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MEASURED OPTICAL PROPERTIES OF SEVERAL PACIFIC FISHES

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Measured Optical Properties of Several Pacific Fishes

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Abstract. Reflectivity and depolarization of six species of fishes were measured using blue and green light. In general, the fish were between 15% and 25% reflective; values were higher in the blue than in the green. Depolarization varies significantly from species to species and may be useful in remote species identification.

1. INTRODUCTION

An effective remote sensing system would be a valuable tool in the management of fisheries. An airborne system is desirable so that fish stocks could be rapidly evaluated over large areas of the ocean. Such a system could be used commercially to locate schools of mature fish for harvesting. It could also be used by regulatory agencies to assess current fish stocks and also to evaluate juevenile populations so that future harvest levels can be set.

For many years, commercial fish spotters have found schools of fish visually from the air.[1-3] During the day, they use color, shape of the school, and movement of fish within the school to determine fish species. Visibility is limited by the quality of the illumination, the roughness of the sea surface, and the turbidity of the water. At night, the species is identified by the pattern of bioluminescence generated as the fish swim through luminescent plankton. Visibility is limited by background illumination (especially moonlight) and by the type and concentration of phytoplankton present.

Some of the difficulties associated with low bioluminescence levels can be partially overcome by electronic imaging devices such as image intensifiers and low–light level video.[3-5] These systems can be designed to be sensitive only to the 470 to 480 nm bioluminescence band and discriminate against much of the background illumination. This combination allows operation at higher altitudes so that a larger area can be covered more quickly. It also allows operation at times when visual observation would be useless.

Perhaps the best candidate for an effective remote fish sensor is airborne lidar. In a lidar system, the illumination level can be adjusted to obtain the desired performance (at least within the limits of available technology). The receiver can be matched to the very narrow laser bandwidth, and a high level of background discrimination can be achieved. Also, the receiver can be range-gated and the depth and thickness of a school of fish can be obtained.

Murphree et al.[6] analyzed the feasibility of airborne lidar for fish detection and performed a qualitative laboratory demonstration. They concluded that airborne lidar was feasible and suggested what a system might look like. Fredriksson et al.[7] observed fish to depths of 10–15 m using a fairly modest laser (< 0.2 mJ) in a laboratory tank. Shipborne tests of the same system were not as encouraging because of highly turbid surface waters during the limited test period. Squire and Krumboltz[3] actually observed fish schools from an airborne platform and succeeded in obtaining the thickness of a school nearly 10 m below the surface. They conclude that improved lidars could detect schools of fish to depths as great as 75 m.

However, two issues need to be addressed before operational fish-detection lidar can be considered: (1) At what depth can fish be observed under various ocean conditions? and (2) Can species be identified reliably? To answer either question, we need more information about the optical properties of the fish involved. Therefore, we measured the optical properties of six species common to the California coastal waters. We measured reflectivity, necessary to calculate depth limitations, and depolarization, which may aid in species identification. The measurements were made at blue and green wavelengths with an Ar^{+}-ion laser.

The target species were northern anchovy (*Engraulis mordax*), jacksmelt (*Atherinopsis californiensis*), yellowtail rockfish (*Sebastes flavidus*), vermillion rockfish (*Sebastes miniatus*), Pacific mackerel (*Scomber japonicus*), and squid (*Loligo opalescens*). Several criteria were used in choosing these particular species. They are all abundant off the California coast and are commercially important. They are all small enough to handle conveniently in the laboratory. Finally, none of them change drastically in appearance at death as many species do.

2. PROCEDURE

Figure 1 is a block diagram of the experimental configuration. Light from the laser propagates across the laboratory and enters a tank full of water. Inside the tank, it reflects off a suspended fish and scatters back to the photomultiplier tubes (PMTs) near the laser. Optics in front of each PMT are used to diffuse the scattered light and select the desired polarization component.

