HOW TUNA SEE A NET

By Frank Hester* and John H. Taylor**

ABSTRACT

The horizontal sighting range of a submerged object in the sea is physically determined by the attenuation and scattering of light over the path of sight and by the contrast of the object with the underwater background. The former is a measurable quantity alpha which varies with locality in the sea. The latter is determined by the shape and reflective characteristics of the target and by the underwater lighting geometry. In this paper these principles are applied to determine and control the underwater sighting range of tuna seines.

Records of tuna seining operations kept by the California tuna fleet over the past dozen years show that more successful sets are made either in turbid water or at night. It looks as though the success of seining operations is limited in part by the fact that in clear water the fish see the net in time to avoid it. Because of this, we have become interested in finding out how a net is seen by tuna. In this article, we will discuss our preliminary findings, including methods for making nets less visible. Also, an understanding of light in the sea can lead to an improvement in seining strategy which might improve the success of the seining operation even using existing nets.

The visibility of objects under water by humans has been studied intensively for the last decade by the Visibility Laboratory of Scripps Institution of Oceanography of the University of California under the direction of Dr. S. Q. Duntley. Much of the information obtained can be applied directly to our problem. For this reason, a cooperative program has been begun between the U. S. Bureau of Commercial Fisheries Biological Laboratory, San Diego, and the Visibility Laboratory, which will extend this knowledge to help us find out how tuna see a net.

The similarity between our problem of tuna seeing a net and visibility by a human observer is plain. However, our problem is complicated in that we can not yet compare the visual ability of a tuna with that of a human swimmer. Also, previous studies have dealt with the visibility of solid objects, whereas, nets have special properties which we have yet to evaluate. Nevertheless, one can apply the results of the previous experiments with humans and solid objects to tuna and nets and come up with some answers. We can make a good guess as to how the distance at which tuna can see nets varies in different fishing grounds. We can predict how this sighting range will change with sun elevation or time of day and cloud cover. And, finally, we can use this information to point out ways to change the visibility of nets.

Sighting range depends on the distribution of the light field under water, the clarity of the water, the nature or type of object we wish to sight, its position in relation to the observer, and the ability of the observer to see. To predict the sighting ranges of submerged objects we should first learn something about the behavior of light under water.

Those of you who have been under water to free a bait net or clear a propeller will recall that light beneath the surface rapidly becomes dimmer with depth; that the brightness of the water background changes with the path of sight, being brightest when looking towards the surface; and that, even in clear water, objects at a distance seem to blur, their outlines becoming less and less distinct as the distance increases.

The rapid dimming of light as one goes deeper is caused by the absorption of light by sea water. This absorption is greatly increased by dissolved material such as one finds near shore and by the very small plants and animals that grow in the sea and often discolor the water. But, even in the very clearest offshore water, light is rapidly absorbed so that, no matter where one is in the sea, this loss of daylight with depth holds true.

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Absorption of light by sea water, however, is not nearly so important to our problem as is the scattering of light by small suspended particles in the water. Just as the beam of a spotlight or the headlights on a car are reflected back or scattered by fog or dust in the air, so is sunlight scattered by the very small (living and dead) plants and animals and the inorganic material such as sand and silt that are present in the sea. Figure 1 shows how a beam of collimated light, that is, light with parallel rays, is scattered. Most of the beam continues in its direction of travel but some of the light is reflected back and some is scattered in other directions.

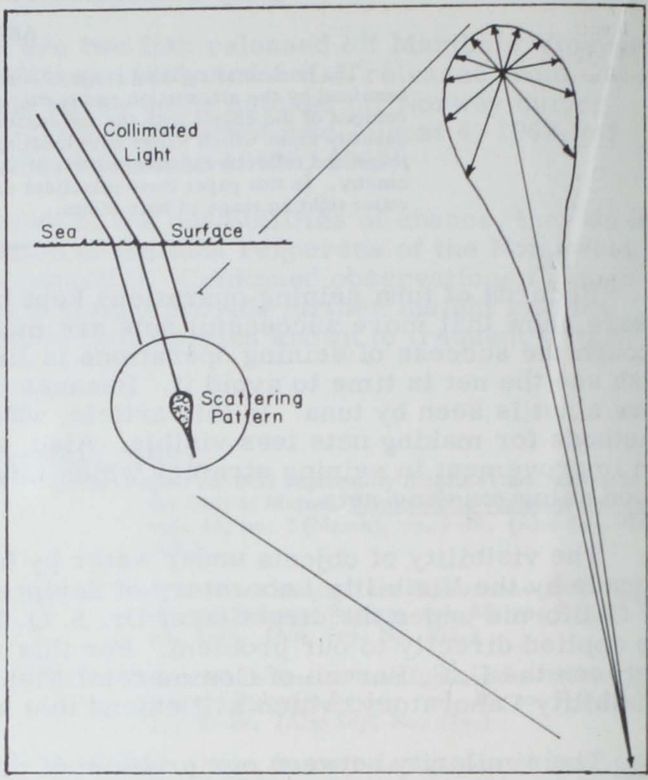

Fig. 1 - Diagramatic representation of the scattering of collimated light by sea water. The length of the arrows in the enlarged picture at the right represents the amount of light being scattered in each direction. By far the greatest amount of light continues in the original direction.

