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FACTORS, MAINLY DEPTH AND WAVELENGTH, AFFECTING THE DEGREE OF UNDERWATER LIGHT POLARIZATION

BY

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ABSTRACT

Field and laboratory comparisons of visual, photographic and photoelectric methods of measuring linear polarization of underwater light demonstrate that satisfactory agreement may be obtained between their results. While laboratory data match closely, several uncontrollable factors, especially changes in cloudiness, increase the variance of field measurements. Of the three, the photoelectric polarimeter lends itself best to the study of degree of polarization in the horizontal plane at various depths. The present report briefly describes the principle of this device and summarizes the results of a series of measurements correlating principally the effects of wavelength ($\lambda$) and depth ($h$) down to 115 m with the degree of linear polarization in submarine illumination ($p$) of water masses having a wide range of turbidities. Although the data so obtained are continuous through 360° in azimuth, most of the analyses have been made for $\theta = 0°, \pm 90°$ and $180°$ with a few for $\pm 45°$, where $\theta$ is azimuth measured from the sun’s bearing, positive to the right, negative to the left. In general, $p$ is maximal near the surface, diminishes rapidly in the first 10–40 m, and then decreases more slowly to some equilibrium level. The maximal $p$, the extent of its rapid decrease, and the equilibrium value all depend strongly on the turbidity of the water, on the cloud cover, and on the proximity and albedo of the bottom. Polarization increases rapidly with transparency in turbid and moderately clear waters but more slowly in extremely clear water. Thus, in quite clear water far from the bottom $p$ may reach 60% or more near the surface, decrease rapidly at greater depths to about 40 m, and then level off slowly to 30% in deep water. Under such conditions, with the solar zenith angle ($i$) not too small, $p$ is maximum for $\theta = \pm 90°$, less for $\theta = 180°$ and least for $\theta = 0°$. With $i$ smaller or with greater turbidity, $p$ at $\theta = 180°$ may equal $p$ at $\pm 90°$; under extreme conditions of this sort $p$ may not vary with $\theta$. The influence of $\lambda$ on $p$ is small but definite, with $p_{\min}$ occurring at blue or blue-green wavelengths; both ends of the spectrum, particularly the longer wavelengths, polarize more strongly. The amplitude

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of the effect of $\lambda$ on $p$ ($\Delta p$) is small when $p$ is small, but $\Delta p/p$ appears relatively constant.

Most of these facts are consistent with the origin of submarine linear polarization by scattering. The degree of polarization decreases when the diffuseness of underwater light increases; that is, it decreases mainly with cloudiness, with depth, with turbidity, and with the $\lambda$ of greatest penetration.

INTRODUCTION

The pattern of linearly polarized light in the sea was first demonstrated in shallow water (Waterman, 1954) and then at greater depths down to 200 m (Waterman, 1955). Later, quantitative measurements were initiated using photographic (Ivanoff, 1955, 1956a, 1956b) and visual (Waterman and Westell, 1956; Waterman, 1958) techniques. A theoretical analysis correlating the degree of polarization ($p$) with the angular distribution of submarine illumination showed that $p$ should decrease both with depth ($h$) and for the most penetrating wavelength ($\lambda$) (Ivanoff, 1957a). However, at that time the available field data were limited to shallow water and were not suitable for studying the effect of $\lambda$. To help remedy these deficiencies, a remote control polarimeter capable of operating down to 120 m and of selecting any of six spectral regions was built (Ivanoff, 1957b). Preliminary measurements with this device showed that polarization does in fact decrease with $h$, but they still did not demonstrate the effect of $\lambda$ (Ivanoff, 1957b).

The present paper reports results of a systematic application of this instrument in Bermuda, where the influence of various factors, mainly $h$ and $\lambda$, on the degree of polarization of submarine light were measured. Also included are comparisons of the two other methods previously used independently by the authors. At the same time, the occurrence and origin of elliptical polarization in the sea was studied, but this work is reported elsewhere (Ivanoff and Waterman, 1958).

INSTRUMENTATION

The Photoelectric Polarimeter. Since the three methods we have used to measure underwater light polarization have already been described (Waterman, 1955; Ivanoff, 1956b, 1957b; Waterman, 1958) they need not be considered in detail. However, the principle of the photoelectric polarimeter must be understood because it provided most of the data presented here; consequently it is diagrammed (Fig. 1) and briefly described. Essentially the photocell, with the aid of the revolving mirror (M), scans the horizontal lines of sight underwater through $360^\circ$ at a rate determined by the mirror's rota-
Figure 1. Photoelectric polarimeter. I, II, water-tight compartments suspended by cable and solidly connected by stiff metal plate, III; C, Westaphot photocell; D, azimuth stabilizing fin; F, changeable interference filters; G, weight to maintain vertical; H, horizontal plane; M, 45° front surface mirror to reflect horizontal light rays into window, W, of chamber I; \( m_1 \), motor to rotate Polaroid P filter (P) at about 2 \( \text{rpm} \) and a half-wave mosaic (Q) at about 500 \( \text{rpm} \); \( m_2 \), motor to change or remove filters in light path; \( m_3 \), motor to rotate mirror at 0.22 \( \text{rpm} \).
tions. The revolving Polaroid filter (P) acts as an analyzer for any linear polarization present in the incoming light, and the rapidly rotating half wave (for $\lambda = \text{ca. } 550$ m$\mu$) mosaic (Q) depolarizes the light from the Polaroid to eliminate the possibility of an artifact arising from variations of photocell sensitivity with plane of polarization. The fact that the Polaroid filter is not a perfect analyzer will result in measured degrees of polarization somewhat smaller than the actual ones, an effect which will be increased to some extent by the finite angular field of the instrument.

