AIRBORNE SPECTROSCOPIC VOLUME REFLECTANCE STUDY

W. Russell McNeil

Final Report
March 31, 1976
DSS Contract SS04.KL347-5-0405
for
CANADA CENTRE FOR INLAND WATERS

W. R. McNeil & Associates Inc.
Toronto

printed on 100% recycled paper
from page 45

W.R. McNeil & Associates Inc.,
was incorporated under the Business Corporations Act on
February 18, 1974.

The Objects for which the Corporation is Incorporated are:

a) *To carry on the business of environmental consultants and all related business.*

b) *To examine and monitor air, water, noise and all other possible forms of environmental pollution*

c) *To carry on the business of designing, manufacturing, constructing, processing accessories, instruments, devices, supplies, attachments and equipment for quality control of environmental pollution.*

d) *To equip, erect, and install the same for use and operation by electricity, compressed air, oil, gas or steam or by any other mechanical means and to service, repair, re-condition the same.*

e) *To undertake and engage in technical, statistical, and scientific research in all commercial, industrial, cultural and scientific fields.*

f) *To publish, print, distribute and deal in same.*

g) *To engage in the investigation and development of products, methods of manufacture and distribution.*

47 Victoria Park Ave.,
Toronto, Ontario,
M4E 3S1
(416) 699-3860

POST-CONSUMER PAPER

This report is printed on 100% post-consumer rag content paper from p45 only due to difficulties encountered in procurement of sufficient quantities of this product in time to meet our production deadline. Until everyone concerned with conservation, the depletion of our forests and the prevention of needless waste demands recycled post-consumer waste paper, papers of all kinds will continue to become more expensive and difficult to obtain.

TABLE OF CONTENTS

Acknowledgements

At York University, the author acknowledges the numerous suggestions and contributions of Dr. John Miller. We gratefully acknowledge the permission of Mr. S. C. Jain for publication of chlorophyll and scattering data presented in this report and for processing of photometer data for the five flights of this series.

The author gratefully acknowledges the assistance of CCIW project leader Mr. J. Jerome and CCRS project leader Mr. W. McColl.

For space, time, advice and guidance, the author would like to acknowledge the kind offices of Philip A. Lapp Ltd.

For his original suggestions of a number of ideas presented in this report, the author is indebted to Dr. Keith Thomson of CCRS.

For typing we appreciate the patience of Ms. Linda Mitchell and for her accurate drafting our thanks to Ms. Sally Lakdawala of York University.

GLOSSARY OF SYMBOLS

a_o	incident diffuse skylight irradiance (Equation(2))
α	wavelength dependent collimated extinction coefficient
b_o	upwelling subsurface irradiance (Equation (2))
b	scattering coefficient
β_s (β_s')	fraction of down (or up) welling irradiance (radiance) scattered into the back direction by the entire atmospheric column beneath the detector.
d	photic depth
i_o	incident collimated sunlight (Equation (2))
K_{ij}	Colour indicies
k_a,k_i	constants dependent on wavelength (Equation (2))
λ	wavelength
R_{az}(R'_{az})	apparent irradiance (radiance) ratio at sensor altitude z
R_v(R'_v)	subsurface volume reflectance (radiance ratio)
ρ	surface irradiance reflectivity (air/water)
ρ_w	surface irradiance reflectivity (water/air)
T^2	two way atmospheric attenuation
z	altitude

LIST OF ILLUSTRATIONS

Figure

LIST OF TABLES

TABLE

1.0 INTRODUCTION

This study was initiated to assess techniques and instrumentation aimed at quantitative water quality diagnostics by means of colourimetric methods. To achieve these quantitative goals we have attempted to provide a remote colourimetric method which when utilized in an operational or research mode, will provide a set of reliable and reproducible water colour data and water colour data products.

To obtain a meaningful colourimetric technique which is both interpretable in terms of water quality variables and reliably reproducible on successive trials, one simply must account for environmental factors. The most significant of these environmental factors are:

(1) Variable illumination
Conditions due to cloud, fog, haze, etc.

(2) Atmospheric backscatter
Absorption and attenuation due to fog, haze and other atmospheric aerosols.

(3) Surface reflection
Due to the air-water interface.

(4) Sun angle

To account for variations in incident illumination, the instrumentation used in this study, was designed to measure the magnitude and spectral composition of the incident radiation.

To remove or minimize the effects of atmospheric backscatter and surface reflection, we have attempted to measure their combined effects, adjust the measured values for spectral effects and subtract these adjusted values from the colourimetric data. In addition, to further minimize these interference terms, we fly at low altitude and select narrow field of view angles with our instrumentation.

To remove the effect of sun angle, we have selected and defined for measurement, parameters which have been empirically and theoretically shown to be independent of sun angle.

1.1 The York/Cress Photometer

The CCRS photometer system used in this study, is capable of simultaneously measuring,in four wavelength bands, the surface reflected radiance as well as the incident solar irradiance. The photometer provides, as its most fundamental data product, a measurement of the apparent surface reflectance (or albedo ratio) in four variable wavelength bands.

The photometer system consists of three units (i) the sensors; (ii) a control unit to manipulate the data or control the sensor functions; and (iii) an analog or digital recording system.

The radiation accepted by the optical system of each of the four photometers is received by a silicon PIN photodiode detector and measured by an electrometer. The electrometer has an automatic range-switching (variable gain) capability over a range of four orders of magnitude in the signal current. The photometer response is presented as a signal analog voltage (0 to 5.0 volts) and a range (or gain factor) represented by one of four different voltage levels. In addition each photometer unit registers the interference filter installed and the field of view (FOV) setting with a 4 bit code and a 3 bit code respectively. Thus each photometer unit provides the following information to the control unit: (i) photometer signal, (ii) range (iii) filter number, and (iv) FOV setting.

The sensor is equipped with a stepping motor that is used (i) to permit radiation from the scene to be measured by the photometer, or (ii) to simultaneously position a mirror on the optical axis of each photometer so that each photometer measures the incoming solar irradiance at the aircraft roof which is carried to the sensor by means of fibre-optic bundles. An opto-electronic detector in the sensor monitors the state of the positioning motor.

The control unit accepts data from the sensor and displays it for the use of the sensor operator. The photometer analog signal is digitized and displayed on the front panel along with the corresponding range.

The central wavelength of the interference filter for each photometer is displayed on the front panel after the control unit decodes the 4 bit code assigned to each filter and generates the appropriate wavelength digits. The photometer FOV selected is decoded and indicated on the front panel by a single digit corresponding to one of the 5 possible FOV settings.

The control unit also provides the operator with the sensor calibration control functions. The time (in seconds) the photometer spends looking down at the water-scene or up at the solar irradiance may be independently selected by means of thumb-wheel switches on the front panel. Zero and 5 volt reference voltages are also available through front panel switches to inject known signals into the data recording unit.

The control unit provides data in analog form for recording on an instrumentation tape recorder (such as CCRS's MINCOM) or a chart recorder. Nine analog outputs are provided. A signal and range output for each of the 4 photometer units and one solar calibration state monitor which indicates with a voltage level whether the photometer is (i) making scene measurements or (ii) solar input measurements or (iii) is in transit between these two states.

The control unit also provides the data in a digital from fully interfaced to CCRS's ADAS. The data supplied to ADAS in 32 bit words contains the following information for each photometer unit: signal, range, photometer number, filter wavelength, aperture setting, solar calibration state, power on or off state, and photometer automatic or manual range-switching state. (Pieau, J. and Miller.J).

1.2 Interpretation of Data

As indicated above, the 4 channel photometer system provides data as an apparent reflectance ratio $R'_{az}(\lambda)$ (or albedo ratio) at aircraft altitude $\underline{z}$, as a function of wavelength λ . The prime in $R'_{az}(\lambda)$ is used to distinguish this function from the irradiance ratio $R_{az}(\lambda)$ which represents an average value of $R'_{az}(\lambda)$ over 2 π steradian. The two are related through the relation (for a perfect diffuser)

$$R_{az}(\lambda) = \pi R'_{az}(\lambda) \qquad (1)$$

Two approaches have been utilized in the provision of data products in this report. The chlorophyll and scattering coefficient data is obtained through an optimization modeling procedure developed by Miller & Jain; the volume reflectance and photic depth (or colour index) parameters are evaluated through an empirical model presented in an earlier study (McNeil R. (1975)). Each of these models is briefly described below.

1.2.1 The Optimization Approach

The model was first introduced by Hulbert (1943) and used by Ramsey

(1968). This two stream radiation model and the solution of the resultant differential equations with surface effects is presented elsewhere (Jain & Miller (1976)). The solution is of the form

$$b_o = k_a a_o + k_i i_o \qquad (2)$$

Where b_o is the upwelling subsurface irradiance, a_o is the incident diffuse skylight irradiance at the water surface and i_o is the incident collimated sunlight. The parameters k_a and k_i are constants dependent on wavelength (i.e. on the absorption and scattering properties of water).

With this model, for a given chlorophyll concentration and scattering property of the water, it is possible to evaluate the value of b_o. But the problem to be solved is the inverse, i.e. given the value b_o, we need to find the water parameters on which its value depends. This requirement converts the problem into an n-dimensional optimization problem. The parameters for which this optimization is performed are the chlorophyll concentration and Mie scattering coefficient.

1.2.2 The Empirical Approach

The essence of the empirical model regards the apparent reflectance

$R'_{az}(\lambda)$ as a sum of contributions from surface, subsurface, and atmospheric sources.

$$R'_{az}(\lambda) = R'_v(\lambda)\{1 - \rho\}\{1 - \rho_w\}\{T(\lambda)^2\}' + \beta'_s(\lambda) + \rho'(T(\lambda)^2)' \quad (3)$$

where ρ' is the water surface radiance reflectance and $R'_v(\lambda)$ is the subsurface radiance reflectance; ρ is the surface irradiance (from sun and sky) from the water surface; ρ_w is the fraction of upwelling irradiance reflected back into the water at the water/air interface; $T'(\lambda)^2$ is the two way attenuation per unit incident irradiance due to atmospheric backscatter $\beta'_s(\lambda)$

Through correction and direct measurement and assumptions outlined in a previous report(McNeil (1975)), it is possible to arrive at a solution of equation (3) for the parameter $R'_y(\lambda)$ or $R_y(\lambda)$ called the volume reflectance (or irradiance ratio). This subsurface parameter is further used to define the sun angle invariant colour index parameters

$$K_{ij}(\lambda) = \frac{R_v(\lambda_j)}{R_v(\lambda_i)} \quad (4)$$

The photic depth parameter d presented as a further derived data product is obtained through the relation

$$d = \frac{\ln(0.1)}{a_w(\lambda_{red})\ K_{red/blue}} \tag{5}$$

where a_w is the absorption due to water at the red wavelength (either 710 nm or 750 nm for this study); and $K_{red/blue}$ is the colour index ratio

$$K_{red/blue} = \frac{R_v(\text{red})}{R_v(\text{blue})} \tag{6}$$

The blue wavelength chosen for this study is 455 nm throughout.

