higher than those recorded by the echosounders ($Z = 10.7$, $p = 0$; $Z = 35.6$, $p = 0$; $Z = 15.9$, $p = 0$; for data from Galicia in 1998, Portugal in 1998, and Galicia in 1999, respectively). The situation was the same in the inner part of the Bay of Biscay ($Z = 12.5$, $p = 0$), suggesting that lidar detected more targets than echosounders. Conversely, in the Garonne area, echosounder records were bigger than those of the lidar ($Z = 2.40$, $p = 0.0081$).

Table 3. Fitted experimental variograms for each data set.

Year	Device	Area	Nugget	Model	Sill	Range	% nugget/model	Estimated variance
1998	Echosounder	Portugal	0.01	Spherical	0.039	6	7	0.00046
		Galicia	0.005	Spherical	0.015	7	10	0.0004
	Lidar	Portugal	0.012	Spherical	0.007	3.5	40	0.000074
		Galicia	0.012	Spherical	0.006	3	33	0.0000076
1999	Echosounder	Galicia	0.01	Spherical	0.0175	7	34	0.000054
		Inner part	0.005	Spherical	0.016	6.5	1	0.003
		Garonne	0.002	Spherical	0.002	6.5	72	0.00012
	Lidar	Galicia	0.004	Spherical	0.002	7	10	0.000054
		Inner part	0.007	Spherical	0.005	11	1	0.00118
		Garonne	0.008	Spherical	0.002	6.5	85	0.00017

Direct HAGC comparison

Data from both devices were directly compared over 22 HAGCs across years and areas (see Table 4 for the main characteristics of each HAGC). A comparison of normalized and transformed energy values produced moderate levels of positive correlation between sensors, which were significant for the case of school processing. The lidar echo-integration method improves slightly the comparison of echosounder and lidar for HAGCs of scattered fish, but generally worsens the comparison for other echo types. This is particularly noticeable for the few HAGCs with large-school detections, which can even result in negative correlations. Combining all types together except large schools gave significant (at $\alpha = 5\%$) or almost significant correlations (with $p < 0.1$) with both lidar signal-processing methods. Relative to 1999, the 1998 HAGCs showed better agreement for the two sensors. Among geographic zones, Galician waters (and all western areas together) obtained the best fit between sensors, while for the Bay of Biscay, correlations were not significant.

Owing to changes in fish aggregation patterns, some HAGCs taken on different days gave lower correlation indices, as observed in HAGC 2 (surveyed by echosounder on 5 September, with a value of 3.23, and by lidar on 7 September, with a value of 0.44) and HAGC 8 (surveyed on 8 September, with a value of 0.66, and on 9 September, with a value of 2.86). On the other hand, HAGC 17 gave large differences in values for both lidar-processing methods, probably related to the quality of the lidar data.

Removing these three points from the data set improved the correlation to 0.65 (in linear scale) or to 0.55 (in log scale; Table 5, Figure 8). Removal of any other additional points barely increased the correlations. With this data set, the correlation for large-school echosounder detections (though based now on just three points) became positive in the school processing for lidar (not negative as before). In general, all the analysis of the school processing for lidar was improved: the 1998 set of HAGCs became statistically significant, and the diurnal correlation among HAGC values was also improved.

The last column in Table 4 summarizes the fraction of fish stocks in the upper 30 m of the water column for each region. In Portugal, the situation was ideal for lidar; the HAGCs corresponded to the shallow waters of the radials of the intensive campaign, and almost all schools were in the upper 30 m. Conditions in the Bay of Biscay were quite good also, with high percentages of schools inside the nominal lidar range, although the actual lidar penetration depth turned out to be <30 m in most areas. The worst cases were in Galicia, especially in 1999. Those HAGCs were mostly in inshore waters with fish very close to the bottom, which made separation of the fish and bottom signals difficult (Figure 8).

Discussion

The stationary comparisons based on the smoothed contour maps of backscattering transformed energies have shown that there is a general consistency between both sensors, so showing the ability of lidar to detect and map the distribution of the targeted fish species. However, lidar (a noisier sensor according to the range and sill values obtained in the variograms presented in Table 3) produced more detections than echosounders (Figures 6 and 7), and the differences were statistically significant. This may be because the relationship between target strengths (backscattered energies) among species (fish and plankton) for each sensor was different, which probably affected the threshold applied to each device. According to this, retained valid echo traces (i.e. energy patches that were above the threshold) would be different and, therefore, so would the subsequent integrated backscattered energies.