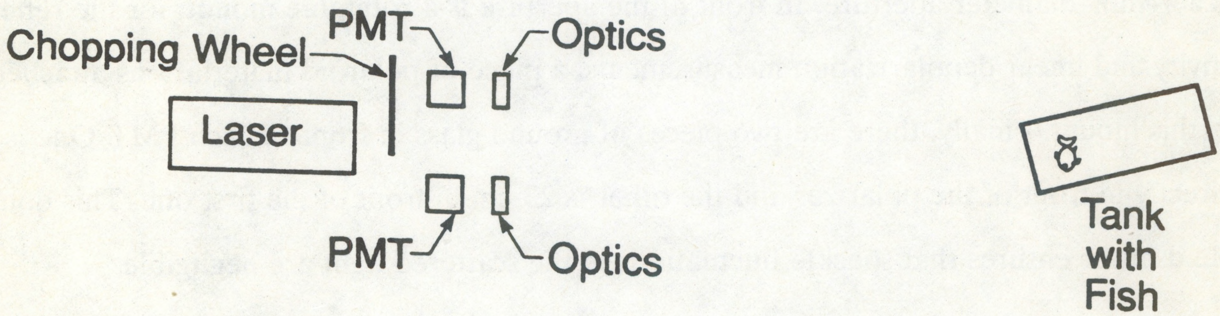

Figure 1. Schematic diagram of laboratory apparatus.

The laser is a vertically polarized Ar^+-ion laser. It was operated alternately on the 488–nm blue line and the 514.5–nm green line with a constant output power of 150 mW. The beam has a 1.3–mm diameter and a 0.6–mrad divergence, which results in a beam diameter of just over 3 mm on the fish. A 286–Hz chopping wheel was placed directly in front of the laser.

The tank was positioned just over 3 m in front of the laser. It was turned at an angle so that the reflection from the front glass surface would not be seen by the detectors. In addition, the back, sides, and bottom of the tank were lined with aluminum that was painted flat black. This eliminated the possibility of multiple reflections off internal glass surfaces. The fish were hung vertically about 5 cm behind the front of the tank.

The PMTs were placed near the laser at a distance of 3 m from the spot on the fish. One PMT was on each side of the beam at a distance of 3.5 cm, so the scattering angle was within 12 mrad of π. We therefore assume that we were very nearly measuring the backscatter properties.

Directly in front of each PMT is a 10–nm–bandwidth optical bandpass filter; one PMT responds only to the blue laser line and the other only to the green. In front of each filter is a 4–mm–diameter aperture. In front of the aperture is a rotatable mount; for the reflectivity and linear depolarization measurements, a piece of polaroid material was attached to this mount. Finally, there are two pieces of ground glass in front of each PMT. One is directly in front of the polarizer and the other is 23 cm in front of the first one. This double diffuser ensures that speckle fluctuations in the scattered light are negligible.

A 100–kΩ load resistor was used on each PMT. The resulting signal was fed into a lock-in amplifier along with a timing reference generated by the chopping wheel. The lock-in was operated with a 1-s time constant. The PMT signal voltage was measured by the lock-in and recorded on a personal computer. The maximum signal was less than 5 μ A, and we were well below the saturation level of the PMT that was used.

Before measuring the voltage levels generated by the fish, we wanted to obtain a calibrated, immersible reference target. We settled on a piece of flat aluminum with 100–grit sandpaper glued to each side. One side was painted flat white and the other flat black. The reflectivities of these were measured by comparison with a $BaSO_4$ reflectance standard. This consisted of a 1–cm–thick layer of packed $BaSO_4$ powder. The final packing density was 1.6 g cm^{-3}. The reflectivity of pressed $BaSO_4$ has been extensively studied.[9-12] Values from 0.98 to 1.0 have been reported for the two wavelengths used here. No studies report significant differences in reflectivity between 488 nm and 514.5 nm. We used 0.99 at both wavelengths as the best available value.

The return signals were measured for the $BaSO_4$, the white sandpaper, and the black sandpaper placed just in front of the tank. The two polarizations were summed, and the reflectivity of each sandpaper target was calculated. The procedure was repeated five times as a check on the repeatability. The mean and sample standard deviation of the sandpaper reflectivities are given in Table 1. Note that the white paint is, in fact, very nearly white. The black paint reflects slightly more of the blue than of the green.

To make the measurements, we thawed a fish and hung it in the tank by its tail. First, it was hung with its back to the beam to simulate a downward-looking lidar. The fish was positioned so that the laser beam was just in front of the dorsal fin. We then recorded the PMT voltage at one color for both the vertical and horizontal polarizations, tuned the laser to the other color, and recorded the other PMT voltage for the two polarizations.