The photic depth parameter is intended as a general water quality indicator and will be a function both of absorption and scattering processes from all substances contained in the water body of interest. Simply defined it is the depth below which photosynthetic energy is unavailable and hence may be interpreted as the aquatic life support zone.

1.3 Conduct Of The Study

1.3.1 Terms of Reference

The contract work statement including reference to relevant sections in this report are included below:

1) specification for development of possible instrumentation hardware and data software or other instrumentation related modification that might be necessary to obtain a quantitative measure of corrected volume reflectance ratios from the 4 channel spectrometer (Appendix A).

2) in liaison with C.C.I.W. and C.C.R.S. plan and carry out flights to coincide as closely as possible with in situ measurements of hydro-optical, chemical, and biological parameters relating to the remote volume reflectance ratio measurements (Section 1.0).

3) process the data and evaluate the results (Sections 2.0 - 7.0).

4) write an operational methods manual relating to spectrometer applications aimed at quantitative remote measurements of water colour parameters in the presence of variable surface, atmospheric, and illumination conditions (Appendix B).

1.3.2 Liaison Mechanism and Flight Procedures

Acting as agent for CCIW, the contractor initially established a liaison mechanism between project leaders at CCRS and CCIW via the following set of recommended procedures which were drawn up after discussion with responsible parties at each agency:

1.0 General Flight Procedures:

1.1 Data Records: To minimize cost it is recommended that photographic data be obtained for a total of no more than 5 sensor line miles along any flight line. The 5 photographic line miles will be the first two, middle, and last two along any flight line. IR data should be collected along the entire flight line along with the photometer data. It is also recommended that in addition to the data record from ADAS and/or MINCOM, that an analog multi-channel recorder record be obtained of all relevant photometer and IR data. This data will be invaluable in rapid assessments of data for planning of subsequent flights. If a suitable multichannel recorder is not available from CCRS, CCIW or York University have indicated that they may be able to provide one.

1.2 Flight Line Definition: All flight lines are listed below. Each flight will be along a straight line segment defined by the relevant ship station coordinates. It is recommended that each line segment commence one mile inshore and terminate one mile inshore.

1.3 Flight Procedure: It is recommended that each flight line be flown twice (as flight lines will average 50 sensor line miles, each flight will total an average of 100 line miles). The recommended procedure will be to fly the first one third line at an altitude of 900m, the middle third of the line at 600m, and the final third of the line at 300m. Returning along the reverse direction, the same procedure will be followed (i.e., 900 m, 600 m, 300 m).

2.0 Flight Dates: A total of six flights are recommended. The actual flight date will be on one day of a three day window selected to match the nearest satellite overpass during the six CCIW cruise dates. The cruise dates and Flight windows are summarized below:

Lake	CCIW Surveillance Cruise	CCRS Overflight
Ontario	June 2-7	June 4,5 or 6
Erie	June 9-14	June 9,10 or 11
Ontario	August 11-16	August 13,14 or 15
Erie	August 25-30	August 25,26 or 27
Erie	October 6-11	October 8,9 or 10
Ontario	October 14-19	October 15,16 or 17

2.1 Flight data criteria: Within any of the three day flight windows, the flight should be flown within three hours of solar noon on either of the first two flight dates if the cloud criteria submitted by Jerome in the original flight request occur. In any case, it is recommended that the line be flown on the third day of the three day window regardless of cloud cover and within three hours of solar noon.

2.2. Flight Personnel: It is recommended that one person familiar with the project be permitted to accompany the aircraft for purposes of maintaining the chart recorder data record and in-flight consultation.

3.0 Flight Lines: We have selected a total of 12 lines (6 per lake). It is recommended that the line closest to ship location at the time of overflight be actually flown. The coordination of this aspect of each flight will originate from CCIW by providing CCRS with ship coordinates at the time of overflight. Further aspects of these logistics will be arranged. The actual lines are summarized (from East to West) below.

4.0 MINCOM Track Record: Tentative arrangements call for allotment of the 14 tracks as follows: Photometer (9) Interferometer (2); PRT-5 (1); Time Code (1); Blank (1)

5.0 I have arranged to make contact with CCIW and CCRS on the morning of each possible overflight. If an affirmative decision to fly is made at that time, CCIW will supply ship estimated coordinates for noon of that day. CCIW will then inform the ship of the flight line which will be flown (see additional samples below). For the June flight, it has been decided to drop lines 002, 004 and 005 as candidates for an overflight. The aircraft (unless other arrangements require) will pick up John Miller, Russ McNeil, and Bill Gault at Toronto International before proceeding to overfly the selected line near solar noon.

6.0 Additional Sampling: Ship sampling of 1 metre chlorophyll, and integrated chlorophyll and suspended load, as well as one meter (or surface) water sample (1 litre) for preservation by freezing will be collected at stations: #12, #8, #9, #43, #42, #41, #82, #9, #81. An additional three or four samples will be obtained along the flight

Line	North Coordinate		South Coordinate		Lake	Miles
	Lat N (Stn. #)	Long W	Lat N (Stn. #)	Long W		
001	44 08 11 (090)	76 49 30	43 38 00 (073)	76 17 18	Ontario	50
002	43 50 42 (062	77 04 24	43 28 36 (071)	76 31 36	Ontario	39.5
003	43 57 00 (043)	78 03 00	43 23 00 (038)	77 59 24	Ontario	40
004	43 49 48 (029)	78 52 12	43 21 36 (035)	78 43 48	Ontario	40
005	43 45 00 (085)	79 05 00	43 17 48 (022)	79 00 18	Ontario	40
006	43 37 24 (008)	79 23 42	43 18 00 (021)	79 07 12	Ontario	33
007	42 49 30 (101)	79 34 36	42 30 48 (006)	79 20 48	Erie	27
008	42 45 06 (095)	80 01 42	42 17 18 (014)	79 44 48	Erie	41
009	42 33 30 (082)	81 30 00	41 52 00 (027)	81 00 00	Erie	60
010	42 14 00 (075)	81 55 00	41 46 24 (028)	81 16 06	Erie	50
011	42 08 06 (073)	82 18 12	41 31 48 (035)	81 42 30	Erie	60
012	41 53 36 (060)	83 16 24	41 30 54 (044)	82 10 00	Erie	65

TABLE I 1975 CCIW Volume Reflectance Flight Line Plans line actually flown. These will be #75, #74, #89, #73, if line 001 is flown; #38, #39, #40, if line 003 is flown, and #21, #20, #19 if line 006 is flown. If no line has been flown before the ship has reached station #22, additional samples will be obtained in any case at stations #21, #20, #19.

7.0 Bob O'Neil of CCRS has kindly allowed us to use a 13 channel Honeywell chart recorder for the June flights.

8.0 John Miller has advised us of the importance of maintaining a consistant experimental in-flight procedure for the duration of a given line. The recommended procedure is as follows: The pilot should inform the photometer operator one minute to sensors on. The photometer operator should operate the manual 5V calibration switch for 30 seconds; the operator should then operate the 0V calibration switch until he hears 'sensors on' (which should be near to 30 seconds). At 'Sensors Off', the operator should depress the 5V calibration for 30 seconds followed by a 30 second interval with the 0V switch depressed.

9.0 Calibration: For purposes of data analysis, a single calibration record of direct to total downwelling irradiance should be obtained on the runway. This involves a partial blocking of the downwelling irradiance port cut in the aircraft. Further aspects of this procedure will be investigated.

The contractor accompanied CCRS project leaders on 4 of the 5 flight dates eventually flown (See Section 5.0). During the last flight of the series, flown October 14th, the contractor was on board the CCIW research vessel "Northern Seal" conducting and observing hydro-optical measurements related to each of the overflights.

1.3.3 Data Processing

Data processing proceeded along two principle routes. In the first case, analog chart recorder data retained by the contractor was a)

b)

Figure (1.1) a) CCIW Research vessel Northern Seal at Cobourg during Lake Ontario Surveillance cruise (Oct 16, 1975).
b) CCRS Aircraft DC-3 (Dakota) C-GRSB at Innotech (Toronto) after Lake Ontario overflight (Aug 14, 1975).

manually reduced, annotated and analysed via in house programmable calculator (HP-65) software developed for this purpose. This data was utilized to assist in selection of optimum wavelengths for subsequent flights and to provide data to York University for application of their 'optimization' routines for chlorophyll and scattering coefficient. In the second data processing route, digital data types were developed and produced from the MINCOM track record by CCRS in 7 and 9 track formats suitable for processing on computing facilities at both York University (IBM) and CCIW (CDC). The final data product set presented in Section 5.0 is that processed through York University facilities.

Photographs of the CCRS and CCIW equipment utilized during the study are illustrated in Figure (1.0).

2.0 DATA EXHIBIT

The set of data presented in Figures (2.1 - 2.5) illustrates the principle of measurement for all airborne data collected during this study. The data presented for this example was collected along Lake Erie flight line (008) on October 6th 1975 (See Table I) at an altitude of 610 m (2000'). The resultant data plots were obtained through manual reduction of the analog record obtained during the flight.

This manual reduction of data yields both the up and downwelling irradiance spectra at the four photometer wavelengths 445 nm, 525 nm, 710 nm and 960 nm along the 65 km flight line track.

The derived parameters i.e. albedo ratio, volume reflectance and colour indices in Figures (2.3 - 2.5) are obtained from the software analysis.

This set of data represents a spatial resolution of about 1 km, considerably less than the digitally analysed products presented in Section 5.0. In fact it is interesting to compare the additional structural features revealed along the same line in data analysed digitally (Section 5.0).

