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Lidar target-strength measurements on Northeast Atlantic mackerel (*Scomber scombrus*)

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A linearly polarized green (532 nm) laser and a digital video camera were used to determine the reflectivity (R) and lidar (LIght Detection And Ranging) target strength (TS) of live mackerel by comparison with a standard calibration target. The measured reflectivity was 0.0141 ± 0.0005 when the receiver was copolarized with the laser and 0.0092 ± 0.0004 when the receiver was cross-polarized. The corresponding TS values were -42.66 ± 0.24 dB for the copolarized channel and -44.86 ± 0.23 dB for the cross-polarized channel. The depolarization ratio (depolarized return over total return) of 0.396 is very different from earlier measurements of sardine, suggesting that depolarization might be useful for species identification.

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Introduction

Mackerel (*Scomber scombrus*) are difficult to assess using standard acoustic assessment methods owing to their lack of a swimbladder (MacLennan and Simmonds, 1991). This results in a very low target strength compared with bladdered fish at typical echosounder frequencies, and an error in species allocation during echo integration can produce a large error in a biomass estimate. Consequently, the Norwegian Institute of Marine Research (IMR) has started a programme to find better assessment tools for the species. Part of this programme is a multi-frequency acoustic survey with the research vessel RV "G.O. Sars" (see Korneliussen and Ona, 2002). In addition, IMR has started a lidar (LIght Detection And Ranging) project.

Under some conditions, lidar can be more effective than an echosounder for estimating the distribution and density of fish. The main advantages of airborne lidar surveys over acoustic surveys are their ability to cover large areas in a short time and an absence of vessel avoidance. The major problems with lidar are depth-range limitations (maximum 50-m depth) and their dependence on good weather (no fog or clouds below the flight altitude). During mackerel summer feeding in the Norwegian Sea, the weather is normally fair, schools are close to or at the surface (above 50-m depth), and vessel avoidance is a problem in acoustic surveys (Misund, 1993; Aglen, 1994). These conditions suggest that lidar may be more effective than an echosounder for surveys of these fish.

Another advantage of lidar over sonar for quantitative surveys relates to the difference in scattering physics. Because of the different scattering mechanisms, the optical target strength of fish is less aspect-angle dependent than is the acoustic target strength at typical echosounder frequencies (Churnside *et al.*, 2001a). Additionally, the acoustic target strength depends on several variable properties of the internal structure of the fish that are difficult to model, including the depth-dependent swimbladder volume, the gonad size, and the stomach content. Optical scattering depends only on external properties of the fish that are not sensitive to depth.

To take full advantage of the lidar, it is important to know the target strength of the fish, which is related to its reflectivity, and to be able to distinguish between different species. The target strength is a measure of the proportion of the incident energy that is backscattered by the target (MacLennan and Simmonds, 1991). Previously, lidar reflectivity of live fish has only been measured for sardine

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(Churnside *et al.*, 1997). That study found that sardine reflected 0.097 of the light when the receiver was copolarized with the laser and 0.031 with a cross-polarized receiver, giving a depolarization of 0.24. Before that study, measurements were made on dead samples of five species of fish and one of squid (Churnside and McGillivary, 1991), with a range of total reflectivity of green light from 0.072 for a species of rockfish to 0.148 for the squid. The depolarization ranged between 0.132 for anchovy and 0.345 for another species of rockfish. The difference in depolarization (i.e. the ratio between cross-polarized and total returns) between the species is important, because it could be useful for species identification. Some measurements have been made of the reflectivity of fish in natural light (Benigno and Kemmerer, 1973), but these are of limited utility in lidar studies because they do not include polarization effects. The use of polarization also seems to have been developed by many marine animals. Polarization-sensitive vision has been discovered in fish (Cameron and Pugh, 1991), octopuses (Moody and Parriss, 1960), squid (Saidel *et al.*, 1983), and cuttlefish (Shashar *et al.*, 2000). It is used by cephalopods to detect zooplankton (Shashar *et al.*, 1998) and fish (Shashar *et al.*, 2000), and also for signalling (Shashar *et al.*, 1996). Therefore, it might be expected that polarization does convey useful information.