In Galician waters in 1999, the offshore detections made by lidar that were not detected by echosounders (Figure 2) may have been layers of plankton together with *Polybius* spp. Both depth and density of these layers varied along the transect, giving a patchy distribution which would be retained as a fish school by lidar. Other thick plankton layers, seen in some parts of the Bay of Biscay in 1999, also scatter light more effectively than sound. Similarly,

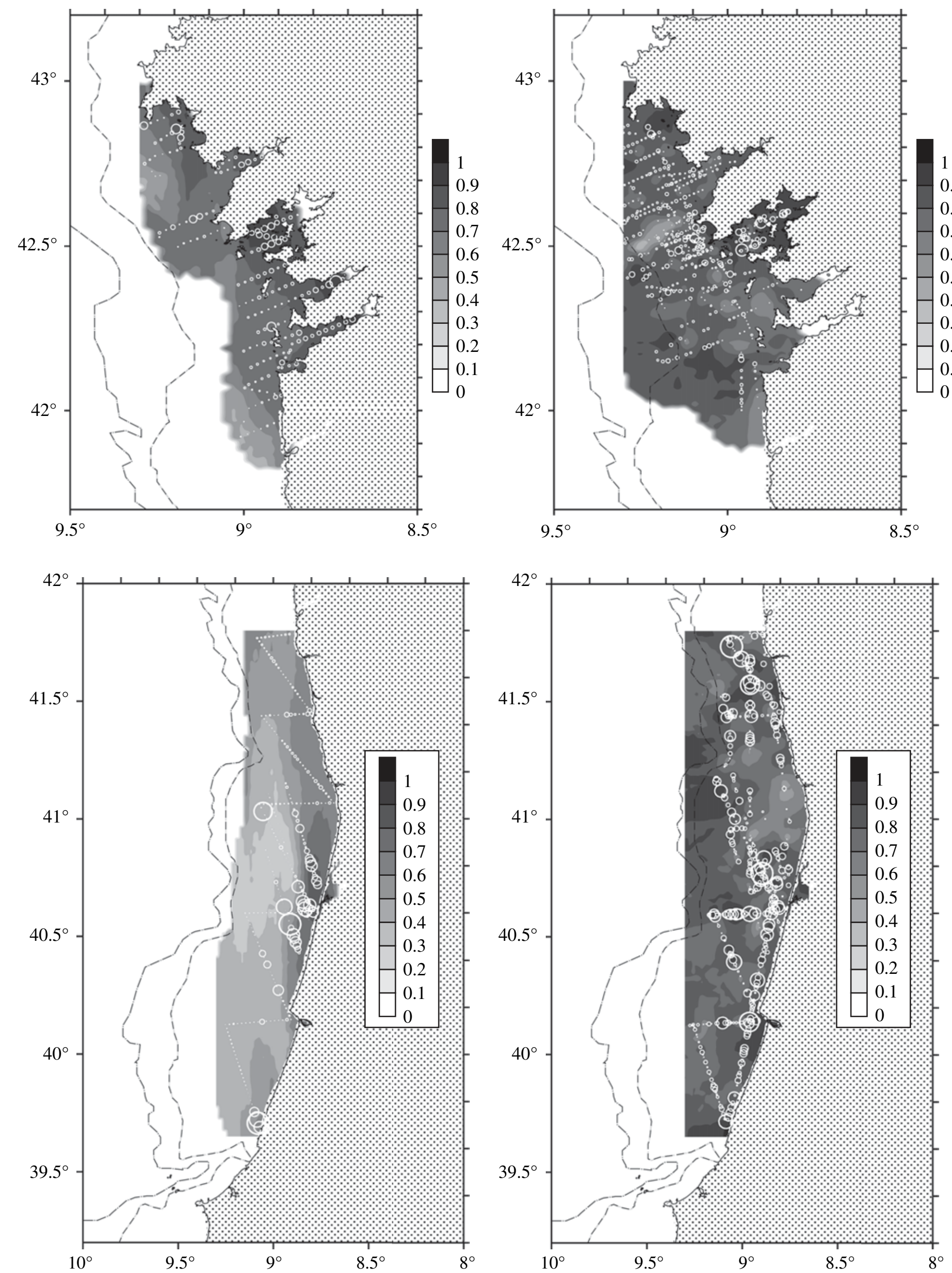

Figure 6. Contour maps made by kriging on log-transformed variables together with the raw backscattering energies represented as circles scaled using the square root method for 1998 data. Top panels, Galicia. Bottom panels, Portugal. Left, echosounder. Right, lidar.