The variation in both intensity and spectral composition of incident radiation from both sun and sky is apparent in Figure (2.1) while an

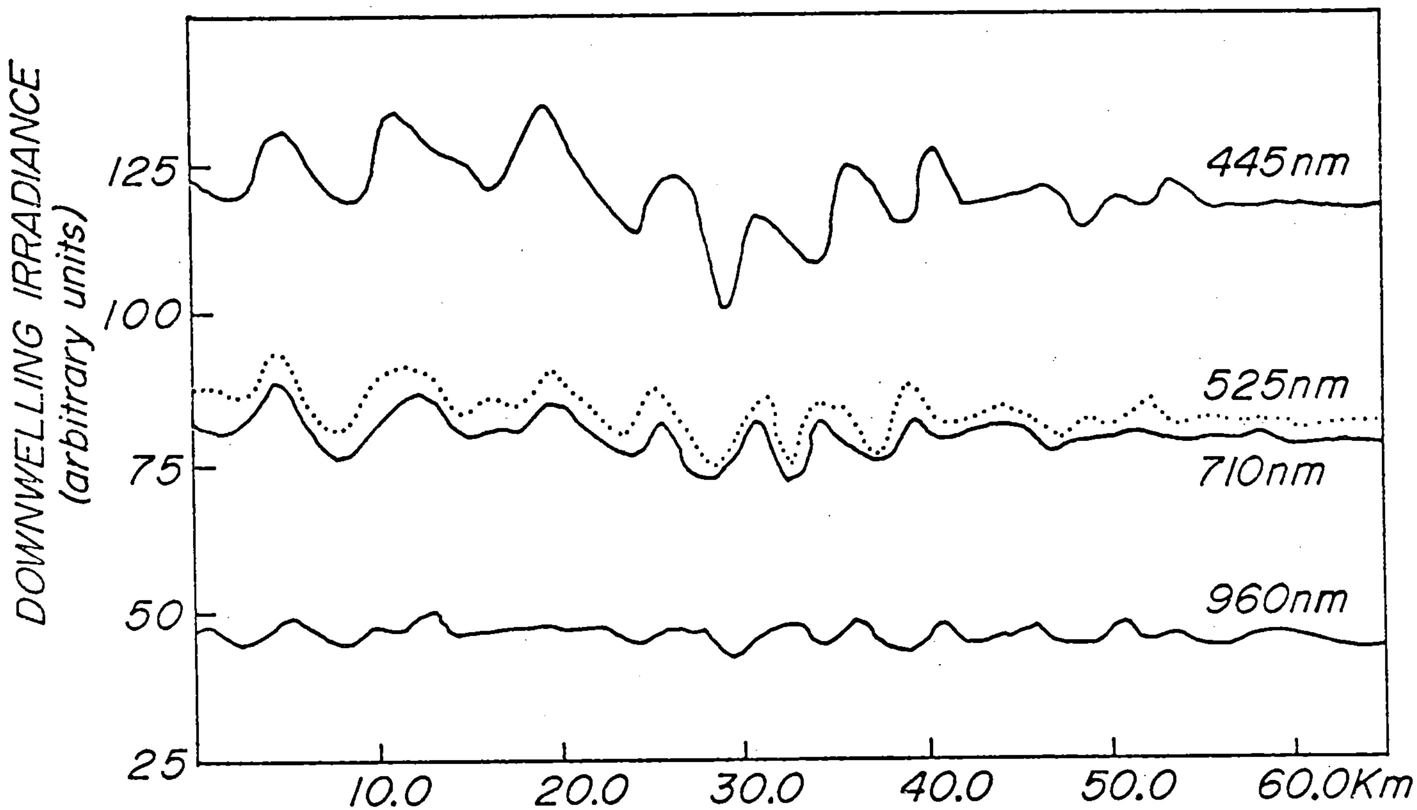

Figure (2.1) Downwelling irradiance along line (008) at 610 m in all four photometer channels (Oct 6, 1975).

undulating wavepattern with half wavelength of the order 5 km is apparent in all four photometer channels, the effect is more noted at shorter wavelengths. The effect might suggest the presence of high level thinly layered clouds. The overall phenomena presents itself as a variation in the mean value of the incident global radiation at aircraft altitude of 10 - 15%. An analysis of data from other flights under completely cloud free conditions has shown mean value variations of this parameter of less than 5% along the flight line.

As a consequence of this 10 - 15% variation in the incident radiation, it would not be possible to infer real structural variations in upwelling radiance patterns (Figure 2.2) of more than 10 - 15% without further data smoothing. Both to improve upon this measurement accuracy and to obtain a physically more reproducible parameter, the upwelling radiance has been normalized to the incident radiation in the derivation of the albedo ratio shown in Figure (2.3). This albedo ratio contains information on atmospheric, surface, and subsurface properties (see introductory comments) which should be limited in relative reproducibility to 10% (sum of the respective 5% errors in the two parameters measured and an estimated 5% error in the determination of system calibration constants is taken into account).

The derived parameters in Figures (2.4) and (2.5) were defined earlier (Introduction). Both of the quantities displayed are defined as

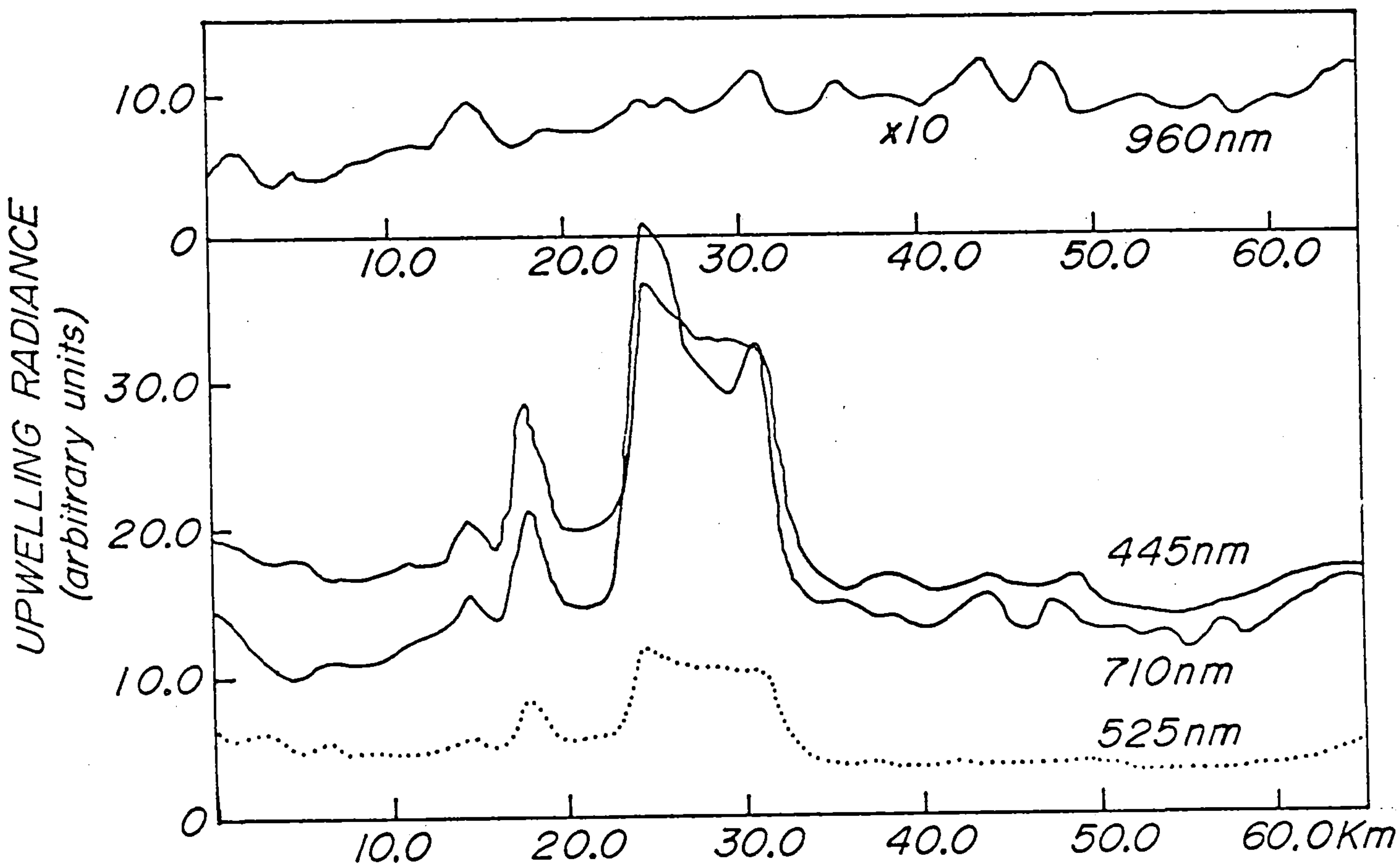

Figure (2.2) Upwelling radiance along line (008) at 610 m in all four photometer channels (Oct 6/1975).