After the four voltages from the top of the fish were recorded, the fish was turned over, and the same four measurements were made from just behind the pectoral fins on the bottom of the fish. This may not have direct application to fishery applications of lidar, but the difference between the top and the bottom of the fish is interesting. Finally, the fish was removed and the two–color, two–polarization measurements were made for both the white and the black sandpaper. The entire measurement sequence thus produced 16 different voltages.

The measurement sequence just described was performed five times for each fish. The only exception to the process described was the placement of the beam on the squid. It was suspended by its tentacles and illuminated at the center of the mantle on the top and the bottom.

After the measurements using linear polarization were completed, the apparatus was modified to use circular polarization. A quartz quarter–wave plate was placed in front of the laser to convert the vertical polarization to right–hand circular at both wavelengths. The polaroid material on each PMT was removed from the rotatable mount and fixed on the aperture so that only vertically polarized light was allowed through. A mica quarter-wave plate at the correct wavelength was attached to each rotatable mount. In one orientation of the mount, left–hand circularly polarized light is converted to vertically polarized light and is detected. When the mount is rotated 90 degrees, right–hand circularly polarized light is detected.

The measurement sequence used for the linear polarization measurements was repeated for the circular polarization measurements. It was also repeated five times for each fish.

3. RESULTS

The first quantity evaluated was the reflectivity of the tops of the fish. Reflectivity was calculated from

$$R_{FISH} = \frac{R_{WHITE} - R_{BLACK}}{V_{WHITE} - V_{BLACK}}(V_{FISH} - V_{BLACK}) + R_{BLACK} \qquad (1)$$

where R refers to a reflectivity, V to a voltage, and the subscripts FISH, WHITE, and BLACK correspond to the fish and to the white and black sandpaper, respectively. Each voltage in this equation is the sum of the voltages for the vertical and horizontal polarizations.

The reflectivity was calculated for each measurement sequence using the mean sandpaper reflectivities from Table 1. The mean and sample standard deviations of the blue and green reflectivity for the five measurements of the top of each fish are presented in Table 2. Several generalizations can be made from these data. The first is that the squid is significantly different from the true fish. The true fish are very dark, with an average reflectivity of 21% in the blue and 18% in the green. Note that Squire and Krumboltz[3] assumed a reflectivity of 50% to describe their observed signals at a wavelength of 530 nm. This value is almost certainly too high. Murphree et al.[6] used 10%, which is too low. The squid is much lighter. Also, the true fish tend to have a lower reflectivity in the green portion of the spectrum than in the blue. The ratio of the green to the blue reflectivity varies from 0.80 for the yellowtail rockcod to 0.87 for the smelt. In appearance, the true fish are all nearly the same dark grey color. The squid has a slightly higher ratio of 0.90.

The corresponding values for the bellies of the fish are presented in Table 3. The reflectivities are much higher and the color differences are much less than for the fish backs. This agrees with the visual observation that the fish bellies are white. We should also point out the high reflectivity and large variation in the mackerel values. The reflection from the center of the belly of this fish contains a specular component. Therefore, the measured reflectivity is very sensitive to the precise orientation of the fish. Since we assumed that we were measuring a diffuse reflectivity, the measured value could be, and was, greater than 1.

We also measured the linear depolarization ratios. This is merely the voltage from the PMT when the horizontal polarization was observed divided by that when the vertical polarization was observed. A ratio of 1 would represent complete depolarization of the scattered light.

Values for the fish backs are presented in Table 4. We note that there are significant differences between the species measured. This suggests that the depolarization ratio may be an important aspect of species identification. Also, we note that the degree of depolarization is higher in the green than in the blue for all species. We currently have no explanation for this feature.

Depolarization ratios for the fish bellies are presented in Table 5. The depolarization ratios are generally larger than for the backs of the same fish. Also, there seems to be less difference between the blue and the green than for the fish backs.

Circular depolarization ratios were obtained by dividing the PMT voltage from left-hand circular light by that from right-hand circular light. Results from the fish backs are presented in Table 6. The circular depolarization ratios are higher than the linear ratios in each case. The trends are similar, however. There seem to be significant differences between species. Species having low or high depolarization ratios with linearly polarized illumination tend also to have low or high ratios with circularly polarized illumination. Circular depolarization is generally higher in the green, although it is about the same for the anchovy and lower for the mackerel.

