

STUDY AND EVALUATION OF REMOTE SPECTROSCOPIC MEASUREMENTS
IN WATER QUALITY SURVEILLANCE

W. Russell McNeil

Final Report
March 31, 1975
DSS Contract 12SQ.KL347-4-0082
for
CANADA CENTRE FOR INLAND WATERS

W.R. McNeil & Associates Inc.
TORONTO

W. R. McNEIL & ASSOCIATES INC.

21 DALE AVE., BOX 629
TORONTO M4W 1K3
416 967-3845

W. R. McNEIL & ASSOCIATES INC.

**21 DALE AVE., BOX 629
TORONTO M4W 1K3
416 967-3845**

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Acknowledgements

The author is indebted to the generosity of the many persons at the Canada Centre for Inland Waters directly and indirectly involved in the successful completion of this contract study.

I would especially like to thank Keith Thomson, Floyd Elder, John Jerome, Bob Bukata, Ed Bruton and Harry MacPhail for their entertaining and fruitful dialogue throughout the year. The assistance of Rosemary Morrison in numerous technical aspects relating to the preparation of this report is very much appreciated.

GLOSSARY OF SYMBOLS

$a(\lambda)$	wavelength dependant absorption coefficient [m^{-1}]
$\alpha(\lambda)$	wavelength dependant collimated extinction coefficient [m^{-1}]
$b(\lambda)$	wavelength dependant scattering coefficient [m^{-1}]
$B(\lambda)$	fraction of $b(\lambda)$ scattered in the back direction [i.e. 90° to 180°]
$\beta_s(\lambda)$	fraction of down (or up) welling irradiance scattered into the back direction by the entire atmospheric column beneath (or above) the detector
$\beta'_s(\lambda)$	fraction of down (or up) welling radiance scattered into the back direction by the entire atmospheric column beneath (or above) the detector
$\epsilon(\lambda)$	wavelength dependant parameter $\beta_s(\lambda)/\beta_s(1\mu)$
ϵ^λ	wavelength dependant diffuse extinction coefficient [m^{-1}]
$F_u(\lambda)$	upwelling radiant flux per unit projected area of a horizontal surface [$Watt/m^2$]
K	colour index
k	constant of proportionality in analytic expression for volume reflectance
$\langle K \rangle$	average particle scattering efficiency
$L_u(\lambda)$	upwelling radiant flux per unit solid angle per unit projected area of a horizontal surface [$Watt/m^2 sr$]
λ	wavelength
n	index of refraction
R	ratio of observed downward irradiance to the irradiance at the top of the atmosphere

$R_a(\lambda)$	apparent <u>irradiance</u> ratio at sensor altitude z and defined as the ratio of up to down-welling irradiance $E_u(\lambda)/E_d(\lambda)$
$R'_a(\lambda)$	apparent <u>radiance</u> ratio at sensor altitude z and defined as the ratio of upwelling radiance to downwelling irradiance $L_u(\lambda)/E_d(\lambda)$ [sr^{-1}]
$R_v(\lambda)$	volume reflectance or irradiance ratio just beneath the water surface
$R'_v(\lambda)$	radiance ratio just beneath the water surface $R_v(\lambda) = \pi R'_v(\lambda)$
$\langle r \rangle$	mean particle radius
ρ	surface irradiance reflectivity [air/water]
ρ_w	surface irradiance reflectivity [water/air]
ρ'	surface radiance reflectivity [air/water]
θ	solar altitude
$T^2(\lambda)$	two way atmospheric attenuation
z	altitude or depth

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1.0 INTRODUCTION

1.1 Remote Sensing Methods in Water Quality Studies (Perspective)

A remote sensing method applied to water quality studies includes any technique whereby information relating to the 'inherent' volume or surface properties of a particular water regime is obtained or deduced from electromagnetic energy which has interacted with the water regime and propagated to a remote detector which will be located on some platform situated above the water surface. For practical considerations, there are two kinds of platforms, satellite and airborne. Remote sensing instrumentation itself may be either active or passive. In an active system, the electromagnetic energy is supplied by some source located on the remote platform (i.e. radar) while passive systems rely upon natural radiation sources (i.e. sunlight)

The nature of the information extracted from the remote detector may be qualitative, semi-quantitative or quantitative depending upon user requirements, instrumental sophistication and interpretive effort. As an example, infrared imagery is capable of conveying information about water temperature. One user interested in pinpointing thermal sources may be satisfied with such qualitative descriptors as 'warmer than' or 'colder than' in the interpretation of such imagery. A second interpreter or user, may have an interest in measuring the net thermal input into a

known body of water from a thermal source (i.e. a power plant) and thus may be satisfied if the information "2°C warmer than the surrounding water" is available. This semi-quantitative measure might in such cases be all that will be required, especially if the temperature of the surrounding waters is known either by inference or available from an independent source (ground truthing craft or data buoys). In the absolute quantitative interpretation of infrared imagery, (i.e. 2°C within known limits, say 20%), a good deal more interpretive effort must be applied. Not only must there be more interpretive effort, there may also be a need for additional out complementary measurements on such phenomena as surface effects and atmospheric contributions to the signal. Thus, a quantitative measurement may indeed be possible, often using existing measurement techniques, but only after some added considerations on the physics of the measurement as well as the measurement process itself.

The current state of the art in remote sensing capabilities as applied to water quality studies includes the instrumental capability to measure, with varying degrees of success (on a quantitative scale as discussed above) the following set of parameters (Elder, 1974).

- 1) Temperature
- 2) Conductivity
- 3) Colour

These three parameters can each be related to various aspects of water quality. Quantitative measurements of water colour for instance (i.e. reflectivity as a function of wavelength), can be related to such non-conservative water quality parameters as biomass, suspended load (or turbidity), light attenuation, and photosynthetic photic zone depth. Conductivity or specific conductance is a measure of the free ion concentration contained in the water from which this measurement is obtained. This can be shown in many instances to be directly related to the total dissolved solids concentration in the water body of interest. As such, conductance may be regarded as a measure of a conserved water quality parameter. Measurements of surface temperature are capable of yielding a wealth of interpretable information not only on thermal structure but also on water dynamics. These three measurables might constitute, when adequately refined, a useful starting point for quantitative remote sensing applications to water quality studies.

For each of the three parameters discussed above, it is important that we consider several aspects of the measurement process not always considered in the past. The following three aspects of the measurement must be considered where quantitative water quality diagnostics are desired:

- 1) The source of energy
- 2) The interference (and other sources of 'noise')
- 3) The existence and validity of the analytic relationships between the measured quantities and the desired in situ parameters.

Most remote sensing studies have not concentrated upon accurate knowledge of these three details. The greater the knowledge of the interrelation of these details - the better the understanding and potential benefits of the remotely gathered data.

1.2 Terms of Reference

The terms of reference for this contract focus upon an evaluation of colour as a remote sensing diagnostic. The contract work statement, including reference to relevant sections and technical appendices reporting on the results of these investigations, is listed below:

You shall measure parameters of water colour by remote means [J] and investigate how these parameters are related to the physical [H], chemical [I], and biological [E] processes in the Great Lakes. You shall study the following specific topics and consult with the Scientific Authority on your findings:

1. Which intrinsic optical parameters can be measured remotely [2, A,B,C,D].
2. The physical limitations of remote measurements due to:[3].
 - i) the intervening atmosphere [3.1]
 - ii) environmental conditions such as clear or overcast skies [3.2, 5, 6]
 - iii) wind and waves [3.3, 6]
 - iv) limitations related to spectroscopy such as bandwidth response and wavelength selection [3.4,F]
 - v) surface slicks such as oil and Algal blooms [3.5].

3. The nature of the relations in situ between the measurement parameters and the physical [H], chemical [I], and biological [E] properties of the particular water body examined, [4,6]
 - i) can optical data be used to discriminate between organic and inorganic particulates [4.1, H]
 - ii) what effect has increasing biomass on the measured parameters? [4.2, A,D,E]
 - iii) which effect has increasing suspended sediment on the measured parameters? [4.3, A,H,J]
 - iv) can in situ scattering measurements be used to determine suspended load and what are the limitations of this method [4.4, H]

1.3 Study Criteria

Before attempting to evolve a methodological approach encompassing the broad based terms of reference listed above, the contractor selected as a guide, the following set of study criteria:

1. The remote sensing approach must be practical. While speculative and esoteric applications of optical remote sensing to water quality are intellectually fascinating, it is difficult to relate many of these applications and related phenomena to present water quality needs.
2. The measured and derived parameters of water colour should be quantitative and reproducible.
3. The remote sensing methodology must as closely as possible attempt to be all weather.
4. Active light sources (i.e. lasers) should be considered within the framework of any model development as 'improved' source systems with numerous advantages for quantitative water colour measurement.

5. The approach should have potential for realistic implementation within the short (i.e. 1-2 years) term and should be applicable to and compatible with existing airborne (and satellite) spectroscopic instrumentation.

2.0 REMOTE SENSING OF HYDRO-OPTICAL PHENOMENA

2.1 Volume Reflectance Spectroscopy Using Passive Techniques

In theory, a complete description of all of the optical properties of a complex ensemble of scattering and absorbing particles would entail a determination of a sixteen component or 4×4 scattering matrix. Each of the sixteen components of such an 'S' matrix will contain independent information on the absorbing, scattering and polarization properties of the scattering medium. Careful interpretation of these matrix elements will then yield valuable information on the size, shape, concentration, orientation and nature (i.e. composition) of the particles composing this scattering ensemble.

In practical situations of real interest, it can be shown that by relaxing the stringent requirements on knowledge of the polarization and angular dependence of these matrix elements, the scattering medium is sufficiently described by measurement of only two quantities. These are the absorption and scattering coefficients of the medium $a(\lambda)$ and $b(\lambda)$. These quantities are regarded as unique or inherent physical properties of the medium from which they are obtained. Many presently used techniques for assessing optical properties of the sea ignore the effect of the absorption term $a(\lambda)$ and make their optical ('turbidity') determinations proportional to only a portion of the

scattering coefficient $b(\lambda)$, measured at some large scattering angle (or range of angles). Such instrumentation, calibrated in JTU's or FTU's - units of little physical significance - can only be correlated to measurements made with instruments of identical optical design that have been calibrated against the same standard 'suspensions' [Austin, R.W.]. Carefully calibrated instrumentation designed to measure either $a(\lambda)$ [absorption meters] or $b(\lambda)$ [scattering meters] or some direct combination of $a(\lambda)$ and $b(\lambda)$ [transmissometers] will yield useful, quantitative information on the inherent optical properties of the sea. Even these measurements however unravel only part of the information on these two quantities for they generally ignore the wealth of spectral information contained in the variation of these two quantities with wavelength.

The object of remote sensing in the context of water quality surveillance is to determine, quantitatively, some effective measurement of water colour which may be reliably related to some combination of these two inherent optical properties of the sea.

Our research has demonstrated [appendix A,B,C,D,] that water colour, quantified as volume reflectance, and expressed as a generalized colour index, may be regarded as directly related

to these inherent optical properties of the sea.

Measurements of water colour, defined as volume reflectance, can moreover be interpreted in a variety of ways to meaningfully classify, and quantify several important aspects of water quality. Furthermore, colour indices may be reliably interpreted to yield meaningful data on photic zone depths, biomass and suspended load.

There have been two major problems associated with attempts to reliably and regularly measure colour index parameters from remote airborne platforms in the past:

- (A) A failure to recognize the importance of simultaneous determinations of the magnitude and composition of the incident irradiance.
- (B) Failure to account and correct for the competing effects of atmospheric and surface phenomena.

Existing instrumentation may be reconfigured to account for these problems. Some readjustment of the remote sensing methodology will of course be required. The results of such efforts, a quantified all weather measure of water colour which is directly interpretable as a measure of certain important aspects of water quality, should be well worth the effort.

2.2 Volume Reflectance Spectroscopy using Active Techniques.

A recognition of the capacity for quantified measurements of water colour through measurements of water colour indices may open new application avenues for optical systems using multi-wavelength lasers as sources. These systems, generally designed for remote applications of bathymetry as well as for fluorescence [see Section 2.3 and Appendix F] might also be considered for operation in a 'reflectance mode' for remote 'all weather' day/night determinations of volume reflectance parameters.

Active-source techniques might also allow simultaneous measurement of surface and atmospheric effects for signal correction. The ambiguity in the shape of the scattering phase function, a problem with passive water colour measurements is also removed when lasers are used as sources. Pulsed laser systems might also allow a measure of reflectance parameters with depth, through application of range gating techniques. The considerable advantages that such 'multi-wavelength' laser-source systems might allow, in addition to their all ready demonstrated potentials for bathymetry, and Raman and fluorescence spectroscopy, warrant their serious attention for continued development.

2.3 Raman and Fluorescence Spectroscopy

In addition to the applications of reflectance spectroscopy,

inherent in measurements of water colour via passive and active techniques, active remote sensing of optical phenomena will also allow extraction of information from application of Raman and fluorescence phenomena. A brief review of the physics of these phenomena is included as Appendix F.

The importance of fluorescence rests in the observation that many substances of biological and chemical origin are seen to exhibit strong broadband and fairly unique fluorescent signatures which are spectrally independent of excitation wavelength.

Fluorescence also exhibits a high quantum efficiency, sometimes of the order of 1%. It must be cautioned that fluorescence mechanisms are a strong function of a number of highly relevant quenching phenomena [temperature, dissolved oxygen concentration, impurity quenching] {Guilbalt,G.,(1967) } - these quenching mechanisms may severely limit the application of fluorescence phenomena in certain applications of quantitative diagnostics, such as individual pollutant species concentrations.

Fluorescence phenomena may better yield important information on the identity of environmental species. A group at the University of Toronto [Measures, et al., 1974] has demonstrated that the time decay of

fluorescence [Fantasia, 1971] is a spectrally dependent quantity that may have unique application in the remote identification of a number of important environmental pollutants.

The application of remote Raman techniques to several aspects of interest to water quality using lasers as sources has recently been successfully demonstrated. A group at York University [Carswell, et al., 1975] in particular, have demonstrated that the Lidar generated Raman signal from the water molecule, a species whose concentration is known, may be used as a normalizing return about which measurements of reflection, fluorescence and even returns from other Raman active species may be referred [Measures et al., 1975].

Subsequent sections of this report deal with various aspects relating to the remote measurement of volume reflectance using passive multi-spectral techniques. Although this basic development will apply to measurements obtained with passive instrumentation, the basic arguments are intended and expected, with some modification, to apply to active-source systems.

3.0 PHYSICAL LIMITATIONS OF REMOTE SENSING MEASUREMENTS

This section will briefly review several of the more important physical limitations imposed upon the remote measurement by a variety of environmental conditions. Any consideration on how remote sensing variables are effected by environmental conditions is equivalent to asking how each of the several terms contained within the transfer equation describing the remote measurement is effected by each of these varying environmental factors. In review, this transfer equation is written as [See Appendix D, Equation (1)]

$$R_a = R_v(1-\rho)(1-\rho_w)T^2 + \rho T^2 + \beta_s \quad (3.1)$$

where the apparent irradiance ratio R_a (i.e. albedo) is represented by contributions dominated by a volume reflectance term $R_v(1-\rho)(1-\rho_w)T^2$, a surface term ρT^2 , and an atmospheric term β_s .

3.1 The Intervening Atmosphere

A study of the variation of the apparent irradiance ratio R_a as a function of wavelength and altitude has been published by White (1971). We have calculated from White's data, the contribution to the apparent irradiance by "path radiance" (or the atmospheric term β_s) for the three wavelengths we have selected

in definition of our colour indices. These data are summarized in Table (3.1) for two different altitudes, (1.5 km and 7.6 km), along with the derived two way atmospheric transmittance term T^2 , obtained from the approximation: $T^2 \approx e^{-2\beta_s}$

<u>Wavelength</u>	<u>Backscatter</u>	<u>Transmittance</u>	<u>Altitude</u>
λ (nm)	β_s/R_a (%)	T^2 (%)	z (km)
430	62%	93%	1.5
430	80%	84%	7.6
530	29%	98%	1.5
530	58%	93%	7.6
630	22%	99%	1.5
630	51%	96%	7.6

Table 3.1 Contribution of 'path radiance', β_s , to the apparent irradiance ratio at 1.5 km & 7.6 km and at 430 nm, 530 nm, and 630 nm [adapted from White (1971)]

As the data in Table (3.1) shows, the path radiance, β_s , contributes a significant proportion of the measured albedo for altitudes as low as 1.5 km and is seen to range in magnitude from 22% of the radiance ratio at 630 nm (1.5 km) to 80% of the measured signal at 430 nm (7.6 km). The two way atmospheric transmittance on the other hand, is seen to be appreciably close to unity as to not significantly alter the

often made assumption that $T^2 \approx 1.0$. Only at short wavelengths and high altitudes is T^2 significantly less than unity [84% at 430 nm and 7.6 km].

3.2 Effects of Clear and Overcast Skies Upon the Apparent Irradiance.

The effect of the variation of the distribution of the incident irradiance upon the apparent irradiance due to overcast skies is threefold. First, under overcast skies, the incoming irradiance is changed from being predominantly direct to almost completely diffuse. There are certain advantages and disadvantages in these situations. The major disadvantage is that although diffuse, the incoming radiation is far from being constant. Consequently, it is mandatory, under overcast skies, to continually monitor the magnitude of the incoming radiation (See Appendix C).

The second major effect upon the apparent irradiance brought about under overcast skies is that the contributions to the apparent irradiance from the surface term ρ , in the Equation (3.1) will be maximum. In addition, it is not possible to minimize the magnitude of the relative contribution of this reflection term to the apparent irradiance by minimizing the instrumental field of view [See Section 5 for a complete description of this technique].

The third major consideration brought about under overcast skies may be an advantage in that under diffuse illumination conditions, the analytic expression for the volume reflectance becomes nearly identical to the expression derived for a Zenith sun [See Appendix A & D]. As a consequence, this removal of the dependence of solar altitude from the volume reflectance under diffuse conditions allows this function to be more reliably interpreted as directly proportional to the scattering coefficient $b(\lambda)$. As a consequence, inferences on the concentrations of suspended load obtained from volume reflectance measurements may be more reliably made under conditions of diffuse illumination (see Section(4.3)).

It is interesting to compute in a manner similar to that done for the term β_s in the previous section, the relative contribution of the surface term ρ to the apparent irradiance ratio R_a under conditions of direct and diffuse illumination. These calculations, done for three solar elevations, [i.e. 32° , 60° and 90°], are summarized in Table (3.2). For purposes of calculation, the inherent volume reflectance values are taken as 2% at 430nm ; 3% at 530nm and 1% at 630nm). The actual magnitudes of the 'emergent' radiance ratios[defined as the first term in Equation (5.2), Section 5] used for these calculations will be 0.0034

at 430 nm; 0.005 at 530 nm; and 0.007 at 630 nm. For simplicity, these calculations are assumed to apply at low altitudes (i.e. $\beta'_s = 0$ and $(T^2)' = 1.0$). The magnitude of the surface term ρ' is obtained from Equation (5.4)[p.37] while the values for the components (θ, R) or net surface reflectance are found in Payne's tables [Appendix G]. The value for the parameter R used in this calculation corresponds to a value for clear skies [i.e. 0.8]

<u>Wavelength</u>	<u>Surface Reflection</u>				<u>Solar Altitude</u>
	<u>Direct</u>		<u>Diffuse</u>		
<u>λ(nm)</u>	<u>ρ</u>	<u>ρ'</u>	<u>ρ</u>	<u>ρ'</u>	<u>θ</u>
430	86%	63%	87%	87%	32°
430	76%	57%	87%	87%	60°
430	72%	50%	87%	87%	90°
530	80%	50%	80%	80%	32°
530	68%	44%	80%	80%	60°
530	64%	38%	80%	80%	90°
630	92%	71%	80%	80%	32°
630	86%	67%	80%	80%	60°
630	84%	60%	80%	80%	90°

Table 3.2 Contributions of surface reflections to apparent irradiance and radiance ratios (ρ, ρ') for three solar elevations for both direct sun (real atmosphere) and diffuse illumination at 430 nm, 530 nm, and 630 nm

3.3 The Effects of Wind and Waves

The effects of wind and waves upon the remote sensing variables may be restated as the 'net effect' of wind-speed induced surface roughening upon the 'time averaged' air/water [i.e. ρ] and water/air [i.e. ρ_w] reflectance terms in Equation(3.1). The phenomena itself is due to variations in the 'average' or 'mean' angle of incidence of the incident radiation. For high solar elevations (i.e. $> 30^\circ$), the mean or time averaged angle of incidence is increased while for low ($< 30^\circ$) elevations this variation will reduce the mean angle of incidence.

The net effect of these phenomena is to slightly increase the time averaged reflection for high sun angles. In contrast, the reflectance for low sun angles is drastically reduced by wave action.

In a recent study, Austin [Jerlov, N.G. (1974)] has determined the magnitude of the time averaged variation upon the two terms ρ and ρ_w in Equation (3.1) for wind speeds from zero to 16m/s [35 Knots]. At a 30° solar elevation, ρ is found to be 15% larger for wind speeds of 16 m/s than for zero wind speed [i.e. $\rho(\theta = 30^\circ) = 0.0709$ at 16m/s and 0.0610 at 0 m/s]. At larger elevations, this effect is reduced [i.e. $\rho(\theta = 60^\circ) = 0.039$ for 16m/s and 0.0222 for 0 m/s].

At low sun angles, ρ is very much reduced. For $\theta = 10^\circ$, the reflectance is reduced by 42% at wind speeds of 16 m/s [i.e. $\rho (\theta = 10^\circ) = 0.2046$ at 16 m/s and 0.3502 at 0 m/s].

The quantity ρ_w or 'time averaged' water/air reflectance term in Equation (3.1) is nearly independent of sun angle and is seen to decrease in magnitude with increasing wind speed by as much as 4.5% [i.e. $\rho_w = 0.462$ at 16 m/s and 0.485 at 0 m/s].

The sample calculation summarized in Table (3.3) illustrates the 'net' effect of variations in wind speed upon the apparent irradiance ratio parameter R_a brought about by changes in ρ and ρ_w . In each case, the quantity R_a is calculated from Equation (3.1) with T^2 taken as unity; β_s/R_a as 0.29 [i.e. 240 m altitude in Table (3.1)]; and a value of 0.03 for the volume reflectance R_v .

<u>θ</u>	<u>Wind speed (m/s)</u>				<u>Solar</u>
	<u>0</u>	<u>4</u>	<u>10</u>	<u>16</u>	<u>Elevation</u>
0.097		0.102	0.108	0.110	30°
0.048		0.049	0.050	0.051	60°
0.047		0.047	0.047	0.048	90°

Table (3.3) Effect of wind speed upon the apparent irradiance ratio R_a as a function of solar altitude θ .

When a flat surface is roughened by wind, the image of the sun formed by specular reflection 'explodes' into glittering points. This phenomena, called 'glitter', is more noticeable for solar elevations of 30° - 35° [Jerlov, (1968)]. For practical interest to remote sensing, glitter can be avoided in the radiance measurements by judicious choice of instrumental field of view.

For certain applications however, glitter patterns may be utilized as an indication of sea slope and a possible key to certain dynamical features - a careful interpretation of this phenomena could yield valuable information on a number of lake dynamics related phenomena [Bukata, R.P., McColl, W.D., 1973].

3.4 Bandwidth Selection and Wavelength Response.

A selection of the suitable bandwidth for application to remote sensing is an important consideration in the measurement of volume reflectance parameters.

If spectral bandwidth is too large, certain desirable absorption features in the reflectance phenomena may be smoothed and obscured.

Too narrow a selection of bandwidth on the other hand will result in unnecessary reduction in signal.

Grew [1973], in a study on the reflectance properties of phytoplankton on inland lakes, determined, from a laboratory study, that 5 nm was an optimum choice for sufficient resolution of reflectance phenomena. The laboratory absorption spectra obtained by Grew for successive degradations of spectral bandwidths is illustrated in Figure (3.1). The smoothing of certain salient spectral features in these absorption spectra for bandwidth selections in excess of 10 nm is especially evident in this demonstration.

The selection of optimum wavelengths will be dependent upon the nature of information desired. For reflectance phenomena which are controlled by the absorption properties of the substances contained in the water - usually phytoplankton, knowledge of the absorption properties of the dominant phytoplankton species in the particular water regime would be useful in selection of optimum wavelengths.

The absorption spectra of four different phytoplankton species [Grew, 1973] shown in Figure (3.2) illustrate the above discussion.