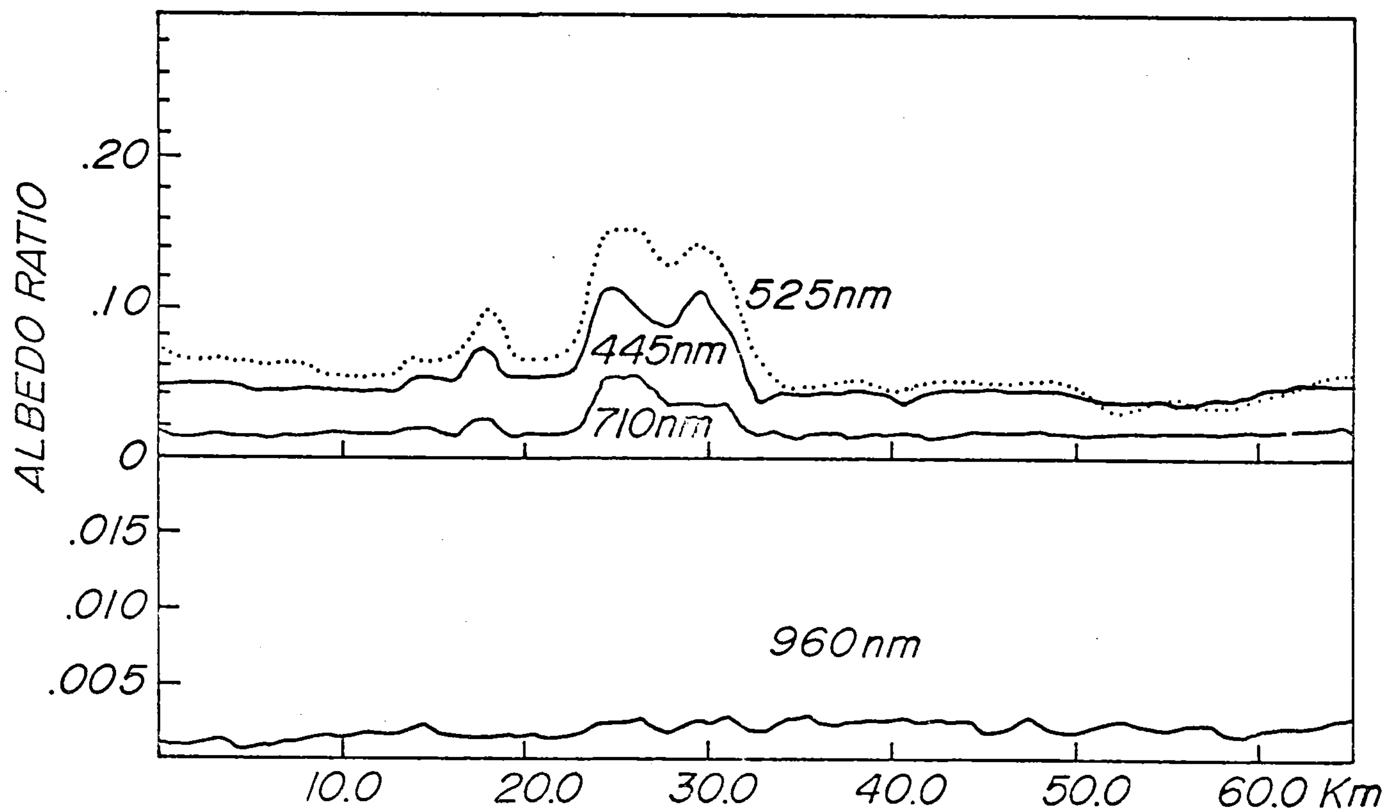

Figure (2.3) Albedo ratio (apparent reflectivity) along line (008) in all four photometer channels (Oct 6, 1975).

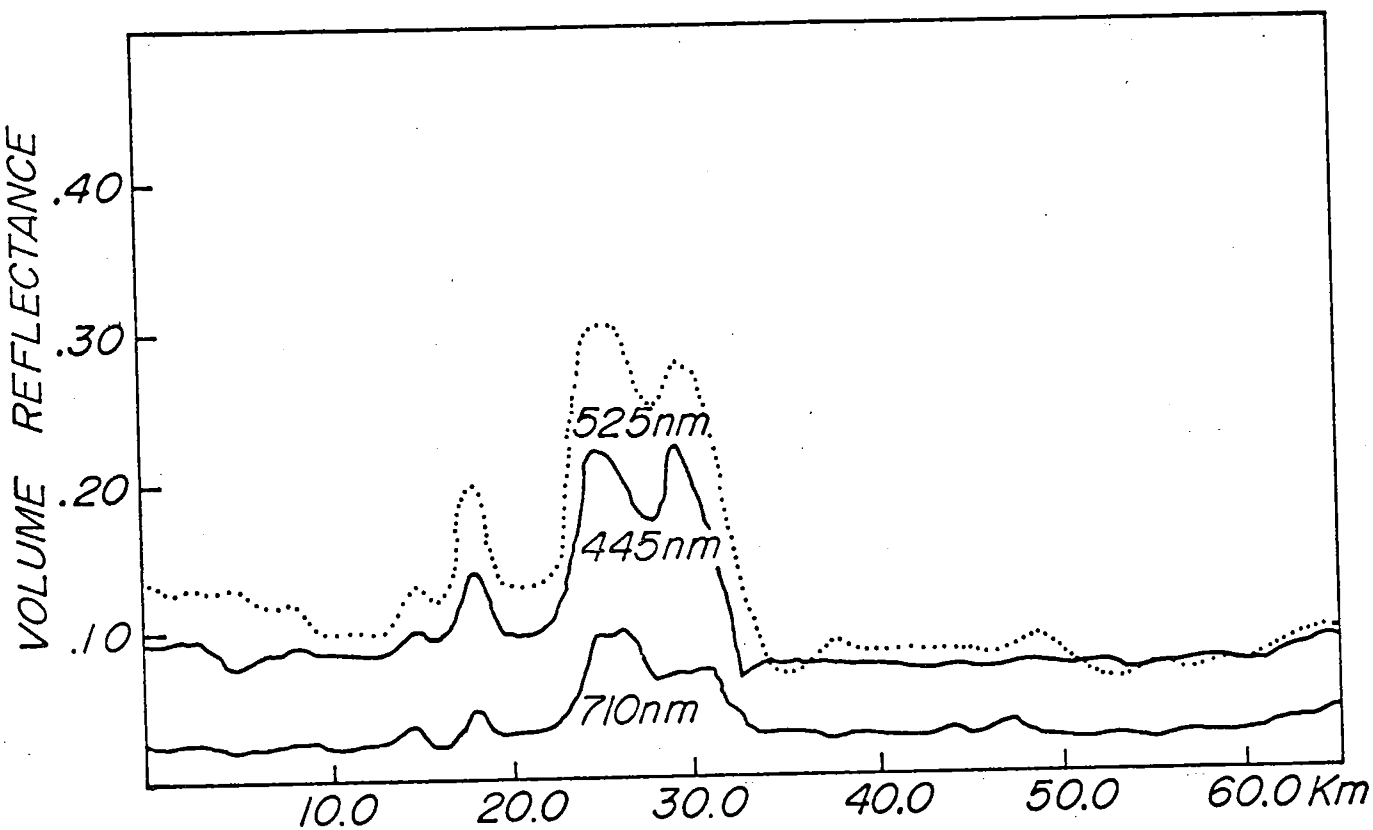

Figure (2.4) Volume Reflectance along line (008) (Oct 6, 1975).

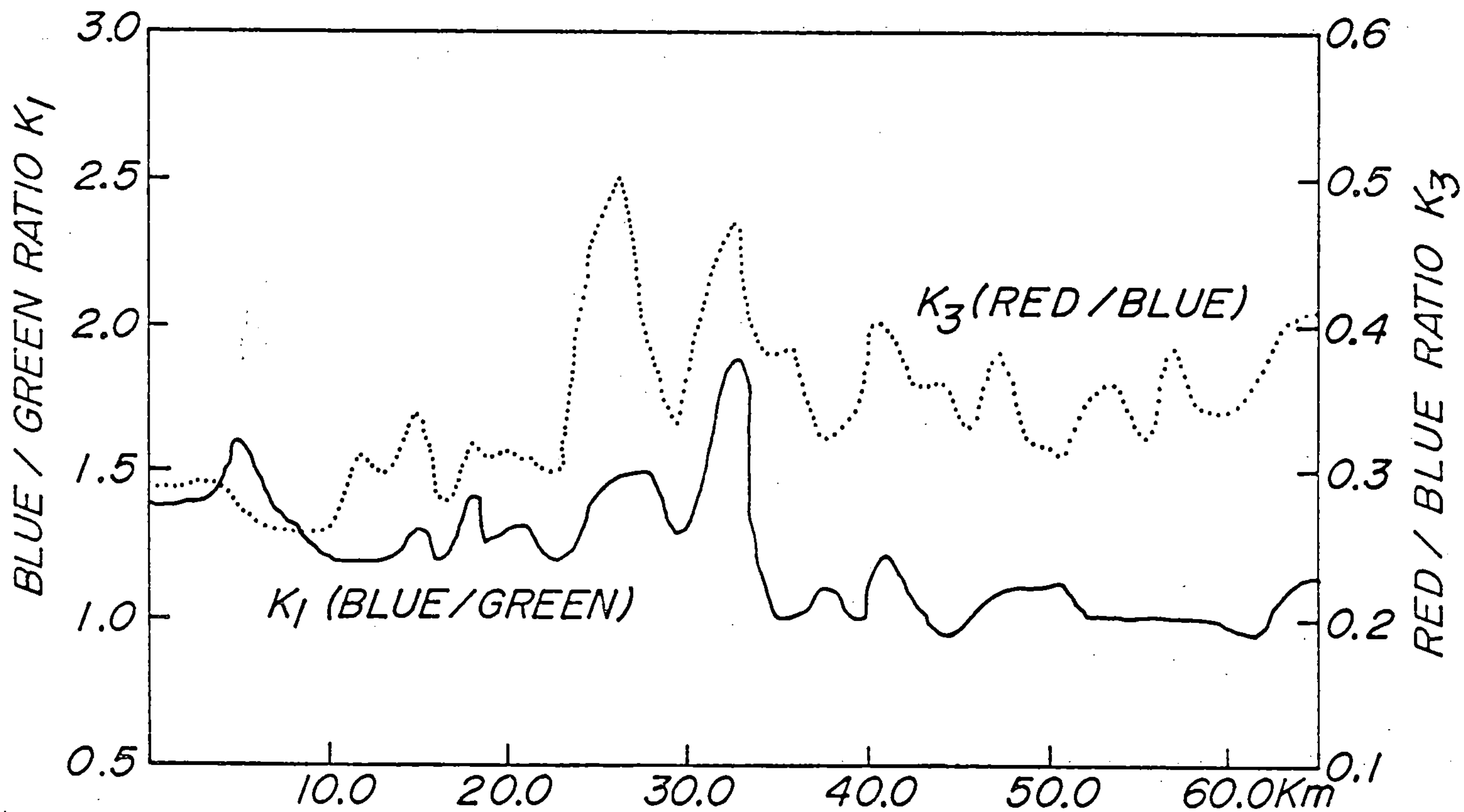

Figure (2.5) Colour indicies K_1 and K_3 obtained along line (008) at 610 m (Oct 6, 1975).

ratios of two albedos. Consequently, the accuracy of determination of the derived parameters will be expected to be of the order of 20% to 30%.