fish without swimbladders do not scatter sound as effectively as fish with swimbladders, whereas differences in optical scattering between fish species do not depend on whether or not the fish has a swimbladder. This could explain the detections made in southern Galicia (off the Ría de Vigo) by lidar in 1999, where the echosounder detected very little. In that area, concentrations of juvenile mackerel, which do not have a swimbladder, were detected by both echosounder and fishing, but they produced very low echo-integration values, compared, for example, with sardine. Lidar, on the other hand, would produce similar backscattering energies for the same two fish species.

Lidar has a smaller target-strength difference than sound between plankton and fish, and between fish with and

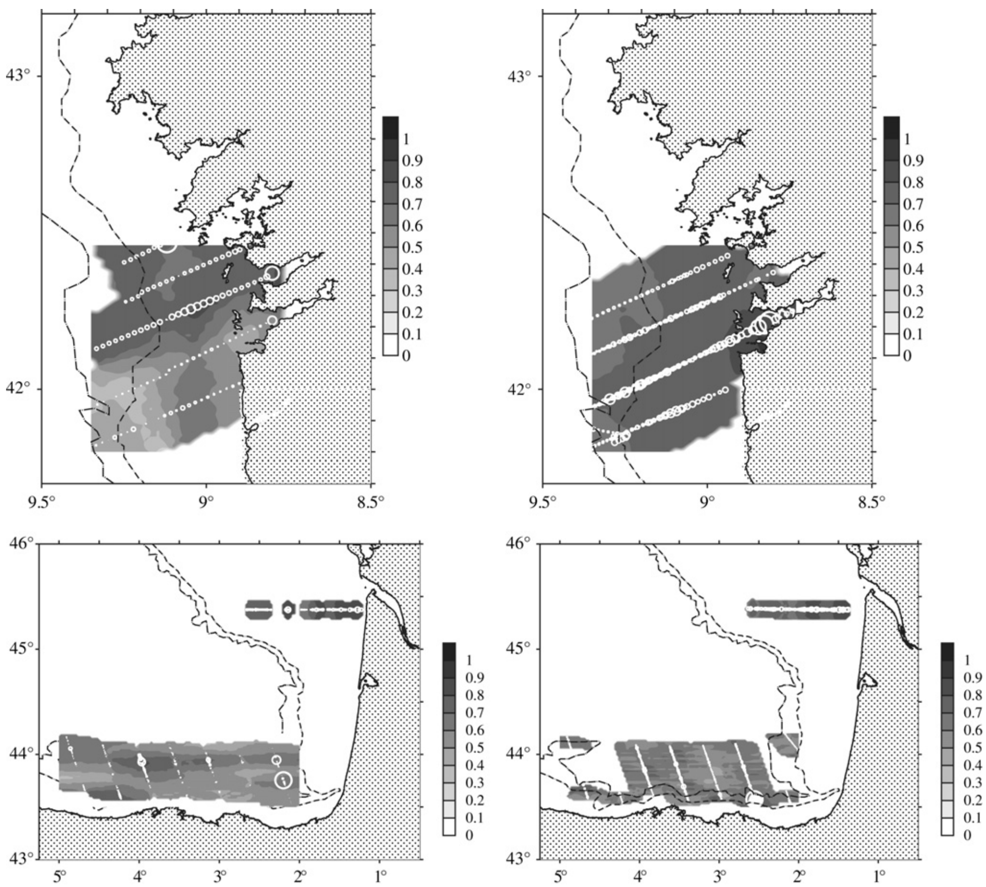

Figure 7. Contour maps made by kriging on log-transformed variables, together with the raw backscattering energies represented as circles, scaled using the square root method for 1999 data. Top panels, Galicia. Bottom panels, Bay of Biscay. Left, echosounder. Right, lidar.

without a swimbladder. This leads to noisier data, which make it more difficult to set a signal-threshold level to discriminate plankton from fish, than echosounders, and further complicate attempts to obtain a conversion from energy to fish biomass. As a consequence, it is clear that complementary fishing surveys for species identification of lidar detections are necessary. In addition, it is necessary to study the light reflectivity properties of fish and plankton targets, including polarization effects and the effects of school patchiness in the global signal return if we are interested in making lidar biomass estimations. Nevertheless, it is always advisable to select survey periods in which the fish schools are not mixed with plankton layers or other non-target scatterers.