The further possibility of artifacts due to pressure birefringence originating in the window (W) of chamber I is minimized or excluded by using a special type of plexiglass. This shows but little birefringence under pressure, and even this small amount would be appreciable only for rays deviating considerably from the optical axis. The photocell is connected by an insulated cable (not shown in Fig. 1) to a shock mounted galvanometer on the ship's deck. Because of the rotation rate of the Polaroid, a fast indicating instrument is required with a time constant shorter than 2 sec.

The dimensions of the optical system are such that the beam being measured illuminates nearly the whole photocell surface (about 61 mm in diameter). The sensitivity of the latter, which is maximal for a horizontal pencil of parallel light, decreases to 75% for a ray inclined to the horizontal by 7°. It is well known that the current produced by a barrier photocell is proportional to the irradiance so long as the latter is low and the cell feeds into a low resistance. In the case of the Westaphot cell and galvanometer (internal resistance = 680Ω) used here, the response is linear within 1% so long as the illuminance does not exceed 12 lux and the loading current is less than 2$\mu$A. This was generally the case in our measurements, made either with colored filters or without filters at considerable depths. On the other hand, without filters at shallow depths the conditions necessary for a linear response were not present. However, the error so introduced for $I_{\text{max}}$ and $I_{\text{min}}$ is always reduced in the calculation for $p$ (see p. 291).

Between the depolarizer and the photocell a series of interference filters (Table I) can be inserted as desired by remote control. One of these is a narrow band blue-green element (Balzers Filtraflex B-40); the other five are broad band filters (Balzers Filtraflex Series K). To study the effects of wavelength accurately, the transmission curves of the various colored filters used should be corrected for spectral distribution of the submarine light, which itself varies with $h$ and $\theta$. However, since the influence of $\lambda$ on underwater polarization is weak, the maximum transmission of each filter for white light is used here. The slight displacement of the observed points relative to $\lambda$ which
results from the corrections concerned would scarcely affect our conclusions. On the other hand, the effect of $\lambda$ on the polarizing properties of the Polaroid filter in the instrument is a significant one and is discussed below.

**Comparison with Earlier Methods.** While nearly all of the present data were obtained with the photoelectric polarimeter, a series of comparative measurements were made both in the field and in the laboratory to contrast this instrument with the two others previously used. The questions of present interest are: first, whether the photographic and visual techniques provide essentially the same information on submarine polarization as does the photoelectric method; second, whether all of these various instruments are equally versatile and accurate in obtaining the desired data.

To the first question the evidence of five parallel series of field measurements made in inshore waters down to 18 m provides essentially an affirmative answer. In general the $p$ determined by each of the three methods under as closely identical conditions as possible showed satisfactory agreement when average values are considered (these varied from 7-22% at the different stations and under the prevailing meteorological conditions). However, the relatively low degree of polarization of the waters studied, and particularly the variable cloudiness of the sky (often inevitable), had an adverse effect on the precision of all of these measurements. Nevertheless, in the only set of data where $p$ was as much as 20%, the differences between the three methods just exceed 5% in absolute value.

These comparative measurements also showed clearly the relative advantages and disadvantages of the three methods. In accuracy the visual and photoelectric techniques were superior to the photographic; in either of the first two techniques the absolute error of a single measurement does not exceed 5% whereas in the photographic technique it may exceed 5%. The photoelectric instrument is more convenient for collecting much data since, unlike the other two, it does not require a SCUBA diver to operate it; this also removes any restriction to relatively shallow depths. On the other hand, the present photoelectric instrument is less versatile than the others because it operates only in a horizontal plane; furthermore, it does not permit measurement of the polarization plane. However, since data on $p$ are particularly needed and since many measurements are required to determine the influence of $h$ and $\lambda$ on $p$, this is the instrument of choice for present purposes.

Almost perfect agreement between the visual and photoelectric methods of determining $p$ was found in the laboratory (Fig. 2). Here
a light source whose degree of polarization could be varied by changing the angle of a pile of glass plates in the beam was measured. This suggests that measurements made in the field by these methods are also closely comparable although the difficulties of field work usually increase considerably the variance of such data.