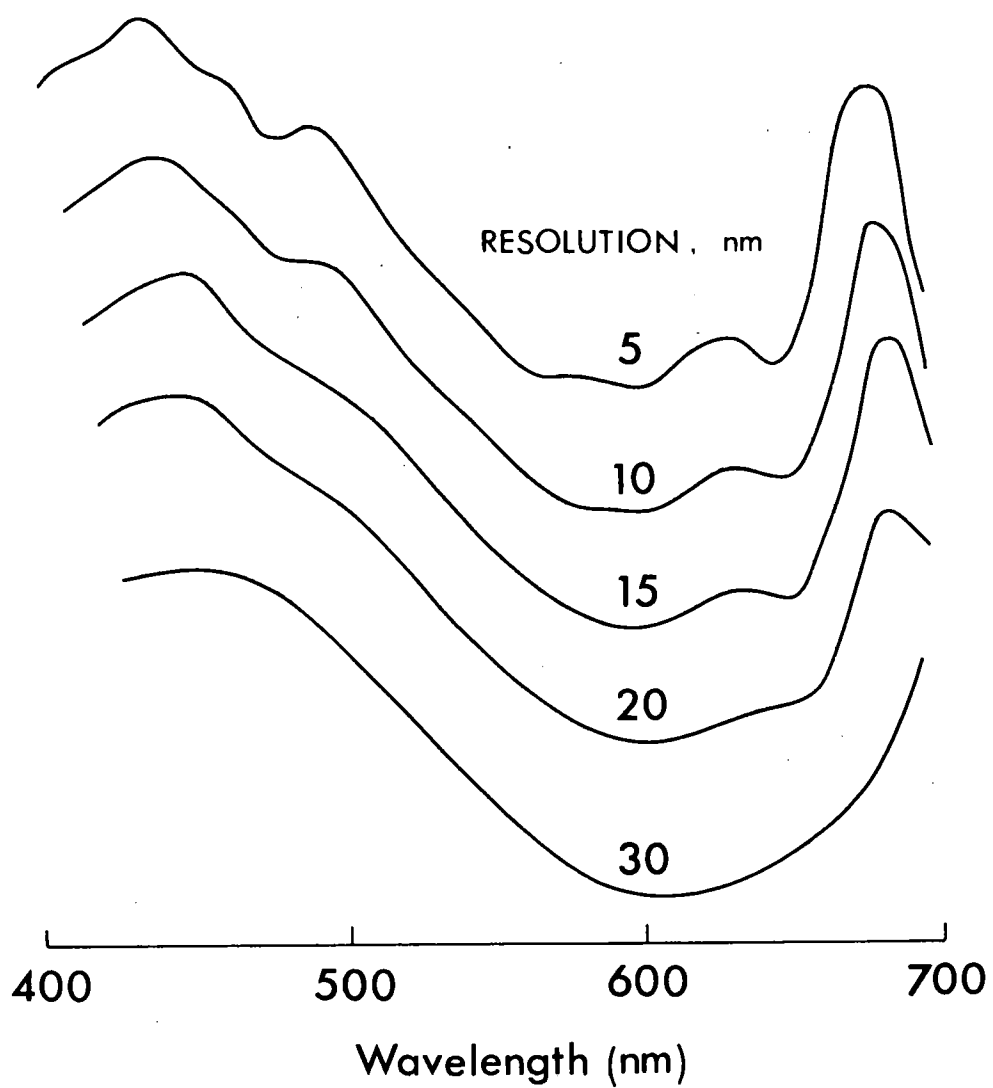


Figure (3.1) Laboratory absorption spectra of *ISOCHRYSIS GALBANA* obtained from successive degradations in spectral resolution [from Grew, 1973].

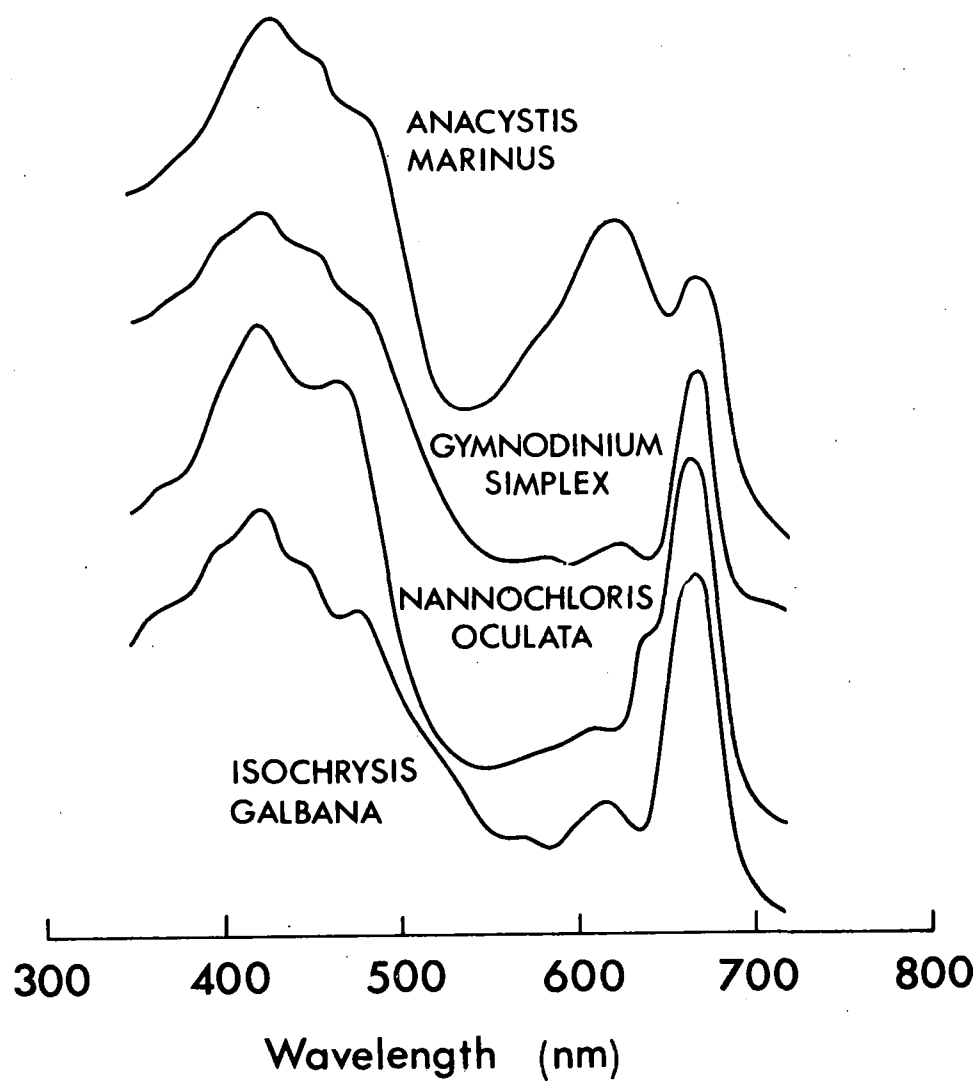


Figure (3.2) Laboratory absorption spectra for four selected species of phytoplankton [from Grew, 1973].

Our selection of wavelengths at 430 nm, 530 nm and 630 nm is affected by such absorption curves. For most plankton species, there is an absorption maximum near 430 nm with a broad minimum between 500 nm and 650 nm. The absorption properties of water however increase quickly for wavelengths greater than about 600 nm. The choice of 630 nm as a useful 'normalizing' point in the definition of colour indices [i.e. the index $K_3 = R_V(630 \text{ nm})/R_V(430 \text{ nm})$] is based on this observation as such a choice successfully avoids the sharp absorption maximum exhibited by most plankton species around 675 nm [Fig. 3.2]. The above discussion on bandwidth selection and wavelength response apply exclusively to remote sensing applications to reflectance spectroscopy.

For most applications of fluorescence spectroscopy optimum bandwidth selection will be the same as above (i.e. 5 nm) as fluorescence spectra 'mirror' absorption spectra [See Appendix I]. For potential applications to Raman spectroscopy, bandwidth and spectral selection requirements will be a strong function of the fine structure of individual Raman lines [See Figure F.1].

3.5 Surface Slicks (oil and algae)

The controlling factor governing the effect upon water colour measurements from substances, such as oil and algae, floating on the surface will arise from the incremental energy added to or subtracted from the apparent irradiance by the reflection contribution of the floating substances. The enhanced surface contribution to the apparent irradiance ratio will be partially compensated by a reduction in the apparent irradiance of the volume reflectance component [see Equation 3.1].

The magnitude of the surface contribution to the apparent irradiance reflectivity for oils will be determined by the Fresnel reflectance formula (for unpolarized radiation and normal incidence):

$$\rho \text{ (oil)} \approx \frac{(n-1)^2}{(n+1)^2} \quad (3.2)$$

Where n in Equation(3.2) is the index of refraction of the floating substance. For most oil types, n will usually range, depending upon oil API, over a range of values from 1.4 to 1.6 [as opposed to a value of 1.34 for water].

The resultant values for ρ will then range (for normal incidence) over values from 2.78% (for $n = 1.4$) to 5.33% (for $n = 1.0$).

It is useful to recognize that these enhanced reflection contributions, computed for normal incidence only, are 32% (for $n = 1.4$) to 153% ($n = 1.6$) greater than the contribution that would be obtained from the water surface alone.

Summarized in Table(3.4) is a sample calculation of the resultant effect upon the apparent reflectivity R_a which would arise from oils of varying n as well as for a floating algae patch ($\rho \approx 10\%$). The calculation assumptions are similar to those obtained for the data in Table(3.3) for a solar altitude of 90° and zero wind speed.

R_a	ΔR_a	<u>Surface Phenomena</u>
0.047	-	Water ($n=1.34$)
0.038	- 19%	Oil #1 ($n=1.4$)
0.051	+ 8.5%	Oil #2 ($n=1.5$)
0.064	+ 36%	Oil #3 ($n=1.6$)
0.111	+ 136%	Algae patch ($\rho = 10\%$)

Table (3.4) Apparent irradiance reflectivity R_a and incremental change in R_a from oils of varying n .

The values for R_a listed in Table (3.4) were obtained from the assumption that the first term contribution to R_a in Equation (3.1) is zero when the oil or algae patch is present.

An interesting observation obtained on perusal of the data in Table (3.4) is that oils of low n may actually bring about an anomalous (negative) signal change, while oils of large n should be 'seen' in the apparent reflectivity as significant signal enhancements.

For detection, mapping, identification, surveillance and thickness determinations of oil spills, a multi-sensor approach should eventually yield an effective solution. Existing airborne surveillance systems [Edgerton, (1975)] have demonstrated that oil detection and mapping is feasible at ranges up to 12 nmi using SLAR; while IR methods afford the 'best' demonstrated capacity for oil thickness mapping.

For eventual remote identification of specific oil types, a combination of IR, reflection, fluorescence and even laser-Raman techniques might be successful.

4.0 IMMERSION SENSING OF HYDRO-OPTICAL PHENOMENA.

Immersion sensing of hydro-optical properties by absorption and/or reflection spectroscopy may be considered from two points of view. First, for purposes of 'ground truthing', the most suitable 'operational' parameter must be the volume reflectance function $R_v(\lambda)$ spectrally determined from shipboard immersion spectroscopic instrumentation similar to the airborne systems. However, an alternative aspect of immersion sensing would view the in situ measurement of volume reflectance (or similar parameter) as an 'inferior' approach to more quantitative measurements of the absorption and scattering properties of water by direct techniques.

As a result of an awareness of this 'dual' aspect in any approach to immersion sensing, the operational and research measurements of hydro-optical properties within the Remote Sensing section at CCIW are divided into two classes. The first class of measurements consists of the immersion sensing of the following parameters (with typical sensors used given in parenthesis):

- (1) Transmittance (transmissometer).
- (2) Scatterance (Küllenberg scattering meter)
- (3) Diffuse attenuation (spectrometer).

The results of a series of measurements of these parameters on the Great Lakes as well as their application in the study of a number of limnological properties is published elsewhere [Thomson et al, 1974].

For purposes both of 'ground truthing' and optical classification of lakes, a second class of measurements is also now regularly obtained:

- (1) Volume Reflectance (spectrometer)
- (2) Colour index (Colour Index meter; {Thomson,et al})

These two classes of measurements are not mutually exclusive. Data on scatterance, absorptance and attenuance, obtained by the first class of measurements has been and continues to be crucial in establishing the functional validity of the deductions obtained from the immersion measurements of volume reflectance and colour indices.

4.1. The Use of Optical Data to Discriminate Between Organic and Inorganic Particulates.

For purposes of this discussion, the reader is referred to technical data included as Appendices F, H, and I.

The results of an extensive series of optical profiling measurements of transmittance and scatterance on Lake Huron appear

to indicate that an often observed decrease in the magnitude of the attenuation coefficient α ($= a + b$) in the region just beneath the thermocline [Figure (H.2)] may be attributed to an increase in the relative concentration of detrital material in this region. This phenomena, more quantitatively expressed in the observed behaviour of the 'indicatrix' α/b , also may have a simple physical interpretation. Phytoplankton, in becoming detritus through expiration, loses much of its fat soluble content; this loss is reflected as a relative increase in detrital density. The detrital material on becoming negatively buoyant can penetrate through the thermocline and into the hypolimnion. As a result, the relative concentration of detrital material in the water column should be maximum just below the thermocline.

Above and below the thermocline, the parameter α/b appears, from a study of a number of these profiles, to regularly approach two limiting values. These values (1.4 within the epilimnion and 1.3 within the hypolimnion) may be characteristic of the predominately biogenic (organic) and minerogenic (inorganic) particle types expected to exist within these regimes. These observed characteristic values of the parameter α/b are summarized in Table (4.1).

<u>Particulate Material</u>	<u>Depth (m)</u>	<u>α/b</u>	<u>Limnological regime</u>
Organic	0-20	1.4	Epilimnion
Detrital	20-40	1.2	Thermocline
Minerogenic	40-70	1.3	Hypolimnion

Table (4.1) Characteristic values for indicatrix α/b within three limnological regimes.

4.2. Effect of Biomass Upon Measured Optical Parameters.

Summarized in Table IV [Appendix D] are the results of a series of applications of linear regression analyses relating colour index measurements to concentrations of chlorophyll a as obtained from the 1974 Lake Huron/Georgian Bay Survey cruise data. These data would appear to indicate that meaningful correlations between colour index variables and biomass can be obtained from a careful interpretation of volume reflectance parameters.

For a variety of theoretical and practical reasons, some variation of the 'corrected' blue/red colour index [i.e. K_3-K_2] should eventually provide a basis for universal application to the remote estimation of biomass. This index is defined in such a way as to remove the contributions from suspended inorganic sediment from the analytic expressions relating chlorophyll and volume reflectance. Such a corrective approach might eventually minimize or even eliminate the absolute need for 'ground truthing' of reflectance data.

The fundamental validity of the approach relating these measurements of colour to biomass concentrations, by manipulations of the analytic expressions for volume reflectance, appear to be confirmed by the theoretical calculations which have been summarized as Appendix E.

4.3 Effect of Suspended Load Upon Measured Parameters.

Experimental confirmation of a linear relationship between suspended load and reflected light has recently been demonstrated [Ritchie et al, 1974]. These studies also confirm that the optimum wavelength regime for observation of this phenomena lies between 600 nm and 800 nm. The basis for this latter observation may be attributed theoretically to the small contribution in the reflected signal from absorption mechanisms within this wavelength range.

An attempt to quantitatively relate volume reflectance measurements to suspended load may be obtained by combining the semi-empirical expression for the mass concentration parameter, $\langle \text{conc} \rangle$, [Appendix H, Equation (H.4)] with the analytic expression for the volume reflectance parameter $R_v(\lambda)$ [Appendix D, Equation 7] to obtain ($\lambda = 630 \text{ nm}$)

$$\langle \text{conc} \rangle = \frac{4.6 a_w (630 \text{ nm})}{B} R_v (630 \text{ nm}) \quad (4.1)$$

where we have replaced in Equation (4.1) the term $(a_w + Bb)$ with $a_w(630 \text{ nm})$; while the parameter k (Equation D.7) is replaced by the parameter B (Equation D.8)-this is expected to be a valid approximation in the QSS model (Appendix D) for zenith sun or for diffuse illumination.

Utilizing a typical value of 1% for B along with the known value for $a_w(630 \text{ nm})$ {i.e. ≈ 0.23 }, Equation (4.1) may be approximated as

$$\langle \text{conc} \rangle \approx 106 R_v (630 \text{ nm}) \quad (4.2)$$

It is useful to compute from Equation (4.2) values for $\langle \text{conc} \rangle$, from the experimentally determined colour index data on $R_v(630 \text{ nm})$ listed in Tables II and III [Appendix D]. These calculations have been summarized in Table (4.2)

<u>Water Regime</u>	<u>$R_v (630 \text{ nm})$</u>	<u>$\langle \text{conc} \rangle$ (ppm)</u>
Mid Lake Huron.	0.0041	0.4
Blue Mean.	0.0061	0.7
Green Mean.	0.0084	0.9
Red Mean.	0.0160	1.7
Saginaw Bay.	0.0510	5.4

Table (4.2) Values for Suspended load $\langle \text{conc} \rangle$ obtained from Equation (4.2) for values of $R_v(630 \text{ nm})$ given in Appendix D [Table II & III].

The values for <conc> listed in Table (4.2) are obtained for total suspended load (i.e. organic and inorganic together).

Values for the parameter <conc> are no longer generally obtained during routine survey cruises on the Great Lakes. Measurements of this parameter in the past do however indicate that this calculated range of values is representative [K. Rodgers, 1975].

4.4. In situ scattering measurements.

Several useful applications of in situ scattering measurements in the determination of suspended load are summarized in Appendix H. In essence, these studies have shown that there are sound theoretical reasons to expect a linear relationship between suspended load and carefully determined light scattering measurements. The principal physical limitations of such methods rest upon the several assumptions upon which the relation relating scatterance to suspended load is determined. These are in review.

- 1) Assumption that the mean particle specific gravity is near unity.
- 2) Assumption that the mean relative particle index of refraction is 0.05.
- 3) Assumption that the mean particle size distribution (diameters) ranges between 0.2 μ and 20.0 μ .
- 4) Assumption that the particle ensemble is random, irregular and polydisperse.

- 5) Assumption that the incident (scattering) wavelength chosen is close to 0.6μ (red light)
- 6) Assumption that the radiance measurement obtained by the 'Integrating scattering meter' is accurately proportional to the scatterance b .

These 6 assumptions may act in certain instances to limit the usefulness of this technique. For general application however, there are good reasons to expect a meaningful relationship between suspended load and scatterance. Perhaps of more importance to practical applications of scatterance, is the non-destructive capacity such measurements have for real time studies of variations in mass concentrations with depth. Used in conjunction with simultaneous multi-wavelength measurements of transmittance, scattering profile data should provide an invaluable source of information not only on the concentration but also on the character of the particles within a water column.

5.0 ILLUSTRATED EXPERIMENTAL PROCEDURE

The following illustrated example will show step by step, the series of calculations and corrections required for a single calculation of a set of colour indices from an airborne platform equipped with the instrumental capabilities outlined in Appendix A and C.

In practice, in order to minimize the contributions to the apparent reflectance (Equation 1, Appendix D) due to surface and atmospheric effects, a measurement of the upwelling radiant flux $F_u(\lambda)$ within a suitable solid angle $\Delta\Omega$ is determined. The resultant radiance value ($L_u(\lambda) = F_u(\lambda)/\Delta\Omega$) is compared with the incident, or downwelling irradiance $E_d(\lambda)$ to obtain the quantity $R'_a(\lambda)$. After correction for surface and atmospheric effects, the quantity $R_V(\lambda)$ can be obtained from the relation

$$R_V(\lambda) = \pi R'_V(\lambda) \quad (5.1)$$

The resultant transfer equation will be written

$$R'_a(\lambda) = R'_V(\lambda) \{1-\rho\} \{1-\rho_w\} (T(\lambda)^2)' + \beta'_s(\lambda) + \rho' (T(\lambda)^2)' \quad (5.2)$$

where the primes in Equation (5.2) indicate that these quantities have been minimized. Note that the value ρ in the first term of Equation (5.2) is not primed. The quantity ρ' is a measure of the diffuse (sky) reflectance in the total surface reflectance.

Step 1. Near IR Measurement

Considerations similar to those outlined in Appendix D will yield from the near infrared (1μ) measurement the expression

$$R'_a = \rho' + \beta'_s \quad (5.3)$$

where we have assumed that atmospheric conditions are such that $\rho'(T^2)'$ is not significantly smaller than ρ' .

Step 2. Calculate ρ'

The quantity ρ' may be calculated from data supplied in Payne's tables [Appendix G] if the parameters θ (solar altitude) and R (fraction of observed downward irradiance to the irradiance at the top of the atmosphere) are known. Each value (θ, R) determines a unique value for the net surface albedo $\rho(\theta, R)$. If it is assumed that the quantity R is a reasonable measure of the fraction of direct irradiance in the total downwelling irradiance, then the value for $\rho'(\theta, R)$ will be determined by the approximation

$$\rho'(\theta, R) = \frac{1}{\pi} [\rho(\theta, R) - R\rho(\theta, R)] \quad (5.4)$$

where $\rho(\theta, 1)$ is the fraction of direct reflectance in the total reflectance $\rho(\theta, R)$

Step 3. Solve for $\beta'_s(1\mu)$

Use the value for ρ' calculated from Equation (5.4) to solve for β'_s in Equation (5.3)

$$\beta'_s = R'_a - \rho' \quad (5.5)$$

Step 4. Correct β'_s for wavelength dependence

In correcting for the wavelength dependence of the atmospheric term, the following functional form is useful

$$\beta'_s(\lambda) = \epsilon(\lambda)\beta'_s(1\mu) \quad (5.6)$$

where $\beta'_s(1\mu)$ was determined from Step 3. Values for the parameter $\epsilon(\lambda)$ will vary somewhat depending upon the nature of the atmospheric aerosol. Under most 'real' atmospheric conditions, where scattering in the lower atmosphere arises mostly from a complex ensemble of polydisperse particles of varying shapes, the parameter $\epsilon(\lambda)$ is only weakly dependent upon wavelength. Values for $\epsilon(\lambda)$ may be derived from published data for various 'real' atmospheres. At the wavelengths of interest in the derivation of colour indices (i.e., $.4\mu$, $.5\mu$, $.6\mu$), data on atmospheric extinction in the lower atmosphere published by Zuev(1970) will yield the following parameter values for $\epsilon(\lambda)$

λ	1.0μ	0.6μ	0.5μ	0.4μ
$\epsilon(\lambda)$	1.0	0.75	1.05	1.20

Step 5. Calculate $\rho'(T^2(\lambda))'$

In this calculation of the third term in Equation (5.2), the effects of atmospheric absorption upon the net atmospheric attenuance (or transmittance) are assumed to be small. We thus assume the approximation

$$(T^2(\lambda))' \approx e^{-2\beta'_s(\lambda)} \quad (5.7)$$

The surface term ρ' is nearly independent of wavelength throughout the visible; as a consequence, $\rho'(T^2(\lambda))'$ is determined.

Step 6. Solve for $R_v(\lambda)$

It is now possible to solve for the volume reflectance by combining Equations (5.1) and (5.2) to yield

$$R_v(\lambda) = \frac{\pi}{(1 - \rho)(1 - \rho_w)(T^2(\lambda))'} \{R'_a(\lambda) - \{\beta'_s(\lambda) + \rho'(T^2(\lambda))'\}\} \quad (5.8)$$

Step 7. Calculate colour indices

The desired and 'inherent' optical quantities (Appendix D) are defined from the relation

$$K(\lambda_{ij}) = \frac{R_v(\lambda_i)}{R_v(\lambda_j)} \quad (5.9)$$

Suitable software coupled to existing data handling hardware such as ADAS (CCRS), could provide the above 'corrections' in real time.

6.0 WATER COLOUR AND WATER QUALITY

It has recently been suggested (Robertson,1975), that certain aspects of water colour might formally and quantitatively be related to water quality in a manner which is independent of the actual nature of the substances which bring about such changes in water colour. In this section, a numerical example for the absolute values and allowable upper limits for several useful hydro-optical parameters is provided according to a suggested variation on Robertson's criterion.

The criterion, as adapted here for potential application in Remote and Immersion sensing of Quantitative hydro-optical parameters might be stated as follows:

Prolonged human activity should not be such as to decrease the mean depth of the photic or life support zone by more than 25 % over one daylight period or by more than 10 % for more than one daylight period over seasonal norms.