According to our simple modeling, the volume reflectance and related parameters (i.e. colour indices), and their derivatives, photic depth, etc. are unique functions of absorption and scattering properties of water or at least may be so related in a meaningful way. The Blue/Red index K_3 for example has been found to correlate substantially with shipborne chlorophyll a measurements (McNeil (1976)). Consequently, one might expect higher chlorophyll a concentrations on the South side of the lake as expressed by higher mean values for K_3 in Figure (2.5) with several subtantial maxima in the long point plume region which lies between 20 to 40 km.

The Blue/Green index K_1 appears to be related inversely to K_3 with somewhat lower values on the South side of the lake. The index K_1 is not however expected to be a strong indicator of biomass variations.

3.0 FLIGHT LINE REPRODUCIBILITY

Reproducibility of data obtained by techniques described in the previous section is illustrated for repeated flight line coverages on two occasions in Figures (3.1) and (3.2). Figure (3.1) is a superposition of the albedo ratios R'_{az} at the green wavelength 525 nm as obtained from three consecutive overflights along Lake Ontario flight line 006 (See Table I) on October 14th 1975. The lines, labeled L1, L2 and L3 in the figure were repeated in order at an altitude of 305 m from South to North (line 1),North to South (line 2), and South to North (line 3).

The structural similarities of these data is evident upon careful inspection. The two lines flown in the same direction L1 and L3 differ only in magnitude and displacement from one another along track. A study on the variation of the small scale structural features suggests a relative precision of measurement for these features of at least 10% and would appear to confirm the error estimates indicated in the discussions in the previous section. This observation might find direct application in the construction of two dimentional plots of colour, a natural extention of any one dimensional technique.

In the macroscale, the magnitude of R'_{az} from flight line to flight line varies over a range of from 15% to near 35% from mid lake to near shore regions. As much of this observed variation will be due to flight line displacement (limited to precision of aircraft navigation) - an effect which will have its greatest apparent effect upon the

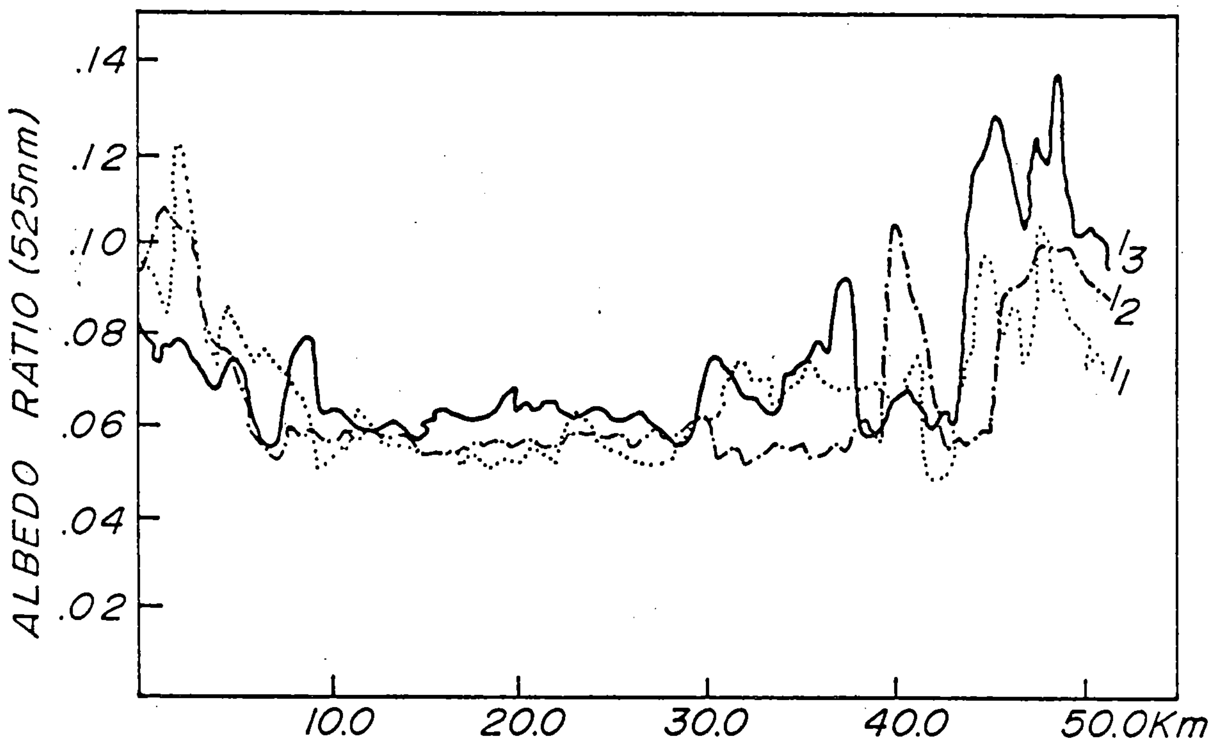

Figure (3.1) Superposition of three consecutive measurements of the albedo ratio at 525 nm obtained along flight line (006) (Oct 14, 1975), at 305 m.

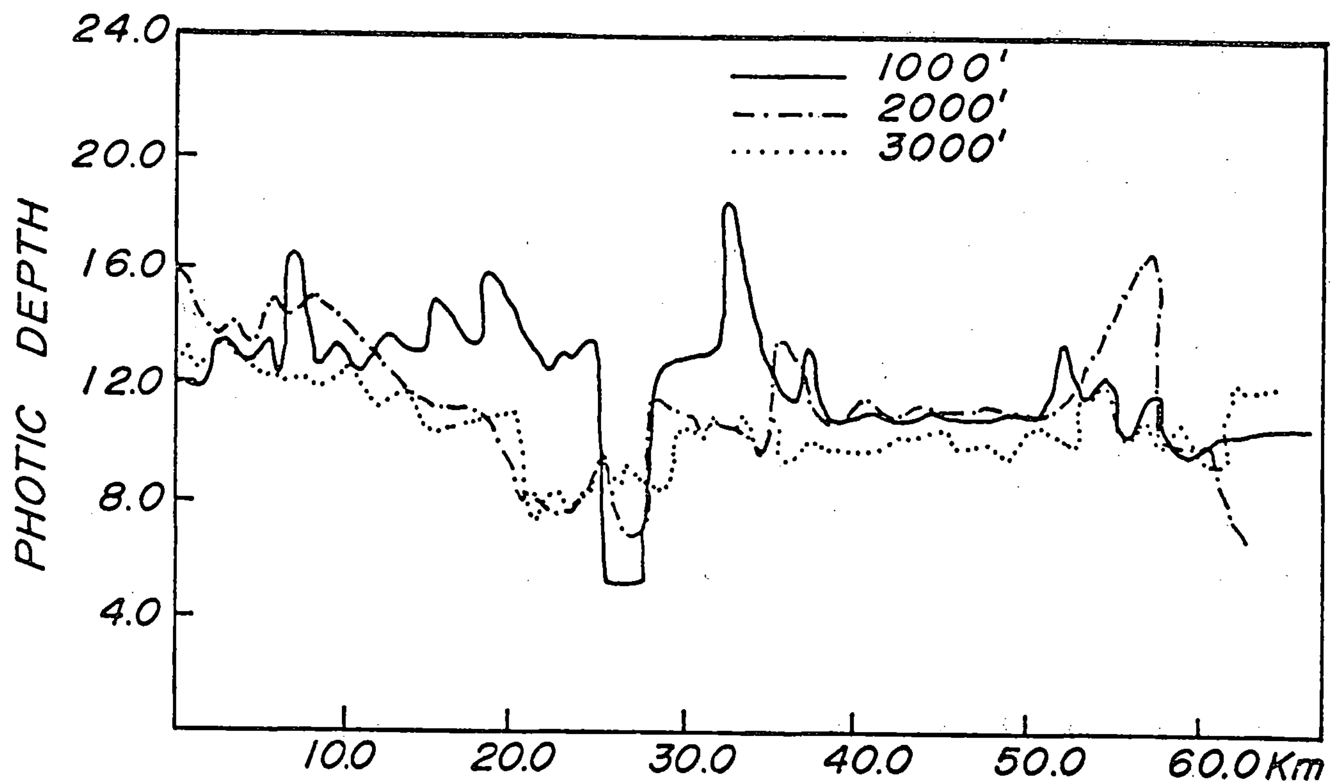

Figure (3.2) Superposition of three successive determinations of the photic depth parameter d, obtained along Lake Erie flight line 008 at three altitudes (Oct 6, 1975).

albedo in the near shore regions, the observed mid lake variations of the order of 15% should be a more characteristic experimental measure for the upper limit for flight line reproducibility.

The albedo derived parameters(i.e. photic depth, colour indices etc.), should then be reproducible to better than 30% relative.

Figure (3.2) is a display of photic depth transits of Lake Erie on October 6th 1975 at three different altitudes as labeled. The experimental variation of this parameter even under these varying altitudes ranges in the figure over a range from 20% in regions showing little optical variability to near 50% within the long point plume - an optical feature with small scale spatial and temporal variability.

Thus is would appear that derived parameters such as photic depth are measureable within a determinable accuracy of at least 30%. The absolute magnitude of precision of the derived parameters would be subject to a further inclusion of calibration errors of 10 - 15%.

4.0 CORRECTIVE PROCEDURES

Corrective adjustments to data obtained under less than ideal remote sensing conditions,which are intended to allow for passive variations in the magnitude and spectral distribution of global radiation from both sun and sky,might extend the range of operating conditions under which optical remote sensing missions may be flown.

The two extraneous phenomena most susceptible to distortion of quantitative optical data are atmospheric backscatter and surface reflection. The combined effects of these phenomena are discussed in the single example illustrated in Figures (4.1 - 4.5).

This data was obtained under varying conditions of surface illumination at two different altitudes (305 m and 915 m) over flight line 001 (Table I)

The best data, that obtained at 305 m is contrasted with data obtained along the same flight line at 915 m. In Figure (4.1), the albedo ratio R'_{az} at 960 nm, is displayed along with the incident downwelling irradiance I_d (in arbitrary units) for both flight lines.

