

I.6 Inherent and Apparent Optical Properties of Hydrosols The three simple models describing light fields in the seas and lakes of the earth, as developed in Sec. 1.3, may now be considered as reasonably established descriptions of radiative transfer in natural hydrosols. For as we have seen in our brief survey of their applications in Sec. 1.4 and 1.5, they can be used both to organize our accumulated empirical knowledge of natural *light fields* by means of faithful symbolic representations of our observations, and also to encourage, via simple mathematical manipulations, the exploration of

SEC. 1.6 OPTICAL PROPERTIES 119

new and deeper physical phenomena connected with light fields in **the sea**. Implicit in the structure of these models are the optical properties we introduced during their construction, such as α , σ , s , α , and K .

Now, if the theoretical equations of hydrologic optics may be viewed as the **bones** of the subject, then certainly the optical properties α , ν , $+c$ and the various related properties

are the meat of the subject. Indeed, the equations provide the essential form of our discipline; but the numerical values of their parameters provide it with useful substance. It is our purpose in this section to sort out the principal optical properties used in hydrologic optics and to indicate their representative magnitudes. It is not our purpose at this time, however, to optically catalog the seas and lakes of the world; such a task still awaits a definitive effort, and lies outside the province of a work devoted to the theoretical principles of the subject.

Operational Definitions of the Inherent Optical Properties

The fundamental inherent optical properties of hydrologic optics are the *volume attenuation function* α , and the *volume scattering function* Q . They are *inherent* in the sense

that their magnitudes for each wavelength depend only on the substances comprising the hydrosol and not on the geometric structure of the various light fields that may pervade it. The properties α , and ν are *fundamental* in the sense that the entire theory of hydrologic optics (and indeed radiative transfer theory) can be constructed from, them, given the concept of the radiance function and the equation of transfer. The greatest contributions an experimental scientist can make to hydrologic optics at this stage of its development (or to any other branch of radiative transfer) lie in the detailed study --on physical, chemical, and optical levels--of these two fundamental properties, along with the simultaneous documentation of the light fields in optical media.* Chapter 13 is devoted to a detailed exposition of the operational definitions of these and other properties. Our immediate aim is to introduce these concepts with a minimum of preamble, though a full and deep understanding of them can come only after the contents of at least Chapters 2, 3, 8, 9 and 13 are mastered.

The Volume Attenuation Function

The volume attenuation function α provides a measure of the loss of radiant flux from a beam of photons of a given wavelength induced by: (a) scattering of flux out of the direction of the beam without change in wavelength or: (b) by scattering of flux of the beam with a change of wavelength, or. (c) by outright absorption of some of the radiant energy

*Important problems concerning the physical makeup of a and o also await interested theoreticians, See problem III of Chapter XVI, Ref. [251].

2 INTRODUCTION VOL. I

FIG. 1.67 Arrangement for an operational definition of volume attenuation function,

into a form of non-radiant energy. A particularly effective method of defining a is by means of the beam transmittance function using the fact that radiance differences of simultaneous beams propagate precisely in an exponential manner along close parallel paths.

Figure 1.67 depicts two parallel closely spaced paths of length r in an optical medium. The initial radiances at the beginning of the paths are N_1 and N_2 , and matters are arranged so that the medium is homogeneous in the vicinity of the paths and *that the path* radiances of the two paths are essentially the same, and of common value N_0 . If T_r is the common fraction of photons comprising N_1 and N_2 transmitted along each path without having been scattered or absorbed, then by (24) of Sec. 1.3 the apparent radiances.

$$N_1 = N_0 T_r + N_1 r$$

and

$$N_2 = N_0 T_r + N_2 r$$

measured at the end of the path may be used to find *the beam transmittance* T_r by means of the relation.

It is very easy to see, using (1), that if two paths of

SEC. 1.b OPTICAL PROPERTIES 121

arbitrary lengths r and s are placed end-to-end to form a new straight path of length $r+s$, then:

and:

and also:

$$0 = T_r T_s \quad (2)$$

$$\frac{T_{rs}}{T_r T_s} \quad (3)$$

$$T_0 = 1 \quad (4)$$

The second property is the multiplicative (or semigroup) property of beam transmittance. It is the basis of the exponential representation of T_r . Indeed, let us write:

$$T_{r+s} = T_r T_s$$

The quantity a_r is the (*empirical*) *volume attenuation function* because it gives the average amount of loss of radiance of a beam per unit length of travel of a beam of unit radiance.