Based on this knowledge of mackerel behaviour and the advantages of the lidar, IMR used the NOAA Environmental Technology Laboratory's Experimental Oceanographic Fisheries Lidar (FLOE) to map the distribution and the density of mackerel in the Norwegian Sea and to test the efficacy of the lidar as a survey tool during July 2002. After completing the flights in the Norwegian Sea, the lidar was brought to the IMR station at Austevoll from 26 to 28 July 2002, to measure the reflectivity and the target strength of live mackerel related to size with both co- and cross-polarization. This paper presents the results of those measurements.

Material and methods

The target-strength measurements were conducted on live mackerel in a $12 \times 12 \times 10\,\mathrm{m}^3$ enclosure at Austevoll. The enclosure was partly covered to reduce direct sunlight and surface reflection, because the camera did not have a narrow-band optical filter to exclude background light. The measurements were conducted during periods of light wind, when the surface disturbance was negligible. A total of 151 mackerel were included in the study. Fork lengths of the fish were estimated from the video images by comparison with the known target dimensions. The average was 30.9 cm and the standard deviation was 3.4 cm. No attempts were made to influence the behaviour of the fish, so it was as natural as possible under the conditions.

Measurements were made using a laser and a video camera. The laser was the one from the FLOE lidar, a Neodymium-doped, Yttrium Aluminum Garnet (Nd:YAG) laser. This laser has a pulse length of 12 ns and a repetition rate of 30 Hz (Churnside *et al.*, 2001b). The light was converted from an infrared wavelength (1064 nm) to visible green (532 nm) through a non-linear optical crystal. A negative lens in front of the laser increased the beam divergence. The receiver was an off-the-shelf Panasonic digital video camera fitted with a rotatable polarizing filter.

The laser illuminated the fish and a calibration target from above the surface of the water. The camera was mounted next to the laser to image the illuminated area. They were about 2 m above the surface, tilted 15° from vertical to decrease surface reflections. This same angle is used in lidar surveys for the same reason. The laser beam was diverged to illuminate a circular area of approximately $1\,\mathrm{m}^2$ on the surface, covering the camera field of view. A 12.7-cm^2 target (Labsphere Spectralon) with a known reflectivity of 0.20 was lowered into the pen within the laser beam. This target is a very good approximation to an ideal diffuse reflector, and has a 0.50 depolarization ratio, to provide a reflectivity of 0.10 in the plane copolarized with the laser, and 0.10 in the cross-polarized plane. The target was suspended by monofilament line at the four corners, with a weight beneath it to maintain horizontal orientation.

The video signal was recorded under a variety of conditions. The polarizer on the camera was orientated parallel and perpendicular to the polarization of the laser. The target was suspended at depths of 30 cm and 80 cm below the surface. For each combination of these, data were recorded with the laser on and also with it off to measure the background light.

The digital images were transferred to a computer, and some were selected for inclusion in the study using several criteria. There had to be at least one mackerel within the laser beam, and no fish covering the target. The fish had to be at about the same depth as the target to avoid attenuation differences for the two paths. Images were also rejected if the image distortion caused by surface waves was too severe. Image selection to this level was done manually and was straightforward when the target was in the shallow position. When the target was in the deeper position, there was more shadowing of both the target and the fish by fish swimming shallower, and finding suitable images was more difficult. Also, determination of when the distortion was too severe was something of a subjective judgment, although a float around the pen kept the surface smooth, except for the occasional gust of wind. Figure 1 is an example of an image used in the analysis.

In each laser-illuminated image, the outlines of the target and of the fish were defined manually, and several quantities were calculated. First, the maximum pixel value in the green channel within the target area was found, then the number of pixels within each outline was counted by the computer. The size of each fish was estimated from the known size of the target.