From 20 to 45 km the quantity I_d remains fairly constant for both lines. After about 47 km there is a marked reduction in I_d of about 50% for the higher altitude data. This is due to a cloud layer which had moved into the flight region and extended to the

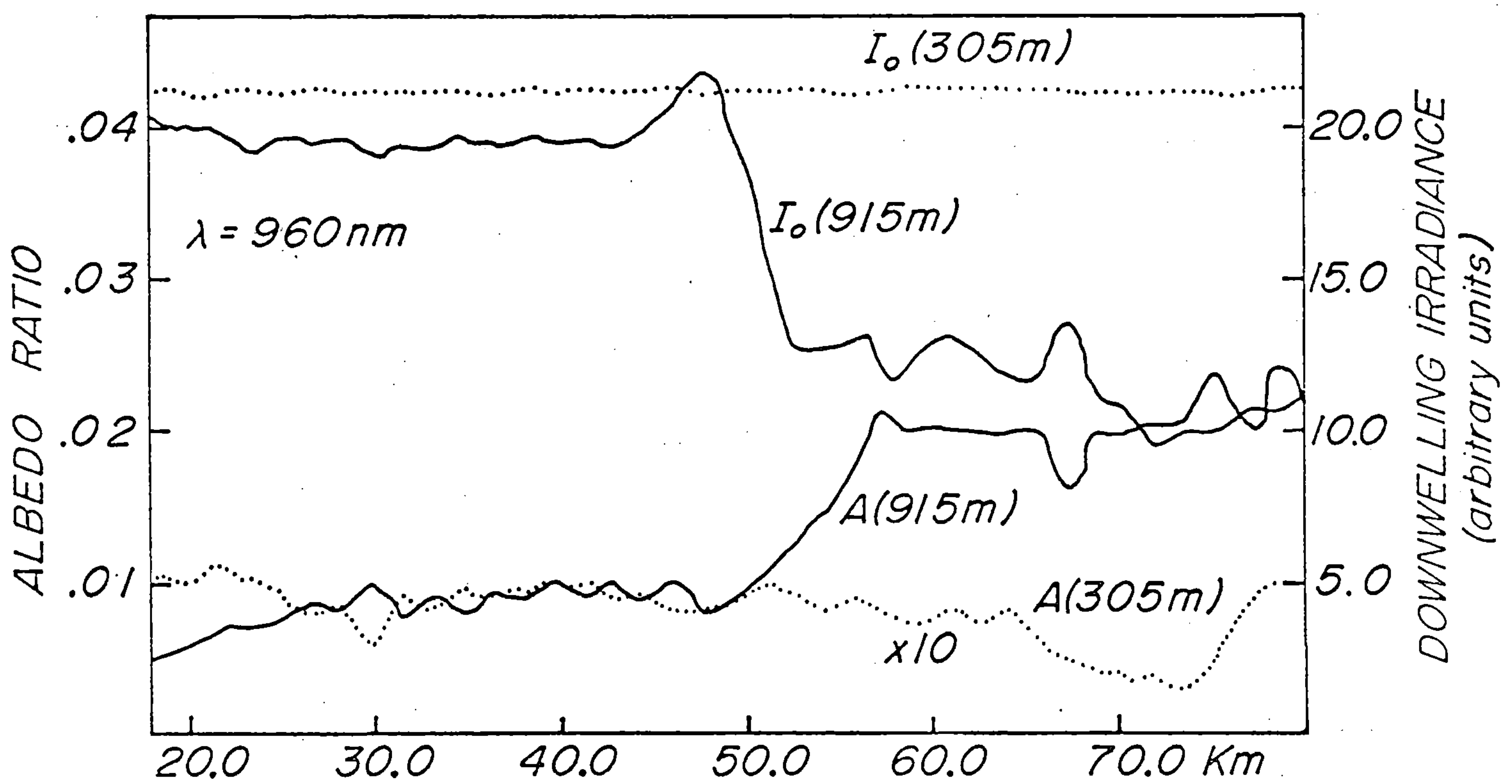

Figure (4.1) Albedo ratio and down-welling irradiance (both at 960 nm) obtained from two consecutive overflights along Lake Ontario flight line (001) at two altitudes (305 m and 915 m) (June 4, 1975).

South shore (80 km). The most obvious effect upon albedo induced by this reduction in I_d is an increase of nearly 100% (i.e. from .01-.02) over the cloud covered region of the line. This is expected and due to the removal of much of the direct sunlight component in the global radiation from the incident irradiance mix. As the albedo parameters obtained at other wavelengths are expected to be a mix of both surface and subsurface terms, this increase in the predominately surface term (960 nm) will distort the albedo values at other wavelengths.

The second notable feature displayed in the albedo ratio at 960 nm at 915 m is in the albedo signal magnitude which is nearly a factor of ten larger than the comparable values obtained at 305 m (Note expanded scale for albedo at 305 nm). This observed effect is no doubt due to atmospheric backscatter.

The application of the corrective approximation for the derived parameter R_y at both 560 nm and 445 nm is shown in Figures (4.2 - 4.5).

For the cloud free part of the line, the albedo is seen to lie about 15% and 25% larger for the higher altitude data at 560 nm and 445 nm respectively (Figure (4.2) and (4.4)). The volume reflectance is obtained from the albedo ratio through the following algorithm

$$R_v(\lambda) = \frac{\pi}{(1 - \rho_w)}\{R'_{az}(\lambda) - (\beta'_s(960\ \text{nm}) + \rho'(960\ \text{nm}))\} \qquad (7)$$

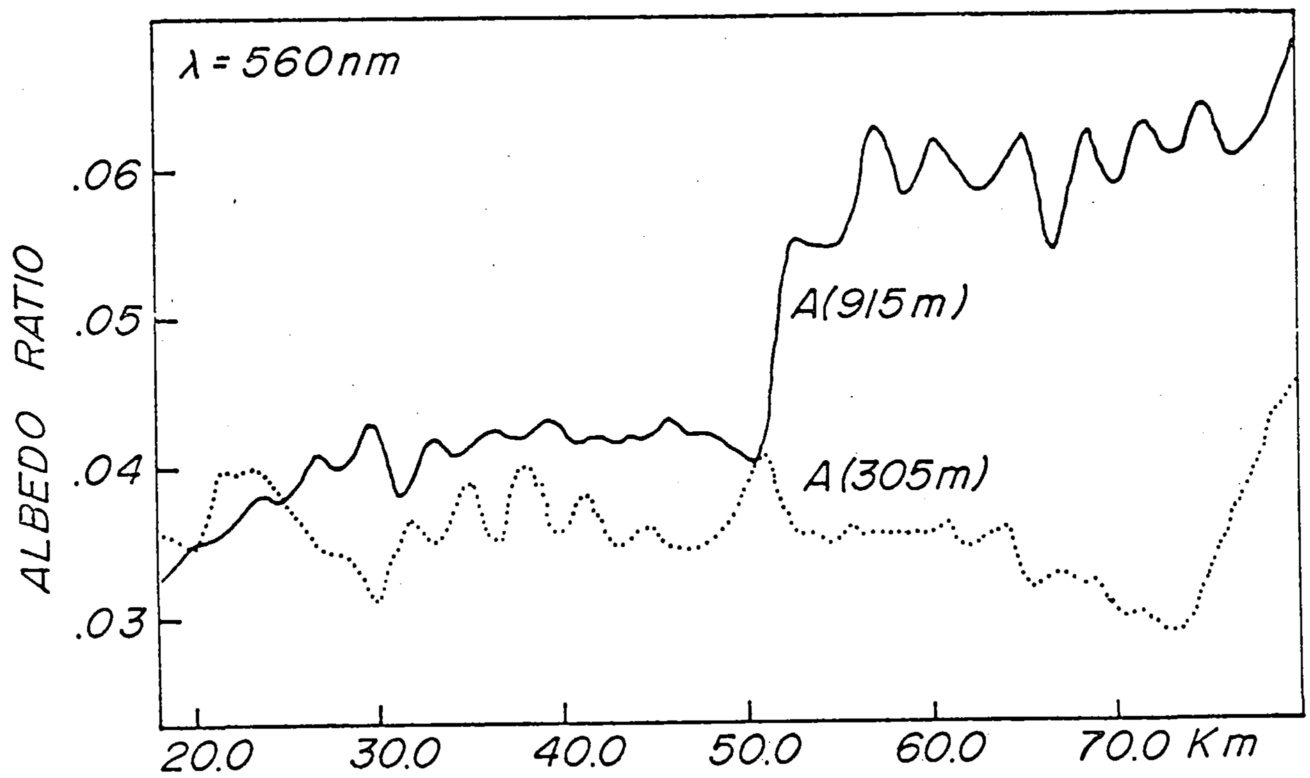

Figure (4.2) Albedo ratio (560 nm) at 305 m and 915 m before 'correction' (Lake Ontario line 001; June 4, 1975).

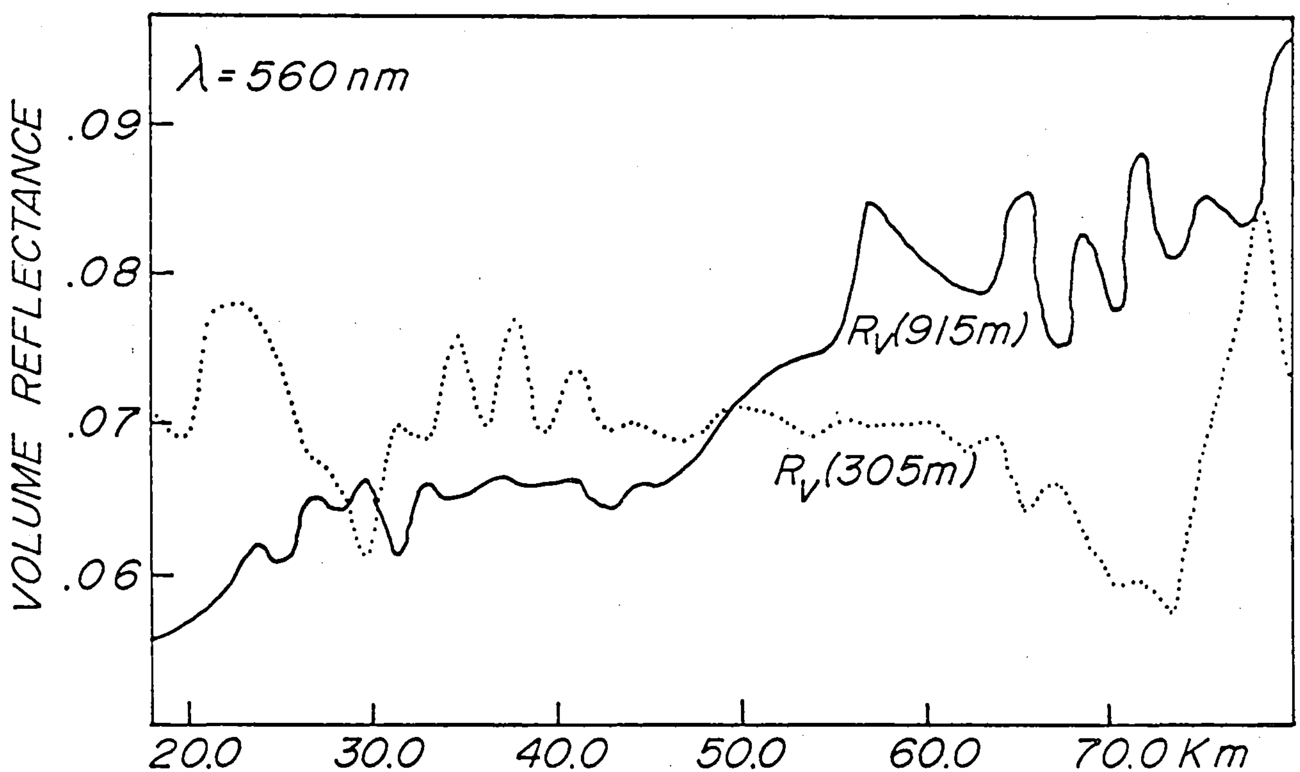

Figure (4.3) Volume reflectance (corrected albedo ratio) at 305 m and 915 m (Lake Ontario line 001; 560 nm; June 4, 1975).