To see this let N be an initial *radiance starting out along* a path of length r . Then $N^0 T_r = N_r$ is the *residual radiance*, i.e., the radiance left over in the beam after r scattering and absorption losses over the path. Hence $N - N_r$ is the actual radiance lost, and $(N - N_r)/r$ the average loss per unit length of the path. Dividing by N^0 we arrive at (5).

Now consider a path of length $r+s$. Then by (3) and (5):

$$T_{r+s} = T_r T_s$$

$$\frac{d}{dr} T_r = -a_r T_r$$

Using the definition of derivative applied to T_r , and letting $s \rightarrow 0$, we have.

$$\frac{dT_r}{dr} = -a_r T_r$$

$$\frac{d}{dr} \ln T_r = -a_r$$

where we have written:

$$\lim_{s \rightarrow 0} \frac{T_{r+s} - T_r}{s} = \frac{dT_r}{dr}$$

From (4) and (6)

for homogeneous media, This is the basic connection between beam transmittance and the *volume attenuation function* a defined in (7). The function a has dimensions of L^{-1} , and therefore units of (meter)⁻¹. Observe that by (2), a_r and hence

a is a non-negative quantity: "From (8) we have:

$$3 \quad \text{INTRODUCTION} \quad \text{VOL. I}$$

FIG. 1.68 Arrangement for an operational definition of volume scattering function. which together with (1) provides a useful operational definition of a . For a further discussion of these ideas see Secs. 13.2, 13.4 and 13.5.

The Volume Scattering Function

A small volume of an optical medium is irradiated through a small set of directions of solid angle Ω about a direction \hat{s} by a radiance N_0 of a given wavelength, and the scattered radiant flux in the direction \hat{s}' , at an angle θ with \hat{s} , is observed to be N_r , where r is the length of the line of sight through the volume. The volume is in the form of a parallelepiped whose dimensions are $r \times r \times cr$, where c is a constant. Then we write

$\int_{\Omega} \frac{dQ}{r^2} = 4\pi$

Further,

we write:

for $\lim_{r \rightarrow 0} \int_{\Omega} \frac{dQ}{r^2} = 4\pi$

and call σ the *volume scattering function*. A more detailed discussion of σ is given in Sec. 13.6, and in Sec. 18 of Ref. [251]. The dimensions of σ are $L^{-1}(\text{sr})^{-1}$ and hence its units

SEC. 13.6 OPTICAL PROPERTIES 123

are $(\text{meter})^{-1}(\text{steradian})^{-1}$.

The reason for choosing (11) as the basic definition of $\sigma(e)$ is that it yields at once the relation:

$$\sigma = \frac{N_r}{N_0}$$

N^*

$$\sigma = N \int_{\Omega} \frac{dQ}{r^2} \quad (12)$$

which with care can be made to blossom into:

and which in turn is the standard representation of the path function in general radiative transfer theory. The correct logical order of appearance of N^* and σ in the theoretical construction of radiative transfer theory is given in the systematic discussions of Chapter 3.

An alternate form of $\sigma_{r,n}(e)$ is given by writing

$$\int_{\Omega} \frac{dQ}{r^2} = \frac{J_r}{H^0}$$

for $\int_{\Omega} \frac{dQ}{r^2} = \frac{J_r}{H^0}$

where $H^0 = N^0 Q$, V is the volume (e.g., in this case cr^3) of the scattering region in Fig. 1.68, and J_r is the radiant intensity of the scattered flux. Clearly

$$\sigma_{r,n}(e) = \frac{J_r}{N^0 Q} \quad (13)$$

(13)

and so the two definitions are equivalent. (A careful proof of this is given in Sec. 18 of Ref. [251].) It is found that σ depends, in virtually any given practical setting, only on the angle e between the incident direction \mathbf{i} and the scattered direction \mathbf{e} .

Hence it is possible in practice to write " $\sigma(x; \mathbf{i}; \mathbf{e})$ " in the more compact way " $\sigma(e)$ ", adopted above.