![Figure 2](image_url)

**Figure 2.** Laboratory comparison of visual and photoelectric methods of measuring degree of polarization ($p\%$). Abscissa shows angle of inclination of a pile of glass plates used to produce partially polarized light. Photoelectric measurements, open circles; visual measurement, solid circles (see text).

**Effects of Incomplete Polarization.** While these comparative studies were being made, the same laboratory set-up was used with the photoelectric polarimeter to test the influence of the various filters in the instrument on the polarizing properties of its Polaroid P analyzer. Average results of five measurements at one inclination angle of the glass plates are shown in the last column of Table I. The results are between 51.7 and 52.1\% without filter and with filters $K_2$, $K_3$ and $K_5$.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Approx. max. transmission $\lambda$ (m$\mu$)</th>
<th>Band width for $40%$ transmission (m$\mu$)</th>
<th>$%$ polarization* by Polaroid P analyzer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_1$ (violet)</td>
<td>415</td>
<td>380–430</td>
<td>48.0</td>
</tr>
<tr>
<td>$K_2$ (blue)</td>
<td>445</td>
<td>430–465</td>
<td>51.8</td>
</tr>
<tr>
<td>$K_3$ (blue green)</td>
<td>490</td>
<td>460–500</td>
<td>51.9</td>
</tr>
<tr>
<td>$K_4$ (yellow green)</td>
<td>550</td>
<td>515–570</td>
<td>50.4</td>
</tr>
<tr>
<td>$K_5$ (orange)</td>
<td>600</td>
<td>580–610</td>
<td>51.7</td>
</tr>
<tr>
<td>B-40 (blue green)</td>
<td>500</td>
<td>494–506</td>
<td>50.4</td>
</tr>
<tr>
<td>Without filter</td>
<td>—</td>
<td>—</td>
<td>52.1</td>
</tr>
</tbody>
</table>

* See text for explanation of this partially polarized test source.
but at 500 m\(\mu\) (B-40) and 550 m\(\mu\) \((K_1)\) the Polaroid’s polarizing properties apparently diminish slightly; at 450 m\(\mu\) \((K_1)\) they definitely diminish.\(^2\) If the Polaroid actually transmits at “extinction” a fraction \(kP\) of the incident linearly polarized light and if \(k\) is zero without filter as well as with filters \(K_2\), \(K_3\) and \(K_5\), then the above figures give the following coefficients: \(k = 0.019\) for \(K_4\) and B-40, \(K = 0.052\) for \(K_1\). These permit corresponding corrections to be made in the measured \(p\);\(^3\) this has been done in all data given below.

In the next section the new information obtained with the photoelectric polarimeter serves not only to illustrate the capabilities of the instrument but to provide quantitative data on several aspects of submarine light polarization.

**RESULTS**

1. **General Factors**

Two examples of the type of records obtained with the photoelectric polarimeter are shown in Figs. 3 and 4. While the mirror (M) sweeps through the horizontal plane (one revolution taking about 4.5 min) and if the incoming light is polarized linearly, the photocell output to the galvanometer undergoes a series of oscillations from maximum to minimum that arise from rotations of the Polaroid (one turn taking about 32 sec). If these maxima and minima are plotted, the two curves so obtained in turn oscillate between maxima and minima which occur respectively in the bearings of the sun and the anti-sun. Provided the azimuthal position of the polarimeter does not change, the time intervals between these points of zero slope are equal; when they were not, boat drift was usually responsible; this was minimized, when necessary and possible, by fore and aft anchors. When the mirror faces the metal plate (Fig. 1, III) connecting the lower pressure case of the instrument to the upper one, there is a sudden decrease in the apparent light level,\(^4\) but this artifact is usually easy to eliminate, as shown in Figs. 3 and 4.

\(^2\) The decreased polarization of violet light by the filter used is in accord with the average data published by its manufacturer although the slight dip at 500 and 550 m\(\mu\) is not. The latter, however, is not crucial for our argument.

\(^3\) The increased submarine polarization at the extreme violet end of the spectrum was not noticed in the first measurements with the photoelectric polarimeter (Ivanoff, 1957b) because the decreased polarizing properties of the Polaroid filter at these wavelengths was not considered.

\(^4\) In the earlier version of the polarimeter (Ivanoff, 1957b) three brackets connected the two main parts of the polarimeter. The resulting three minima in the records made the analysis of the results more difficult and less certain. The replacement of the three brackets with a single supporting plate greatly increases the accuracy of the present measurements.
Figure 3. Photoelectric measurements obtained in very clear water with solar zenith angle about 33°. Data taken at 1345, 27 August 1957, St. 1 (Fig. 5); bottom, 2500 m; Secchi disc reading, 50 m. Polarimeter at 16 m using the 500 mμ narrow band filter. Maximal galvanometer readings during rotation of Polaroid, solid circles; minimal ones, open circles. Dotted line indicates shadowing effect of metal plate which connects two chambers of polarimeter. Broken vertical lines A-E indicate five positions of mirror for which the degree of polarization was calculated from equation 
\[ p = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \].