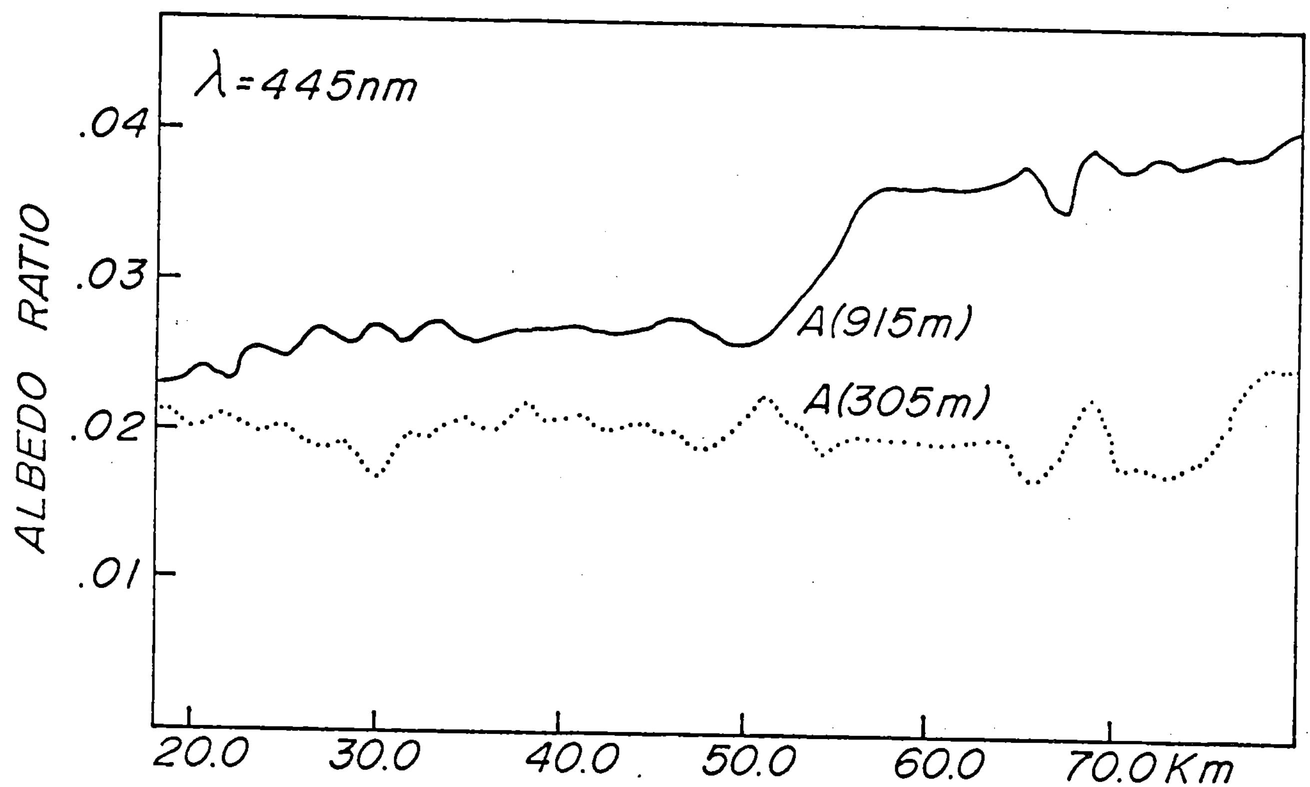

Figure (4.4) Albedo ratio (445 nm) at 305 m and 915 m before 'correction' (Lake Ontario line 001; June 4, 1975).

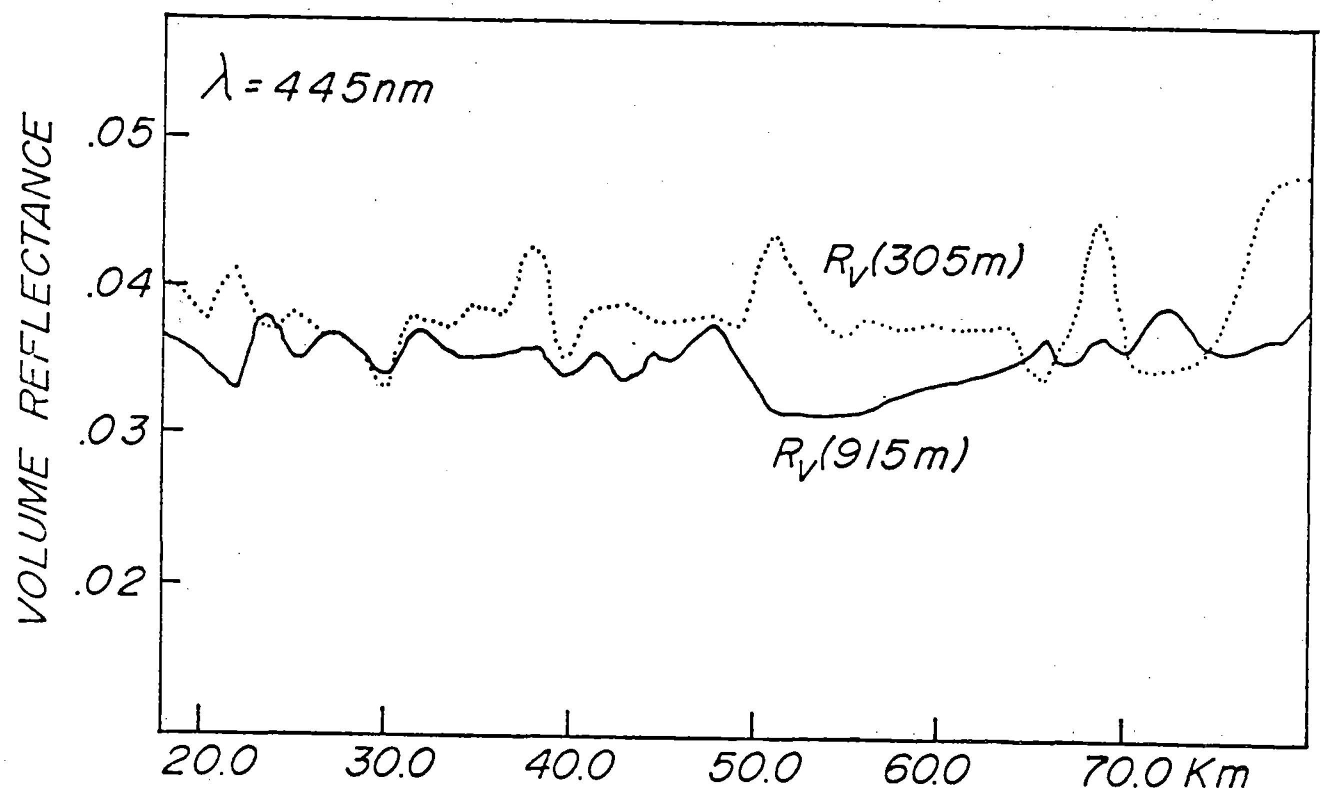

Figure (4.5) Volume reflectance (corrected albedo ratio) at 305 m and 915 m (Lake Ontario line 001; 445 nm; June 4,1975).

where ρ_W is taken as 48% (McNeil, 1975); T^2 and $(1-\rho)$ are approximated as unity; R_V'(960 nm) will be zero (see Equation (3)) under arguments outlined in the previous report.

The application of the above correction in obtaining the data in Figures (4.3) & (4.5) does not significantly affect the cloud free regions (already determined to within experimental error); however, the 445 nm data (Figure (4.5)) appears to be somewhat more precise so that the 'corrected' approach appears to be effective within experimental tolerance.

Over the cloud covered portion of the line (47-30 km), the corrected data in Figures (4.3) & (4.5) appears to be limited in its success at 560 nm in reducing the albedo differences between the two lines from about 100 % to near 35 % (Figure (4.3)). The precision of correction at 445 nm (Figure (4.5)) does however appear to fall within experimental tolerance for the entire line.

5.0 DATA PRODUCTS

In this section, we present, for the five flight dates of this series, the derived data products which we feel best represent the optimum interpretive approach for these techniques. Each of the five data sets contained in Figures (5.4 - 5.8) contains an analysis of the albedo ratio (in a), the volume reflectance (in b), chlorophyll a concentration (in c), scattering coefficient (in d) and photic depth (in e).

The actual flight lines flown, two on each of Lakes Erie and Ontario, are illustrated, along with the location of the pertinant CCIW monitor stations in Figures (5.1) and (5.2). All relevant information relating to each of the five flight dates is summarized in Table II.

Imagery from Landsat II , obtained on June 2nd corresponding to the June 4th line (U01)is displayed in Figure (5.3) along with imagery from part of the Toronto to Niagara line (006),which was flown both on August 14th and again on October 14th.