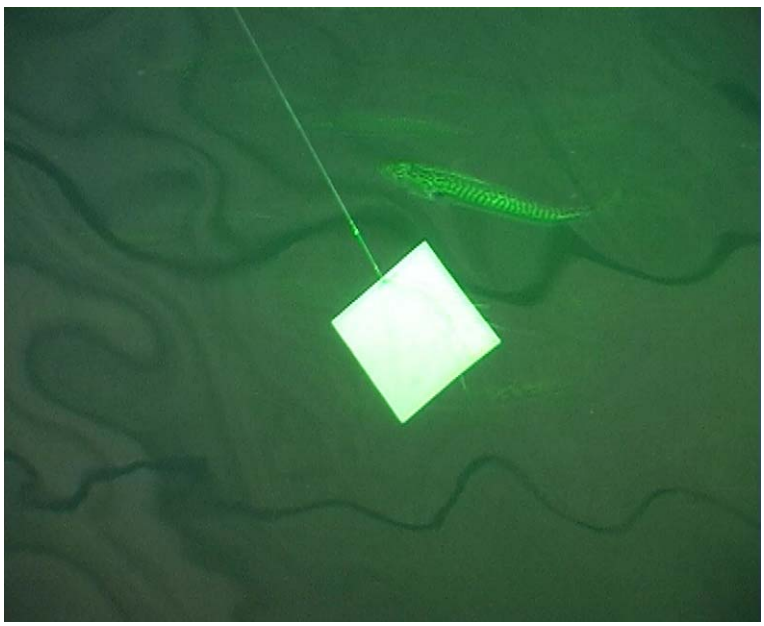

Figure 1. Typical frame from the videotape, showing the target and mackerel at a depth of 30 cm. Frame dimensions are 78 cm × 64 cm.

The standard deviation of the measured target area averaged about 9% of the mean when the target was 0.3 m deep, and about 13% when the target was at 0.8 m. These values are probably within the errors of manual digitization, and they suggest that distortion by surface waves was not a serious problem with the measurement.

In each of the selected images, the largest pixel intensity of the green channel in the target region was found, and the image was discarded if this value was equal to the digitizer saturation value of 255. If a large area of the target region was saturated, the actual average intensity could be much larger than the measured value. A single saturated pixel would probably produce a small error, but these cases were discarded anyway. The return from fish was always lower than that from the target, so it was not necessary to examine the fish regions for saturation. The number of pixels within the region identified as target and the number within the region identified as fish were then noted, and the average digitizer value for each of these regions in both the green and the blue channels was calculated.

The next step in data processing was to correct for the camera's non-linearity. The non-linear response of the green channel through the complete camera/recorder/player/digitizer system was measured in the laboratory using green laser light. Figure 2 shows the measurements and a polynomial fit given by

$$L = 657I - 765I^2 + 363I^3,$$

where L is the digitizer-output level and I is the illumination relative to the value that produces an output of 255. A second measurement of the green and blue channels using white light verified that this is also the response of the blue channel. The curve is very close to that of a gamma correction of 1.8, but the polynomial is more accurate and will be used. Pixels within the selected regions of the selected images were corrected for the camera non-linearity, using a look-up table based on the curve in Figure 2.

Next, a correction for background light was made by subtracting $1.08 \times$ the blue-channel value from each green-channel value. The coefficient is the average value of the green-to-blue ratio in the target when the laser was not on. Therefore, it represents the level of green background light expected for a measured level of blue background light.

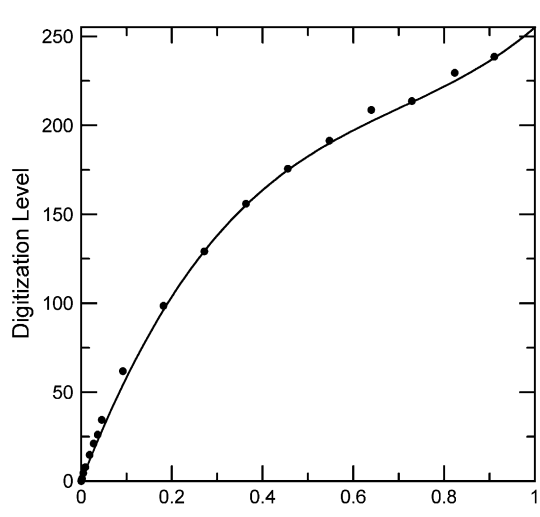

Figure 2. Measured values (symbols) and polynomial fit (line) for the non-linear response of the camera used in the study.

After applying the corrections, the reflectivity and the area of each fish were estimated. The average pixel value in the green channel was calculated for the target region to obtain I_t and the fish region to obtain I_f. With no polarizer on the receiver, the average reflectivity of the fish R would be calculated as

$$R = 0.2\frac{I_f}{I_t}.$$

For a co- or cross-polarized receiver, the copolarized or cross-polarized reflectivity is given by

$$R = 0.1\frac{I_f}{I_t},$$

where the change from 0.2 to 0.1 is due to the depolarization of the target. The area of each fish was calculated from the area of the target (0.0161 m^2) and the ratio of the number of pixels in the image of the fish, N_f, to the number of pixels in the image of the target, N_t.