The angular difference (θ) between azimuth of instrument’s line of sight and sun’s bearing is 0° for A and E, ±90° for B and D, and 180° for C. Computations for p are as follows:

A. \( p = \frac{(106 - 45)}{(106 + 45)} = 40.4\% \)
B. \( p = \frac{(61 - 20)}{(61 + 20)} = 50.6\% \)
C. \( p = \frac{(48 - 16)}{(48 + 16)} = 50.0\% \)
D. \( p = \frac{(74 - 24)}{(74 + 24)} = 51.0\% \)
E. \( p = \frac{(105 - 46)}{(105 + 46)} = 39.1\% \)

Within errors of measurement, p is the same at this station for θ = ±90° and 180° (av. 50.5%), but it is definitely smaller at θ = 0° (av. 39.7%). If the effect of wavelength on the polarizing properties of the Polaroid filter is adjusted, the averages become 40.8% for θ = 0° and 52.0% for θ = ±90°, 180°. The ratio of maximal to minimal horizontal radiances which occur at θ = 0° and θ = 180° respectively, is \( \frac{(106 + 46)}{(48 + 16)} = 2.4 \).

For a given θ the ordinates for the two curves connecting the maxima and minima are proportional respectively to \( I_{\text{max}} = I_{n/2} + I_p \) and \( I_{\text{min}} = I_{n/2} \), where \( I_n \) and \( I_p \) are respectively the unpolarized and linearly polarized fractions of the incident light. Hence the polarization factor is
Figure 4. Photoelectric measurements obtained in less clear water (Fig. 5, St. 3) than those in Fig. 3 and with a greater solar zenith distance (about 67°). Data taken at 1630, 26 August 1957. Polarimeter at 5.4 m, using the 500mμ narrow band filter; bottom, 15 m; Secchi disc reading, 10 m. Symbols and method of plotting as in Fig. 3. The corresponding degrees of polarization in various azimuths are: A. 4.7%, B. 18.3%, C. 12.5%, D. 18.4%, E. 4.3%, F. 18.2%, and G. 13.1%. Obviously, although the percent polarization is less over-all, it varies considerably more with azimuth here than in Fig. 3. On an average, \( p = 4.5\% \) when \( \theta = 0^\circ \), 12.8% when \( \theta = 180^\circ \), and 18.3% for \( \theta = \pm 90^\circ \). With the \( \lambda \) correction for the Polaroid, these become 4.6%, 13.1% and 18.8% respectively. The ratio of maximal to minimal radiance is \( (111 + 101)/(27 + 21) = 4.4 \).

Theoretically then the two curves allow \( p \) to be computed in any horizontal line of sight so long as variation in this parameter is greater than errors of measurement. These curves also indicate the angular distribution of radiance in the horizontal plane, since this is proportional to \( I_\alpha + I_p = I_{\text{max}} + I_{\text{min}} \).

**Effects of Azimuth.** Results have been analyzed mainly for \( \theta = 0, \pm 90 \) and \( 180^\circ \), although for measurements around sunset (Fig. 9) \( \theta = \pm 45^\circ \) is also included. Three different patterns are clear in the various series studied. 1) In some cases \( p \) is maximal when \( \theta = \pm 90^\circ \), intermediate when \( \theta = 180^\circ \), and minimal when \( \theta = 0^\circ \) (Figs. 8, 11, 13, 15). 2) In other cases \( \theta = 0^\circ \) is also minimal, but \( p \) is essentially
equal for $\theta = \pm 90^\circ$ and $\theta = 180^\circ$. Consequently these latter two have been averaged (Figs. 7, 10, 12, 14, 16). 3) Still others, mainly in turbid waters, show the same $p$, within errors of measurement, at all azimuths.

Effect of Transparency. The measurements here reported can be used incidentally to illustrate the influence of the water's clarity on $p$. The Bermuda area is of considerable interest in this respect since a wide range of transparencies from very clear Sargasso Sea water to highly turbid inshore regions can be conveniently studied. The stations occupied in the present measurements are numbered from 1 to 5 on a scale of increasing turbidity (see Fig. 5). Since transparency measurements were not a primary part of our 1957 summer program, Secchi disc readings provide the only information available on water
transparency at the time of polarization measurements (Fig. 6). As is well known, such data are limited among other things by the observer, the state of the water surface, and the relative solar bearing (e.g., the sunny side of the ship in one instance gave a reading of 19 m, the shady side 25 m; in another case the readings were 45 and 58 m respectively). Nevertheless, the correlation between Secchi disc readings and degree of polarization is striking.