The definition of the depth of the photic zone may be determined in any number of ways. For purposes of these calculations, we have defined the photic depth specifically as the 10% light level for natural light for a wavelength of 430 nm. The value 10% is used as

the numerical values for the photic depth derived from this 10% definition closely approximate measured values for this parameter using other techniques. The choice of 430 nm in the definition of photic depth corresponds to a chlorophyll absorption maximum. However, at 430 nm, a number of additional factors could contribute to reductions in photic depth. Absorption from dissolved and 'yellow' substances, as well as suspended particulates (organic and inorganic) will be observable at this wavelength. The removal of the light due to these many possible contributing factors at this wavelength should be a most sensitive measure of the depth below which photosynthetic production can not efficiently occur. Any reduction in this depth by the additional introduction of colour arising from human activity will in effect compress (by remarkable degree in oligotrophic waters) the life support or photic zone depth. Any real and prolonged reduction in this depth by a significant amount 'forces' all life within the lake to a shallower zone. The effects of this reduction in photic depth upon the entire ecosystem within the lake can be complex in the extreme. In effect however, the process contributes directly to and is an effective measure of the premature aging or eutrophication of a body of water.

The data summarized in Table (6.1) represents the numerical values for a variety of hydro-optical parameters corresponding to the five optical regimes determined from experimental measurements on Lake Huron and Georgian Bay (Appendix D, Tables II and III).

<u>WATER COLOUR</u> <u>REGIME</u>	<u>COLOUR</u> <u>INDEX</u>	<u>ABSORPTION</u> <u>COEFFICIENT</u>	<u>DEPTH OF</u> <u>PHOTIC ZONE</u>	<u>EXTINCTION</u> <u>COEFFICIENT</u>	<u>TRANSMITTANCE</u>	<u>EQUIVALENT</u> <u>MASS</u> <u>CONCENTRATION</u>
	K_3	$a(430 \text{ nm})$	$z(10\%)$	$\alpha = a + b$	$100e^{-\alpha}$	$<\text{conc}>$
	-	(m^{-1})	(m)	(m^{-1})	$(\%)$	(ppm)
<u>MID LAKE</u> <u>HURON</u>	0.19	0.05	46	0.20	82	0.69
<u>BLUE WATER</u> <u>MEAN</u>	0.27	0.06	38	0.24	79	0.83
<u>GREEN WATER</u> <u>MEAN</u>	0.41	0.10	23	0.40	67	1.38
<u>RED WATER</u> <u>MEAN</u>	0.79	0.19	12	0.76	47	2.62
<u>SAGINAW</u> <u>BAY</u>	2.52	0.60	3.8	2.4	9	8.3

Table (6.1) Colour index K_3 ; derived absorption coefficients $a(430 \text{ nm})$ and photic zone depths $z(10\%)$; and equivalent extinction coefficients, transmittances, and mass concentrations, for the five optical regimes on Lake Huron (Appendix D, Tables II & III)

The pertinent optical parameter from a remote sensing point of view is the colour index K_3 listed in the second column of Table (6.1)

The absorption coefficient in the third column of Table (6.1) is obtained in each case from the definition of K_3

$$a(430 \text{ nm}) \approx a_w(630 \text{ nm})K_3 \quad (6.1)$$

where it is assumed that the absorption at 630 nm is dominated by absorption due to the water molecule (i.e. $a_w(630 \text{ nm})$). This assumption should be valid over expected ranges of absorption values (see Table (E.1))

The photic or life support depth, $z(10\%)$, in column four, is obtained from the relation

$$z(10\% @ 430 \text{ nm}) = \frac{\ln(0.1)}{a(430 \text{ nm})} \quad (6.2)$$

The above relation assumes that the photic depth, which is regulated by the diffuse attenuation coefficient, is closely approximated by the absorption term.

The collimated attenuation coefficient $\alpha(430 \text{ nm})$ listed in the fifth column, is included for reference. The actual magnitude of α is obtained in this case from the empirical relation (Jerome, J., et al., 1975)

$$(b/a)_{430 \text{ nm}} \approx 3 \quad (6.3)$$

From Equation (6.3), α may be 'reconstructed' (i.e. $\alpha \approx 4a$).

The collimated transmittance, as would be read from a transmissometer, and which is defined by α , is listed in the sixth column.

The last column in Table (6.1), lists the equivalent mass (or volume) concentration of suspended particulates which would be required to yield equivalent values for the parameters T, α, z and K_3 .

The numerical values for this mass concentration are obtained from the relation

$$\langle \text{conc} \rangle \approx 4.6b \quad (6.4)$$

the derivation of which is included in Appendix H.

If a water quality criteria based upon some variation of that suggested above were adopted, the decrease in the photic or life support zone by the defined (25%) degree would occur for changes in the numerical values of the parameters in Table (6.1) by amounts summarized in Table (6.2)

This 25% compression of the 46 m photic depth for the oligotrophic mid lake Huron waters for example, would be observable as a net

<u>WATER COLOUR</u> <u>REGIME</u>	<u>COLOUR</u> <u>INDEX</u>	<u>ABSORPTION</u> <u>COEFFICIENT</u>	<u>DEPTH OF</u> <u>PHOTIC ZONE</u>	<u>EXTINCTION</u> <u>COEFFICIENT</u>	<u>TRANSMITTANCE</u>	<u>EQUIVALENT</u> <u>MASS</u> <u>CONCENTRATION</u>
	K_3	$a(430 \text{ nm})$	$z(10\%)$	$\alpha = a + b$	$100e^{-\alpha}$	$<\text{conc}>$
		(m^{-1})	(m)	(m^{-1})	$(\%)$	(ppm)
<u>MID LAKE</u> <u>HURON</u>	+ 0.05	+ 0.01	- 13	+ 0.05	- 4	+ 0.17
<u>BLUE WATER</u> <u>MEAN</u>	+ 0.07	+ 0.02	- 9.5	+ 0.06	- 5	+ 0.21
<u>GREEN WATER</u> <u>MEAN</u>	+ 0.10	+ 0.03	- 5.7	+ 0.10	- 6	+ 0.35
<u>RED WATER</u> <u>MEAN</u>	+ 0.20	+ 0.05	- 3.0	+ 0.20	- 8	+ 0.66
<u>SAGINAW</u> <u>BAY</u>	+ 0.60	+ 0.15	- 0.9	+ 0.60	- 4	+ 2.10

Table (6.2) Allowable upper limits on the parameters listed in Table (6.1) according to the suggested water colour-water quality criteria.

increase in the colour index K_3 from values near 0.19 to values near 0.23. As the data in Tables (6.1) and (6.2) indicate, this resultant 13 m decrease in the photic zone depth could occur by increasing by as little as 0.17 ppm, the equivalent concentration of particulate material in suspension. This same effect could also be deduced or 'monitored' by the immersion measurements of the diffuse attenuation coefficients or alternatively, reliably inferred from the equivalent reduction in path transmittance (i.e. for mid lake Huron this would be equivalent to a reduction in T by 4 % from 82% to 78 %).

At the other extreme, the reduction in the photic depth of the eutrophic Saginaw Bay waters by 0.9 m (i.e. to 1.9 m from 2.8 m) would occur with an introduction of the equivalent of 2.1 ppm of particulate into suspension. This would be a much higher tolerance than would be the case for mid lake Huron.

It is important to recognize that all of these very real changes in water quality could be inferred directly and quantitatively both from remote and immersion sensing of hydro-optical parameters.

From a water quality viewpoint, it is not important whether these reductions in the photic depth are brought on by dissolved or suspended (organic or inorganic) material. What is important to realize is that these reductions can be quantitatively measured in a way which is independent of the nature or composition of the material causing the change.

7.0 CONCLUSIONS

1. Quantitative airborne spectroscopic measurements of water colour, defined as volume reflectance and determined by either passive or active techniques, can be related to the inherent or intrinsic hydro-optical properties of the sea (or lake). This inherent volume reflectance data cannot however be obtained remotely, unless provision is made for correction of the albedo (the quantity actually measured), for atmospheric and surface effects (Sections 2.0 & 3.0)
2. Albedo corrections for the above mentioned effects can be reliably made through application of techniques similar to those outlined in this report (Section 5.0)
3. In situ or immersion sensing of hydro-optical properties confirm that it is possible to meaningfully relate volume reflectance parameters to biomass, total suspended load, and photic depth (Section 4.0).
4. Certain aspects of water colour can be directly related to water quality in a manner which is independent of the nature of the substances causing the observed changes in water colour. The photic or life support depth in particular, a quantity which can be conveniently measured by both remote and immersion sensing, can be shown to be uniquely related to trophic state and hence could form the basis for a water colour/water quality criterion (Section 6.0).

8.0 RECOMMENDATIONS

It is recommended that:

1. Consideration be given to initiation on an operational basis, of a routine programme of measurements of water colour (as defined herein), utilizing existing airborne instrumentation, but modified wherever possible to account for the atmospheric and surface effects discussed in this report.
2. Immersion sensing systems, in their design, should incorporate provision for measurement of volume reflectance parameters.
3. The importance and potential benefits to water quality surveillance of establishing an effective water quality criteria based upon water colour be recognized. Some variation of the criterion suggested in this report should be adopted.

APPENDIX AQUANTITATIVE WATER COLOUR MEASUREMENT BY REMOTE SENSING

This presentation contains an outline of several important considerations required for a quantitative remote determination of intrinsic water colour parameters. The well established volume reflectance parameter is suggested as a useable remote sensing variable which is amenable both to modeling and to ready interpretation as long as the physical limitations imposed both by the atmosphere and the water surface are taken into account. A discussion on the merits of active remote sensing techniques is included along with a brief resume of several of the more interesting 'technique' developments which could be applied to the quantitative remote sensing of water colour.

This paper was presented at the 2nd. Canadian Symposium on Remote Sensing held in May, 1974, at the University of Guelph, and has been published in those proceedings.

PREFACE

Before any determination of a water quality parameter by remote means is attempted, an awareness of three important objectives will be required: First, for purposes of quantitative analysis, we must determine what intrinsic optical parameters are amenable to remote sensing. Second, having determined the desired set of [optical] parameters, it is necessary to incorporate, in a useable remote sensing model, the several physical limitations imposed by the atmosphere and water surface -limitations which do not affect the in situ measurements of these same optical quantities. Third, we must determine what best limnological interpretation can reasonably be applied to the corrected optical data. A resume of progress in these three study areas is included below.

1 VOLUME REFLECTANCE - AN INTRINSIC OPTICAL PARAMETER

Defined as the ratio of up to downwelling irradiance as measured just beneath the water surface, the wavelength dependant volume reflectance function [often called the irradiance ratio] has long been known [JERLOV] to be a relatively invariable [i.e. not a strong function of solar angle] optical parameter and as such may be regarded as a reasonably intrinsic optical quantity. Stimulated by developments in remote sensing, the volume reflectance function has recently been given analytic meaning [GORDON & BROWN; GORDON]. According to these studies, the volume reflectance function

$R_V(\lambda)$ is shown to be both proportional to the wavelength independent particle scattering coefficient b and inversely proportional to the diffuse extinction coefficient ϵ^λ so that

$$R_V(\lambda) = \frac{kb}{\epsilon^\lambda} \quad (1)$$

where k is a constant which depends upon the shape of the particle-dominant scattering phase function.

Knowledge of the volume reflectance parameter $R_V(\lambda)$ as a function of wavelength λ will yield valuable optical information on the absorption and scattering properties of the water body under study.

The application of suitable algorithms on $R_V(\lambda)$ would then yield quantitative information on a variety of limnological parameters including: biomass, sediment loading, Secchi depths, extinction coefficients (both collimated and diffuse) and the photosynthetic photic zone depth.

2 THE REMOTE SENSING MODEL

Having determined a suitable optical parameter, such as the volume reflectance function, one must incorporate into a useable remote sensing model, the various atmospheric and surface reflectance terms which effectively interfere with an accurate determination of $R_V(\lambda)$.

In terms of the apparent reflectance or albedo $R_a(\lambda)$, which is the quantity which would actually be measured at aircraft or satellite altitude z , $R_v(\lambda)$ may be expressed in the following manner.

$$R_v(\lambda) = \frac{1}{1 - \rho} \frac{1}{1 - \rho_w} ([R_a(\lambda) - \beta_s(\lambda)]/T^2(\lambda) - \rho) \quad (2)$$

where $\beta_s(\lambda)$ is the fraction of incident light backscattered into the receiver by the atmospheric column beneath the remote platform; $T^2(\lambda)$ is the diffuse two-way atmospheric attenuation coefficient along the path; ρ is the fraction of sky and sun light reflected from the water surface; and ρ_w is the fraction of diffuse upwelling light reflected back into the medium [i.e. water] at the water-air interface.

Thus, in order to determine the interpretable parameter $R_v(\lambda)$ remotely, knowledge of the atmospheric $[\beta_s(\lambda), T^2(\lambda)]$ and reflectance $[\rho, \rho_w]$ terms must also be remotely and preferably simultaneously obtained in some independant manner - these corrections may then be applied through Eqn.(2) to yield $R_v(\lambda)$.

The problems inherent in a determination of these interference or 'noise' terms may not be insurmountable. They may in fact have some elegant solutions- several suggestions of which are discussed in some detail elsewhere [MCNEIL & THOMSON].

3 INTERPRETATION

The utilization of volume reflectance to obtain data of limnological interest depends of course upon user need. For any rapid 'quick look' but quantitative survey, knowledge of the extinction properties of a particular water regime may often be all that would be required. In these cases, a measure of $R_v(\lambda)$ at two or three preselected wavelengths would be all that may be necessary. According to this proposed method, one could obtain the limnologically interesting diffuse extinction coefficient $\bar{\epsilon}$ by taking the ratio of the two measured reflectance parameters so that from Eqn.(1) we would obtain

$$\frac{R_v(\lambda_1)}{R_v(\lambda_2)} = \frac{\epsilon^{\lambda_2}}{\epsilon^{\lambda_1}} = K_{12}(\lambda) \quad (3)$$

where we have designated this ratio as K for convenience of notation

If the two chosen wavelengths were a combination of any two of 430 nm, 530 nm, or 630 nm, one could use an interpretive approach developed by VOLLENWEIDER [see also THOMSON et al.] for in situ application. According to the Vollenweider approach, the mean extinction coefficient $\bar{\epsilon}$ may be expressed in terms of the wavelength dependent coefficients ϵ^{λ} at any of the other three wavelengths λ_i through relations of the form

$$\epsilon^{\lambda_i} = x_i + y_i \bar{\epsilon} \quad (4)$$

where x_i and y_i are known regression coefficients at each λ_i and have been [or may be] determined for the water regime of interest. Thus, $\bar{\epsilon}$ could be determined from the expression

$$\bar{\epsilon} = \frac{Kx(630) - x(530)}{y(530) - Ky(630)} \quad (5)$$

where K is defined by Eqn.(3).

According to a second approach [MCNEIL & THOMSON] one could apply a variety of algorithms and limnologically reasonable assumptions for each of any suitable combination of reflectance values directly to obtain information on sediment loading, biomass, Secchi depth (photic zone) etc. - and all from an accurate spectral determination of $R_v(\lambda)$

One theoretical example of how sediment and chlorophyll data may be extracted from reflectance spectra is illustrated in Figure (1). This figure illustrates the behavior of $R_v(\lambda)$ as chlorophyll a [in Fig.(1a) and for $\lambda = 400$ nm] and suspended sediment [in Fig.(1b) and for $\lambda = 700$ nm] are separately varied over the ranges of interest for most limnological applications. These calculations are based upon manipulations of Eqn.(1) using techniques and assumptions outlined elsewhere [MCNEIL & THOMSON].

In summary, one can utilize properly corrected reflectance data to obtain information which is interpretable in terms of quantitative parameters

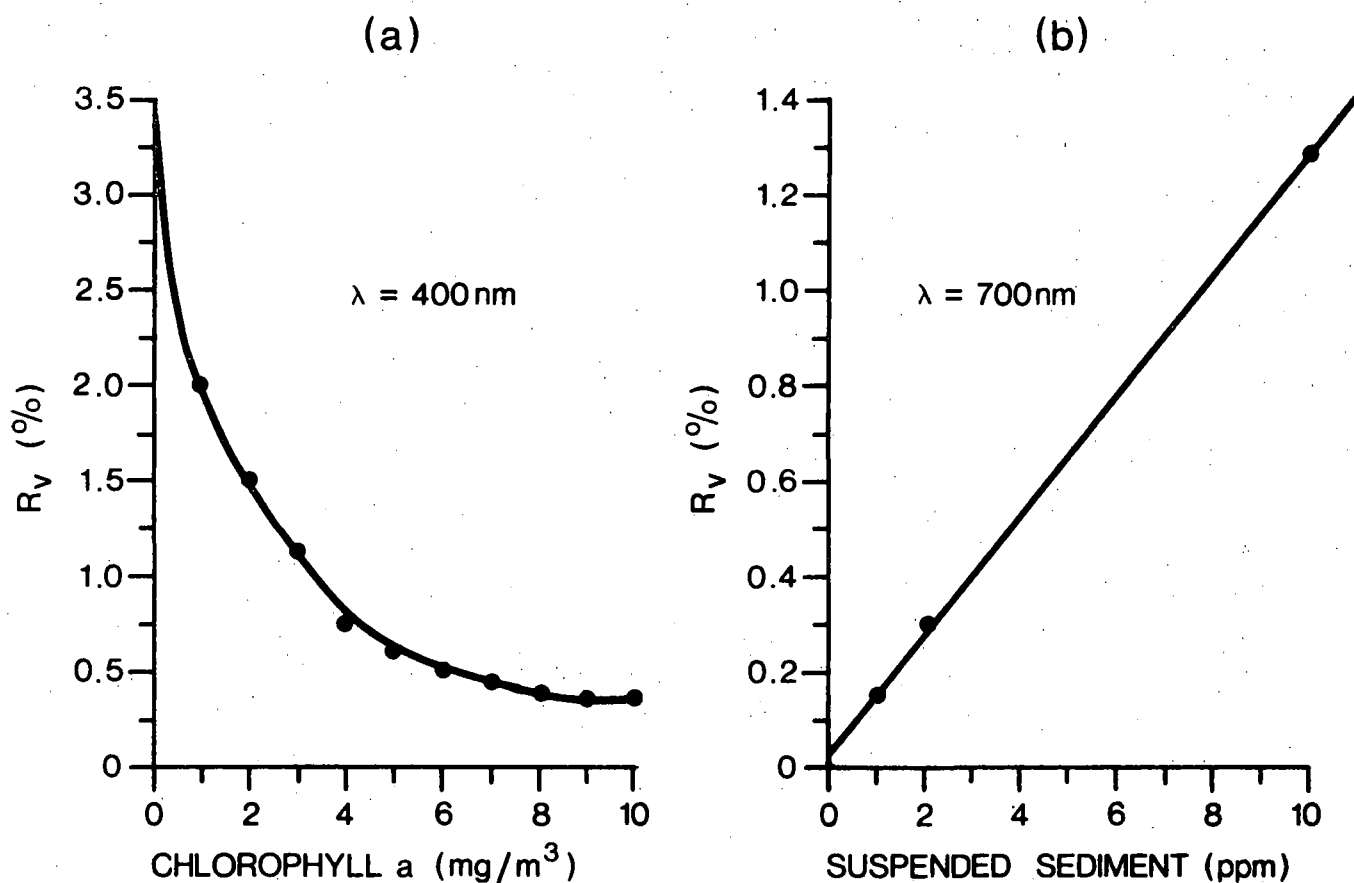


Figure (1) Variation of volume reflectance with concentration of chlorophyll a (in (a)) and suspended sediment (in (b))

of limnological interest. The ultimate accuracy of this data will be a strong function of the various model assumptions applied in each case. These models are however, amenable both to empirical verification through careful laboratory analysis and thereby refinement where and when needed.

4 ACTIVE REMOTE SENSING

In substance, active remote sensing in the visible portion of the electromagnetic spectrum consists of utilizing some form of artificial light as source. The laser is usually employed for this task.

There are several advantages inherent in active remote sensing. These include higher spectral intensities than available from natural light [i.e. from four to ten orders of magnitude depending upon conditions and source] along with an immediate twenty-four hour monitoring capability. In addition, an active technique will enable a study of reflectance phenomena which would be free from ambiguities in the shape of the scattering phase function-a problem where natural light is regarded as source [i.e. due to variations both in the distribution of sun and sky light and in changes in solar angle]. The high degree of laser beam collimation and directionality is responsible for this advantage.

The high spectral intensity of the laser source also allows, as an additional 'spin-off' advantage, access to the now embryonic areas of remote fluorescence and Raman spectroscopy.

Operating in short pulsed modes, laser sources will also allow for information retrieval as a function of depth and to high accuracy [i.e. better than one centimeter resolutions are possible]-through the now well

developed technique of range-gating.

Careful safety and cost considerations must be weighed before routine deployment of laser based systems. However, neither of these factors should eventually negate the numerous advantages of an active system.

It is probable that some of the most useful remote sensing information will eventually arise from work in laser applications to simple reflectance spectroscopy utilizing tunable pulsed and CW laser systems as sources.

5 SENSOR CAPABILITIES

The brief summaries outlined below are intended as a short review of a few of the more interesting 'technique' developments, using a variety of instrumental configurations, which have been, or may be, applied to the quantitative remote measurement of water colour parameters.

5.1 ERTS 1 The utilization of multispectral scanning techniques as especially exemplified with the ERTS 1 resource satellite imagery, is now beginning to reap some dividends in its application to quantitative water colour studies. This has been especially evident in the apparent utility of ERTS to clearly delineate sediment laden coastal-type waters from clearer sediment-free water regimes.

Both the use of the raw digital tape data [rather than the preprocessed imagery] and the manipulation of this data through considerations of a) atmospheric effects; b) surface phenomena; and c) the application of semi-empirical algorithms to the several operational ERTS 1 channels, is now beginning to show some limited quantitative success as evidenced by recent studies [BUKATA & BRUTON; LANGHAM & ROCHON; GOWER & DANIEL; PARIS].

In its present configuration however, ERTS 1 data is far too broadband [spectral bandpass of 100 nm vs. an ideal of 5 nm] and limited [the very important 400-500 nm band is missing] for accurate quantitative remote sensing of water quality parameters. For classification studies and water regime delineation studies ERTS is superb.

5.2 PHOTOGRAPHY The capacity for unique applications of conventional photographic techniques has been successfully demonstrated by PIECH. The Piech SCS or Scene Color Standard technique basically utilizes natural objects as control standards for the determination of volume reflectance parameters.

Before any attempt to use photography as a quantitative tool in remote measurements of water colour one would be advised to carefully examine the SCS and similar techniques as a minimum effort.

5.3 SPECTROSCOPY Aerial spectroscopy in its many and diverse forms offers

the best promise for quantitative remote sensing both from a developmental and experimental basis.

Numerous passive spectral studies which have either been successfully flown [e.g. MILLER et al.; GREW; KERR] or simulated on the ground or near the surface [e.g. RITCHIE et al.; BLANCHARD & LEAMER; WALKER et al.] have demonstrated that spectroscopy is capable of providing information on water quality of a quantitative nature.

Despite these demonstrations, no single spectrometer-based sensor is as yet capable of providing all of the information required for quantitative studies. These instrumental requirements are based on considerations discussed earlier and are summarized below:

- [a] The ability to simultaneously record both the up and downwelling irradiance [or radiance or both] components within selected increments of the visible spectrum with a minimum spectral resolution of 5 nm [GREW].
- [b] The ability to simultaneously and separately record the effects due to atmospheric backscatter and surface phenomena.
- [c] The operational sensor must be packaged with due regard for cost, alignment and other environmental factors [i.e. aircraft vibration], and should be engineered with due regard for the addition at a later date,

of an artificial source for active remote sensing studies and depending upon user need.

Information currently available indicates that spectrometers based upon reticon arrays [WALKER et al.] or image-intensifier OMAs [JEFFERS] offer a number of practical advantages in terms of speed, signal to noise, gating ability, spectral response, cost and suitability for aircraft or satellite use. These advantages appear at present to favour these devices over conventional PMT based spectrometers.

5.4 ACTIVE TECHNIQUES Active, airworthy and operational lidar systems, with potential for application to water quality studies have been successfully demonstrated by a number of investigators [CARSWELL et al.; O'NEIL et al.; MUMOLA & JARRETT; BRISTOW et al.; LEVIS et al.; HICKMAN & HOGG; FANTASIA; KIM].

Most of these studies have concentrated on a utilization of either bathymetry (for pulsed sources) or fluorescence spectroscopy (for CW sources). with varying degrees of success.

No active system can currently be said to be available for routine survey work. The real success of a lidar based technique lies in its potential bathymetric capability which used in conjunction with remote reflectance spectroscopy may yield well determined information

on volume reflectance as a function of wavelength and depth. Aside from the loss of ambiguity in the shape of the scattering function; the laser based system is also able to more accurately determine-and by a direct method-the atmospheric and reflection terms discussed earlier.

6 SUMMARY

The quantitative measurement of water quality parameters from remote platforms will likely be based upon the accurate measurement of reflected light. A simple, intrinsic, and easily interpretable optical parameter which is readily amenable to remote measurement is the wavelength dependent volume reflectance function $R_v(\lambda)$.