The reflectivity R, as defined above, is not the actual reflectivity of fish skin. It is the reflectivity of a hypothetical object that scatters the same amount of light directly back towards the source as does the fish, but that scatters light with the same angular dependence as the target. Thus, R is a somewhat artificial quantity, but it is useful because the reflectivity of a flat, diffuse object is a familiar property.

The volume-backscatter coefficient is commonly used to calculate lidar-signal levels. It is given by

$$\beta(\pi) = \frac{RAM}{\pi},$$

where A is the average cross-sectional area of the fish in the beam and M is the number of fish per unit volume.

To relate this to more common acoustic quantities, we use the definitions of MacLennan *et al.* (2002). (Note that the intensity, as used in that paper, refers to the quantity called irradiance in optics, and has units of W m^{-2}.) Target strength is defined as

$$\mathrm{TS} = 10\log_{10}(\sigma_{bs}),$$

where σ_{bs}, the backscatter cross-section, is defined as

$$\sigma_{bs} = r^2 I_{bs}(r)10^{0.1ar}/I_{inc},$$

where r is the measurement distance and a is the attenuation. From this, we obtain the result that

$$\mathrm{TS} = 10\log_{10}\left(\frac{AR}{\pi}\right).$$

Note that the volume-backscatter coefficient, $\beta(\pi)$, is just the product of the backscatter cross-section σ_{bs} and the number density M.

Results

The main results for R and TS are listed in Table 1. For reasons described below, the values measured at a depth of 30 cm are preferred. Therefore, $R = 0.0141 \pm 0.0005$ in the copolarized channel and $R = 0.0092 \pm 0.0004$ in the cross-polarized channel, to produce a total reflectivity of 0.0233 ± 0.0006 and a depolarization of 0.396 ± 0.014. The target strengths were $\mathrm{TS} = -42.66 \pm 0.24$ dB for the copolarized channel and $\mathrm{TS} = -44.86 \pm 0.23$ dB for the cross-polarized channel.

The corrections for camera non-linearity and for background light were significant, but not so large that the results are invalid. The average correction for non-linearity in all samples was 26% of the uncorrected reflectivity, with values ranging from 12% to 42%. The average correction for background light was 14% of the value after correction for non-linearity, with values ranging from 0.3% to 59%. The average total correction was 35% of the uncorrected value, with values ranging from 11% to 69%. The magnitude of the total correction was less than 50% in more than 95% of the samples, so we expect the corrected values to be reliable.

The effects of changing illumination on the background correction were small, justifying the use of the average values of the green-to-blue ratio for all samples. The measured values for the different experimental configurations ranged from a minimum of 1.03 to a maximum of 1.15. If we use the smallest value for all samples, the results differ by <1% of the values in Table 1, except for the value for cross-polarized reflectivity at a depth of 30 cm, which is 1.4% higher. If we use the largest value, that same value is 1.7% higher, and all others differ by <1%. These differences are so small that the average ratio was used throughout.

The difference between the values measured at a depth of 30 cm and those measured at 80 cm is thought to be caused by a bias towards selecting fish shallower than the target when the target was at 80 cm. In the shallower data, it was fairly easy to tell when the fish were at about the same depth as the target, but this was much more difficult when the target was deeper. We note that the ratio of the average target size in the images from the two different

Table 1. Target depth, polarization condition, number of samples n, reflectivity R, and target strength TS for the four measurement conditions of the experiment

Depth (cm)	Polarization condition	n	R	TS (dB)
30	Co-	46	0.0141 ± 0.0005	-42.66 ± 0.24
30	Cross-	49	0.0092 ± 0.0004	-44.86 ± 0.23
80	Co-	18	0.0175 ± 0.0009	-40.89 ± 0.54
80	Cross-	38	0.0117 ± 0.0005	-43.16 ± 0.28

depths was 1.40. From geometrical considerations we would expect this to be 1.37, a difference of about 2%. Based on the consistency of this result and our expectations, we would expect the average fish size to be the same at the different depths. The actual measured values show the average fish size to be 1.17× larger when the target was deeper. This would suggest that the average fish depth was closer to 64 cm than to 80 cm. The average reflectivity would appear different because of the different geometry, and we can correct the reflectivity under the assumption that the average fish size is actually the same in both sets of measurements. The resulting reflectivities are 0.0149 for the copolarized case and 0.0100 for the cross-polarized case. The difference is about 6% of the recommended value or 0.9× the combined statistical error for the copolarized case. For the cross-polarized case, the corresponding values are 8% of the recommended value or 1.3 × the statistical error. Therefore, it seems plausible that the difference between the measurements at 30 cm and at 80 cm is caused by a bias in the depth of observed fish when the target was at 80 cm.