Circular depolarization ratios from the fish bellies are presented in Table 7. These are higher than those for the fish backs. In fact, they are generally near 100% depolarizing. The notable exception is the mackerel, which was about 200% depolarizing. This seems to be related to the specular reflection, because the measurements with the highest reflected power in the measurement set also had the greatest depolarization. However, the specific mechanism is unknown.

4. CONCLUSIONS AND DISCUSSION

We conclude that reflectivities of 15 to 25% should be used in modeling fish lidar system performance. We also conclude that depolarization ratios are significantly different between species and may be a useful quantity for species identification.

The reflectivities, however, are for dead fish. These numbers must be verified using live fish. Also, the optical properties of other species that change visibly on death must be measured while they are alive.

If depolarization is to be used to identify species, the depolarization caused by particulate scattering in the water column above the fish must be taken into account. If the light illuminating the fish is highly depolarized, the additional depolarization caused by the scattering from the fish will not be noticeable. This effect also requires further study.

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Table 1. Reflectivity of painted sandpaper (in percent)

Sandpaper	blue	green
white	74.3 ± 1.7	74.0 ± 2.3
black	18.0 ± 1.9	14.0 ± 4.2

Table 2. Reflectivity of fish back (in percent)

Fish	blue	green
Anchovy	21.0 ± 0.3	17.4 ± 0.3
Smelt	25.6 ± 1.5	22.3 ± 1.9
Yellowtail rockfish	18.2 ± 0.1	14.6 ± 0.8
Vermillion rockfish	21.0 ± 0.8	17.2 ± 0.8
Mackerel	19.8 ± 0.9	16.0 ± 0.6
Squid	32.6 ± 1.6	29.5 ± 1.5

Table 3. Reflectivity of fish belly (in percent)

Fish	blue	green
Anchovy	46.6 ± 2.2	44.9 ± 4.7
Smelt	63.2 ± 2.0	63.1 ± 2.1
Yellowtail rockfish	44.0 ± 1.4	43.5 ± 4.0
Vermillion rockfish	42.1 ± 2.7	39.0 ± 3.3
Mackerel	92.7 ± 34.5	95.9 ± 32.5
Squid	43.9 ± 1.8	41.4 ± 1.9

Table 4. Linear depolarization of fish back (in percent)

Fish	blue	green
Anchovy	11.3 ± 1.0	15.2 ± 0.6
Smelt	33.0 ± 4.2	37.4 ± 5.9
Yellowtail rockfish	16.0 ± 1.4	18.6 ± 2.7
Vermillion rockfish	47.4 ± 4.5	52.7 ± 4.5
Mackerel	26.4 ± 4.9	28.8 ± 5.6
Squid	41.5 ± 3.6	47.5 ± 3.5

Table 5. Linear depolarization of fish belly (in percent)

Fish	blue	green
Anchovy	41.4 ± 4.0	42.2 ± 4.1
Smelt	69.5 ± 1.9	69.1 ± 9.1
Yellowtail rockfish	71.6 ± 2.3	75.4 ± 14.3
Vermillion rockfish	72.1 ± 2.6	73.6 ± 3.2
Mackerel	33.9 ± 9.5	33.1 ± 7.3
Squid	55.1 ± 2.4	58.4 ± 1.4

Table 6. Circular depolarization of fish back (in percent)

Fish	blue	green
Anchovy	16.8 ± 1.8	16.1 ± 1.3
Smelt	60.9 ± 11.7	66.8 ± 8.6
Yellowtail rockfish	42.6 ± 2.4	43.7 ± 4.5
Vermillion rockfish	67.7 ± 7.6	69.9 ± 5.9
Mackerel	60.2 ± 5.2	53.3 ± 2.8
Squid	57.3 ± 3.3	61.2 ± 3.6

Table 7. Circular depolarization of fish belly (in percent)

Fish	blue	green
Anchovy	80.9 ± 10.8	85.0 ± 10.4
Smelt	106.1 ± 1.8	104.6 ± 2.1
Yellowtail rockfish	107.0 ± 4.3	106.0 ± 2.4
Vermillion rockfish	98.5 ± 0.9	97.4 ± 0.7
Mackerel	195.9 ± 54.2	218.1 ± 46.3
Squid	74.0 ± 1.8	73.4 ± 1.5

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