The proper measurement of volume reflectance or some similar optical parameter involves an accurate and simultaneous determination of atmospheric backscatter and attenuation, as well as the reflectance characteristics of the water surface. The measured albedo [apparent reflectance] must be corrected for these effects before the intrinsic optical data can be obtained.

Sensor configurations which will allow quantitative remote measurements of optical parameters will likely evolve around spectrometer - based OMA type devices which incorporate the sensor configuration

characteristics discussed above.

Active or laser-based remote sensing systems should not be regarded as specialized tools but rather as 'improved source' systems with a number of important advantages as well as several useful applications in Raman and fluorescence spectroscopy.

APPENDIX B

PRINCIPLE OF SIGNAL CORRECTION

An example of the remote sensing approach required for quantitative water colour determinations (Appendix A) is included in this Appendix. Figure (B1) contains three curves labelled R_V (direct), R_V (indirect) and R_a (apparent reflectance). This data was obtained from a launch in early October, near noon under overcast conditions on Burlington Bay, Ontario, using a scanning spectrometer (AB Incentives Quanta meter).

The in situ volume reflection curve R_V (direct) was obtained at a depth of about 30 cm., while the 'remotely' measured apparent reflectance curve R_a was measured at an ('altitude') of 1 meter above the water surface. The quantity R_V (indirect) was obtained from Equation 2 (Appendix A) using the values $\rho_w = 48\%$, $\beta_s = 0$ and $T^2 = 1.0$.

The numerical value of 3.7% for ρ , the surface reflection term, determined the 'best' fit to R_V (direct). In a working airborne instrument, ρ, β_s , and T^2 would be carefully (and simultaneously) measured by methods outlined elsewhere in this report (See Section 5). The 'noise' in the signal R_a and R_V (indirect) is due primarily to surface wave effects. The example is

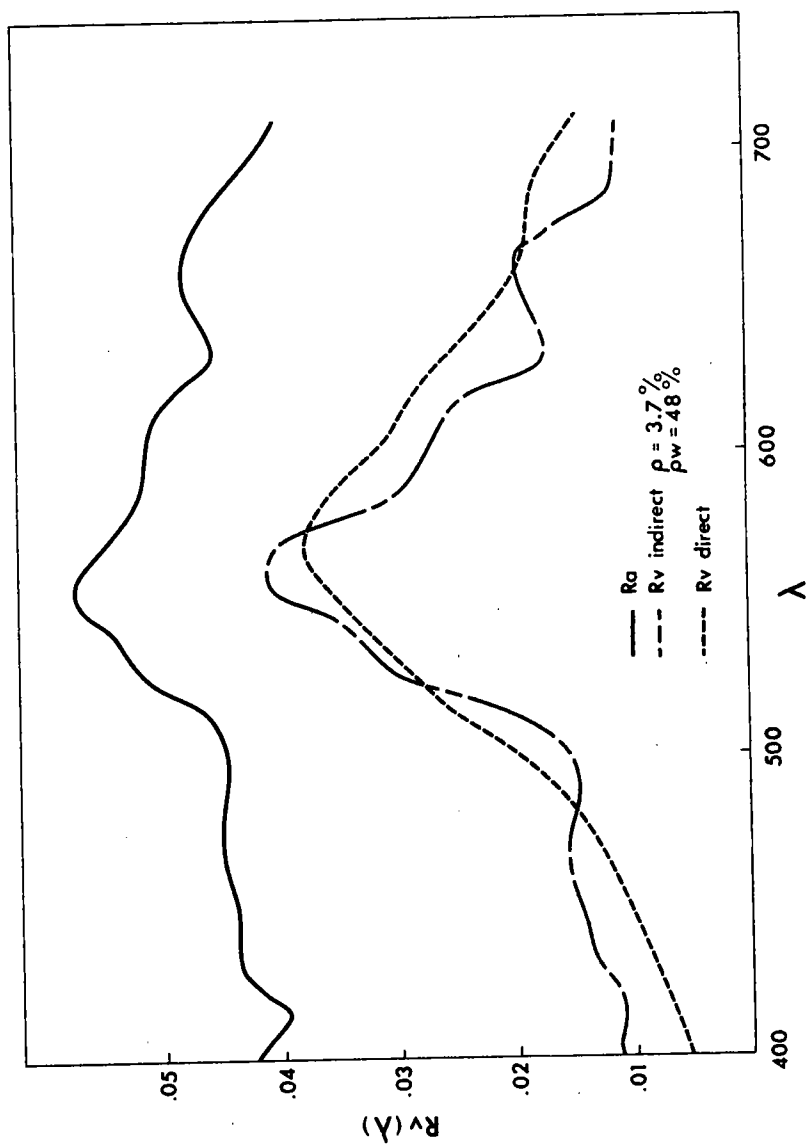


Figure (B1) In situ (direct) and 'remote' (indirect) volume reflectance R_v . The quantity R_v (indirect) was calculated from the apparent reflectance using the values $\beta_s = 0, \rho = 3.7\%$, $\rho_w = 48\%$ and $\tau^2 = 1.0$ in Equation (A2).

illustrative of the necessity of obtaining simultaneous reflection corrections for quantitative remote measurements of water colour (volume reflectance).

APPENDIX CINSTRUMENTAL APPROACH TO WATER COLOUR MEASUREMENT

Illustrated in Figure (C1) is a hypothetical photometer instrument designed to convey the remote sensing instrumental requirements discussed in Appendix A. The instrument itself is an adaptation of a Lidar receiver, details of which are published elsewhere (McNeil, 1973).

As the Figure illustrates, simultaneity of measurement of the up- and down-welling components is accomplished via twin receiver optics (defined by the lenses L_1 and L_2) coupled to a rotating mirror M.

In such a receiving system, up- and down-welling radiance components would be observable as a alternating series of pulses of differing amplitudes. After a statistically suitable sample of paired pulses, each of which defines one $R_V(\lambda)$ value, dispersion (or wavelength selection) could be accomplished by 'stepping' of a filter wheel located below K_1 and contained within Q.

A four-filter wheel, with filters selected at 430nm, 530nm, 630nm, and 1.06μ would enable measurements of the three colour indices defined in Appendix D. The filter at 1.06μ would also enable a first approximation correction for the combined atmospheric and surface reflection effects, also discussed in Appendix D.

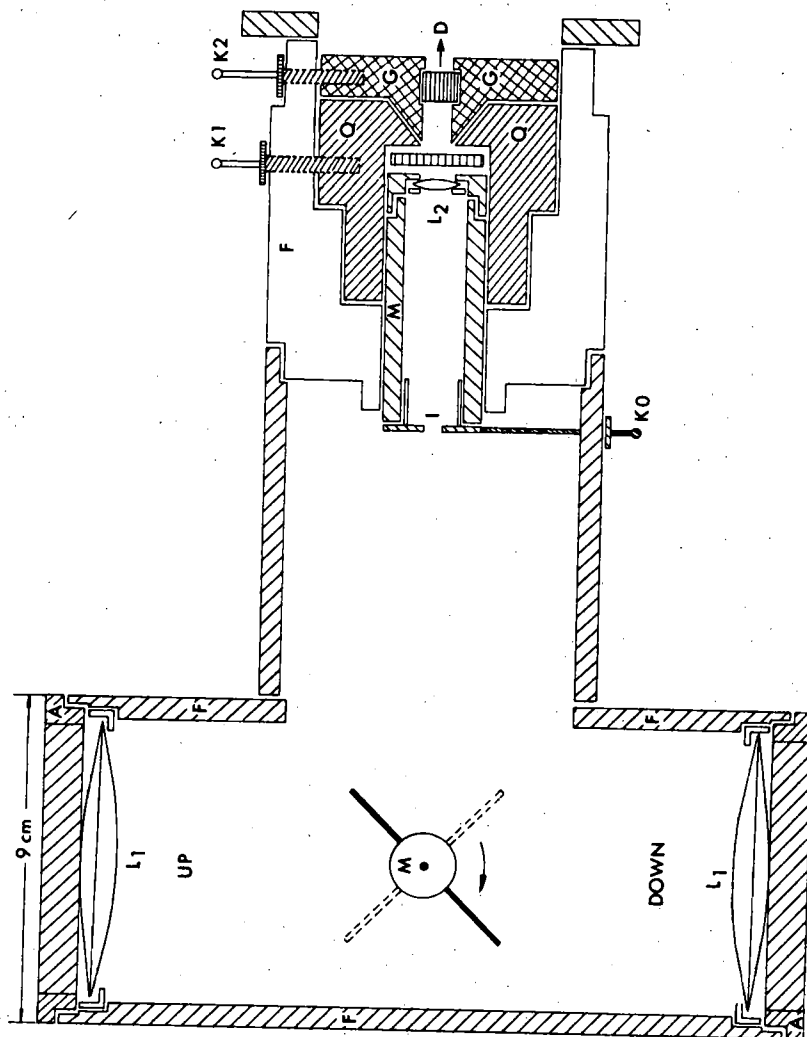


Figure (C1): Hypothetical water colour Photometer: Up- and down-welling radiance optics (L_1 ML_2); Rotating mirror M ; adjustable iris I (through K_0); 'stepping' filter wheel within Q (through K_1); Polarization optics within G (through K_2); detector D

The radiance field of view could be continuously varied through an adjustable iris I controlled by K_0 .

The signal, which would be rendered parallel before passing through the filter wheel contained within Q might then be analyzed by 'optional' polarization optics contained within G and controlled at K_2 .

The fully analyzed signal could then proceed to some suitable detector located beyond D.

APPENDIX DREMOTE SPECTRAL MEASUREMENTS AND WATER QUALITY

The following is a preprint of the paper entitled: "The Application of Remote Spectral Measurements to Water Quality Monitoring", presented to the Aerospace Electronics Symposium in Halifax, during February, 1975. The paper has been submitted for publication in the first issue of the Canadian Journal of Remote Sensing.

The authors of this paper submit that these studies represent aspects of fundamental research which are of fundamental importance to understanding of remote spectral measurements over water.

THE APPLICATION OF REMOTE SPECTRAL MEASUREMENTS
TO WATER QUALITY MONITORING

W.R. McNeil[†], K.P.B. Thomson* and J. Jerome**

A B S T R A C T

The apparent spectral reflectance over a water body measured by some remote means, such as an airborne spectrograph, consists of 3 basic components. These are: the volume reflectance of the water, a reflected component from the water surface and a component due to atmospheric backscatter. However, it is only the volume reflectance which contains information which can be related to the in situ properties of the water body. A model is presented which defines in detail these principal components. Essentially the model illustrates the methodology whereby the volume reflectance function $R_v(\lambda)$ can be extracted from the apparent reflectance data.

The volume reflectance function $R_v(\lambda)$ can then be expressed as a generalized colour index $K_{ij} = R_v(\lambda_i) / R_v(\lambda_j)$. These colour indices conveniently

[†] W.R. McNeil & Associates Inc., 21 Dale Ave., Suite 629, Toronto M4W 1K3

* Canada Centre for Remote Sensing, 717 Belfast Road, Ottawa K1A 0E4

**Canada Centre for Inland Waters, P.O. Box 5050, Burlington, Ontario L7R 4A6

display and quantify the subtle colour characteristics of a water mass. These quantified colour indices are intrinsic optical parameters which may be directly related to the water quality. In addition, other evidence is presented which shows the value of the colour index concept as a water quality surveillance parameter.

I. Introduction

This paper examines the several key concepts which are necessary for a quantitative remote determination of water quality parameters in the visible portion of the electromagnetic spectrum. Most of the discussion pertains to a passive spectral measurement of the apparent irradiance reflectivity of an infinitely deep and homogeneously mixed ocean (or lake). While this development is intended to apply to passive measurements of spectral irradiance, similar arguments will and are intended to apply to active techniques. Although most of the arguments as advanced herein apply to spectral measurements of the irradiance reflectivity, a similar treatment will apply to the limited field of view measurements of the radiance reflectivity of the water body of interest.

The paper assumes that the remote platform from which these irradiance measurements are (or would be) obtained is equipped with the instrumental capabilities to simultaneously measure the up- and down-welling spectral irradiance/radiance as defined herein. The quantity actually measured

from the remote platform is the apparent reflectivity or spectral albedo $R_a(\lambda, \theta, z)$. The relationship between this parameter and volume reflectance $R_v(\lambda, \theta)$ is examined in detail. This is followed by a discussion of selected methods for applying atmospheric and surface reflection corrections to transform the measured apparent reflectance $R_a(\lambda, \theta, z)$ to the basic volume reflectance parameter $R_v(\lambda, \theta)$.

The theoretical discussion is extended to introduce the concept of the generalized colour index. Experimental results are presented which demonstrate the relation of these optical parameters to basic limnological properties.

II Apparent Reflectivity

The apparent reflectivity is defined as the ratio of the upward to downward irradiance measured in a horizontal plane from a remote platform (satellite or airborne) situated at some altitude z , above the sea surface. The apparent reflectivity $R_a(\lambda, \theta, z)$ for solar altitude θ (as measured from the nadir) at wave length λ may be shown to relate to the in-situ irradiance ratio $R_v(\lambda, \theta)$ (usually called the volume reflectance) just beneath the surface through the following simplified radiative transfer expression [McNeil & Thomson]

$$R_a(\lambda, \theta, z) = R_v(\lambda, \theta) \{1 - \rho(\theta)\} \{1 - \rho_w\} T^2(\lambda, \theta, z) + \beta_s(\lambda, \theta, z) + \rho(\theta) T^2(\lambda, \theta, z) \quad (1)$$

where $\beta_s(\lambda, \theta, z)$ is the fraction of the incident irradiance (from sun and sky) which is backscattered into the sensor from the atmospheric column beneath

the remote platform; $\rho(\theta)$ is the fractional irradiance (from sun and sky) reflected from the surface back into the receiver and $T^2(\lambda, \theta, z)$ is the two-way attenuation per unit incident irradiance due to atmospheric backscatter $\beta_s(\lambda, \theta, z)$ and atmospheric absorption $\beta_a(\lambda, \theta, z)$. The quantity ρ_w in the first term of Equation (1) is the fraction of upwelling light reflected back into the sea at the water-air interface. Because of the relatively small variation of the scattering function in the backscatter field, we can assume in a first approximation that this upwelling light is diffuse and unpolarized. Because Fresnel reflection beneath the surface involves total reflection in the interval 48.6 to 90° , ρ_w may be calculated from integration of the expression [Jerlov]

$$\rho_w = \int_0^{\pi/2} \rho(\theta) \sin 2\theta d\theta = 0.48 \quad (2)$$

The quantities $(1-\rho(\theta))$ and $(1-\rho_w)$ in the first term of Equation (1) are often called the Fresnel transmission coefficients of the air-water and water-air interfaces. The first term in Equation (1) is the only term which contains information relating to the absorption and scattering properties of the water itself.

III Correction of the Apparent Reflectivity

Before any realistic attempts are made to reliably relate water colour measurements obtained through Equation (1) to intrinsic water quality parameters, some methods must be devised to determine or estimate the magnitude of the two extraneous terms $\beta_s(\lambda, \theta, z)$ and $\rho(\theta)T^2(\lambda, \theta, z)$ in

Equation (1). For typical aircraft altitudes, sun angles and atmospheric conditions, each of the three terms in Equation (1) may be considered as comparable in magnitude. As a result, it is not normally a reasonable assumption to neglect their combined or singular effects. For low aircraft altitudes, the atmospheric backscatter term, $\beta_s(\lambda, \theta, z)$, may be small. This backscatter term does increase however with altitude and with decreasing wavelength (due primarily to Mie scattering). A more complete discussion of the combined effects of these terms may be found elsewhere [McNeil and Thomson].

There are several possible avenues of approach open to the remote sensing investigator interested in applying corrections to Equation (1). It is possible to identify three distinct approaches in this regard. These we shall identify as direct measurement techniques, modified direct measurement techniques, and differential techniques. Each of these approaches assumes that atmospheric attenuation is small (i.e. $T^2 \approx 1.0$). The essentials of each technique are outlined below.

Direct Measurement Techniques. The principle of the direct measurement is simple. One selects a spectral window somewhere in the near infrared where liquid water is highly absorbant. The highly absorbant nature of liquid water in this region of this spectrum assures that the first term in Equation (1) is negligible. As an example, for the wavelength $\lambda = 1.06\mu$ (Nd laser), liquid water has an absorption coefficient of 400 m^{-1} , [Curcio and Petty]. Thus, an irradiance measurement at this wavelength would yield from Equation (1)

$$R_a(1.06 \mu, \theta, z) = \beta_s(1.06 \mu, \lambda, z) + \rho(\theta) \quad (3)$$

This numerical quantity could then be used, as a first approximation, to correct the spectral reflectance value obtained in the visible spectrum from Equation (1). In fact, this correction may for most practical situations be all that is really required. This simplified correction, however, does ignore the wavelength dependence of the backscatter term $\beta_s(\lambda, \theta, z)$ - this problem might be overcome, however, by some reasonable atmospheric modelling. For example, experimental values of the atmospheric backscatter term along with its wavelength dependence for various real Mie and Rayleigh atmospheres may be found from experimental studies [Zuev]. The principal limitations of this direct measurement technique lie in its failure to separate the two components $\beta_s(\lambda, \theta, z)$ and $\rho(\theta)$. A variation on this direct measurement approach is now being evaluated at York University [Miller].

Modified Direct Measurement Techniques. This method uses the tabulated values of the near IR albedo measurements published elsewhere [Payne]. Payne's interesting and careful study has yielded some very useful corrected albedo or irradiance ratios of the surface reflectance $\rho(\theta)$ at the sea surface as a function of the parameters θ and the radiance distribution parameter R .* This latter parameter is especially useful and has not been used before in the description of albedo but would and should be especially functional for remote sensing applications. Basically, the parameter R is a quantity which varies between 0 and 1. For an isotropic radiance

* Payne actually uses the symbol T for R , which he calls 'atmospheric transmittance'

distribution, as will be found with completely overcast skies, the parameter R will take on the value 0. At the other extreme, for direct sunlight and no atmosphere, the parameter R will assume the value 1. For real atmospheric conditions under completely clear skies, a certain component of the incident irradiance will consist of diffuse indirect scattered sunlight, as a result the parameter R will not normally take on a value greater than about $R = 0.75$. The advantage of this technique is in its reliance on carefully predetermined albedo measurements which are expressed in terms of easily measured parameters (R & θ). By itself, this technique does not allow for the term $\beta_s(\lambda, \theta, z)$ in Equation (1). However, the technique might be directly applicable to low altitude studies where β_s is not appreciable. For general application, it might be best to determine first the parameter $\rho(\theta)$ from Payne's tables. The direct measurement technique as described above will then yield the atmospheric term $\beta_s(\lambda, \theta, z)$. This atmospheric term now may be corrected utilizing assumed atmospheric models [Zuev].

Differential techniques. This technique, described elsewhere [White], applies the second differential to the measured spectral albedo (uncorrected) to obtain a quantity which has been experimentally determined to be reasonably invariant with aircraft altitude. The reason the second differential technique works or has worked under a variety of real situations will be found by examination of the wavelength dependence of the extraneous terms in Equation (1). The third term, the surface reflectance term, $\rho(\theta)$ is nearly independent of wavelength. As a result its first differential will be near 0.

$$\frac{\partial}{\partial \lambda} \rho(\theta) \approx 0 \quad (4)$$

The wavelength dependence of the atmospheric term $\beta_s(\lambda, \theta, z)$ in Equation (1) under many circumstances and for most realistic atmospheres is only weakly dependent on wavelength and normally only in a linear sense. As a result, the second differential of the backscatter term $\beta_s(\lambda, \theta, z)$ will also reduce this quantity to a 0 value.

$$\frac{\partial^2}{\partial \lambda^2} \beta_s(\lambda, \theta, z) \approx 0 \quad (5)$$

When these two assumptions with regard to the wavelength dependence of the two extraneous terms in Equation (1) are applied, one will obtain an expression of the form

$$\frac{\partial^2}{\partial \lambda^2} R_a(\lambda, \theta, z) \approx (1 - \rho(\theta))(1 - \rho_w) \frac{\partial^2}{\partial \lambda^2} R_v(\lambda, \theta) \quad (6)$$

White has shown experimentally that this second differential, which we have defined by Equation (6), is invariant with altitude z in the spectral region 500 nm to 700 nm. A problem with this differential technique lies in its breakdown at wavelengths shorter than 500 nm. A second potential problem lies with the difficulty in interpretation of the results of the second differential in terms of known optical parameters. However, a careful theoretical examination of this problem should overcome this latter difficulty.

IV Interpretation of the Corrected Reflectivity

The parameter we shall be discussing in this section is defined as the ratio of the up- to down-welling irradiance as measured just beneath the water surface. This quantity, simply the irradiance ratio, is often called the volume reflectance function $R_v(\lambda, \theta)$. In several recent studies, [Gordon and Brown, Brown] a theoretical model relating the desired oceanographic parameters to the upwelling irradiances has been obtained. This theoretical model can be described by a modified single scattering approach which is based upon a simple treatment of multiple scattering. This resultant quasi-single scattering QSS model can be used to predict the upwelling distribution of spectral irradiance emergent from the sea. The shape of the radiance spectrum predicted by this QSS model for clear ocean waters has shown encouraging agreement with measurements obtained at the edge of the Sargasso Sea off Cape Hattaras [McCluney]. According to this model, the diffuse volume reflectance parameter of a homogeneous infinitely deep ocean calculated for a radiance distribution incident from the zenith (in water) may be expressed as

$$R_v(\lambda, \theta) = \frac{k(\lambda, \theta) b(\lambda)}{a(\lambda) + B(\lambda, \theta) b(\lambda)} \quad (7)$$

where $a(\lambda)$ and $b(\lambda)$ are the absorption and scattering coefficients of the medium; for normal incidence $B(\lambda, \theta)$ is the fraction of $b(\lambda)$ scattered in the backward direction ($\theta = \pi \pm \pi/2$)

$$B(\lambda, \theta) = 1 - F(\lambda, \theta) = 1 - 2\pi \int_0^{\pi/2} P(\lambda, \theta) \sin \theta d\theta \quad (8)$$

$F(\lambda, \theta)$ in Equation (8) is the fraction of $b(\lambda)$ scattered in the forward direction ($\theta = 0 \pm \pi/2$); $P(\lambda, \theta)$ is the scattering phase function, a normalized quantity which is related to the volume scattering function $\beta(\lambda, \theta)$ by

$$P(\lambda, \theta) = \frac{\beta(\lambda, \theta)}{b(\lambda)} \quad (9)$$

The parameter $k(\lambda, \theta)$ in Equation (7) is a function of θ , $B(\lambda, \theta)$ and n , the index of refraction of the medium. Among other things, the model developed by Gordon and Brown predicts that the analytic form of the irradiance ratio given by Equation (7) will assume the same form for a diffuse distribution of irradiance (i.e. overcast skies). As it stands, the irradiance ratio defined by Equation (7) is a reasonably inherent (or intrinsic) optical parameter. This fact has been shown in a number of studies [Jerlov]. The fact that the parameter defined by Equation (7) is relatively insensitive to variations in sun angle is due to the relatively small variations of the backscatter function in water. Nevertheless, for accurate predictive interpretation of water quality parameters through their relationship to optical indices it would still be desirable to remove this angular dependence from our remotely sensed data.

Figure (1) contains 5 selected reflectance functions obtained from 5 optically unique regions of Lake Huron during the August 1974 survey cruise. The specific areas referred to in Figure (1) are labelled in Figure (2). As a visual inspection will readily verify, the functions shown in Figure (1)

are seen to vary appreciably both in magnitude and shape as well as in their peak reflectance values. In general, the magnitude of these curves can be understood in terms of the numerator of Equation (7). As the absolute concentration of the suspended particulate increases, so will $b(\lambda)$, thus the absolute magnitude of various portions of the curve in Figure (1) will also increase. This will explain the similarity in the shapes and magnitudes of the curves obtained from the St. Mary's River and Saginaw Bay. Both of these regions contain large quantities of suspended particulate matter. These two regions appear to differ however in the shorter wavelength portions of the curve. In particular, for regions around 400 nm, the Saginaw Bay reflectance values are appreciably smaller than those from the St. Mary's River. This phenomena is probably due to the large amount of absorption from the chlorophyll a concentrations in Saginaw Bay. Saginaw Bay waters contain higher levels of chlorophyll a than any other region of the Great Lakes system. This observation agrees with the functional form of the analytic expression for the volume reflectance function, Equation (7), as expressed through the denominator and the effect of chlorophyll on the absorption coefficient $a(\lambda)$. Thus it might be deduced that the St. Mary's River water does not contain as high a concentration of chlorophyll a. At the other extreme, the reflectance parameters obtained from the oligotrophic mid-Lake Huron stations, regions low in both chlorophyll and suspended particulate, are relatively small in magnitude and peaked toward the blue end of the spectrum. A similar behaviour is observed with the reflectance function obtained from the Mackinac waters. The reflectance function obtained from the North Channel waters appears to possess characteristics intermediate between the extremes already discussed.