Note that, to provide reasonably comparable data, the results plotted are limited to $h = 9$ m and $\lambda = 500$ m$\mu$. At other depths somewhat different results would be expected. In deeper more turbid water the decrease in $p$ with $h$ is probably greater so that the average curve would bend still more. If $h$ is less than 9 m, a straighter curve would likely be found to fit the data. In addition, measurements in Fig. 6 include only the case when $\theta = \pm 90^\circ$. Usually this is maximal, but as already noted, it may be equalled under certain conditions at $\theta = 180$ or even $0^\circ$.

Influence of Cloud Cover. Whenever possible, measurements were made while the sun was shining (Figs. 3–21). However, there usually are some scattered clouds in the sky in Bermuda so that the measure-
ments were frequently disturbed by the passage of a cloud in front of the sun. This always decreases $p$, but the actual effects, both on $p$ and on the plane of polarization, depend on the resulting change in directionality of underwater illumination, which varies with different optical conditions of the sky.

2. **Effect of Depth**

In addition to the direct effect of $h$ on $p$, a secondary influence arises where the bottom is close enough to affect significantly the light that is present. As earlier observations showed (Waterman, 1958), $p$ decreases near the bottom, and more so if the latter is light rather than dark. For this reason the present data fall into two categories: a) where there is no bottom influence; b) where there is bottom influence.

![Figure 7. Influence of $h$ on $p$ in clear water at St. I (Fig. 5); bottom, 2900 m; no Secchi disc reading; solar zenith distance ($\theta$) = 60-78°. Solid lines connect points determined without colored filter; broken lines connect points measured with the 500m$\mu$ narrow band filter. The points indicated for $\theta = \pm 90$ and 180° are averages of the two. Data of 22 July 1957.](image-url)

*Far from Bottom.* Two series of measurements were made in 2500-3000 m of water where the optical effect of the bottom is certainly negligible (Figs. 7 and 8). Some of these data were taken without colored filters to increase the instrument’s sensitivity to the low in-
Figure 8. Influence of h on p in clear water at St. 1 (Fig. 5); bottom, 2500 m; S = 50 m; \( \theta \) between 29 and 33°. Broken and solid lines as in Fig. 7. Data of 27 August 1957.

Figure 9. Degree of polarization around sunset at St. 2 (Fig. 5); measured at 5.4 m without filter in moderately turbid water; bottom about 12 m. Sun’s altitude at 1700 was 18°50’; sunset occurred at 1852. At 1815 the solar disc was dim enough to look at with the naked eye; after 1845, the underwater light was too weak for measurement with the polarimeter. Data of 26 August 1957.
tensities present; the rest were taken with the 500 mµ filter (narrow band) which reduces the influence of depth on the band width error. In Fig. 7, where the sun's zenith distance was less than 20° throughout the measurements, the percent polarization is the same within the errors of measurement at both 90 and 180° to the sun's bearing, but it is clearly less in the solar bearing. The data in Fig. 8, which extend down to 115 m, show in addition that at this depth maximal and minimal radiance in the horizontal plane differ by a factor of two toward and away from the sun, with \( i \) between 40 and 45°. The degree of polarization follows the same general trend as in the previous case, but in addition it illustrates two new points.

1) While the differences in \( p \) when \( \theta = 90 \) and 180° do not exceed the experimental errors at depths greater than 60 m, polarization at 180° becomes weaker than at ±90° in shallower depths. This point is discussed later in relation to the effects of azimuth on polarization.

2) Down to 90 m \( p \) decreases more and more slowly when \( \theta = 0° \), but at greater depths it appears to increase again. This matter will also be discussed later where it is shown to be similar to some phenomena observed around sunset (Fig. 9).

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Effect of \( h \) on \( p \) in turbid water at St. 5 (Fig. 5); bottom, 12.5 m; 500mµ narrow band filter used; \( S = 6.5 \) m; \( i \) between 17 and 32°. Note that decrease in \( p \) with \( h \) accelerates slightly beyond 9 m, probably as a result of increased turbidity. Data of 19 August 1957.

**Near Bottom.** Several series of measurements (Figs. 10–13) indicate that in shallow water, when \( p \) is determined in a narrow spectral band centered at 500mµ, it decreases sharply close to bottom. The extent and degree of this polarization decrease probably depend on the clarity of the water, the albedo of the bottom, and the fact that turbidity often increases near the latter. The effect of transparency
Figure 11. Effect of h on p in moderately turbid water at St. 3 (Fig. 5); bottom, 15 m; measured with 500μm narrow band filter; S = 10 m; i between 55 and 57°. Note that decrease in polarization with depth is accelerated at depths greater than 9 m, at least when θ = ±90 or 180°. Data of 26 August 1957.

Figure 12. Effect of h on p in moderately turbid water at St. 4 (Fig. 5); bottom, 21 m; measured with 500μm narrow band filter; S = 11 m; i between 16 and 22°. Decrease in p with depth clearly accelerates with depths in excess of 13 m. At about 18 m, submarine illumination appears to reach an equilibrium condition where p becomes nearly independent of azimuth. Data of 17 August 1957.
may be seen by comparing the above figures where the extent of the bottom influence ranges from 3.5 to 15 m. Close to the bottom \( p \) seems to approach a constant value (Figs. 12 and 13).