The varying performance of lidar under different conditions of fish aggregation structure, plankton-layer intensity, and water turbidity (caused by suspended matter, or zoo- or phytoplankton) have made it difficult to establish a single satisfactory processing method for the different times of day, area, and species. Two types of lidar signal processing have been assessed during the current study; both gave interesting results under some conditions, but further refinement is required. The reflection that lidar obtains from a school of fish must be processed to obtain quantities proportional to the number of fish within the depth resolution. This issue has been considered before (Krekova *et al.*, 1994, Churnside and Hunter, 1996, Churnside *et al.*, 1997), although conversion into biomass requires species identification and experimental knowledge of fish reflectivity and size.

Direct HAGC analyses were performed to understand better the energy and visual-shape properties of particular target types. If we check the correlations annually, the results show better relationships for the set of HAGCs analysed in 1998, likely because there were different types of aggregations and lidar performance was better in 1998. The latter was caused by the need to operate at a lesser repetition rate in 1999. By types, the analysis was limited by the number of observations, which made it more difficult to obtain significant quantitative conclusions. However, the detections made by both sensors of small schools, scattered fish, and pelagic

Table 4. General description of the HAGC characteristics including echo trace type, time of day, date of echosounder survey, date of the corresponding lidar survey, length of HAGC (nautical miles), and the fraction of echosounder returns within the estimated depth coverage of the lidar.

HAGC	Type	Time of day	Date of use of echosounder	Date of use of lidar	Length	Area	Lidar fraction
1	Pelagic layer	Day	06/09/99	07/09/99	17	Bay of Biscay	0.53
2	Scattered	Evening	09/09/99	07/09/99	25	Bay of Biscay	1.0
3	Small	Day	16/09/99	16/09/99	6	Bay of Biscay	0.99
4	Scattered	Day	16/09/99	16/09/99	10	Bay of Biscay	0.59
5	Small	Day	16/09/99	16/09/99	13	Bay of Biscay	0.49
6	Pelagic layer	Day	08/09/99	07/09/99	9	Bay of Biscay	0.67
7	Pelagic layer	Evening	09/09/99	09/09/99	21	Bay of Biscay	1.0
8	Large	Day	05/09/99	07/09/99	14	Bay of Biscay	1.0
9	Small	Day	09/09/99	08/09/99	8	Bay of Biscay	1.0
10	Scattered	Evening	10/09/99	09/09/99	8	Bay of Biscay	0.98
11	Nothing	Day	31/08/99	31/08/99	39	Galicia	0.22
12	Nothing	Day	31/08/99	31/08/99	26	Galicia	0.03
13	Nothing	Day	02/09/99	02/09/99	22	Galicia	0.06
14	Small	Evening	01/09/98	31/08/98	10	Galicia	0.41
16	Large	Day	02/09/98	02/09/98	3	Portugal	1.0
17	Large	Day	01/09/98	02/09/98	3	Portugal	1.0
18	Small	Day	01/09/98	02/09/98	3	Portugal	1.0
19	Small	Day	03/09/98	02/09/98	3	Portugal	1.0
20	Scattered	Night	09/09/98	09/09/98	28	Bay of Biscay	0.73
21	Pelagic/scattered	Night	09/09/98	09/09/98	32	Bay of Biscay	0.79
22	Scattered	Day	15/09/98	15/09/98	73	Bay of Biscay	0.70
23	Large	Day	21/08/98	21/08/98	10	Galicia	0.53
24	Small	Day	21/08/98	21/08/98	8	Galicia	0.24
25	Small	Day	27/08/98	27/08/98	5	Galicia	0.74
27	Pelagic layer	Day	27/08/98	27/08/98	6	Galicia	0.61

layers were significantly correlated. It is not clear why echo-integration processing of lidar signals worked well for scattered fish, but was not as good as school processing for diffuse layers of fish and plankton. Lidar school processing seeks schooling structures and should provide good performance for schooling types, especially large ones, which are easier to detect. Contrary to this expectation, the correlation apparently failed for these large-school structures. This failure may be explained either by a greater shadowing effect on lidar backscattered energy, or by changes in the aggregation pattern or even shoal movements. Nevertheless it has been demonstrated that a consistency in school parameters exists across years and areas (Petitgas *et al.*, 2001; Muiño *et al.*, 2003), which permits this type of comparison. The lower correlation could be due to relative differences in sound target strength between fish and plankton, which are not the same as the differences in optical reflectivity. Hence, experimental research on the polarization-dependent reflective properties of fish and plankton targets should be performed as a basic step in implementing lidar as a routine survey system for fish resources.