For regions of limnological interest, the wavelength independence of b (and hence $B(\theta)$, $F(\theta)$, $P(\theta)$ and $k(\theta)$) is regarded as a reasonable assumption by many research workers. In such waters, dominated by particle scattering (mostly forward scatter), the fraction $B(\theta)$ in Equation (7) will rarely exceed 1-2%. In these situations, due to the comparable magnitudes of the terms $a(\lambda)$ and b , it may be possible to substitute $a(\lambda)$ for $a(\lambda) + B(\theta)b$ in Equation (7).

For a non-normal distribution of incidence radiance, the parameters $k(\theta)$ and $B(\theta)$ in Equation (7) will be defined through Equation (8) by changing the limits on the integral of $P(\theta)$ from $(0, \pi/2)$ to $(\theta, \pi/2 + \theta)$ where θ is the direction of incidence radiance in water as measured from the nadir.

The net effect of the non-normal radiance distribution upon the ratio $R_v(\lambda, \theta)$ is a question of sensitivity. For a sizable range of solar altitudes, the fraction $B(\theta)$ will still constitute a small percentage of b , consequently it should still be possible to write $a(\lambda)$ for $a(\lambda) + B(\theta)b$ in the denominator of Equation (7). Thus, this deviation from a non-normal incidence radiance distribution will more strongly affect the numerator in Equation (7). For these reasons, the generalized colour index $K_{ij}(\lambda)$ as defined below, is expected to be a parameter less sensitive to variations with sun angle. Thus, the colour index may be considered a more intrinsic optical quantity (for remote sensing applications) than the parameter $R_v(\lambda, \theta)$. This generalized colour index may be defined as the ratio of the volume reflectances at any two wavelengths.

$$K(\lambda_i, \lambda_j) = \frac{R_V(\lambda_i)}{R_V(\lambda_j)} = \frac{k(\theta)b}{k(\theta)b} \cdot \frac{a(\lambda_j) + B(\theta)b}{a(\lambda_i) + B(\theta)b} = \frac{a(\lambda_j)}{a(\lambda_i)} \quad (10)$$

The right-hand side of Equation (10) incorporates the various model assumptions, believed to be valid for most regions of limnological interest, on the parameters b , $k(\theta)$ and $B(\theta)$ introduced above (i.e. $B(\theta)b \ll a(\lambda)$ and $k(\theta)b$ independent of λ).

The importance of Equation (10) is two-fold. First of all it implies that the colour index K_{ij} may analytically be expressed, in a first approximation, as the ratio of the absorption coefficients at the two wavelengths of interest. This observation may be extremely useful in the application of the colour indices to measurements of the optical and water quality parameters of interest. Secondly, K_{ij} is independent of sun angle θ . Experimental evidence of this latter observation has been supplied by others [Thomson et al]. In this study, Thomson has defined the two primary colour indices, K_1 and K_2

$$K_1 = \frac{R_V(450 \text{ nm})}{R_V(520 \text{ nm})} \quad (11)$$

$$K_2 = \frac{R_V(560 \text{ nm})}{R_V(520 \text{ nm})} \quad (12)$$

Figure (3) shows examples of the variation of these colour indices over one daylight period as obtained at two different depths. These observations are consistent with those made by other workers [Jerlov, 1972].

In addition to the observations that the colour indices are independent of sun angle, the Thomson study also showed a number of interesting observations on the behaviour of the colour indices. The colour indices

K_1 and K_2 taken at Lake Superior stations in June of 1973 are shown in Figure (4). Transmissometer data from each cruise were also used as a check on the continuity of the individual data points. All of the colour index data shown in Figure (4) were obtained for solar elevations greater than 15^0 . The general variations of both indices for any one month show clearly the change from the more turbid coastal regions of Lake Superior to the clear mid-lake waters. The main turbid areas of the lake are clearly identified by both indices. For example, the largest gradients for both K_1 and K_2 are observed in the Duluth, Thunder Bay, and Whitefish Bay areas. At specific times, turbidity gradients have been identified through colour indices at other locations, such as Marathon in July and September, and Nipigon Bay in September of 1973.

The values of K_1 at the one metre depth, range from 0.1 to 0.3 in very turbid water to 0.7 to 0.9 in mid-lake water. The highest values of this parameter were observed during this June cruise (Figure 4) at mid-lake stations.

The values of K_2 cover the range from 3.0 in extremely turbid water to 0.7 to 0.8 in clear mid-lake water. In general, the values of K_2 in the Duluth area cover the range 1.5 to 2.5. Consistent with the behaviour of K_1 , the lowest observed values of K_2 also occurred in June at the mid-lake stations.

V Colour Indices and Biomass

As mentioned above, in addition to carrying the message that the colour indices are independent of sun angle, Equation (10) also gives us some information on the absorption ratios of the particular water body being studied at the two wavelengths selected. Thus Equation (10) is the starting point for attempts to correlate colour indices with useful limnological parameters. From our analyses of the 1972 and 1973 colour index studies [Thomson, Jerome and McNeil], we have developed three fundamental indices, K_1 , K_2 and K_3 (of which only two are independent)

$$K_1 = \frac{R_V(530 \text{ nm})}{R_V(430 \text{ nm})} \quad \text{Green/Blue} \quad (13)$$

$$K_2 = \frac{R_V(630 \text{ nm})}{R_V(530 \text{ nm})} \quad \text{Red/Green} \quad (14)$$

$$K_3 = \frac{R_V(630 \text{ nm})}{R_V(430 \text{ nm})} \quad \text{Red/Blue} \quad (15)$$

The reason we have selected the wavelengths 430, 530 and 630 nm is that they are centered in the blue, green and red portions of the spectrum. In addition, a large body of experimental data on colour measurements throughout the Great Lakes system has been obtained at these wavelengths. These wavelengths have also been used in previous studies by others [Vollenweider]. Using the functional form of the colour index as defined by Equation (10) we may make some assumptions about the behaviour of the colour indices as defined in Equations (13), (14), and (15). These basic assertions are summarized in Table 1.

<u>PARAMETER</u>	<u>FUNCTIONAL FORM</u>	<u>COMMENTS</u>
K_1	$\frac{a_{cl}(430) + a_p(430)}{a_p(530)}$	Should correlate directly with total absorption and inversely with inorganic absorption.
K_2	$\frac{a_p(530)}{a_w(630)}$	Should correlate with inorganic absorption.
K_3	$\frac{a_{cl}(430) + a_p(430)}{a_w(630)}$	Should correlate directly with total absorption.
$K_3 - K_2$	$\frac{a_{cl}(430)}{a_w(630)}$	Should correlate directly with chlorophyll <u>a</u> alone.

TABLE 1. Functional form expected for colour indices.

The functional form for the indices illustrated in Table 1 are based upon several simple assumptions. They assume for example that the absorption in the red part of the spectrum is due primarily to liquid water itself. They also assume that at 530 nm the absorption is due solely to inorganic particulates $a_p(530 \text{ nm})$. Also, the absorption at 430 nm is attributable to chlorophyll $a_{cl}(430)$ and inorganic particulates $a_p(430)$. The parameter $K_3 - K_2$ shown in the last line of Table 1, is defined in an attempt to correct for the absorption attributable to inorganic particles. This is simply a first approximation to a quantity which can be attributable to absorption from chlorophyll a alone. The parameter $K_3 - K_2$, of course assumes that the inorganic particulates do not have any selective absorption properties in the range between 530 and 430 nm. This of course is intended only as a valid first approximation.

In addition to the colour indices defined by Equations (13) through (15), a fourth quantity, the red reflectance value

$$R_v(630) = \frac{k(\theta)b}{a_w(630)} \quad (16)$$

has been shown by others to be a useful optical quantity which correlates well with the total suspended load [Ritchie et al.]. These four quantities, along with the wavelength of maximum volume reflectance λ^{\max} , have been found useful in the optical classification of a water mass. Typical values for these parameters for blue water ($\lambda^{\max} < 520$); green water ($520 < \lambda^{\max} < 550$), and red water ($\lambda^{\max} > 550$) have been determined from examination of the reflectance spectra obtained from 196 stations on Lake Huron and Georgian Bay over a six-month period in 1974. This information is summarized below. The values given in Table 2 are means of 75 blue water stations, 46 green water stations, and 75 red water stations.

<u>Vector</u>	<u>λ^{\max}</u>	<u>K_1</u>	<u>K_2</u>	<u>K_3</u>	<u>R_v</u>
Blue Mean	< 520 nm	1.6	0.18	0.27	0.0061
Green Mean	520 < λ^{\max} < 550 nm	2.2	0.21	0.41	0.0084
Red Mean	λ^{\max} > 550 nm	2.5	0.41	0.79	0.0160

TABLE II. Colour index mean values. (The linear dependence of the colour indices does not necessarily apply to these mean values.)

These colour indices are the means of a number of stations and exhibit considerable variation within each colour group. The lowest indices have been observed for mid-Lake Huron ($\lambda \approx 500$ nm) (1.3, 0.14, 0.19, 0.004),

while some of the largest red water values are observed from Saginaw Bay ($\lambda = 560$ nm) (4.6, 0.55, 2.52, 0.051). The expected range of these indices is more readily illustrated if they are normalized to the very low mid-lake values as shown in Table III.

Vector	λ^{\max}	K_1	K_2	K_3	R_v
Mid-lake	500	1.0	1.0	1.0	1.0
Blue Mean	480 - 520	1.2	1.3	1.4	1.5
Green Mean	520 - 550	1.7	1.5	2.2	2.1
Red Mean	> 550	1.9	2.9	4.2	4.0
Saginaw	(560)	3.5	3.9	13.3	12.8

TABLE III. Normalized to Mid-Lake Colour Index Values

The range of values for these parameters is greatest for the index K_3 , a factor of 13.3 from mid-Lake Huron to Saginaw Bay. This incidentally closely approximates the ratio of chlorophyll a values for these two locations (i.e. 14.0 for May).

An attempt to establish a correlation between the concentration of chlorophyll a as obtained at each of 154 stations from which the colour indices and chlorophyll a were both obtained is illustrated in Figure (5). The basic colour indices which are used in this correlation regression analysis are defined in Equations (13), (14), and (15). The chlorophyll a values are not surface values but integrated average values which are obtained

from 20 metre water column samples. The laboratory method for determination of the chlorophyll a values is based upon standard spectrophotometric techniques [Parsons Strickland method]. In order to obtain a statistically significant sample, each point illustrated in Figure (5) represents a mean of a number of stations. Each point was selected according to the laboratory result of the chlorophyll study. Thus, each point in Figure (5) represents a mean value of both chlorophyll and colour index obtained from an average of 25 stations on Lake Huron and Georgian Bay over a six-month period. The standard deviations on each colour index point represent an average value of approximately 1/2 of the mean value plotted. The standard deviations on the chlorophyll a values are also means of the same 25 stations and represent a value which is on average about 10% of the chlorophyll a value. The interesting results of these correlations by linear regression are tabulated below (Table IV).

Parameter	Equation of Line	Correlation	Saginaw Bay (mg/m ³)
K_1	$\text{Ch } \underline{a} = 1.8 K_1 - 1.97$	$R = 0.836$	6.3 (18.4)
K_2	$\text{Ch } \underline{a} = 16.0 K_2 - 2.1$	$R = 0.983$	6.7 (18.4)
K_3	$\text{Ch } \underline{a} = 5.0 K_3 - 0.5$	$R = 0.921$	12.1 (18.4)
$K_3 - K_2$	$\text{Ch } \underline{a} = 6.0 K_{32} + 0.2$	$R = 0.840$	12.0 (18.4)

TABLE IV. Results of linear regression on colour indices and chlorophyll a

As the results in Table IV indicate, the correlation coefficients with the various indices K_1 , K_2 , K_3 and $K_3 - K_2$ are quite high. The highest correlation is found for the index K_2 ; while the lowest correlation is found for the

index K_1 [see also Piech et al.]. The index most sensitive to variations in chlorophyll concentration is the red-blue index, K_3 . The index which is least sensitive to variations in chlorophyll is the green-blue index, K_1 . The reciprocal of this green-blue index has been utilized by Piech with some notable success using the photographic SCS (patented) technique. The index which is expected to have the most valid theoretical correlation and general applicability is the corrected red-blue index $K_3 - K_2$. No model such as this can be expected to have any general validity unless it has predictive power. We are currently in the stage of trying to assess these preliminary results in terms of their predictive abilities. For example, the data obtained from Saginaw Bay deals in experimental values of chlorophyll a of 18.4 mg/m³ (Table IV). Utilizing the four expressions obtained from our correlation analyses and given in Table IV, we obtain for the indices K_1 , K_2 , K_3 and $K_3 - K_2$ the values 6.3, 6.7, 12.0, and 12.1 mg/m³ respectively. These values were obtained utilizing the Saginaw Bay colour index values. These experimental values indicate that the indices K_3 and K_{32} appear to predict the chlorophyll a values in Saginaw Bay with more accuracy than the other indices. Theoretically $K_3 - K_2$ should correlate best with chlorophyll a concentrations as was illustrated analytically in Table I.

VI Summary

The data used to perform the correlations discussed in this paper were the result of a major research effort during the 1974 Lake Huron and Georgian Bay cruises. The environmental problems in the collection of these data are severe and it is our belief that a remote platform designed to

obtain these parameters would likely do so with a higher degree of statistical accuracy.

The focus of this paper has been upon the determination of a quantitative intrinsic optical parameter which can be measured remotely and interpreted in terms of water quality parameters. The parameter which we suggest that can be measured remotely is the well-known irradiance ratio or volume reflectance. Before this volume reflectance can be obtained from a remote platform, the albedo or apparent reflectance, which is the quantity which is actually measured at aircraft or satellite altitude must be corrected for the combined effects of surface and atmospheric backscatter. The surface and atmospheric backscatter terms can be removed from the apparent reflectivity by a combination of methods. The most feasible methods which can be applied to the apparent reflectivity for ready and practical correction are the utilization of tabulated values of surface reflection obtained by Payne, in conjunction with a direct measurement method of the total reflectance and backscatter obtained in the near infrared. This data may then be corrected for the wavelength dependence of the atmospheric backscatter through tabulated Mie type backscatter functions. Having corrected the data by these methods, the volume reflectance can be interpreted in terms of the quasi-single scatter model proposed by Gordon and Brown. This model is the basis for the determination of the intrinsic optical parameters of absorption and scattering. The volume reflectance as modelled through Gordon and Brown is however dependent on solar angle. To remove this dependence on solar angle the generalized colour index concept is introduced. This colour index parameter has been shown through a number

of studies to be independent of solar angle and a useful optical classifier. Combining these facts with the analytic expression obtained for the volume reflectance it is possible to show that the colour indices may be related to such optical parameters as biomass (chlorophyll concentration). The first attempt to correlate these colour indices with chlorophyll a concentrations as obtained over a six-month period on Lake Huron and Georgian Bay was illustrated. The results of these studies appear to indicate that the red-blue ratios or a variance of the red-blue ratios appear to achieve the best correlation in terms of both their absolute correlations coefficients and their experimental predictability.

The authors submit that these studies represent aspects of fundamental research which are of vital importance to understanding of remote spectral measurements over water. In addition, we are confident that these results will help to bridge the gap between qualitative and quantitative remote sensing.

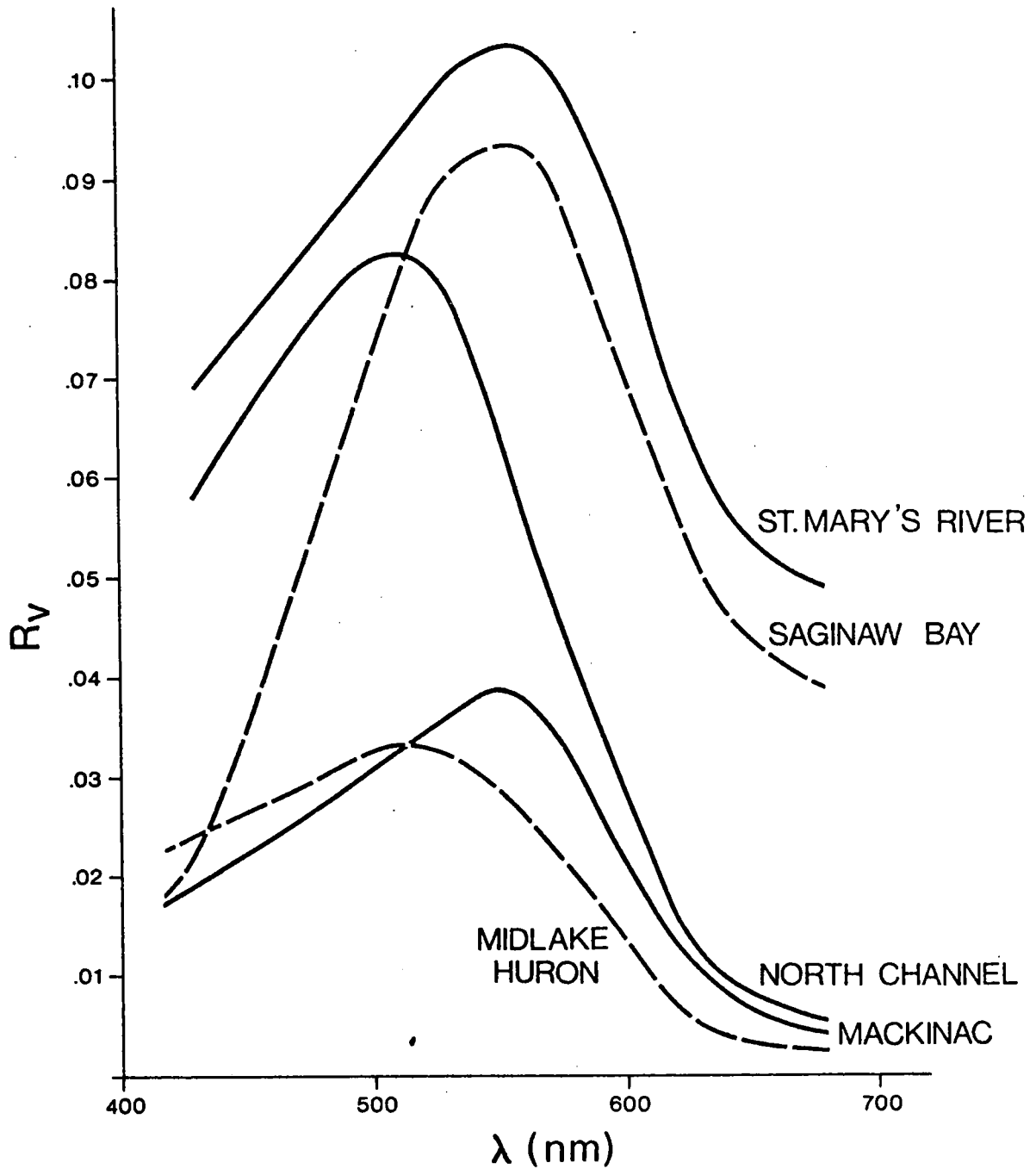


FIGURE (1) Volume reflectance measurements obtained from five selected regions on Lake Huron during the August 1974 survey cruise.

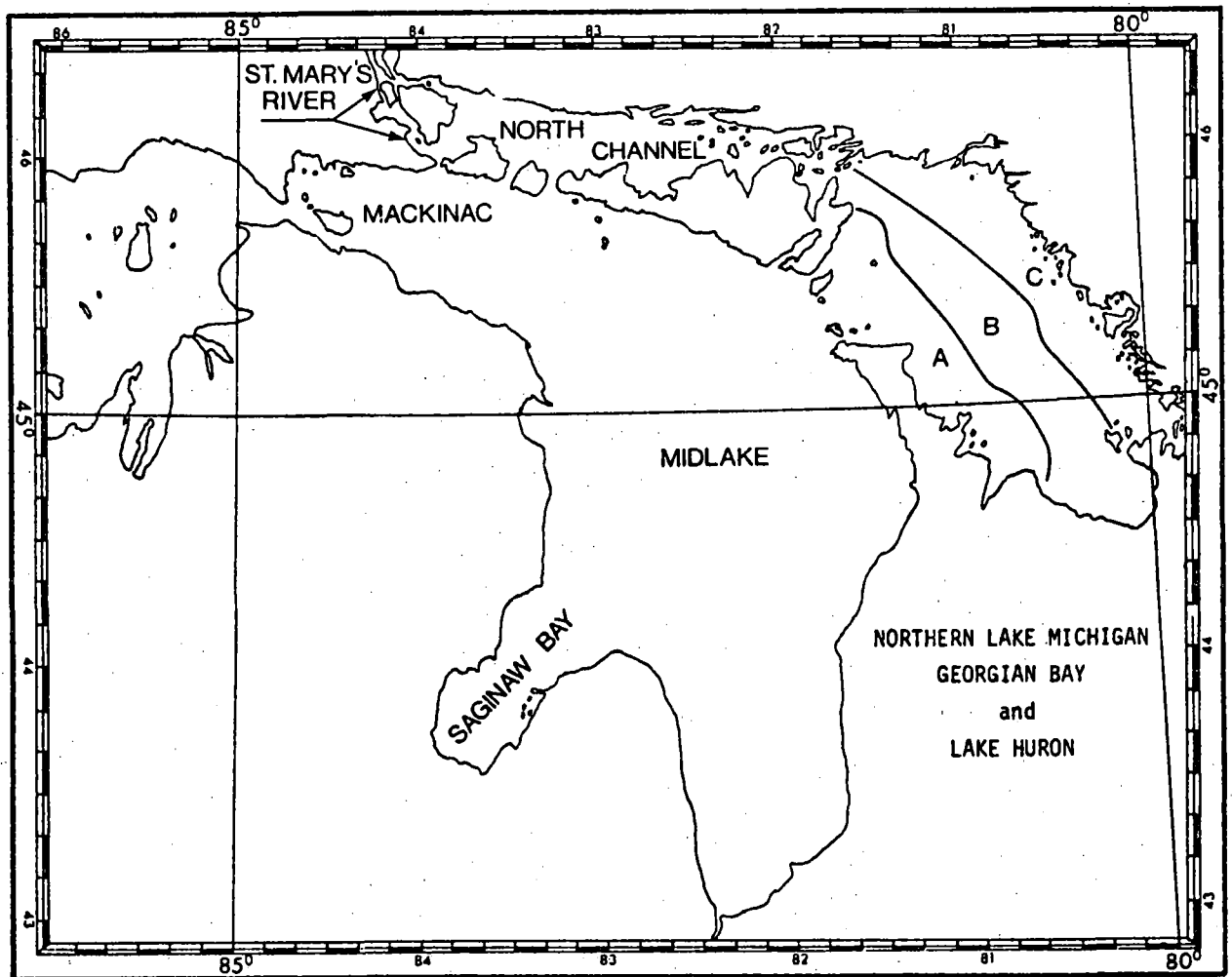


FIGURE (2) Selected Lake Huron and Georgian Bay locations from which data displayed in Figure (1) was obtained.