3. Effect of Wavelength

In general, measurements of \( p \) as a function of \( \lambda \) (Figs. 14–16; Table II) show that \( p \) is greater at the two ends of the visible spectrum, with our highest readings usually at 600m\( \mu \). The minimum occurs between 445 and 500m\( \mu \), with the actual \( p_{\text{min}} \) apparently being correlated with the color of the water mass concerned. Thus the blue waters of the Sargasso Sea (Fig. 14, St. 1) and of Castle Harbour (Table II, St. 5) have \( p_{\text{min}} \) near 450m\( \mu \), while the waters of Harrington Sound (Figs. 15, 16, St. 4), which appear greener, have \( p_{\text{min}} \) close to 500m\( \mu \). The data also show that the change in \( p \) due to \( \lambda \), \( (\Delta p) \), is apparently greatest where \( p \) is large, that is, in clear water and near the surface. As would be expected from these facts, the variation of \( \Delta p/p \) as a function of \( \lambda \), which averages 0.2, seems to be practically independent of turbidity and depth.

In addition, the ratios of maximal (\( \theta = 0^\circ \)) to minimal (\( \theta = 180^\circ \)) radiance measured in various azimuths decrease toward the short
wavelengths. Although the variations of $i$ in the different series of data prevent a quantitative analysis, the ratio appears to decrease toward shorter wavelengths down to the lower spectral limit of our filters. This should be compared with the fact that the ratio of submarine irradiance coming from above to that coming from below is known to pass through a minimum at a $\lambda$ shorter than that of maximum transparency (Jerlov, 1951).

Figure 14. Effect of $\lambda$ on $p$ when $h$ is 16 m in clear water at St. 1 (Fig. 5); bottom, 2500 m; $S =$ 50 m; $i$ between 29 and 33°. Without colored filters, $p$ at $\theta = 0^\circ$ was 39.8%, and at $\theta = \pm 90$ and $180^\circ$ $p$ was 49.4% (av.). Data of 27 August 1957.
Figure 15. Effect of $\lambda$ on $\rho$ when $h = 5.5$ m in moderately turbid water at St. 4 (Fig. 5); bottom, 21 m; $S = 13$ m; $i$ about 24°. Without colored filters, $\rho$ at $\theta = 0°$ was 25.7%, and at $\theta = \pm 90°$ and $180°$ $\rho$ was 34.3% (av.). Data of 30 August 1957. Cf. Fig. 16, where conditions were essentially the same except for $h$.

Figure 16. Effect of $\lambda$ on $\rho$ when $h = 14.5$ m in moderately turbid water at St. 4 (Fig. 5); bottom, 21 m; $S = 13$ m; $i$ about 25°. Without colored filters, $\rho$ at $\theta = 0°$ was 12.4%, and at $\theta = \pm 90°$ and $180°$ $\rho$ was 15.8% (av.). Data of 30 August 1957.
### TABLE II. SUMMARY OF THE EFFECTS OF $\lambda$ ON $p$

<table>
<thead>
<tr>
<th>Station*</th>
<th>Bottom depth</th>
<th>$h$</th>
<th>Clarity</th>
<th>$S^{**}$</th>
<th>$i$</th>
<th>$\theta = 0^\circ \theta = 90^\circ, 180^\circ$</th>
<th>$p_{\text{min}}$</th>
<th>$p_{413 \text{m} \mu}$</th>
<th>$p_{650 \text{m} \mu}$</th>
<th>$\Delta p \dagger$</th>
<th>$\Delta p/p_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Fig. 14)</td>
<td>2500</td>
<td>16</td>
<td>clear</td>
<td>50</td>
<td>20-33</td>
<td>39.8 49.4</td>
<td>48.9</td>
<td>50.2</td>
<td>56.8</td>
<td>9.2</td>
<td>0.19</td>
</tr>
<tr>
<td>1 (Fig. 15)</td>
<td>2900</td>
<td>18</td>
<td>clear</td>
<td>45</td>
<td>21-23</td>
<td>—</td>
<td>—</td>
<td>—</td>
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* See Fig. 5.

** Secchi disc reading in meters.

\[ \Delta p \dagger = \Delta p_{413 \text{m} \mu} - p_{\text{min}} + \Delta p_{650 \text{m} \mu} - p_{\text{min}}. \]
DISCUSSION

The preceding data may be discussed from several points of view; probably the most important points relate to 1) the angular distribution of \( p \) underwater, and 2) the angular distribution of submarine light itself.