Coastal and bottom topography and oceanography are very different throughout the region addressed here, which can affect lidar performance and operation. Along the Iberian Atlantic coasts, upwelling events are common in summer, and they contribute to the presence of fog, which diminishes the lidar capability. The Galician region has a narrow continental shelf, with depths <50 m close to the coast, a rough substratum, and narrow fjord-like Rías that occupy a large portion of the coast. The waters inside the Rías, such as those very close to shore in Galicia and Portuguese waters, are very productive and turbid, which will often limit lidar water penetration to the upper 15 m. Low-altitude aircraft operations within the Rías can be limited by safety considerations, especially at night. On the other hand, the Bay of Biscay has a narrow (south, Spain) or wide (north, France) continental shelf, with a stable water column. There, waters are neither as productive nor as turbid, so lidar penetration is optimal, reaching about 25 m (on average) during daylight in offshore waters inhabited by juvenile pelagic fish, and even deeper at night (about 35 m).

Applicability of lidar to survey juveniles of pelagic species in the area

Juvenile anchovy, sardine, and mackerel exhibit several common aggregation patterns and behaviour characteristics that make them potentially suitable for applying lidar technology. All are found in the upper layers of the water column, and, to a great extent, within the range of lidar. Also,

Table 5. Spearman and Pearson correlation between echosounder and lidar energies among HAGCs according to several aggregation criteria of target types (log energy values scaled to the mean per year and area). Results are given for the two types of lidar energy processing.

Criterion	*n*	R_S	R_P	*p*	r^2	R_S	R_P	*p*	r^2
Total	22	0.47	0.55	0.01	0.30	0.24	0.35	0.11	0.12
By type									
Small	7	0.96	0.90	0.01	0.81	0.46	0.42	0.35	0.17
Large	3	0.5	0.53	0.65	0.28	−0.50	−0.63	0.57	0.40
Pelagic layer	4	1.0	0.93	0.07	0.86	0.0	0.02	0.98	0.0
Scattered	5	0.20	0.50	0.39	0.25	0.50	0.77	0.13	0.59
Small + pelagic layer + scattered	16	0.54	0.57	0.02	0.32	0.41	0.44	0.09	0.20
By time									
Day	17	0.37	0.44	0.08	0.19	0.15	0.31	0.23	0.09
Evening	5	0.60	0.72	0.17	0.52	0.20	0.58	0.31	0.33
By year									
1998	10	0.61	0.68	0.03	0.46	0.39	0.68	0.03	0.46
1999	12	0.19	0.45	0.14	0.21	0.14	0.25	0.44	0.06
By area									
Bay of Biscay	11	0.28	0.36	0.28	0.13	0.18	0.12	0.73	0.01
Galicia	8	0.74	0.77	0.02	0.60	0.48	0.65	0.08	0.42
Portugal	3	0.50	0.93	0.23	0.87	−1.0	−0.78	1.43	0.60
Galicia + Portugal	11	0.74	0.74	0.01	0.54	0.31	0.60	0.05	0.36
By type in 1998									
Small	3	1.0	0.88	0.31	0.78	0.50	0.99	0.11	0.97
Large	3	0.5	0.53	0.65	0.28	−0.5	−0.63	0.57	0.40
Pelagic layer + scattered	4	1.0	0.90	0.10	0.81	0.80	0.76	0.24	0.58
By type in 1999									
Small	4	1.0	0.98	0.02	0.95	0.60	0.51	0.49	0.26
Pelagic layer + scattered	5	0.20	0.15	0.81	0.02	−0.10	−0.11	0.86	0.01

they concentrate in schools during daylight and disperse at night in pelagic layers, barely distinguishable from plankton, so making daylight the appropriate diel period for surveying.