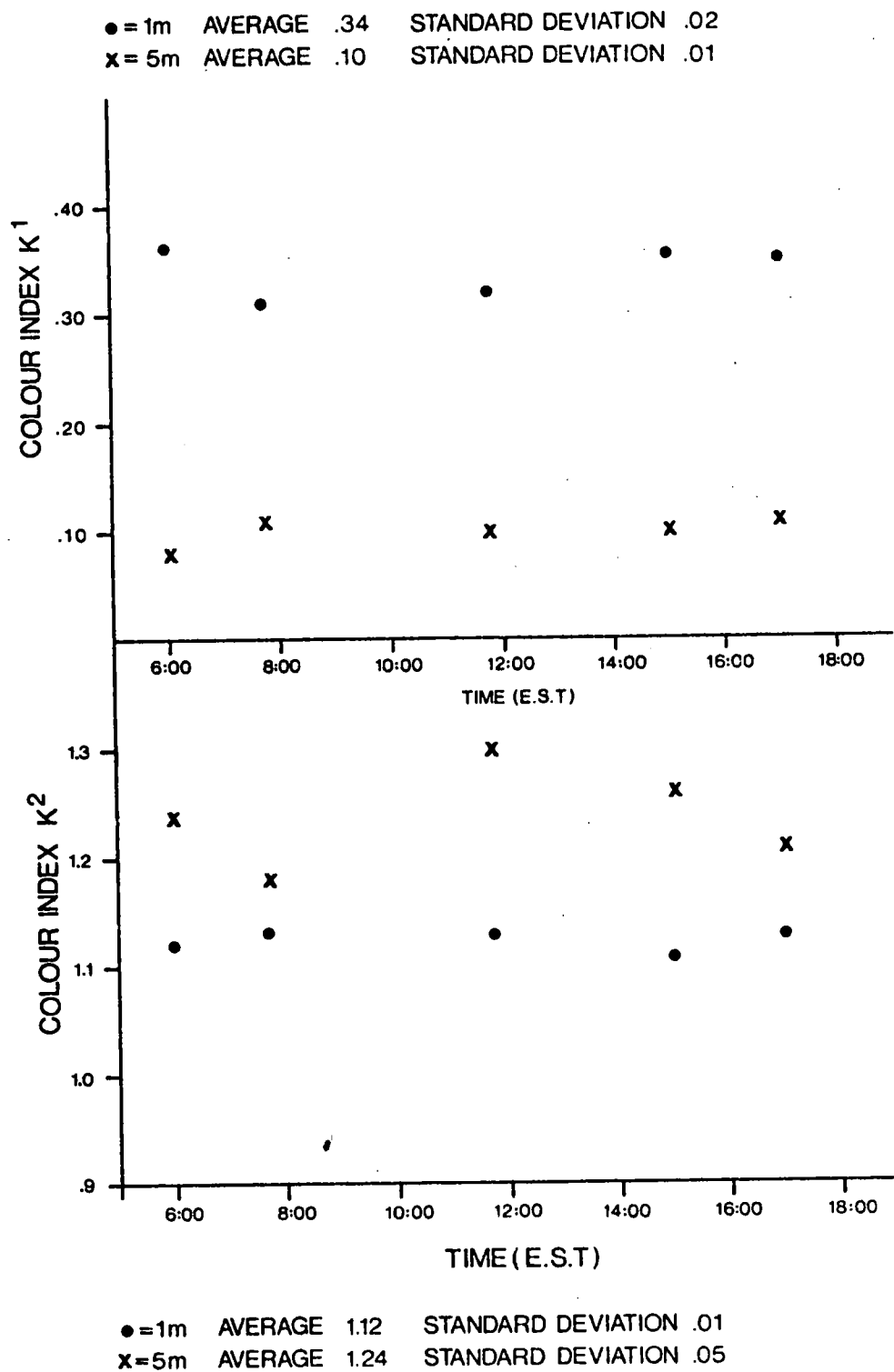
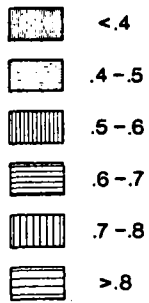
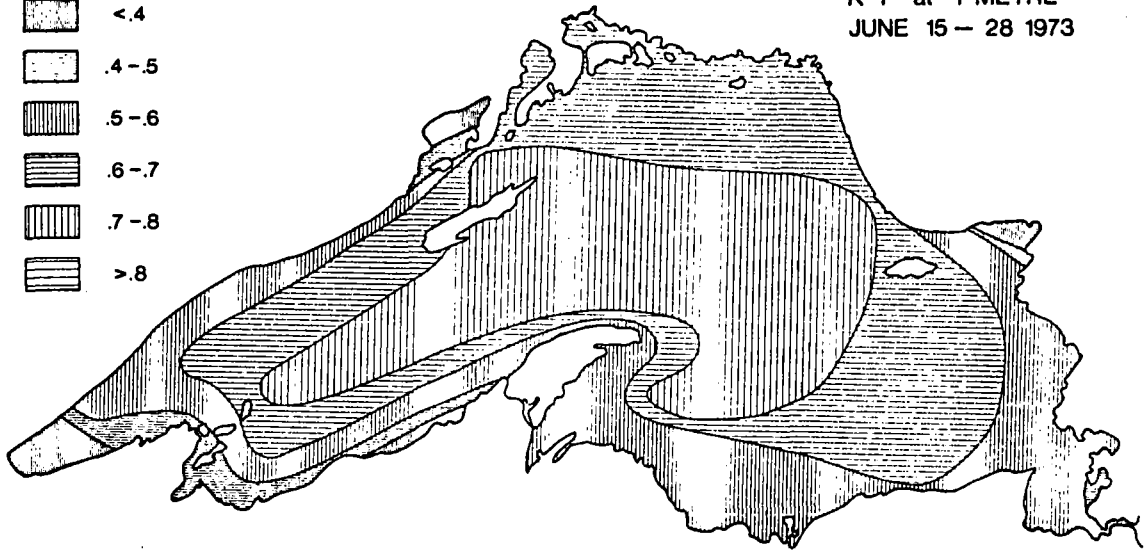


FIGURE (3) Variation of the colour indices K1 and K2 over one daylight period.

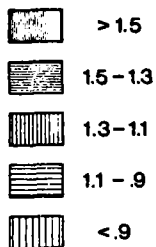
LEGEND K 1



K 1 at 1 METRE
JUNE 15 - 28 1973



LEGEND K 2



K 2 at 1 METRE
JUNE 15 - 28 1973

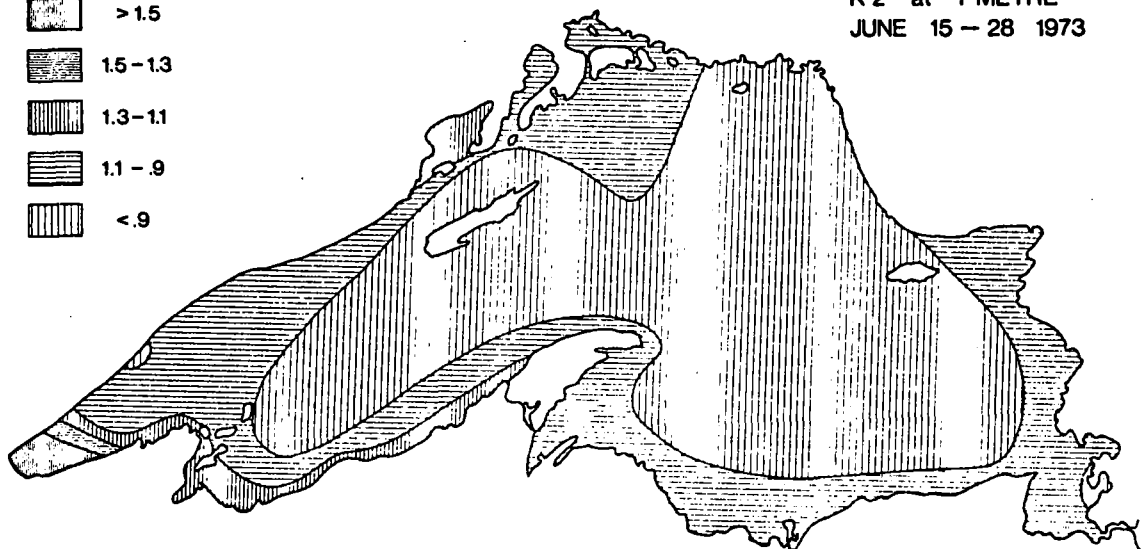


FIGURE (4) Colour indices for Lake Superior, June 1973 (a) K1 at 1 metre and (b) K2 at 1 metre.

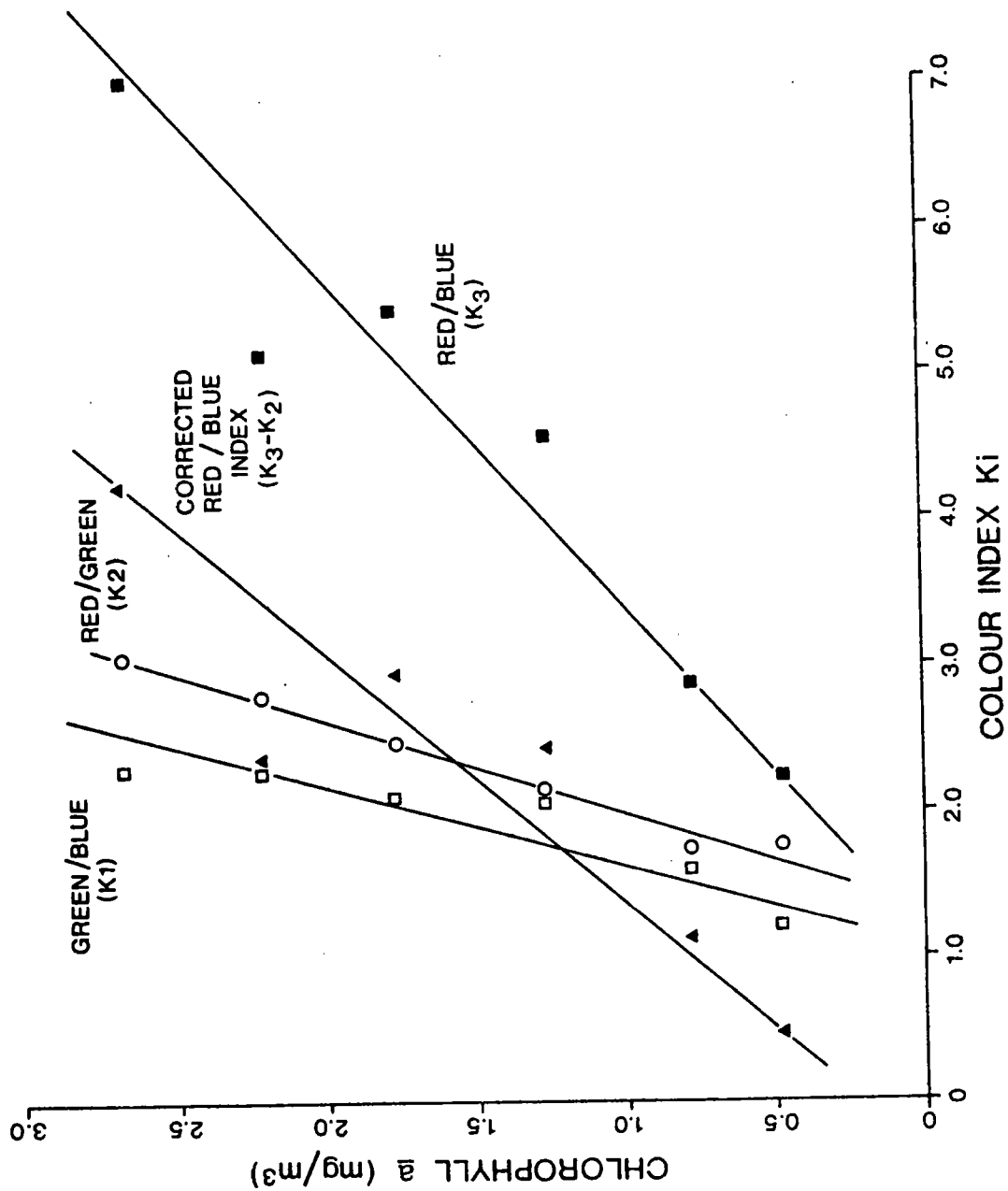


FIGURE (5) Linear regression on colour indices from a total of 154 stations on Lake Huron and Georgian Bay over a six-month period (1974). Standard errors of estimate for the co-ordinates (x,y) are $(\pm 0.13, \pm 0.25)$ for K_1 ; $(\pm 0.02, \pm 0.03)$ for K_2 ; $(\pm 0.28, \pm 0.13)$ for K_3 and $(\pm 0.39, \pm 0.25)$ for $K_3 - K_2$.

APPENDIX E

BIOMASS AND COLOUR INDICES, THEORY AND EXPERIMENT

Illustrated in Figure (E1) is a comparison of the experimental and theoretical interrelation between chlorophyll a and the colour indices K_1 (Green/Blue) and K_3 (Red/Blue). The experimental curves for these indices are those discussed in Appendix D. The theoretical curves are obtained from data published elsewhere (Yentsch, 1960).

The combined absorption coefficients for chlorophyll a and pure water (James & Birge, 1938) used to calculate these colour indices are listed in Table (E1)

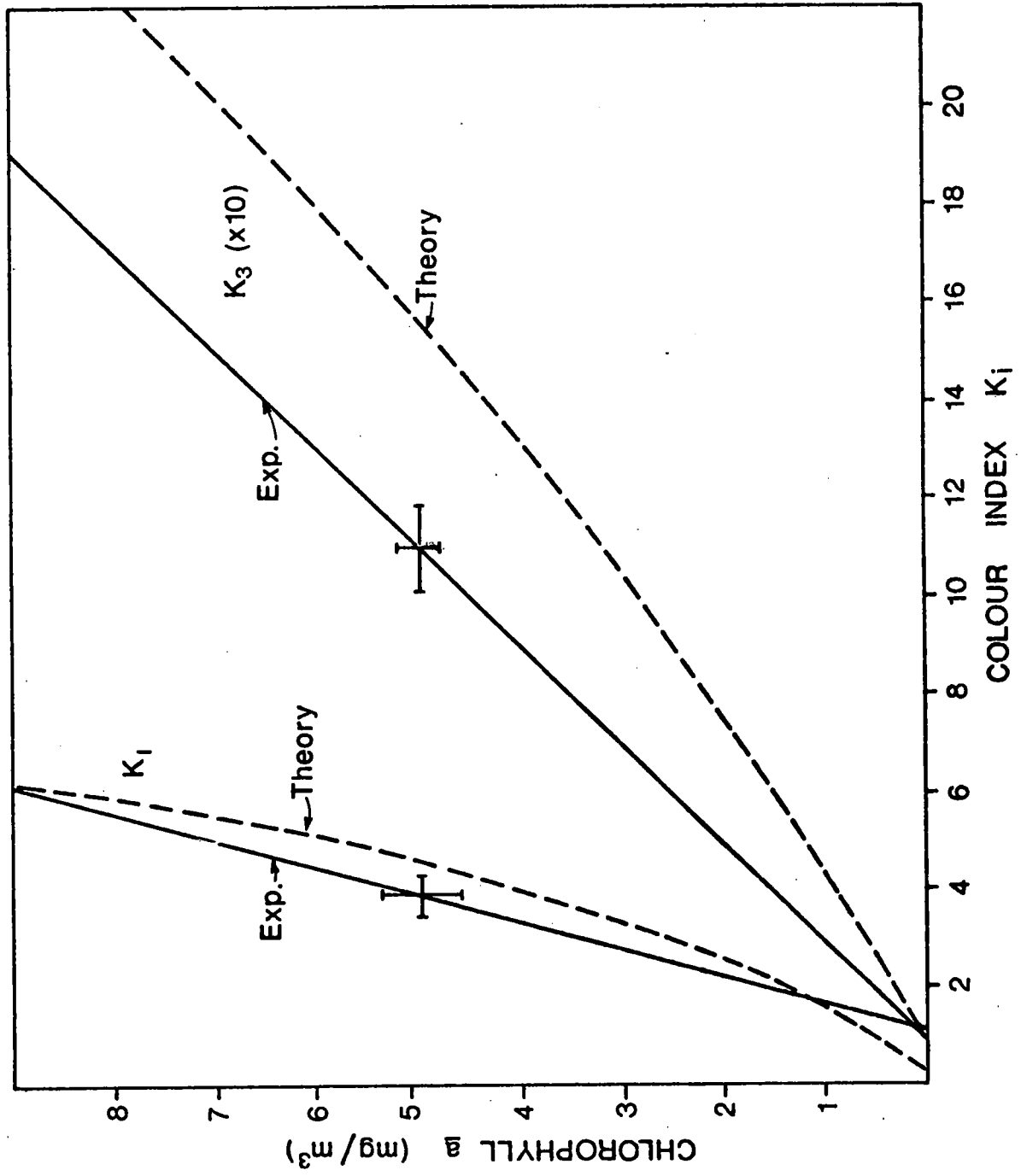


Figure (E1) Comparison of experimental, and theoretical curves obtained for the colour indices *K*₁ and *K*₃.

<u>Chlorophyll a</u> (mg/m ³)	<u>$\lambda=430$ nm</u> $a_w + a_{cl}$ (m ⁻¹)	<u>$\lambda=530$ nm</u> $a_w + a_{cl}$ (m ⁻¹)	<u>$\lambda=630$ nm</u> $a_w + a_{cl}$ (m ⁻¹)
0	0.026	0.062	0.240
0.5	0.068	0.066	0.246
1.0	0.110	0.069	0.249
2.0	0.194	0.077	0.258
3.0	0.278	0.85	0.267
4.0	0.362	0.092	0.276
5.0	0.446	0.099	0.286
6.0	0.530	0.107	0.295
7.0	0.614	0.114	0.304
8.0	0.698	0.122	0.313
9.0	0.782	0.129	0.322
10.0	0.866	0.136	0.331

Table (E 1): Combined absorption coefficients for pure water and Chlorophyll a (adapted from Yentsch (1960)).

APPENDIX FCHLOROPHYLL: ABSORPTION, RAMAN AND FLUORESCENCE SPECTRA

The chlorophyll molecule in its lowest electronic state will absorb energy at wavelength λ . This broadband absorption spectra of chlorophyll a (optical density in relative units) is illustrated in Figure (F1). The excited molecule will re-emit this energy through a combination of four possible routes:

- 1) Resonance Radiation
- 2) Rayleigh Scattering
- 3) Raman Scattering
- 4) Fluorescence (or Luminescence)

With resonance radiation, the absorption is via electronic states but the absorbed light is re-emitted before the molecule has had time to undergo molecular interactions. The probability of this resonance process is very small in most practical situations (except low pressure gasses). If the absorbed radiation exactly matches an electronic absorption line of the molecule, resonance may be sharply enhanced. Such phenomena are accessible using tunable lasers as optical sources. This may eventually allow specific pollutant detection (See Kildal, H. 1971) especially for in situ applications.

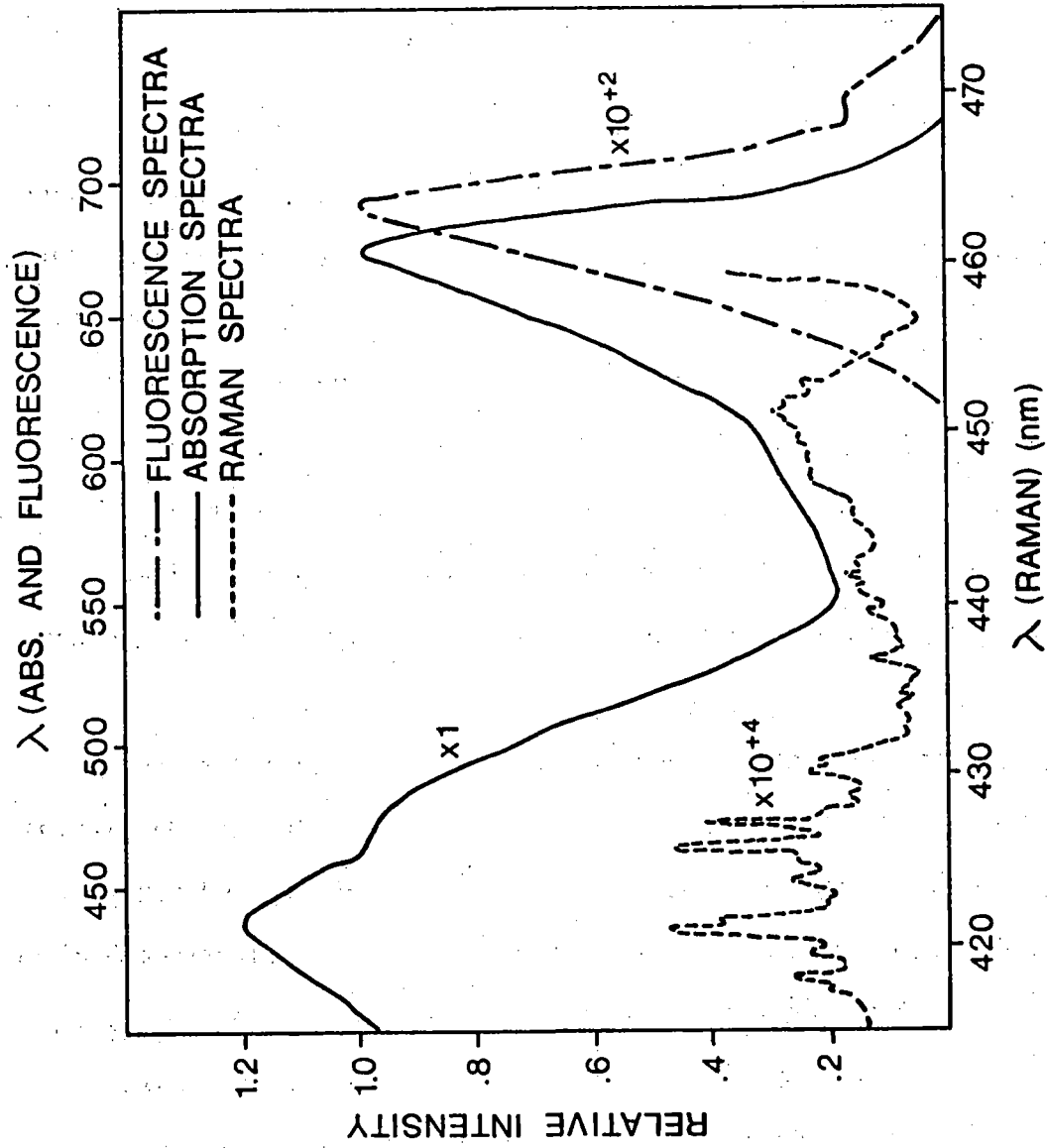


Figure (F1) Comparison of absorption, fluorescence, and Raman spectra of chlorophyll 11.

Rayleigh scattering may be described quantum mechanically as a virtual two photon process of absorption and re-emission which is both spontaneous and the most probable of the four de-excitation mechanisms.

Raman scattering is similar to Rayleigh scattering except that vibrational energy is added to or subtracted from the incident energy. As a result, the Raman scattered energy is different from the incident energy. The probability that this process will occur in liquids is about 10^{-4} the probability of the Rayleigh emission. Consequently, Raman intensities will be very low. A portion of Raman spectra of chlorophyll d (Lutz & Kleo, 1974) for excitation at 460 nm is illustrated in Figure (F1). Raman spectroscopy offers an excellent mechanism for specific chemical analyses utilizing lasers as sources.

With fluorescence, the incident energy is absorbed via electronic states of the molecule and re-emitted over time at longer wavelengths and over a broad spectrum closely mirroring the absorption spectrum of the molecule. The difference in energy is lost as heat through other mechanisms. For each photon absorbed, the probability of re-emission as fluorescence is a complex function of wavelength, temperature, the presence of impurities and other quenching mechanisms. As a rule of thumb, this probability is of the order of 1%.

Much of the fluorescence from chlorophyll a occurs in a broad spectrum centered about 685 nm (Figure (F1))(Friedman E.S., Hickman G.D., 1972), closely mirroring the broad absorption peak centered at 675 nm. An important property of the fluorescent mechanism is its temporal dependance. The fluorescent intensity as a function of time $I(t)$ is related to the lifetime of the excited state τ through

$$I = I_0 \cdot e^{-t/\tau} \quad \text{F1}$$

Where I_0 is the initial fluorescent amplitude. Time dependence has also been shown to be wavelength dependent - a phenomena some have suggested might form a basis for species identification (see Section(2.3)).

APPENDIX GPAYNE'S SMOOTHED ALBEDO VALUES

The following is a compilation of Payne's (1972) grouped and smoothed surface albedo measurements (See Appendix D). According to the approach we have suggested, these results could be very useful to remote sensing. A complete description on the use of this table is supplied in the text.

Each element $P(\theta, R)$ in Table (G1) corresponds to a given distribution R of direct and diffuse radiation for solar altitude θ . Completely diffuse illumination corresponds to the situation $R = 0$.

For practical use to remote sensing, only values of $P(\theta, R)$ for $\theta > 30^\circ$ are shown. Under real conditions, values of $P(\theta, R)$ for $R > 0.8$ do not occur.

R	SOLAR ALTITUDE θ									
	32°	34°	36°	38°	40°	42°	44°	46°	48°	50°
.00	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.05	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.10	.060	.061	.060	.060	.060	.060	.060	.060	.060	.060
.15	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060
.20	.060	.060	.060	.060	.060	.060	.060	.060	.059	.060
.25	.061	.061	.060	.060	.060	.060	.060	.059	.059	.059
.30	.063	.062	.061	.060	.060	.060	.059	.059	.059	.059
.35	.065	.064	.062	.062	.060	.060	.060	.059	.059	.059
.40	.068	.067	.065	.063	.062	.061	.060	.060	.060	.059
.45	.072	.071	.068	.066	.065	.063	.062	.061	.060	.059
.50	.076	.073	.069	.067	.065	.064	.062	.060	.059	.058
.55	.077	.074	.069	.066	.063	.061	.059	.057	.056	.055
.60	.076	.073	.068	.064	.060	.058	.056	.054	.053	.051
.65	.074	.069	.065	.061	.057	.055	.052	.050	.049	.047
.70	.071	.065	.061	.057	.054	.051	.049	.047	.045	.043
.75	.067	.062	.058	.054	.050	.047	.045	.043	.041	.039
.80	.064	.060	.055	.051	.047	.044	.042	.039	.037	.035
.85	.062	.058	.054	.050	.046	.042	.040	.036	.035	.033
.90	.061	.057	.053	.049	.045	.041	.039	.034	.033	.032
.95	.061	.057	.052	.048	.044	.040	.038	.033	.032	.031
1.00	.061	.056	.052	.048	.044	.040	.038	.033	.032	.031

Table (G 1) Payne's Grouped and smoothed albedo values.