1. Effects Dependent on the Angular Distribution of \( p \). The angular distribution of percent polarization in the sea is still poorly known since the photographic (Ivanoff, 1956b, 1957a) and visual (Waterman and Westell, 1956; Waterman, 1958) measurements which have been made are few and quite incomplete. However, the function may roughly approximate Rayleigh's equation, at least beyond the critical angle. If so, \( p = \sin^2 \alpha/1 + \cos^2 \alpha \), where \( \alpha \) is the angle between the parallel rays of underwater sunlight and the direction of scattering (i.e., line of sight). Provided this equation holds and if only horizontal lines of sight are considered (as in the above measurements), \( p \) should be maximal for all solar zenith distances when \( \theta = \pm 90^\circ \) and it should be minimal for \( i = 0^\circ \) and \( 180^\circ \), except when \( i = 0^\circ \) and when \( p \) is the same for all azimuths. At both minima, percent polarization should be equal and directly related to the sun's altitude above the horizon. The difference between maximal and minimal \( p \) is least when three parameters have particular values: 1) The zenith distance must be minimal so that the axis of best symmetry of submarine illumination makes a maximal angle with the horizontal plane. 2) The depth should be great because it is well known that the axis of best symmetry of submarine light's angular distribution approaches the vertical at increasing depths (see Jerlov, 1951). 3) The water must be turbid because this produces vertically symmetrical light distribution at shallower depths.

These various points have largely been verified by measurements in the field. Thus the degree of polarization observed in horizontal directions normal to the sun's bearing is independent of \( i \) (Waterman and Westell, 1956: fig. 6), but in the sun's bearing \( p \) decreases as \( i \) increases (Waterman and Westell, 1956: fig. 7). Similarly, the present results demonstrate that variation in \( p \) with azimuth increases as the sun approaches the horizon (for example, compare Figs. 3 and 4), decreases as depth increases (see Fig. 8 at \( \pm 90^\circ \) and \( 180^\circ \) to the sun's bearing), and may become practically zero in turbid water.

The underwater direction of maximum radiance (apparent direction of the sun) may differ from the axis of best symmetry for the angular distribution of submarine illumination, but it is not known whether the direction or the axis is the more significant for underwater polarization. Here the two terms will not be distinguished even though they may not be strictly equivalent.
On the other hand, a relation not predicted by Rayleigh's equation appears again in the present results, namely that lower degrees of polarization occur more consistently in the sun's bearing than they do in that of the anti-sun. This agrees with results obtained previously with the photographic technique (Ivanoff, 1956b: 54; Ivanoff, 1957a: figs. 9 and 10) but not with those found visually (Waterman and Westell, 1956: fig. 8).

In summary then, Rayleigh's equation appears to hold for submarine polarization only as a first order approximation; this we have assumed also in our analysis of underwater elliptical polarization (Ivanoff and Waterman, 1958). It is not surprising that the equation provides only a rough approximation; in the first place, most of the light scattering by sea water is not Rayleigh scattering; in the second place, the combination of sun, sky and ocean have a plane of symmetry which passes through the sun's bearing rather than an axis of symmetry. This plane of symmetry may disappear when the sun's contribution becomes small relative to that of the sky, as in cloudy weather or at sunrise or sunset. The distribution of radiance in the sky must then be important. Thus the percent polarization may be greater at 180° than at ±90° (Fig. 9) when the solar zenith distance is greater than 80°. This could be the effect of some clouds which increased the radiance of the sky in an azimuth different from the sun's bearing.

Much of the problem of angular distribution of submarine polarized light remains to be studied from both experimental and theoretical points of view.

2. Effects Related to the Angular Distribution of Submarine Light.

As a result of field observations on underwater polarization, a theory was proposed which accounts simultaneously for the effects of tur-

In the latter data the polarization for θ = 0° did in fact average less than for θ = 180°, but the variation hardly seems significant there, since maxima at +90 and -90° differ by greater amounts.

Recently measurements of the degree of polarization have been made in sea water samples illuminated by a parallel beam of artificial light (Ivanoff, 1958a, 1958b). In these waters, which were collected in the Mediterranean Sea between Nice and Corsica, polarization varied from 45 to 67% for surface waters but was as much as 75, or even 77%, in deep waters. Optically pure water under the same conditions would produce 80% polarization. Furthermore, some samples which were rather turbid and had the milky appearance of a colloidal suspension gave readings of 88% polarization. In certain of these samples, spheroidal particles 1-3µ in diameter were visible under the microscope. Thus the shape of the particles may have an important influence since the degree of polarization is known to be greater for spheroidal particles.
bidity, sky overcast, depth, nearness to bottom, and wavelength (Ivanoff, 1957a). The theory may be summarized as follows: 1) With parallel light, the degree of polarization in light scattered by sea water depends mainly on the optical properties and dimensions of the suspended particles; its actual value increases as the dimensions of the particles decrease. 2) In daylight, submarine polarization decreases for a given water type with the diffuseness of the light.