Volume Total Scattering Function and

Volume Absorption Function

If $\sigma(e)$ is integrated over all Ω , we obtain the volume

total scattering function S ; where we write:

' S ' for

00

$$a(\theta) \sin \theta \, d\theta \quad (14)$$

The angle θ is measured around the direction E' (in Fig. 1.68) as a hinge. Clearly we have:

$$Q(A) \sin \theta \, d\theta \quad (15)$$

5 INTRODUCTION VOL. I

By splitting up the domain of integration $[0, w]$ into $[0, w/2]$ and $[w/2, w]$ and writing*:

$n/2$

$||f''$

$$\text{for } \int_{n/2}^w \sin \theta \, d\theta \sim Q(\theta) \sin \theta \, d\theta \quad (16) \quad \theta=0$$

$$\sin \theta \, d\theta \quad (17)$$

$n/2$

We then have:

$$S =$$

$f + b$

(18)

where f and b are the (volume) forward and *backward scattering functions* for collimated radiant flux.

The volume *absorption function* a comes in the back door of the theory by writing

"a"

$$\text{for } a-s, \quad (19)$$

but it redeems itself by possessing the following remarkably powerful operational form:

$$\int_0^1 dh \cdot r \cdot h(z) \, dz$$

(20)

discussed in the closing paragraph of Sec. 1.4 (see in particular (90) of Sec. 1.4, and also Sec. 13.8).

Considered together, the three operational formulations of a , a , and a in (9), (10) and (20), respectively, form a complete, mutually consistent, independent set of experimental means of determining these inherent optical properties of natural or artificial hydrosol. An ideal scientific study of a given hydrosol would determine a , a , and a using these independent means, and then check consistency by requiring the three sets of data to satisfy the relation:

$$\int_0^{2\pi} \int_0^\pi a(\theta) \sin \theta \, d\theta = a-a$$

(Z1)

0

In other words, the measured a values are first integrated to yield the left side of (21). Then the measured a is subtracted from the independently measured a , and, hopefully, this difference is equal within a reasonable error allowance, to the computed a -integral, for each wavelength from the infrared to the ultraviolet parts of the electromagnetic spectrum, and for each point in a hydrosol at which the

*The general definitions are given in (1), (2) of Sec. 9.6.

SEC. 1.6 OPTICAL PROPERTIES 125

three determinations were made. This check is expected to hold, in principle, for all unpolarized light fields (Sec. 13o 11)

Selected Physical Measurements of the Inherent Optical Properties

The following three tables provide representative samples of the inherent optical properties a , a_s , f , b and a_v , measured for distilled water, ocean water, and lake water.

The measurements were made by Tyler (300] and may serve as an example of the careful and consistent types of measurements that maybe used to optically document the natural waters of the world. Such types of measurements, when performed for a sufficiently finely spaced set of wavelengths, will begin to move hydrologic optics into its final stage of development as a mature scientific discipline.

In Table 1 the distilled water was of the commercially available kind, and is not "distilled" in the strictest sense of the word. The two samples do, however, provide a reason

ably good basis for comparison with the a 's of natural hydrosols. The wavelength band for the measurements was centered at 522 ± 80 mu. The results compare favorably with those of Hulburt [115]. The Table 2 measurements were made in January 1961 in the four numbered locations shown in Fig, 1.69, and over the same wavelength band used for Table 1, Table 3

33°40'

33°20'

33°

32°40'

a_v

IIW 40

	0 SAN PEDRO BAY	
ANTA CATALIN	83 3	

	1	
SAN CLEME TE		

lots 20

FIG. 1.69 Locations of Tyler's measurements off Southern California coast, winter 1960-1961, and as recorded in Table 2. (Fig. 1 from [300], by permission)

126 INTRODUCTION

VOL . I

TABLE 1

Scattering properties of commercial "distilled" water samples. Bandwidth limited by a

Wratten No. 57 filter,

Sample

Volume attenuation coefficient a/m

Volume total scattering coefficient

s/m

Volume absorption coefficient a/m

Forward scattering coefficient f/m

Backward scattering coefficient f

Ratio f/s

Volume scattering function $a(e)$

.062

.047

.40845

.00457

.0536

,0424

*00763

.00396

/m

.00082

.040620

,900

870

o0

10		
20	.00648	.00316
30	.40223	.04107
40	.040941	.000520
50	.000473	.000294
60	.000271	.000191
70	.004181	.000128
80	.000140	.000096
90	.000117	.000083
100	*000110	.000079
110	.000118	.000082
120	.000126	.000092
130	.000134	.000102
140	.000139	.000112
150	.000146	.000119
160	.000171	.000141
170	.000193	.000161
180	.000201	.000169

B
(From [300], by permission)

SEC. 1.6
OPTICAL PROPERTIES

127

TABLE 2

Scattering properties of Pacific Coastal and offshore water at the Stations shown in Figure 1.69. Bandwidth limited by a Wratten No. 57 filter.