R	SOLAR ALTITUDE θ									
	52°	54°	56°	58°	60°	62°	64°	66°	68°	70°
.00	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.05	.061	.061	.061	.061	.061	.061	.061	.061	.061	.061
.10	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060
.15	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060
.20	.060	.060	.060	.060	.060	.060	.060	.060	.060	.060
.25	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059
.30	.059	.059	.059	.059	.059	.059	.059	.059	.059	.059
.35	.059	.059	.059	.059	.058	.058	.058	.058	.058	.058
.40	.059	.058	.058	.058	.057	.057	.057	.057	.057	.057
.45	.058	.057	.057	.057	.056	.055	.055	.055	.055	.055
.50	.057	.056	.055	.055	.054	.053	.053	.052	.052	.052
.55	.054	.053	.053	.052	.051	.050	.050	.049	.049	.049
.60	.050	.049	.048	.048	.047	.046	.046	.045	.045	.045
.65	.046	.046	.044	.044	.043	.042	.042	.041	.041	.040
.70	.043	.042	.041	.040	.039	.039	.038	.038	.037	.036
.75	.039	.038	.037	.036	.036	.035	.035	.034	.033	.032
.80	.035	.035	.034	.033	.033	.032	.032	.032	.029	.029
.85	.032	.032	.031	.030	.030	.030	.030	.029	.027	.027
.90	.031	.030	.029	.028	.028	.028	.028	.027	.026	.026
.95	.030	.029	.028	.027	.027	.026	.026	.026	.025	.025
1.00	.030	.029	.028	.027	.026	.026	.026	.026	.025	.025

Table (G 1) (Continued)

R	SOLAR ALTITUDE θ							
	72°	74°	76°	78°	80°	82°	84°	86°
.00	.061	.061	.061	.061	.061	.061	.061	.061
.05	.061	.061	.061	.061	.061	.061	.061	.061
.10	.060	.060	.060	.060	.060	.060	.060	.060
.15	.060	.060	.060	.060	.060	.060	.060	.060
.20	.060	.060	.060	.060	.060	.060	.060	.060
.25	.059	.059	.059	.059	.059	.059	.059	.059
.30	.059	.059	.059	.059	.059	.059	.059	.059
.35	.058	.058	.057	.058	.058	.058	.058	.057
.40	.057	.056	.056	.056	.056	.056	.056	.056
.45	.055	.054	.053	.054	.053	.053	.054	.053
.50	.051	.051	.050	.050	.050	.050	.051	.050
.55	.048	.047	.047	.047	.046	.046	.047	.046
.60	.044	.043	.043	.043	.042	.042	.043	.042
.65	.040	.039	.039	.039	.038	.038	.038	.038
.70	.036	.035	.035	.034	.034	.034	.034	.034
.75	.032	.032	.031	.031	.031	.030	.030	.030
.80	.029	.029	.028	.028	.028	.028	.027	.028
.85	.027	.027	.026	.026	.026	.026	.026	.026
.90	.026	.025	.025	.025	.025	.025	.025	.025
.95	.025	.025	.025	.025	.025	.025	.025	.025
1.00	.025	.025	.025	.025	.025	.025	.025	.025

Table (G 1) (Continued)

APPENDIX H.APPLICATIONS OF LIGHT SCATTERING IN HYDRO-OPTICS

Summarized within, are several new experimental and theoretical observations resulting from efforts to focus upon the in situ nature of hydro-optical scattering measurements and the concentrations and character of the particulate material responsible for the observed scattering phenomena.

As a result of these studies, we are able to infer that scattering, especially when used in conjunction with measurements of transmittance, can yield data which is meaningfully interpretable in terms of particle concentrations and particle types. These applications of hydro-optics are non-destructive, requiring no chemical analysis, and can be made in situ using available optical technology.

For practical applications of scattering theory to situations of limnological interest, only 'real' particle ensembles are considered in this section. Several experimental studies have shown, (Owen, 1974), that "real" particle ensembles are both polydispersed (broad distribution of sizes) and irregular in shape. For such a particle ensemble, the scattering coefficient b (m^{-1}) for a number concentration of N (m^{-3}) particles can be expressed as

$$b = \pi \langle K \rangle N \langle r \rangle \quad (\text{H } 1)$$

where $\langle K \rangle$ is the 'average' scattering efficiency of the particle ensemble and $\langle r \rangle$ is the mean particle radius.

The parameter K in Eq (H 1) is a function of the quantity ρ , called the 'size parameter' of the particle ensemble. The size parameter ρ is in turn a function of $\langle r \rangle$, $|m-1|$, the relative particle/water refractive index, and λ , or wavelength of the incident (or scattering) light.

This functional relationship is expressed as

$$\rho = \frac{4\pi \langle r \rangle}{\lambda} |m-1| \quad (\text{H } 2)$$

The experimental function $\langle K \rangle$ for a 'real' polydisperse ensemble of irregular particles is shown on Figure (H 1) (c) (Hodkinson, 1963). Also shown in Figure (H 1) are the theoretical functions for K for single monodisperse particles as calculated from Mie theory in (a). The curve for a polydisperse ensemble of spheres is also shown (Van de Hulst, 1957) in (b)

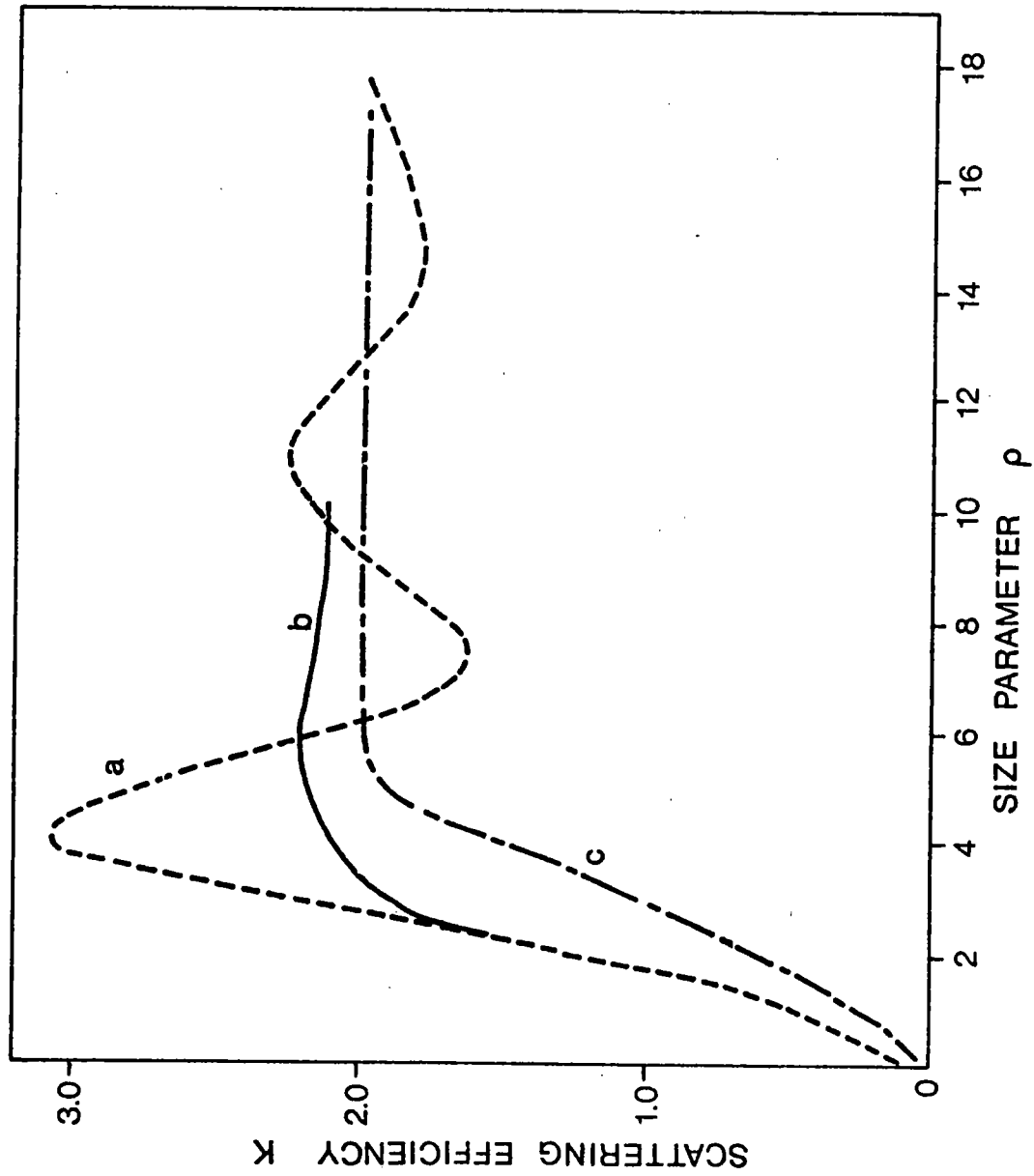


Figure (H1) Scattering efficiency as a function of size for (a) monodisperse ensemble of spheres, (b) Polydisperse ensemble of spheres, (c) Polydisperse ensemble of irregular particles (from Owen, R.W., 1974)

The relative refractive index value of 0.05 for $|m-1|$ is usually chosen as the most likely value for surface waters having small sediment loads. True values of this index are seen to be converging on this value (Gordon & Brown, 1972; Carder et al, 1972; Zaneveld & Par, 1973).

It is interesting to compute from the information supplied in Figure (H1)(c), the value for the scattering coefficient b (m^{-1}) which might be expected from a particle ensemble of known composition and concentration.

In table (H 1), this theoretical computation has been summarized for a range of mean particle radii (i.e. 0.1μ to 100μ). The calculation is performed in each case for fixed values of the parameters λ (i.e. 600 nm) and 0.05 for $|m-1|$. The number concentration N (cm^{-3}) for each $\langle r \rangle$ corresponds to a mass concentration of 1 ppm (or $1g/m^3$, or 1 mg/l, or $1\mu g/cc$) assuming a mean specific gravity near 1.0 for suspended particles of biogenic (organic) origin. The mean number concentration N , may then be computed for each mean radius from the relation

$$N = \frac{1}{\frac{4}{3} \pi \langle r \rangle^3} \quad (H 3)$$

The results of the computation summarized in Table (H 1) are of interest to hydro-optical studies for several reasons. Firstly, the observed reduction in K with particle radius, for particles smaller than about 6.0μ acts in such a way as to just compensate for the enhanced scattering which would be expected for these ensembles. This observation is not expected from theory and allows, as a result, scattering measurements to be interpreted in terms of mass or number concentration in a meaningful way without absolute need for simultaneous measurement of $\langle r \rangle$.

<u>Mean Particle Radius</u> $\frac{\langle r \rangle}{(\mu)}$	<u>Concentration</u> N (cm^{-3})	<u>Scattering Efficiency</u> K	<u>Scattering Coefficient</u> $b = \pi \langle K \rangle N \langle r \rangle^2$ (m^{-1})
0.1	2.39×10^8	0.023 (?)	.17 (?)
1.0	2.39×10^5	0.23	.17
2.0	2.98×10^4	0.64	.24
3.0	8.84×10^3	1.10	.27
4.0	3.73×10^3	1.60	.30
5.0	1.91×10^3	1.95	.29
6.0	1.11×10^3	2.0	.25
7.0	6.96×10^2	2.0	.21
8.0	4.66×10^2	2.0	.19
9.0	3.28×10^2	2.0	.17
10.0	2.39×10^2	2.0	.15
100.0	2.30×10^{-1}	2.0	.015

Table (H 1) Scattering coefficient b computed for a range of mean particle sizes $\langle r \rangle$ (Concentration 1.0 ppm; $|m-1| = .05$; $\lambda = 0.6\mu$)

For biogenic particles in particular, measurements of scattering coefficients may be related to mass concentration through relations of the form

$$\langle \text{Conc} \rangle \approx 4.6 \, b \quad (\text{H } 4.)$$

The value 4.6 in Eq. (H 4) is obtained as the mean value of the reciprocal of the value for b over a range of $\langle r \rangle$ from 1 to 10 μ (Table H 1).

There is good reason to expect that the semi-empirical formula given as Equation (H.4) will be valid under a variety of situations of interest to hydro-optics. The technique may in particular be valuable in profiling measurements relating to productivity studies.

Typical of an experimental analysis of in situ profiles of the parameter b obtained as a function of depth at a number of stations on Lake Huron and Georgian Bay during the CCIW Series of Survey Cruises (1974), is the example shown in Figure (H.2). The scattering coefficient b is reduced from data obtained using an Integrating scattering meter (Jerlov 1961, Jerlov 1968 p19f), and is shown here to a depth of 75 m. Also profiled in Figure (H.2) are the α ($\alpha = a + b$) and temperature (T) profiles simultaneously obtained at the time of this b sounding. Also illustrated in the figure is the absorption coefficient a (480 nm) derived from the relation

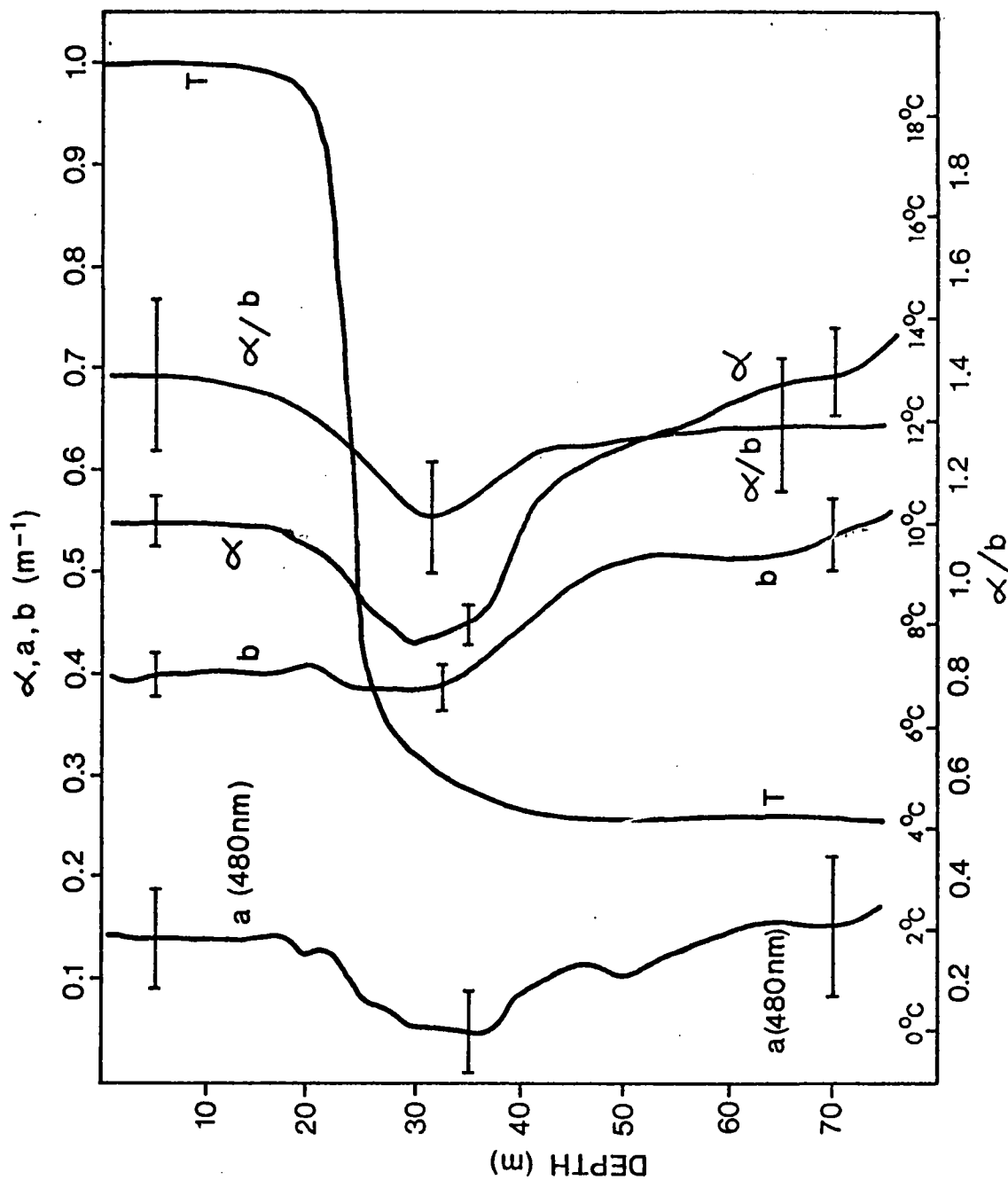


Figure (H2) Attenuation, scattering and absorption coefficients and indicatrix α/b , obtained along with temperature sounding on Georgian Bay (August, 1974).

$$a(480) = \alpha(480) - b(600 \text{ nm}) \quad (\text{H.5})$$

This relation assumes the wavelength independence of b .

The indicatrix defined by α/b , is also plotted in this figure.

There are a number of features of interest in this analysis which are summarized in the comments which follow.

The decrease in α near 30m, in the region of the thermocline, is not reflected in the scatterance b . The scatterance is seen to remain relatively constant at 0.4 to this depth. This observed decrease in attenuation (α) must consequently arise from a decrease in the absorbance $a(\lambda)$ of the particles giving rise to this scatterance b .

The above observation indicates a fundamental change in the character of the particles giving rise to the scatterance b .

This observed minimum in α is more quantitatively (independent of b) reflected in the ratio α/b which is seen to attain its minimum value near 32m.

A probable explanation of the observed change in the absorbing character of these particles at 32m is that the fraction of detrital material is maximum at or near this absorption minima.

This explanation can be supported by examination of the optical (i.e. absorbing) characteristics of detrital and organic particles composing the ensemble.

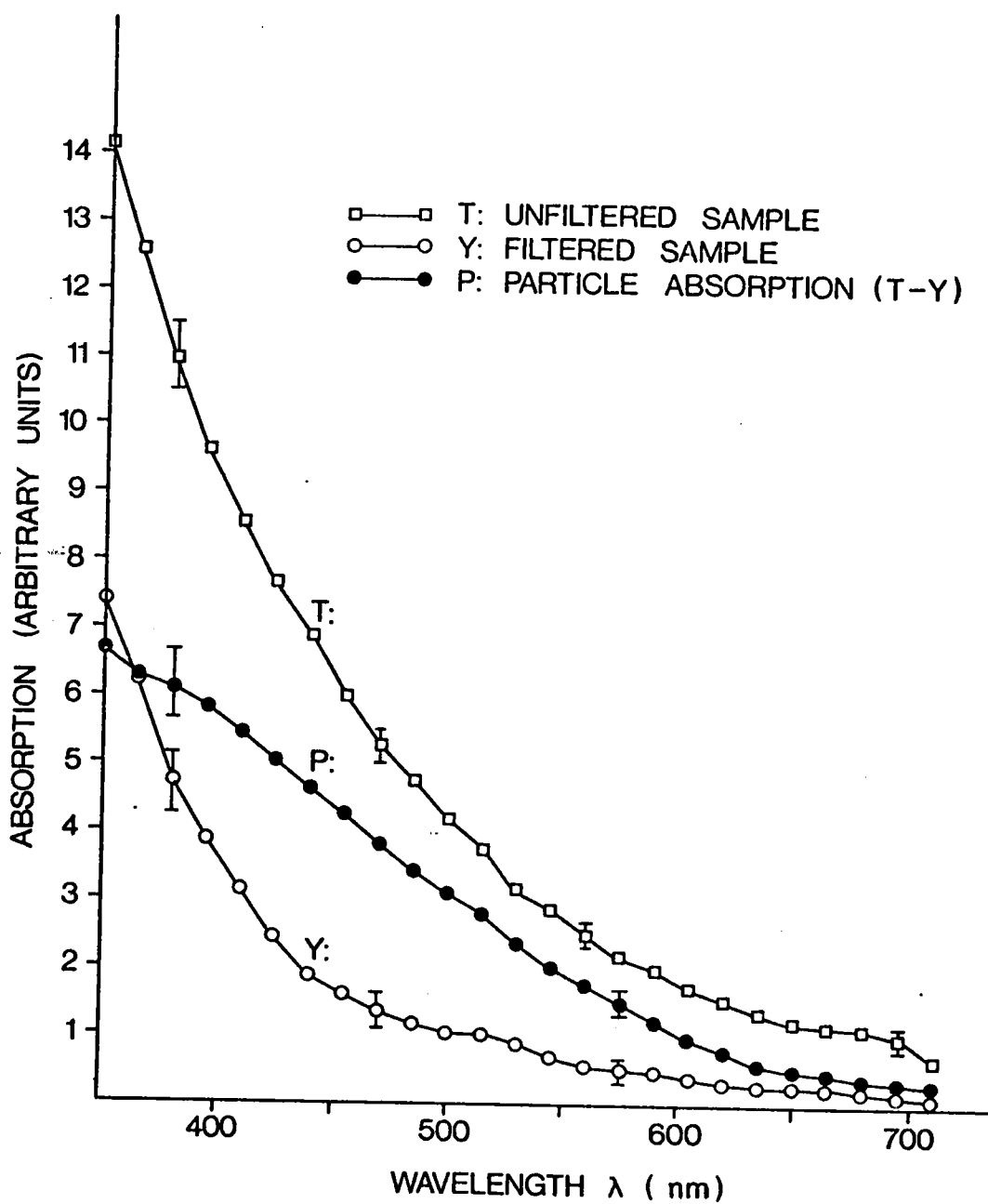
Below 32 m, the scatterance, b , is seen to increase to values in excess of 0.55 at a depth of 75 m. This increase in scatterance may likely be attributed to an increase in mass concentration of the order of 40% over surface water concentrations. (i.e. 1.8 to 2.5 ppm). The ratio α/b attains a value asymptotic to 1.3 at these depths; this value is about 7% less than the surface value of 1.4 but 8% greater than the minimum value of 32m. This variation with depth of the indicatrix α/b has been a consistent observation of these profiling measurements.

In summary, these observations appear to indicate that the hydro-optical application of scattering techniques can be exceedingly useful in specification of the character (through the indicatrix α/b) and concentrations (through Equations of the form Eq. H.4) of suspended material in a water column.

APPENDIX ILABORATORY SPECTROPHOTOMETER TESTS ON FILTERED WATER SAMPLES

Figure (I1) is typical of a series of spectrophotometer spectral scans of the absorption properties of particle laden water samples obtained from several stations on Lake Ontario. These curves, labelled T, P, and Y, in the figure, are obtained from comparing the spectral signatures of unfiltered (T) and filtered (Y) water samples to a control sample of distilled water over a 10 cm. path length using a Unicam Model SP 1800 UV spectrophotometer. The resultant curves represent the combined effect of absorption due to suspended particles and dissolved substances together in T and dissolved substances alone in (Y) where the curve Y is obtained after sample filtration (0.2 μ filter). The curve labelled P in Figure(I1) is obtained from the relation $P = T - Y$ and represents the absorption due to suspended particles alone. The near linear shape of P is in agreement with results obtained by others (Yentsch, 1961, see Appendix E)

While the absorption contribution from substances contained within the filtered sample certainly represents less than one quarter of the total absorption throughout most of the visible spectrum, this 'Y' contribution rises quickly for wavelengths less than 450 nm to values in excess of 50 % of the total absorption near 350 nm.



Figure(I1) Laboratory spectrophotometer spectra of filtered, Y, and unfiltered (corrected), T, water samples from Lake Ontario.

This rapid and exponential rise in absorption due to substances contained within the unfiltered sample must arise from dissolved substances as the fraction of suspended material having sizes less than 0.2μ is small.

It would therefore appear that the optical laboratory tests confirm the presence of dissolved substances as deduced from the in situ optical measurements.

APPENDIX J.

ST. CLAIR RIVER STUDY

This study was conducted in order to assess, using optical, laboratory, and remote sensing methods, the effects of shipping and dredging operations upon the ambient suspended sediment levels in the St. Clair River.

The following is a brief summary of some of the more important observations and conclusions arising from this study.