To support this theory an attempt has been made to derive the variation in the amount of polarization from changes in the angular distribution of submarine illumination. These rough calculations were intended to determine merely whether or not the order of magnitude of the theoretical effect is comparable to the measurements. Such analysis is misleading if it suggests that polarization is dependent on the angular distribution of light. In fact, both phenomena are dependent on the same parameters, such as surface irradiance and optical properties of the water, rather than on each other. However, their variations usually occur together in the same direction. Thus, when underwater illumination becomes more diffuse, the degree of polarization diminishes. This should be the case for more turbid waters, overcast skies, increased depth, greater bottom reflection and the most penetrating wavelength. The data here reported support these predictions of the theory.

Previous work had shown that the degree of submarine polarization may reach 60% in quite clear water at shallow depths (Ivanoff, 1957a), decreasing proportionately at greater turbidities (Waterman, 1954; Waterman and Westell, 1956; Ivanoff, 1957a). This decrease is illustrated from the present data by Fig. 6. These data also seem to show that in the clearest water the percent polarization varies least as a function of the Secchi disc reading. Previous evidence had suggested the contrary, namely that \( p \) changes most rapidly in the clearest waters (Ivanoff, 1957a: 50–52). However, to evaluate these discrepancies, one must consider precisely what is meant by clarity and how it is determined. Both the amount of underwater polarization and the Secchi disc reading are complex functions of the optical properties of sea water, and the data in Fig. 6 permit no conclusions to be drawn relative to the way in which these functions are interrelated. All that may be said from present evidence is that, for clear waters, the depth to which the Secchi disc is visible changes more rapidly than does the degree of polarization. Contrary to a previous assumption, \( p \) does not seem to provide a particularly sensitive means of distinguishing various clear waters one from another. On the other hand, the measurement of polarization is more precise with greater \( p \), which in fact occurs in the clearest waters.
As mentioned above, a decrease in the degree of polarization was regularly observed whenever the sun was covered by clouds, which agrees with previous findings (Waterman, 1954; Ivanoff, 1957a). Similar effects occur at sunset (Fig. 9) when the relative importance of sky light increases and when irradiance becomes more diffuse. However, it is important to emphasize that, although a completely overcast sky and a blue sky with no sun (at sunrise and sunset, or with a dense cloud covering merely the sun) produce less polarization underwater than does the direct sunlight itself, their influences are not identical. Thus, at angles less than the critical angle, sky polarization is not visible in the former but is visible in the latter case; also, the plane of polarization is more or less horizontal in overcast weather but it may behave in quite a different manner at sunset with a clear sky, possibly as a result of the latter's polarization (Ivanoff and Waterman, 1958).

Our data show that $p$ decreases with depth (irregularities in these measurements being due to either errors in measurement or optical heterogeneity of the water) and approaches a limit of about 30% in very clear sea water. Some previous observations (Waterman, 1955) suggested that polarization in deep water is as great as that near the surface, but the strong interference pattern still recorded in the crystal analyzer at 200 m may have a more likely interpretation in the much narrower deep water light spectrum (Ivanoff, 1957a: 41). Other measurements made by the visual method (Waterman, 1958) indicated a slight increase in the percent polarization at certain depths. On the basis of present data this could be due to an error in measurement, to a change in the sky overcast during measurements, or possibly to the effect of a local increase in the water's clarity. But the last possibility implies that in a clearer layer of water the illumination becomes less diffuse again, which is unlikely.

Wavelength has a definite but small influence on the degree of submarine polarization. Present results agree with the sole previous measurement (made by the photographic method; see Ivanoff, 1957a) and with the fact that it is for the most penetrating wavelengths that underwater light is most diffuse (Johnson and Liljequist, 1938). Since diffuseness of illumination and polarization by scattering are inversely related, one would thus expect that minimum polarization in very clear sea water would occur near 475m$\mu$. The apparent correlation observed between the $\lambda$ for $p_{\text{min}}$ and the color of the water in the present results is mentioned above.

Two circumstances have already been cited which influence the degree of polarization in the sun's azimuth in a special way involving both the angular distribution of $p$ and that of submarine radiance. In deep water, $p$ for the sun's bearing passes through a minimum and then
increases again (Fig. 8). The same thing happens at sunrise or sunset (Fig. 9), when this has also been observed at $\theta = \pm 45^\circ$. Such phenomena could result from opposing effects of an increase in the diffuseness of underwater illumination, which decreases polarization, and a reduced obliquity in the light, which augments polarization in the sun's bearing.

Actually the diffuseness of the light increases with depth and with the sun below the horizon while the axis of best symmetry of the angular distribution of radiance tends toward the vertical with depth and with $i$ near $0^\circ$. Hence the degree of polarization would decrease while the first of these effects predominated and would then increase again when the second factor became predominant. In Fig. 8, curves $A$ and $B$ may come together horizontally where the angular distribution of submarine illumination becomes a symmetrical figure of rotation around the vertical. Degree of polarization would then be independent of azimuth regardless of the sun's zenith distance. Unfortunately this equilibrium depth is too great in the Sargasso Sea to be reached with our present instruments.

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