Scattering of light in the sea is very important also in determining the distance at which objects can no longer be distinguished from the underwater background. In fact, scattering is so important that a special instrument has been designed to measure it. This instrument shines a collimated light beam through a known amount of water, usually 1 meter, to a photocell receiver. This receiver is similar in principal to a photographic light meter. By knowing the amount of light at the source and the amount reaching the receiver, the loss of light energy over the known distance between source and receiver can be calculated. This loss is proportional to the loss due to absorption and scattering over that distance. This loss is by custom referred to by the Greek letter alpha (α). The dimensions of alpha can be natural log units per meter or, in our case, per foot ($\frac{\text{ln}}{\text{ft.}}$). A quantity like this is difficult to visualize so frequently the value of ($\frac{1}{\alpha}$) is used. This value is called the attenuation length and expresses the distance of water required to reduce the brightness of our light to about its original brightness. For example, alpha in figure 3 is 0.05 ($\frac{\text{ln}}{\text{ft.}}$). Attenuation length ($\frac{1}{\alpha}$) then would be 20 feet. This means that if we separated the light from the receiver in our alpha meter by 20 feet the receiver would show that the light was about $\frac{1}{3}$ its original brightness.

Attenuation length is a measure of water clarity. Short attenuation lengths (large values of alpha) are associated with dirty, turbid nearshore water, whereas, long attenuation lengths (small values of alpha) are usually found offshore. The table gives some values of alpha attenuation length measured in the Pacific Ocean.

A surprisingly large number of objects can be seen about four times the attenuation length under water. This is, of course, an approximation and requires certain conditions to prevail. For most dark objects this approximation is very useful in predicting, once alpha has been measured, the underwater sighting range.

If we now combine the two properties of sea water we have discussed, namely, absorption and scattering, a very interesting feature of the underwater light field becomes apparent. Previously, we noted that the brightness of the water background changes, depending on our path of sight. This is because, as the collimated rays of the sun enter the water, some are scattered and some continue in the original direction of travel. All the rays, however, are subject to steady weakening from absorption. Near the surface and looking up, there will be a bright spot corresponding to the position of the sun. As one goes deeper, this bright spot will tend to become less distinct due to scattering.

Surface Values of Alpha (α) and Attenuation Length ($\frac{1}{\alpha}$) at Various Locations in the Pacific Ocean
(The horizontal sighting ranges for many objects in the sea by human observers are about four times the attenuation length. Sighting ranges of tuna nets vary between 3 and $3\frac{1}{2}$ times the attenuation length.)

Location	α ($\frac{\ln}{ft.}$)	Attenuation Length in ft. ($\frac{1}{\alpha}$)
San Diego Bay (May 1964)	0.70	1.43
La Jolla (April 1964)	0.18	5.56
Catalina Island		
(August 1963)	0.06	16.70
(June 1964)	0.16	6.25
Morgan Bank (February 1962)	0.12	8.33
Socorro Island (February 1962)	0.05	20.00
Mexico - off Acapulco (February 1962)	0.04	25.00
Costa Rica		
Inshore (July 1962)	0.26	3.84
Offshore (July 1962)	0.05	20.00
Hawaii (April 1964)	0.03	34.20

Also, those rays traveling at an angle will have to go farther than those which are scattered straight down and, therefore, they will have been subject to absorption by the water for a longer distance by the time they reach the same depth than the light scattered straight down. At some depth, then, the rays travelling the longer distance will have been absorbed to the point where they are not so strong as the light traveling straight down and the brightest spot in the underwater field will have moved until it is directly overhead. The rest of the light field becomes gradually darker as the path of sight changes from directly overhead to straight down. That this would occur was first proposed over 30 years ago and, in 1960, John E. Tyler of the Visibility Laboratory of the University of California, experimentally demonstrated that this actually does happen. Depending on the amount of scattering and absorption, the depth at which this occurs will vary from a few feet in very dirty water to several hundred feet in very clear water.