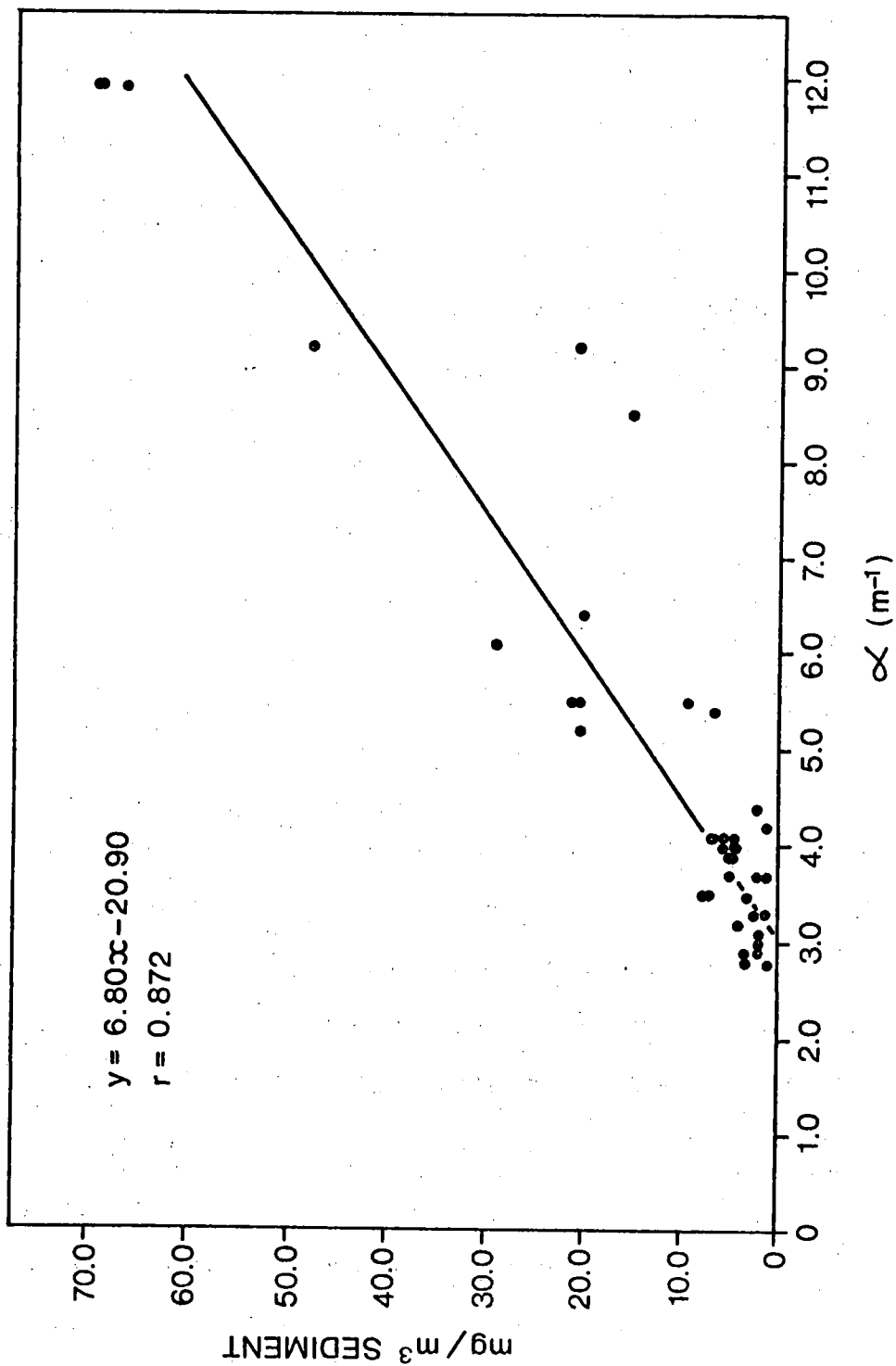


Figure (J1) Linear regression on laboratory measured suspended sediment concentrations and collimated attenuation coefficients for measurements obtained in the St. Clair river test area.

Observational Summary

J.1. Air

Observations of note, made from the air on July 24, 1974 included: (1) There was a well-defined sediment 'plume' of several hundred feet in width in the vicinity of the extreme south western end of the St. Clair River cut off. This 'plume' extended in a south westerly direction with well-defined boundaries which indicated higher than ambient (i.e. Lake St. Clair ambient) concentrations of sediment within the plume and along the track of the main shipping channel into Lake St. Clair.

J.2. ERTS Imagery

Satellite imagery* of the test area available at CCIW revealed a well-defined line extending from the south western tip of the St. Clair River cut-off across Lake St. Clair towards the Detroit River and along a track which is apparently coincident with the main shipping lane across Lake St. Clair. This line, of several hundred feet in lateral extent, is most readily observable in Band 5 (i.e. 600 to 700 nm). This feature is generally agreed to be attributable to a high level of sediment loading along the shipping lane across Lake St. Clair. It should be noted that this feature may not always be so apparent. A number of hydrodynamical factors may combine to obscure this feature at any given time. This feature has however, been observed in the past, and may provide a strong clue to the effects of shipping across Lake St. Clair.

* 8 July 74 C N42-56/W 082-45 N N42-50/W 082
-39 MSS-4, 5 & 6 SUNFL58 AZ121
196-09969-P-1-A-P-1L CCRSE1715-1539D-4.56

J.3. Ground

Experiments performed on the ground by DPH and CCIW personnel included transmissometer soundings and water samplings obtained and conducted according to prearranged techniques and consistent with generally accepted experimental procedures. The experiments were conducted to assess the effects of dredging and shipping operations upon the ambient concentrations of particulates in the area. The data shown in Figure (J.1) is presented in terms of the coefficient of extinction α - where α is obtained from the $\frac{1}{4}$ meter transmissometer reading $T_{\frac{1}{4}}$ - from the relation

$$\alpha = -4 \ln (.01 T_{\frac{1}{4}}) \quad (J.1)$$

where $T_{\frac{1}{4}}$ is expressed as a percentage.

J.3.1 Ambient values of α

Data obtained about the test sight and at various locations across the channel and under conditions where no shipping was taking place - north-east of the single dredging operation yielded values of α in the range 2.8 to 3.5 m^{-1} (i.e. $\alpha = 3.15 \pm .35$). The upper limit on α (3.5 m^{-1}) was used in all subsequent calculations.

J.3.2 Water Sampling

A number of water samples were obtained coincident with the transmissometer soundings over the two day period. Thirty eight of these samples were

laboratory filtered, dried and weighed. The α vs. sample weight linear regression analysis for these samples is illustrated in Figure (J.1). The resultant analysis shows reasonable correlation with the laboratory results ($r = 0.872$). The non-zero residue on A (or α) is due primarily to absorption due to dissolved substances in the water. According to Figure (J.1), the ambient value $\alpha = 3.5$, corresponds to a particulate loading of 2.90 ppm (or mg/l) which agrees well with known values of this parameter in this region.

J.3.3. Sediment Profiling

Under equilibrium conditions the distribution of relative concentration in an open channel flow is described by relations of the form (Krishnappan, 1974).

$$\text{Concentration} = \left\{ \frac{N_a \left(1 - \frac{N-N_a}{1-N_a} \right)}{N_a + (1-N_a) \frac{N-N_a}{1-N_a}} \right\} \frac{1}{x^m} \quad (\text{J.2})$$

where m = relative intensity of flow

x = constant (0.4)

N = depth/depth of channel

N_a = scaled depth

For the very fine silt particles characteristic of the lower St. Clair River delta region (i.e. test sight) and for the characteristic

flow values for the region; (particle settling rates of 1.0 cm/sec; and flow rates of 30 to 90 cm/sec) it can be shown that: (a) once put into suspension, particles will remain in suspension for their entire residence time in the channel and (b) the concentration of particulates (or mass concentration) will be relatively uniform with depth.

Experimental evidence for this latter phenomena was obtained by depth profiling of α at various times after ship passage and dredge operations.

J.4 Dredging Operations

Sediment concentrations in excess of ambient values were readily detected as far as 2800 feet down stream of the dredging operation. Near the dredge and within a 100' radius of the dredge, sediment concentrations are found to exceed ambient values by at least 460%.

J.5 Ship Traffic

Observations were obtained on turbidity plumes generated by a number of ships on passage both down and up stream in the channel. The results of α values from most of these samples yielded maximum values of α of the order 5.0 within three to six minutes of ship passage.

CONCLUSIONS

Due to the nature of the sediments and the current flow patterns in the test area, both shipping and dredging operations may significantly contribute to ambient particulate levels in the region. This is an unavoidable conclusion based on theoretical grounds and is a result of the fact that due to the slow settling rates of the particles and fast flow conditions in the channel, sediments just do not have time to settle out of suspension.

Although it is not possible to directly compare the effects of one ship vs. the effects of one conventional dredging operation - as the former acts as a line source while the latter a point source; the results of our study do appear to indicate that in the shipping channel both operations can be comparable in effect.

Conservatively, either operation, a single ship (i.e. with 27 foot draught) or a single dredge, may increase ambient particulate concentrations by at least 4.6 within a 100 foot radius of either operation.

The effects of a ship on ambient levels may be highly depth dependent. Visual turbidity plumes do however occur in clear water regions for depths in excess of two or three times a ship's draught.

Assuming that a channel flow rate of 1 foot/sec., and a 460% increase over ambient sediment value (13.3 mg/l) as obtained from our measurements, is representative of test site conditions, these data would imply a sediment deposition of 7.5×10^4 tons per mo. at the end of the St. Clair cut off due to shipping alone. This value, representing 7% of a similar ambient flow calculation should be considered significant. Worded otherwise, the effects of shipping operations must effectively represent at least 7% of the natural sediment deposition outside the cut off region. This calculation assumes the channel has time to just recover after a ship passes or a ship frequency of one every 90 minutes.*

*Assuming average ship speed of 10 knots in the five mile long channel.

REFERENCES

- Austin, R.W., (1974), 'Problems in Measuring Turbidity as a Water Quality Parameter', Visibility Laboratory, Scripps Institute of Oceanography, U. of California, 92152
- Austin, R.W., (1974), in Jerlov, N.G., Nielson, E.S., (1974), 'Optical aspects of Oceanography', Academic Press, London & New York
- Bukata, R.P., McColl, W.D., (1973), 'The Utilization of Sun Glint in a Study of Lake Dynamics', Proc. #17, Rem. Sens. and Water Resources Management, 351-368
- Carswell, A.I., Bell, R.W., Houston, J.D., Pal, S.R., Petaherych, S., (1975), 'Remote Raman Spectroscopy', Can. J. Remote Sensing, 1, to be published
- Edgerton, A.T., Maurer, Lt. A., (1975), 'Flight Evaluation of U.S. Coast Guard Airborne Oil Surveillance System', in Proc. Conference on Prevention and Control of Oil Pollution, San Francisco, March, 1975
- Elder, F., (1974), Applied Research Division, Canada Centre for Inland Waters, Burlington, Ontario, personal communication
- Grew, G.W., (1973), 'Signature Analysis of Reflectance Spectra of Phytoplankton in Inland Waters', 2nd Annual Remote Sensing of Earth Resources Conference, Proc. (F. Shahroki, Ed.), Vol. II, UTSI, Tullahoma Tenn., 37388
- Guilbault, G.G., (1967), 'Fluorescence, Theory, Instrumentation, & Practice', Marcel Dekker Inc., New York
- Jerlov, N.G., (1968), 'Optical Oceanography', Elsevier Publishing Company, Amsterdam, London & New York
- Jerome, J., McNeil, W.R., Elder, F., (1975), 'Hydro-optical parameters for description and classification of Lakes by Remote and Immersion Sensing', Proc. 18th Symposium IAGLR, to be published
- Measures, R.M., Houston, W.R., Stephenson, D.G., (1974), Optical Engineering, Nov-Dec (1974), 494-501 [see also Can. J. Remote Sensing, 1, (1975)]
- Ritchie, J.C., McHenry, J.P., Schiebe, F.R., Wilson, R.B., (1974), 'Relationship of Reflected Solar Radiation and the Concentration of Sediment in the Surface Waters of Reservoirs', Proc. 3rd Symp. on Remote Sensing of Earth Resources (ed. F. Shahroki), 3, UTSI, Tullahoma, Tenn, 37388
- Robertson, (1975), Attachment #1, 'Proposed Objective for Turbidity', Minutes of the Water Quality Objectives Sub-Committee Meeting, Standing Sub-Committee of Research advisory Board on Scientific Basis for Water Quality Criteria, Feb 11, 1975

Rodgers, K., (1975), Head, Basin Investigation and Modeling Section, Applied Research Division, Canada Centre for Inland Waters, Burlington, Ontario, personal communication

Thomson, K.P.B., Jerome, J., McNeil, W.R., (1974), 'Optical Properties of the Great Lakes', Proc. 17th Symp. IAGLR, McMaster University,

Thomson, K.P.B., Jerome, J., McPhail, H., (1974), 'A Simple Colour Meter for Limnological Application', Scientific Series # 49, Inland Waters Directorate, CCIW, Burlington, Ontario

White, P.G., (1971), 'High Altitude Remote Spectroscopy of the Ocean', Proc. Soc. Photo. Opt. Inst. Eng., 27, 111-114, Nov. 1971

Zuev, V.E., (1966), 'Atmospheric Transparency in the Visible and the Infrared', Russian Translation, U.S. Dept. of Commerce Clearinghouse, TT 69-55102, Springfield, Va. 22151

REFERENCES (APPENDIX A)

Blanchard, J.B., Leamer, R.W., (1973), "Spectral Reflectance of Water Containing Sediment", Remote Sensing and Water Resources Management, Proc #17, (ED. Thomson et al.), 339-347

Bristow, M.P.F., Houston, W.R., Measures, R.M., (1973), "Development of a laser fluorosensor for Airborne Surveying of the Aquatic Environment", NASA Conf. on the use of Lasers for Hydrographic Studies, Sept 12, 1973, Wallops Island, Virginia

Bukata, R.P., Bruton, J.E., (1974), "ERTS-1 Digital Classifications of the Water Regimes Comprising Lake Ontario", Proc. 2nd Cdn. Symp. on Remote Sensing

Carswell, A.I., Sizgoric, S., McNeil, W.R., (1974), "Underwater Probing with Laser Radar", 1973 CASI Symposium on aerospace electronics, to be published CASI Journal

Fantasia, J.F., Hard, T.M., Ingrao, H.C., (1971), "An Investigation of Oil Fluorescence as a Technique for Remote Sensing of Oil Spills", Report # DOT-TSE-USCG-71-7, Trans. Syst. Centre, Dept. of Transport, Cambridge, Mass.

Gordon, H.R., Brown, O.B., (1973), "Irradiance Reflectivity of a Flat Ocean as a Function of its Optical Properties", App. Op., 12, 1549-1551

Gordon, H.R., (1973), "Simple Calculation of the Diffuse Reflectivity of the Ocean", App. Op., 12, 2803-2804

Gower, J.F.R., Daniel, I., (1974), "Water Colour Measurements using ERTS Computer compatible Tape Data", Proc. 2nd Cdn. Symp. on Remote Sensing

Grew, G.W., (1973), "Signature Analysis of Reflectance Spectra of Phytoplankton in Inland Waters", 2nd Annual Remote Sensing of Earth Resources Conf. Proc. (F. Shahroki, Ed.), Vol. II, UTSI, Tullahoma, Tenn., 37388

Hickman, G.D., Hogg, J.E., (1969), "Application of Airborne Pulsed Laser for Near Shore Bathymetric Measurements", Remote Sensing Env., 1, 47-58

Jeffers, S., (1974), "Evaluation of an Intensifier Optical Multichannel Analyser for Remote Sensing", Report Submitted to the Dept. of Energy, Mines and Resources, March 1974, CRESS, York University, Toronto

Jerlov, N.G., (1968), Optical Oceanography, Elsevier Publishing Co., Amsterdam, London and New York

Kerr, H.S., (1973), "Multispectral Remote Sensing Camera System", SPAR report prepared for: CCRS (DS&S Contract PL 23413-1-0297 S/N OPL1-0159

Kim, H.H., (1973), "New Algal Mapping Technique by the Use of an Airborne Laser Fluorosensor", App. Op., 12 # 7, 1454-1459

Langham, E.J., Rochon, G., (1974), "Quelques Applications du Satellite ERTS-1 au control et a la gestion des eaux au Quebec", Proc. 2nd Cdn. Symp. on Remote Sensing

Levis, C.A., Swarner, C., Prettyman, C., Reinhardt, G.W., (1973), "An Optical Radar for Airborne Use over Natural Waters", Proc. Ocean 73, 76-83

McNeil, W.R., Thomson, K.P.B., (1974), "Remote Measurement of Water Colour and its Application to Water Quality Surveillance", Proc. 3rd Symposium on Remote Sensing of Earth Resources, (F. Shahrokhi, Ed.), Vol. III, UTSI, Tullahoma, Tenn, 37388

Miller, J.R., Shepherd, G.G., (1973), "Airborne Spectroscopic Measurements over Water", CASI Journal, 19, # 10, Dec 1973, 521-524

Mumola, P.B., Jarrett, O., (1973), "Multiwavelength laser Induced Fluorescence of Algae in-vivo: A New Remote Sensing Technique", 2nd Joint Conf. on the Sensing of Env. Pollutants

O'Neil, R.A., Davis, A.R., Gross, H.G., Kruus, J., (1973), "A Remote Sensing Laser Fluorometer", Report available from: Water Science Subdivision, Inland Waters Directorate, Environment Canada, 562 Booth St., Ottawa, K1A 0E7

Paris, F.F., (1974), "Coastal Zone Mapping from ERTS-1 Data using Computer Aided Techniques", Proc. 2nd Cdn. Symp. on Remote Sensing

Piech, K.P., Walker, J.E., (1971), "Aerial Color Analysis of Water Quality", presented at Jan. 1971 meeting of American Society of Civil Engineers, Phoenix, Arizona

Ritchie, J.C., McHenry, J.R., Schiebe, F.R., Wilson, R.B., (1974), "The Relationship of Reflected Solar Radiation and the Concentration of Sediment in the Surface Waters of Reservoirs", Proc. 3rd Symp. on Remote Sensing of Earth Resources, (F. Shahrokhi, Ed.), Vol III, UTSI, Tullahoma, Tenn., 37388

Thomson, K.P.B., Jerome, J., McNeil, W.R., (1974), "Optical Properties of the Great Lakes", manuscript available through: Remote Sensing Section, CCIW, Burlington, Ontario

Vollenweider, R.A., (1961), "Relations Existing in the Spectral Extinction of Light in Water", Mem. Ist. Ital. Idrobiol., 13, 87-113

Walker, G.A.H., Buchholz, V.L., Camp, D., Isherwood, B., Gower, J.F.R., (1974), "A Silicon Diode Array Spectrometer for Ocean Colour Monitoring", Inst. of Astronomy and Space Science, U.B.C., Vancouver, B.C.

REFERENCES (APPENDIX C)

McNeil, W.R., (1973), "Lidar Atmospheric Polarization Diagnostics" PhD thesis,
York University, Toronto.

References (Appendix D)

- Curcio, J.A., Petty, C.C. (1951) "The near infrared absorption spectrum of liquid water", J. Opt. Soc. Am., 41, 302-304.
- Gordon, H.R., Brown, O.B. (1973) "Irradiance Reflectivity of a Flat Ocean as a Function of its Optical Properties", App. Op. 12 # 7, 1549-1551.
- Gordon, H.R. (1973) "Simple Calculation of the Diffuse Reflectance of the Ocean", App. Op., 12 # 12.
- Jerlov, N.G. (1968) "Optical Oceanography", Elsevier Publishing Company, Amsterdam - London - New York.
- Jerlov, N.G. (1972) "Significant Relations Between Optical Parameters of the Sea", Symp. on Optical Aspects of Oceanography, Copenhagen, In Press.
- McCluney, W.R. (1974) "Ocean Color Spectrum Calculations", App. Op., 13 # 10, 2422-2429.
- McNeil, W.R. (1974) "Quantitative Water Colour Measurement by Remote Sensing", Proceedings Second Canadian Symposium on Remote Sensing, (ed. G.E. Thompson), August 1974, Vol. 2, p 710-715.
- McNeil, W.R., Thomson, K.P.B. (1974) "Remote Measurement of Water Colour and its Application to Water Quality Surveillance", Proc. 3rd Symposium on Remote Sensing of Earth Resources, (ed. F. Shahrokhi), UTSI, Tullahoma, Tenn., 37388.
- McNeil, W.R. (1975) "Study and Evaluation of Remote Spectroscopic Measurements in Water Quality Surveillance", Quarterly Reports #1,

- #2, #3 (July 1, 1974, Oct. 1, 1974, Jan. 1, 1975); D.S.S. Contract 12SQ.KL347-4-0082 for Canada Centre for Inland Waters, W.R. McNeil & Associates Inc.
- Miller, J.R. (1974) York University, Centre for Research in Experimental Space Science, private communication.
- Payne, R.E. (1972) "Albedo of the Sea Surface", J. Atmos. Sci., 29 # 5, 959-970.
- Piech, K.R., Schott, J.R., Stewart, K.M. (1974) "SI90 Interpretation Techniques Development and Application to New York State Water Resources", Interim Report, Calspan Corp. (Buffalo, N.Y.) # YB-5298-M-V.
- Ritchie, J.C., McHenry, J.P., Schiebe, F.R., Wilson, R.B. (1974) "Relationship of Reflected Solar Radiation and the Concentration of Sediment in the Surface Waters of Reservoirs", Proc. 3rd Symp. on Remote Sensing of Earth Resources (ed. F. Shahrokhi) Vol. 3, UTSI, Tullahoma, Tenn. 37388.
- Thomson, K.P.B., Jerome, J., McNeil, W.R. (1974) "Optical Properties of the Great Lakes", Proc. 17th Symp. IAGLR, McMaster University.
- Thomson, K.P.B., Jerome, J., MacPhail, H. (1974) "A Simple Colour Meter for Limnological Application", Scientific Series # 49, Inland Waters Directorate, CCIW, Burlington, Ontario.
- Vollenweider, R.A. (1961) "Relations Existing in the Spectral Extinction of Light in Water", Mem. Ist. Ital. Idrobiol., 13, 87-113.
- White, P.G. (1971) "High Altitude Remote Spectroscopy of the Ocean", Proc. Soc. Photo. Opt. Inst. Eng., 27, p 111-114, Nov. 1971.
- Zuev, V.E. (1966) "Atmospheric Transparency in the Visible and the Infrared", Russian translation, U.S. Dept. of Commerce Clearinghouse, TT 69-55102, Springfield, Va. 22151

References (Appendix E)

Yentsch, C., (1960) "The Influence of Phytoplankton Pigments on the Colour of Sea Water", Deep-Sea Res., 7, P. 1-9

James H. R. Birge, E.A., (1938) "A Laboratory Study of the Absorption of Light by Lake Waters" Trans. Wisconsin Acad., 31, 11-154

References (Appendix F)

Friedman, E.J., Hickman, G.D., (1972), "Laser Induced Fluorescence in Algae - A new Technique for Remote Detection". Sparcom, Inc., 4660 Kenmore Ave., Alexandria, Va., 22304

Kildal, H., Byer, R.L., (1971), "Comparison of Laser Methods for the Remote Detection of Atmospheric Pollutants" Proc. IEEE, 59 #12, 1644-1663.

Lutz, M., Kléo, J., (1974), "Diffusion Raman de résonance de la chlorophyll d", C. R. Acad. Sc. Paris t. 279, 1413-1416

REFERENCE (Appendix G)

Payne, R.E., (1972), "Albedo of the Sea Surface", J. Atmos. Sci.,
29 # 5, 957-970

REFERENCES. (APPENDIX H)

Carder, K.L., (1970), "Particles in the Eastern Pacific Ocean: Their Distribution and Effect upon Optical Parameters".

Ph.D thesis, Oregon State Univ.

Gordon, H.R., Brown, O.B., (1972) "A Theoretical Model of Light Scattering by Sargasso Sea Particulates", Limno. Oceano., 17, 826-832.

Hodkinson, J.R., (1963), "Light Scattering and Extinction by Irregular Particles Larger than the Wavelength", P 87-100, In M. Kerker (Ed.) Electromagnetic scattering, Macmillan.

Owen, R.W., (1974), "Optically Effective Area of Particle Ensembles in the Sea", Limno. & Oceano., 19(4), 584-590.

Jerlov, N.G., (1961), "Optical Measurements in the Eastern North Atlantic", Medd. Oceanografiska Inst., Goteborg 30, 40pp.

Jerlov, N.G., (1968), "Optical Oceanography", Elsevier Oceanography Series, 194 pp.

Zaneveld, J.R.V; Par, H, (1973), "Method for the Determination of the Index of Refraction of Marine Particles Suspended in the Ocean", Mar. Biol., 7, 305-318.

REFERENCES (Appendix J)

B.G. Krishnappan, (1974), Hydraulics Division, CCIW, Burlington,
personal communication