Station number

3

Volume attenuation coefficient a/m

.736

.129
 .118
Volume total scattering coefficient s/m
 .125
 .01094
 .01420
 .0120

Volume absorption coefficient a/m
 Forward scattering coefficient f/m
 Backward scattering coefficient b/m
 Ratio f /s
 Volume scattering function 6(8)

.611	.1181	.1038	.099
.119	.01010	.01321	,0110
.00630	.000847	.000982	,000984

.950	.925	.930	.915
------	------	------	------

00

10

20	.1014	.00881	.01192	.00959
30	.0360	.00268	.00358	.00313
40	.0152	.00117	.00145	,00129
50	.00739	.000616	.000698	.000661
60	.00419	.000356	000396	,000388

70	.00266	.000232	000253	000249
80	.00181	.000164	.000179	.000175
90	.0013	.000132	.000145	.000142
00	.00109	.000120	.000134	.000130
10	.000940	.000120	.000135	
20	.000903	.000124	.000146	.000146
30	<u>.000912</u>	<u>.000134</u>	000158	000159
40	.000944	<u>.000145</u>	<u>.000175</u>	.000176
50	.001003	.000156	.000192	90001
60	.001028	.400175	.000202	.000208
70	.001036	.000191	.000206	.000219
80	.001037	.000197	.000207	000223

(From [300], by permission)

128 INTRODUCTION

VOL . I

TABLE 3

Volume scattering function for Lake Pend Oreille, Idaho, Spring 1960 before and after a high wind: Bandwidth limited by a Wratten No. 45 filter.

Sample date, , April 26, April 27

Volume attenuation coefficient a/m , , .589, .949

Volume total scattering coefficient, , ,

S/m , , .258, .585

Volume absorption coefficient a/m , , .331, .324

Forward scattering function f/m , , .248, .559

Backward scattering coefficient b/m , , .00976, .0256

Ratio f/s , , .960, .955

volume scattering function, $a(\theta)$, , ,

$\theta = 40^\circ$, ,

, 14° , ,

, 20° , .222, .470

, 30° , .0715, .9166

, 40° , .0291, .0758

, 50° , .0137, .0380

, 60° , .00712, .0206

, 70, .00416, .0121
 , 80, .00271, .00780
 , 90, .00198, .00559
 , 100, .00162, .00448
 , 110, .00147, *00394
 , 120, .00143, .00379
 , 130, .00145, .00372
 , 140, .00149, *00371
 , 150, .00156, .00383
 , 160, .00163, .00396
 , 170, .00168, .00406
 , 180, .00170, .00410

(From [300], by permission)

SEC. 1.6 OPTICAL PROPERTIES , 129

1.0

z a v a W H N X W H W w

z

r

z 0 z

W J O 7

z o 60 / o o 140 SCATTERING ANGLE (DEGREES)

LAKE

.FIG. 1.70 Plot of Tables 1, 2, 3.

summarizes Tyler's Lake Pend Oreille measurements of the Spring of 1960. The wavelength band in this case was centered at $480 \pm 64 \text{ m}\mu$. These tabulations are compared graphically in Fig. 1.70 wherein *the* relative clarity of the waters may be seen at a glance. Curves 3, 4 of Table 2 essentially coincide in the figure.

Figure 1.71 provides three more comparisons of distilled, lake and ocean waters. In this case, the distilled water measurements were by Dawson and Hulburt [63], the lake water measurements by Duntley [78], and the Atlantic (between Madeira and Gibraltar) measurements by Jerlov [123]. The latter graph is keyed in with the measurements listed in Table 4 below. The lake measurements by Duntley are of particular interest because of the relatively small angles for which a was obtained using special equipment [78]. A detail of a for the range 0.5° to 1.7° is given in Fig. 1.72. The ordinates of the lake curve in Fig. 1.71 are continued in Fig. 1.72.