We can picture the shape of the underwater light field as approximating an egg. If the observer is inside this egg, the distance from the observer to the shell can represent the brightness of the background for any particular path of sight. The greater the distance to the shell, the brighter the background. On overcast days at all depths, and on sunny days with a zenith sun, or below the depth we just discussed, the brightest area or greatest distance to the shell will be overhead at the zenith and the darkest area will be straight down at the nadir (fig. 2 (a)). The dimensions of the egg will change with depth as will the degree to which it is tipped from the vertical. If we cut the egg with a horizontal plane, we find that the brightness of the background looking in any direction is as represented in figure 2 (c), being a circle in the first case where the egg is upright and an ellipse in the second case where the egg is tipped.

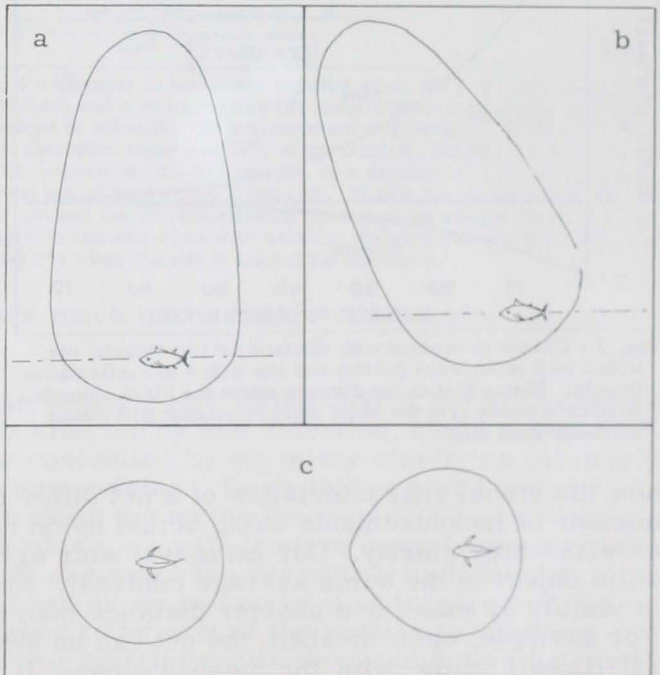

Fig. 2 - A typical shape of the under water light field. The greater the distance from the eye of the fish to the side of the egg the brighter the background for that path of sight. (a) represents the shape on overcast days or for a zenith sun. (b) represents the shape on cloudless days when the sun is not overhead. (c) shows the shape of the field on the horizontal planes indicated by the dotted lines in (a) and (b).

The ability of a human being to distinguish from its background has been the subject of numerous experiments and observations. We are, of course, dealing with a fish, not a man; as noted earlier, we do not know yet how well a fish can see under water. Our problem, however, deals primarily with the ability to distinguish contrasts, that is, to detect differences in brightness, and in this ability, fish and humans are probably more nearly alike than they are in other respects. We will assume for the moment that fish and man detect contrast about the same so that we may come up with some estimates of net-sighting ranges.

Seeing an object means that in some way we can detect a difference between the amount or kind of light energy coming from various parts of the object and that coming from its background. Under water, where colors rapidly disappear leaving only blues and greens, we are more interested in the difference in intensity rather than color of light energy. We call the difference between the object and its background its contrast. We can assign numbers to contrast by defining it as the brightness of the object, this is, the amount of light being received from the object, minus the brightness of the background, all divided by the brightness of the background. Or, if we call the object brightness B_t and the background brightness B_o, then contrast $C = \frac{B_t - B_o}{B_o}$. From this, you can see that contrast can assume values ranging from minus one (when the object reflects no light at all and the background does reflect light) to some very large positive number when the object reflects a great deal of light and the background does not. In other words, contrast is negative when the object is darker than its background and positive when the object is lighter than its background. Experiments with humans show that objects whose contrasts are equal numerically are seen equally well whether the sign of the contrast is positive or negative. This is to say that even a perfectly black object (contrast -1) will have the same sighting range as a light object with a contrast of +1. (The light object being, therefore, twice as bright as the background.) Since light objects are often several times brighter than their background, they are usually more visible than dark ones.

When both the object and its background are equally bright, contrast is zero and the object is invisible. Actually, with the human and probably the fish, contrast does not have to be zero but only close to zero for an object to be invisible.