Because of the possible bias of the deeper data, we investigated the length dependence only for the data taken at 30 cm. For the copolarized data, 46 fish were used with a mean length of 30.6 cm and a standard deviation of 3.1 cm. This is a fairly narrow range of lengths, but there is a statistically significant dependence of TS on length: $\mathrm{TS} = -53.5 + 0.354L$, where L is the fork length in cm. The correlation between TS and length is given by $r^2 = 0.45$, and the significance of the regression is 3×10^{-7} by the F-test. For the cross-polarized data, 49 fish were used with a mean length of 29.8 cm and a standard deviation of 2.6 cm. The regression produces $\mathrm{TS} = -51.9 + 0.238L$, but there is more scatter in the data. Specifically, $r^2 = 0.15$ and the significance is 6×10^{-3}. Note that more measurements are required to extend the length dependence beyond the relatively narrow range of fish size used here.

The depolarization was calculated assuming that the co- and cross-polarized components are statistically independent, but a violation of this assumption would not affect the results significantly. We performed a Monte Carlo simulation assuming that the co- and cross-polarized components were Gaussian, with the measured means and variances. Using 10 000 uncorrelated samples of each, the calculated depolarization was 0.397. For the same number of perfectly correlated samples, the value was 0.390, a difference of <2%.

Discussion

This study demonstrated that mackerel reflect 0.0141 of the incident laser light in the plane copolarized with the laser and 0.0092 in the cross-polarized plane, giving a depolarization of 0.396. Churnside *et al.* (1997) previously showed that sardine give a copolarized return of 0.097 and a cross-polarized return of 0.031, a depolarization of 0.24.

The large difference in depolarization between mackerel and sardine suggests that depolarization can be used for species identification. Recording both the copolarized and cross-polarized lidar return requires two receivers, one for each polarization. There are two options for implementing a dual-polarization lidar. The most straightforward is to use a separate telescope for each polarization channel. The copolarized return is much larger than the cross-polarized return, so the second telescope can be much smaller than that currently used for the cross-polarized lidar if the size of the camera port in the aircraft is a limitation. Alternatively, a single telescope can be used, with a polarizing beam splitter to separate the two channels just in front of the detectors.

A dual-polarization lidar should also be beneficial when using the lidar in areas with great amounts of plankton, as is the case in the Norwegian Sea in July. Plankton depolarize the light to a lesser degree than do fish (Churnside *et al.*, 1997), so the plankton layers can be found as areas with less depolarization. Polarization effects have been used successfully to detect solid targets (Lewis *et al.*, 1999) and scattering layers (Vasilkov *et al.*, 2001). These studies show that there can be a significant advantage to using depolarization, even when depolarization of the incident light by multiple scattering from small particles is considered.

The effect of tilt angle was not treated in this study. The side of the mackerel is quite different from the top in colour and will probably give other values for reflectivity. Calculations of optical and acoustic scattering for sardine suggest that the angular dependence is less for lidar than for an echosounder (Churnside *et al.*, 2001a). In the example of that paper, a 15° tilt will change the lidar target strength by about 2 dB, while it will change the acoustic target strength at 38 kHz by about 8 dB.

The fish included in this experiment were swimming as naturally as possible within the pen. Frames containing fish that were swimming on their side through injury or other factors were not included. Even so, the angular distribution of fish in the open ocean may be different, depending on their behaviour when observed. This will affect the target strength. Fish with obvious skin lesions were not included. We do not expect the target strength of fish in the open ocean to be significantly affected by skin lesions, either. Even if 1% of the surface of all fish in a school were affected by some disease that increased the reflectivity over those areas by several times, the net result would be an error of only a few per cent.

There are several things that could be done to improve the measurement technique. A calibration target with lower reflectivity would reduce the dynamic range required and increase the accuracy. A horizontal camera in the water would help to discriminate against images where the fish are above or below the target. A narrow-band optical filter

like that used in field measurements would eliminate the need to estimate and remove background light. A camera with a linear response would eliminate the need to correct for the non-linearity. These changes are recommended for implementation in future measurements.

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