190

PACIFIC

PURE

.0001
 PURE
 J 0

0 30 60 90 120 150 180
 SCATTERING ANGLE (DEGREES)

FIG. 1.71 Plots of data taken at various times and locales by Dawson and Hulburt (pure), by Duntley (lake), and by Jerlov (Atlantic). See text for details. (Fig. 9 from [78], by permission)

N
 W t - W V
 z a u z
 z W N
 a u N
 W J 0

1,4 1.6 1.8 2.0
 ,4

SCATTERING ANGLE (**DEGREES**)

FIG. 1.72 Extreme detail of forward scattering values of volume scattering function in Duntley's lake water curve of Fig. 1.71.

SEC. 1.6 OPTICAL PROPERTIES 131

TABLE 4

Comparison between relative values of the scattering function. (All data normalized at 90°)

	In vitro measurements			In situ measurements		
Angle	Poole	1(1945) Hulburt	Kozlyan- inov	1(1960) Sasaki	1(1961) Jerlov	Tyler (1961)
8	and Atkins (1954)	Chesa- peake Bay	(1957). East China Sea	Japan Trench	East North Atlantic	Califor nian coast
	English Channel					

	blue light	white light	blue light	576 mU	465 mp	522 mu
1°			7200			
5°			1100		(690)	
10°	232	247	312		292	
20°	62	61	62	39	74	67
30°	18	22	22	22	23.5	20
45°	6.0	8.5	t).9	5.5	7.5	6.7
60°	2.5	3.0	3.1	209	2.96	2,70
75°	1.5	1.4	1.8	1.2	1.72	1,51
90°	1.0	1.0	.1-00	1.0	L 00	1.00
105°	0.82	1.0	0.49	0.8	4.95	0.91
120°	0*67	1.2	0.44	0*7	1.05	0.94
135°	0090-	1 * 5	0', so	1'0	1.30	1,0S
150°		2.2		1.2	1.55	1.18
165°		3.1			1.90	1.38
180°					(2*12)	1.44

(From [127], by permission)

This shows how, in the space of 1° , near-forward scattering values soar two more orders of magnitude. The associated *wavelengths* are those transmitted by a No. 61 Wratten filter.

Further comparisons of a values are made in Table 4 (patterned after [127]), Observe that Tyler's measurements are those listed for location 2 in Table 2. The main purpose of Table 4 is to show the remarkable similarity in shape of the o curves, after normalization at 90° . This fact is reproduced graphically in Fig. 1.73. The curve labeled "Duntley (Green)" in Fig. 1.73 is the normalized lake curve of Fig. 1.71. The remaining references for the o values of Table 4 and Fig. 1.73 are as follows: Atkins and Poole [6], Hulburt [115], Kozlyaninov [144], Sasaki et. al. [271], and Jerlov [123]. A relatively recent and somewhat extensive experimental study of

v in the Atlantic was made by Spilhaus [290]. This work makes new progress toward workable classifications of optical media via the volume scattering function. The highly forward scattering character of **natural** waters observed in all of the preceding results is one of the

15 INTRODUCTION VOL. I

J 0

KOZLYANINOV(BLUE)-t POOLE a ATKINS (BLUE)) TYLER (GREEN)

DUNTLEY (GREEN)

60 90 120 150 180

SCATTERING ANGLE (DEGREES)

FIG. 1.73 Illustrating the stability of shape of the volume scattering function as measured in various locations and times. See text for details. (Fig. 12 from [78], by permission)

outstanding, and not yet fully understood features of the function* In particular, does the o-curve have a vertical or horizontal tangent at D° ? Despite the absence of detailed knowledge, we know that the high forward scattering is due principally to the great variety of dissolved and suspended *organic and mineral matter* in the sea. The ebb and flow of the life processes and geologic processes within natural hydrosols constantly alters the concentration of these substances, and the basic Rayleigh-type scattering that-absolutely pure water would exhibit is heavily masked by-the **scattered** lip t produced by these 'foreign' substances. If water in its pristine state is examined optically, then (cf. [b3]) the scattered radiance N_r in (10) would have the general form:

$N_r(e \sim JI)$

+ B $\cos z_8$)

(22)

where A and B are suitable *constants* (see [63]J. Observe that $N_r(9,a)$ increases sharply for the smaller wavelengths,

SEC, I.6 OPTICAL PROPERTIES 133

thereby tending to suffuse extensive masses of very pure water with scattered blue light, much in the way that the clear sunlit atmosphere above one's head appears blue to the sight. *It was shown* by Kalle [132] that the relatively heavy concentration of decaying organic matter in the form of phenolhumic acids and carbohydrate-humic acids (or melanoidines), respectively contribute the brownish and yellowish components to the otherwise clear blue water, the net result being the blue-green appearance of most natural hydrosols. Hence the greater the concentrations of these organic materials, the yellower or browner the water will become. Unlike the sharp λ^{-4} wavelength-behavior of scattered light in pure water, we have, by contrast in oceanic or lake water which contain *particles and organisms* whose dimensions are large compared with wavelengths of light, the scattered light nearly independent of wavelength. Hence when one measures $a \sim (a+s)$ or k (aD $aD+$) as a function of wavelength and observes great variations, these variations are due principally to the absorption mechanism operative in the solutes and suspensoids within the water. For example, while the scattered light in pure water increases nearly 10 fold as λ goes from 700 to 400 m μ , the absorption coefficient for plankton-infested water or for suspensoids of the yellow substance increases on the order of 100 fold over the same range (cf., e.g., [115]). By virtue of these reasons, the striking similarity of shape of the a curves in Fig. 1.73 becomes more understandable. If this sensitivity of a to wavelength λ is sufficiently weak, a great simplification of the documentation of optical properties of natural waters is possible; for then the burden of describing the spectral variation of the inherent optical properties falls on a or, equivalently, a : Table 5, adapted from Hulburt [115], gives the spectral dependence of a , s , and a for two types of water. These tabulations bear out the rationalizations enunciated above. Table 6 shows the spread of a values over oceanic regions, as found by Jerlov [122],

TABLE 5

Spectral dependence of volume attenuation (a), total scattering (s) and absorption functions (a) for distilled and Chesapeake Bay waters (per meter)

Wavelength m μ	Distilled a s a	Bay a s a
400	.08 .038 .042	
420	.061 .030 .0431	.800 .175 .625

440	.046.025	.021	0628,180	.448
480	.037.017	.020	.447 .180	.267
520	.040.013	'0028	.351 .180	.171
560	.0530009	.044	.323 9180	.143
600	.197.007	.190	.429 .180	.249
640	.292.005	.287	.500 .180	.320
680	.406.004	.402	.589 .180	.409
700	.576.004	.572	,740 .180	.560

(From [115], by permission)

17

INTRODUCTION

VOL. I

TAB LE b

Representative values of the volume attenuation function for various oceanic locations for 480 mp wavelength.

Caribbean

Pacific N. Equatorial Current Pacific counter current Pacific Equatorial Divergence

Pacific S. Equatorial Current Gulf of Panama

Galapagos Islands

Location

.a/meter Attenuation length
 1/a meters

.125

8

.083

12

.483

12

.100

10

.111	9
.167	6
250	4

(From [122], by permission)

Before concluding this brief survey of the inherent optical properties of natural hydrosols we wish to point up an apparent dissimilarity between the spectral dependence of a in air and in water. The dissimilarity is with respect to the fine structure of the a -dependence of a . In the meteorologic optics context, a experiences rather spectacular increases and decreases in values at frequent intervals along the X-axis (see, e.g., Refs. C1281, (296), and (177)), where a decreases rapidly to some minimum at λ , the atmosphere is said to have a *window at λ* , for the beam transmittance $T_r = e^{-a(X)r}$ will have a a -maximum at λ , and so one can 'look through' the atmosphere with relative ease using light having wavelengths in the immediate neighborhood of λ . The infrared region of the spectrum, e.g., μ has windows through the atmosphere, and this fact has important consequences for communication applications of radiative transfer theory. These observations lead one to consider the possibility of a fine structure for a in natural waters. This possibility does not seem too bright, at least on the basis of Table S. However, perhaps the measurements of a yielding the values in Table 5 were too crude, and accordingly smeared out possible sharp dips in a . That is, the minimum of a in the vicinity of 480 μ for distilled water may harbor a still sharper minimum if the spectral resolution of a -meters were increased. Recently, a careful spectroscopic study of a for "battery-grade" distilled water was made in the region from 375 μ to 685 μ by Drummeter and Knestrick (68]. The spectral resolution achieved by the grating spectrograph used was .02 μ . A path of water of .75 meters was used for the transmission experiment. Variations of a per meter as small as two parts in a hundred were capable of detection by the apparatus, i.e., the apparatus could detect changes Δa of 2×10^{-2} m^{-1} . No spectral fine structure of a of any significance was detectable.