Of the many useful observations which have come out of the Visibility Laboratory, perhaps the one which relates changes in contrast to alpha is most important for our problem. Their experiments have shown that, for horizontal paths of sight, the contrast between an object and its water background diminishes exponentially with distance. This change in contrast with distance is shown for a black target and a white target in figure 3. As long as we know three things: The brightness of the target, the brightness of the water background, and alpha, we can calculate the distance at which it will no longer be visible (insufficient contrast for seeing), assuming that we are looking horizontally, that the target is bigger than a certain size, and there is sufficient light. Equally interesting, we can work backward and calculate the brightness an object must have at some specified distance so that it will be invisible against a given background.

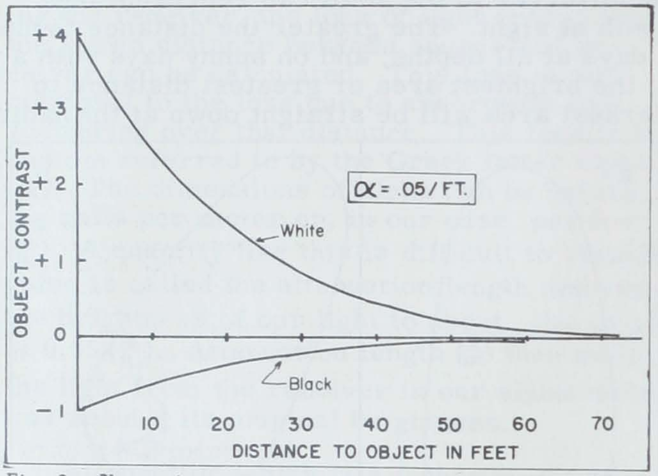

Fig. 3 - Change in contrast with distance for two objects, one with a high reflectance (white) and one with a low reflectance (black). Notice that at the distance where the black object's contrast is nearly zero the white object's contrast still differs markedly from zero.

The preceding strictly applies only to solid objects above a certain minumum size. To date, there has been no attempt to discover how the visual characteristics of a net differ from those of a solid object. We have made a number of measurements using actual nylon net samples to show how sighting distance changes with water clarity. Our measurements agree in general with what we would predict for a solid object of the same average contrast. However, we find that a net with the meshes open is visible by man for a shorter distance than if it is bunched up so that it appears to be solid. For example, open-meshed, the net can be seen horizontally 102 feet away in the clear water off Hawaii while, with the meshes closed, it can be seen 138 feet away. Similar measurements made off San Diego showed that, open, the meshes could be seen 36 feet and, closed, 41 feet away.

If the underwater light field is as in figure 2 (a) so that the background brightness does not change with azimuth, we would expect the sighting range to be the same regardless of the azimuth of the path of sight. We have seen, however, that on sunny days near the surface, the background brightness does change with azimuth and that the water is brighter in the direction of the sun and darker looking away. As long as the object we are considering has such a low reflectance (looks black) that it is always much darker than the background, its contrast will always be close to minus one and the sighting range will not change greatly with azimuth. This is shown in figure 4 by the curve labeled "net" and corresponds to a newly tarred nylon net with its meshes tightly bunched. The other curve represents the sighting range of a flat white surface that reflects 91 percent of the light falling upon it. This surface is held vertically in the water with its flat side directed toward the observer. You will notice that when viewed in the direction of the sun its contrast is also negative. As its azimuth changes, its surface becomes brighter until its contrast reaches zero at a relative bearing of about 25°. From this point on it becomes brighter and brighter, its contrast now being positive, until, at 90°, it has as great a positive contrast with the background as the dark net does a negative. At this point, the sighting range of the net and the white target should be the same.