There are also some common drawbacks in directly applying lidar to juvenile sardine and mackerel that need to be taken into account. Juveniles of both species share coastal Iberian Atlantic waters, mixed in different proportions with respect to each other, as well as with respect to other species (either adults or juveniles). This requires that a lidar survey be combined with an echosounder and fishing survey to assure the identification of the different species in the area. Also, the area of this study has several environmental features (described in the previous subsection) that tend to reduce lidar capability compared with oceanic waters. Finally, lidar detected schools in the offshore part of the area, where echosounders did not. This is likely because patches or layers of plankton are retained as a valid fish echo trace.

Juvenile anchovy are widely distributed throughout the upper layers of the Bay of Biscay. For that species, the medium-sized and largest schools of anchovy were detected by lidar, but small schools were hard to discriminate from the normal empty signal return, or from plankton layers. Therefore, although lidar surveys during daylight should, in principle, be able to detect these juveniles (particularly given the coverage), the relatively poor correlation in the HAGC analysis for the Bay of Biscay indicates a need for further study to discriminate reliably between juvenile fish schools and aggregations of plankton.

Therefore, for these potentially suitable species, lidar surveys could supplement a minimal echosounder cruise that would provide identification and biological sampling and estimation of the biomass of schools. From this perspective, it would seem that lidar surveys could improve the accuracy of an echosounder survey by adapting the number and the length of surveyed tracks to the total distribution of these juveniles shown by the lidar survey. Such a survey design would speed up the survey and reduce the total cost.

Conclusions

The positive correlation between lidar and echosounder backscatter, along with the visual correspondence observed in the kriged maps, suggest that lidar is able to detect and map aggregations of juvenile anchovy, sardine, and

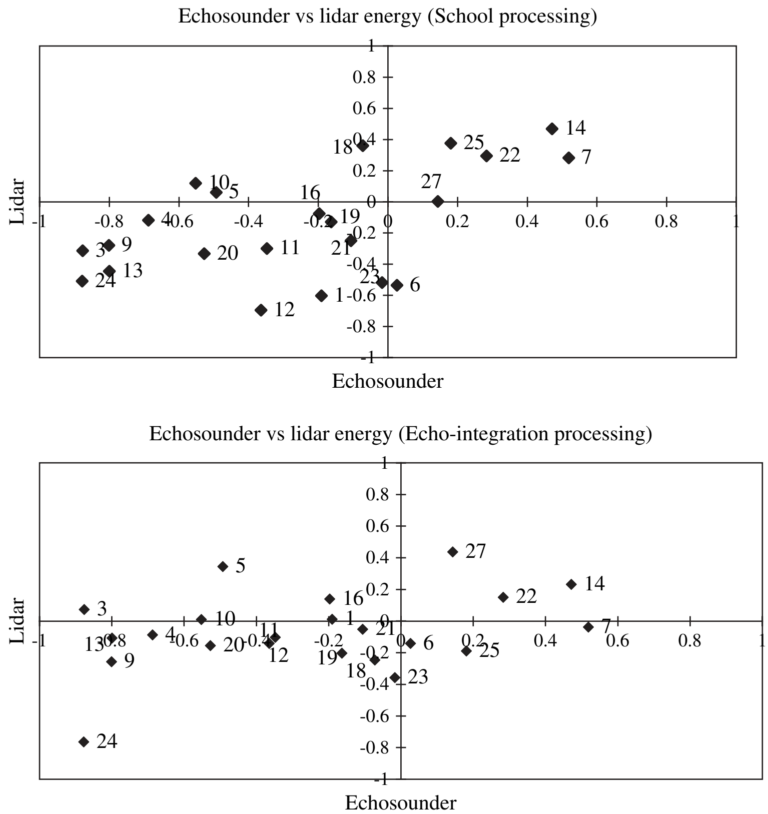

Figure 8. Scatterplots of echosounder and lidar energies (school and echo-integration lidar energies) for the different HAGCs.

mackerel. However, fish and plankton are difficult to discriminate in lidar data, and there are virtually no data available on optical target strengths for the different fish and plankton species present in the surveyed areas. Additionally, both the school and echo-integration processing algorithms failed to detect all possible aggregations of juvenile fish. Therefore, for airborne lidar to provide quantitative measures of fish distribution and abundance, significant progress must be made in the following areas: (i) modelling and measuring optical target strengths by size for the dominant fish and plankton species; (ii) improving species discrimination algorithms in lidar signal processing; and (iii) combining airborne lidar, shipborne echosounder, and direct sampling into a survey design to exploit the advantages of each platform and technique.

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