SEC. 1.6 OPTICAL PROPERTIES 135

Operational Definitions of the Apparent Optical Properties

The apparent optical properties of a natural hydrosol are those radiometrically determined scattering- and absorbing-induced quantities which generally depend on the geometrical structure of the light field (1, e., whether the light field is more or less collimated or diffuse) but which have enough regular features and enough stability to be entitled to the appellation, "optical property". The main apparent optical properties are all measurable by means of the four irradiances: $I^+(z, \pm)$ and $H(z, \pm)$. (See (9), (10) of Sec. 1.1.) Thus we write:

$$I^D(z, \pm) \text{ for } h^z \sim \quad (\text{Distribution (23)})$$

$H(z,t)$ functions)

"K (z,+) Itfor1 dH (z, ±) (K-functions for (24)

$H (z \pm dz$ irradiance)

"k (z)" for dh(z) (K-function for (25)

$h(z) dz$ scalar irradiance)

"R(z,t)" for H (z J) (Reflectance func

$H(z,t)$ tion for irradiance)

The distribution functions are simple indicators of the collimatedness or diffuseness of the light field in the downward (-) or upward (+) flows. The three K-functions are the depth **rates of** decay of the various irradiances. They are in principle generally distinct, though numerically they are quite close in value. The R functions give the reflectance of the entire medium to upward (+) or downward(-) flux at level z. Each of these is implicitly a function of wavelength. The theory of their interconnections is quite simple and will be discussed briefly in the following section. Their full theory is established in Chapters 9, 14 and 13. Table 7, adapted from (306]. is a representative sample of the magnitudes of these properties.

These measurements were made in the spring of 1957 before the onset of the plankton bloom and appearance of the thermocline. The lake-was essentially homogeneous so that the values of a, s, and a are representative of the entire medium, As the biologic activity within the lake increases throughout the remainder of'the year, the values of a, s and a will rise accordingly, thereby providing an optical biometer of such activity. Furthermore, since 95% of. the radiant energy content of the lake is essentially confined to within 3 diffusion lengths $1/K$ of the surface (cf., (98) of Sec. 1.4) and is therefore within the arena of most biologic activity, we would expect the homogeneity of the lake to disappear with the onset of spring and summer. Furthermore, rain run-offs will introduce still further mixtures of organic and inorganic materials into the entire body of the lake and change the optical properties. In short, it appears quite possible for

TABLE 7

The apparent and inherent optical properties of Lake Pend Oreille at depth 29 meters and for a wavelength band centered on 480 ± 64 mV

Property	28 April 1957 Computed from Radiance Dist. (sunny)	16 March 1957 Measured Directly. (overcast)	Calculated Indirectly
D(29 +			
<u>D(29,₉</u>			
K(; ⁻⁹			
K(29 -	:169/m	.184/m	
<u>R(29,₉+))</u>			
<u>R₂₉</u>			
<u>a C22)</u>			
<u>s(292</u>			.325/m
a (29)			

(From [306],, by permission)

one to form an optical portrait of the biology and geology of a lake or oceanic region by monitoring its a , a , a and K , at given times over a yearly cycle. The more of these properties one records, the more complete will the optical portrait be, and the more likely will be the usefulness of the findings to scientists in neighboring disciplines to hydrologic optics;

In order to increase our intuitive and objective knowledge about the relations between the clarity of water and its a and K properties, we append Table 8, adapted from [74]. This table, while ostensibly a rather limited sample, exhibits some interesting relations between a and K . For example the list of values shows a remarkable stability of the ratio K/a considering the range of waters in which the measurements were made. Thus while a varies over an eightfold range and K over a sevenfold range, K/a varies only over about a twofold range. The stability of K/a within a given region of water is even greater, indicating a possible basis for simple rules of variation of a and K which may be used to estimate one of those properties in the absence of, the other. This stability of K/a will be seen to be an important factor in the description of the shape of the light field at moderate and great depths in the seas and lakes (Sec. 10.7, in particular (29) of Sec. 10.7),

SEC, 1,6 OPTICAL PROPERTIES
137

TABLE 8

A sampling of a , K values for the 480 ± 64 mu range.