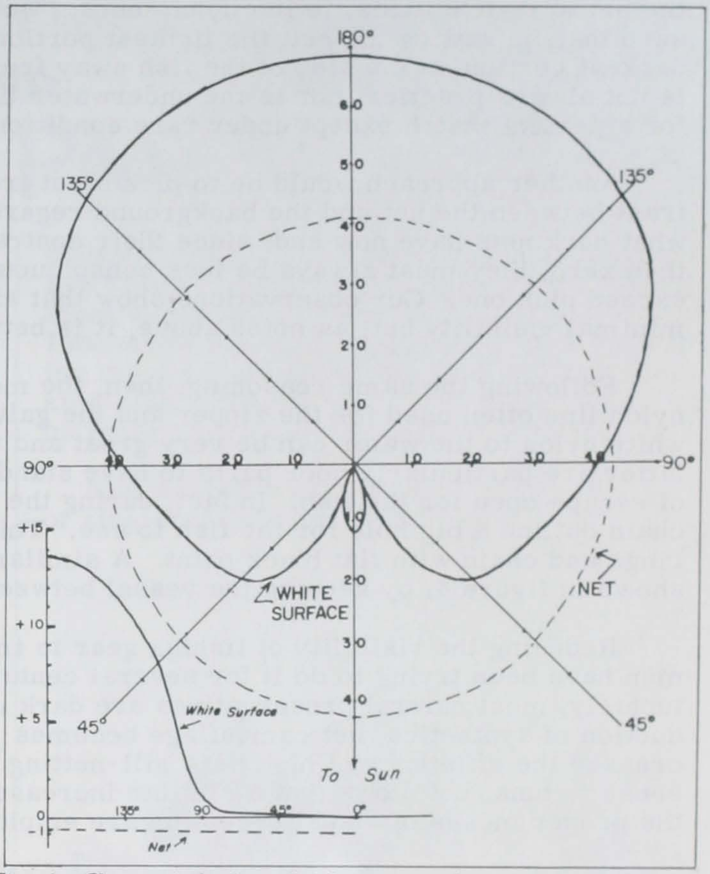

Fig. 4 - Changes in horizontal sighting range for a net sample (meshes bunched) and a white surface (91 percent reflectance submerged) with changes in azimuth. This experiment was made off La Jolla Calif. Sun elevation angle was 58°, α was 0.08/ft. Depth was 30 ft. Changes in contrast for the two samples at a distance of 3 ft. from the observer are plotted at the lower left. Notice the small variability for the net and the large variability for the white surface (from a slight negative contrast when seen between the observer and the sun to almost +14 when the sun is behind the observer).

Between 90° and 180°, the contrast of the white object becomes increasingly positive and the sighting distance exceeds 60 feet. The net curve under the same condition only shows a change of 1 foot between the two extreme positions. This experiment was done off San Diego in April 1964. Had this experiment been done in Hawaiian waters in April, the white surface would have been visible over 215 feet instead of only 60 feet. Generally it is true that light-colored objects such as purse rings, galvanized chain, and expecially white nylon line, are much more visible under water than dark objects.

So far, we have shown that the visibility of an object under water during the day is dependent on its contrast with the background. This is affected by sun elevation, cloud cover, and depth. The distance over which it can be seen is controlled by the water clarity as measured by alpha. This knowledge now can be applied to tuna seining. To do this, we will assume that the way to increase the rate of success is to make the net as inconspicuous as possible. Since the rate of success is fairly high in murky water, we will concern ourselves with clear, offshore waters. Two courses are open to us: we can make the net nearly invisible by matching its contrast to that of the water background or we can make it of transparent material. This second choice may, in the future, prove to be part of the answer to catching skipjack in clear water. However, it is unlikely that existing multi-thousand dollar nets will be abandoned immediately, so we will confine ourselves to considering ways of decreasing the visibility of the nets presently used in the fishery.

The basic idea of camouflage is to hide an object by making it look like something else, often the background. In the case of a tuna seine, there is nothing else to look like but the background. We want the brightness of the net to match the background brightness as nearly as possible for any path of sight. Since the brightness of the background varies, as we have seen, along different paths of sight, we would have to darken and lighten various portions of the net to match. This, in itself, of course, would not be enough for we would have to make sure that, in setting the net, the lightest portion was between the fish and the sun and the darkest portion on the side of the fish away from the sun. Laying out the net in this manner is not always practical nor is the underwater light field always the same so we cannot hope for a perfect match except under rare conditions.

Another approach would be to pick a net treatment that would result in a negative contrast between the net and the background regardless of the path of sight. Actually, this is what dark nets have now and, since their contrast can never exceed minus one or be greater than zero, they must always be less conspicuous than a light-colored net whose contrast can exceed plus one. Our observations show that existing nets are too dark for them to have minimal visibility but, as noted above, it is better to have too dark a net than too light a net.

Following the same reasoning, then, the most conspicuous parts of the net are the white nylon line often used for the zipper and the galvanized chain and rings. The contrast of the white nylon to the water can be very great and the rings and chain are not far behind. These latter are particularly poor parts to have stand out since they tend to outline the only avenue of escape open for the fish. In fact, during the last few minutes of pursing, the rings and chain outline a big hole for the fish to see. This effect could be reduced by darkening the rings and chain with flat black paint. A similar reduction in contrast could be obtained, as shown in figure 4, by keeping the vessel between the sun and the net.

Reducing the visibility of fishing gear to improve success is nothing new. Trout fishermen have been trying to do it for several centuries, net fishermen for a lesser time. Fortunately, most natural preservatives are dark and this is beneficial. Today, with the introduction of synthetics, net camouflage becomes practical. Monofilament has certainly increased the efficiency of high seas gill-netting. Since vision is perhaps the most important sense to tuna, it follows that a similar increase in success is possible for the tuna fishery if the proper means of visual deception are employed.