Coronados Islands Mexico (depth* 3 to 10 meters T San Diego Ba and A roaches (Average of a at w 93".n 2 meter of the bottom)	w 0.499 meter	0.180 meter's	.361
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Open Sea Southwest of Point

Loma	0,439 meter ^s	0,177 meter ^s	.404
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Coast at Mexico-California

border	0,654	0,226	,346
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San Diego Harbor Opening	0.727	0.162	.223
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Zuniga Point, Harbor Opening	1,065 l 0,396		.372
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Entrance Channel, South	1.156	0.280	.242
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Entrance Channel, North	1.770 0.565	.320
North Bend of Harbor	1,462 0.584	,400
Midpoint of Harbor Pocket	3,20 1.07	.334
Proceeding East through		
<i>traits o Juan e uca to</i>		
miralt Inlet (Averages		
o, ata rom 5'to 30 meters		
depth)		
Ocean <i>Entrance</i>	0, 543 meter 0.262 meter	,9483
	0.630 0.278	.442
Central Region	0.600 0.315	.525
	0.724 ¹ 0,9321	.445
Opposite Victoria, Vancouver		
Island	0,651 0,340	.522
Fresh Water Lakes *		
<i>E1 Capitan</i> Reservoir (Aug.		
1955), San Diego County		
(turbid water)		
	1,853 meter ^s 1,062 meters,	575
Diamond Island Field Station		
(Summer 1956) Lake Winnipe		
saukee, N,11, (moderately		
clear)		
	0.756 0.374	.495

Lake Pend Oreille, Idaho (Apr

1957) (Clear water) 0,413 0.195 ,472

The coefficients a and K were found to be the same at all depths at these locations and times.

23 INTRODUCTION VOL. I

Preliminary Observations on the Classification of Natural Hydrosols

From the preceding samplings, we see that one of the difficulties in forming a well-rounded optical picture of a natural hydrosol from most of the currently existing literature in hydrologic optics is that each investigator has looked at only one or two fragments of the entire radiometric picture according to his momentary interests. As a result, such findings have only transient interest because they *cannot* be incorporated by subsequent investigators into any systematic study of the radiative transfer processes occurring in the hydrosol. It is true that the preceding examples are very helpful in forming an intuition of the *principal optical* properties of natural hydrosols.

However, the completeness of experimental studies to the degree shown in Tables 1, 2, 3 are all too rare and we can be hopeful that they will be emulated by other investigators in future scientific studies of light fields in oceans and lakes. The recent works of Tyler cited above and those of Jerlov [125], [126], [127], have begun to show a trend in the direction of exhaustive systematic optical analyses of natural hydrosols. Thus in Jerlov's work [127], potentially fruitful classifications of different types of ocean waters are made, and are elaborated in the book version of [125]. For example, Fig. 1.74 shows a *classification of ocean water types* by means of the irradiance

MEMO

a

FIG. 1.74 Irradiance transmittance for a 10 meter layer of water, as sampled by Jerlov, and illustrating a possible classification scheme for natural hydrosols. (From [127], by permission)

SEC. 1.7 MODES OF CLASSIFICATION 139

transmittance e^{-Kz} of a given layer of water ($z = 10$ meters in this case) as a function of wavelength. While it would be generally more desirable and more directly useful to simply plot the K -function for $H(z, \lambda)$ as a function of λ , even as they stand, the graphs give an informative picture of the five general types of oceanic water encountered by Jerlov in his long series of careful studies of Atlantic and peripheral waters. These graphs could be of even greater service if someday they or their kind are supplemented by similar plots of a as a function of λ , along with K , as a function of both λ and X , if the patience and funds for such a pioneering effort could ever be

assembled, The rationale behind these observations will be outlined in the following section.