All imagery from the nearest Landsat overpasses for the other flight dates was of insufficient image quality for reproduction.

Ground based correlational data obtained from CCIW vessels have been plotted in Figures (5.4) - (5.8). These data include surface chlorophyll

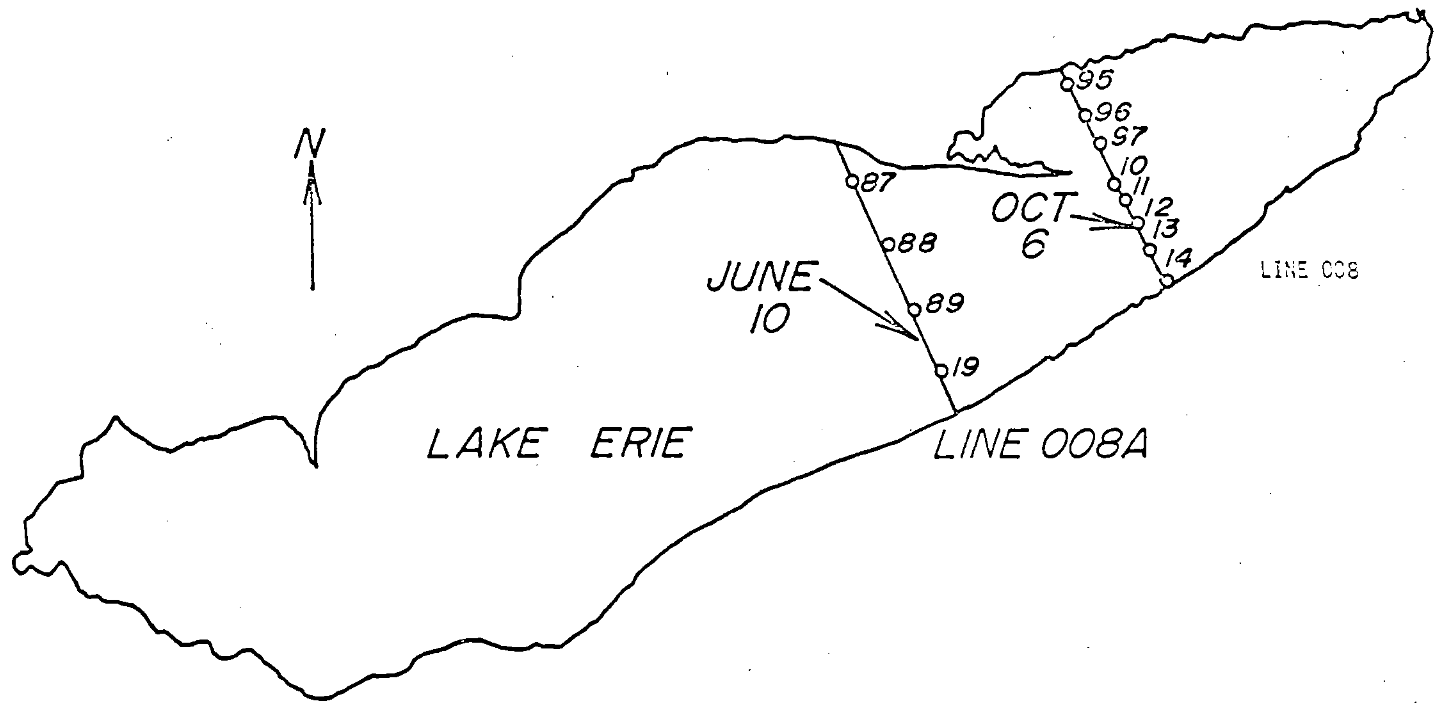

Figure (5.1) Lake Erie flight lines flown during 1975 Volume Reflectance series

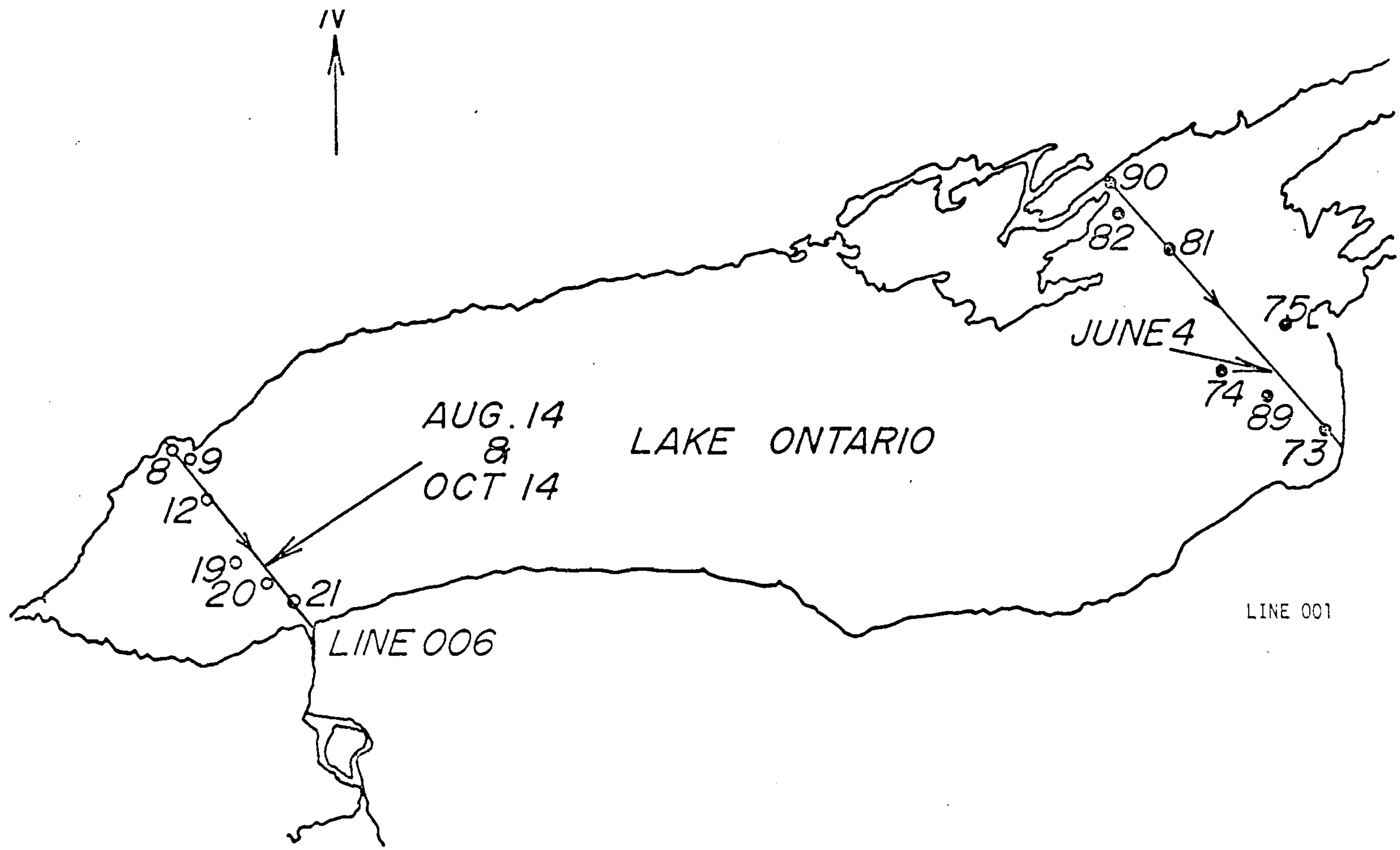

Figure (5.2) Lake Ontario flight lines flown during 1975 Volume Reflectance series.

Flight Date	June 4/75	June 10/75	Aug 14/75	Oct 6/75	Oct 14/75
Lake & line	Ont (001)	Erie (008A)	Ont (006)	Erie (008)	Ont (006)
Direction	S-N	S-N	N-S	S-N	S-N
Data Record	MINCOM	MINCOM	MINCOM	MINCOM	MINCOM
Digitization	HP-65	HP-65	HP-65	CCRS	CCRS
Length (km)	80.3	79.5	51.7	65.2	51.7
Start (GMT)	$16^{0}29'40''$	$15^{0}20'25''$	$16^{0}24'21''$	$19^{0}18'27''$	$18^{0}13'00''$
End (GMT)	$16^{0}56'00''$	$15^{0}38'15''$	$16^{0}35'00''$	$19^{0}35'27''$	$18^{0}25'50''$
Duration	28'20"	17'50"	10'39"	17'00"	12'50"
Altitude (m)	305	305	915	305	305
Filter (chl)	445 nm	445 nm	445 nm	445 nm	445 nm
" 2	587 nm	560 nm	525 nm	525 nm	525 nm
" 3	750 nm	750 nm	750 nm	710 nm	710 nm
" 4	960 nm	960 nm	960 nm	960 nm	960 nm
CCIW cruise	75-22-005	75-22-104	75-22-101	75-22-110	75-22-014
Monitor Stn	090(June 4)	087(June 11)	008(Aug 13)	095(Oct 7)	008(Oct 16)
"	082(June 4)	088(June 10)	009(Aug 13)	096(Oct 7)	009(Oct 16)
"	081(June 4)	089(na)	012(Aug 12)	097(Oct 7)	012(Oct 16)
"	074(June 4)	019(na)	019(Aug 16)	010(Oct 11)	019(Oct 15)
"	075(June 4)	-	020(Aug 16)	011(Oct 11)	020(Oct 20)
"	089(June 4)	-	021(Aug 16)	012(Oct 11)	021(Oct 20)
"	073(June 4)	-	-	013(Oct 11)	-
"	-	-	-	014(Oct 11)	-
Atmosphere	Part Cloud	haze	clear	clear	clear
Analysis	HP-65,IBM	HP-65,IBM	HP-65,IBM	HP-65,IBM,CDC	IBM
Other Sensor	PRT-5	PRT-5	PRT-5	-	OMA
	Photography	Photography	Interferometer		
Client	CCIW	CCIW	CCIW	CCIW	CCRS
CCRS Tape	0837	0839	-	0250	0251
Landsat Ref	20131-15120	20133-15235	20223-15225	20259-15223	20259-15223
" Date	June 2/75	June 4/75	Sept 2/75	Oct 8/75	Oct 8/75

TABLE II 1975 CCIW Volume Reflectance series overflight data Summary

a)
b)
c)

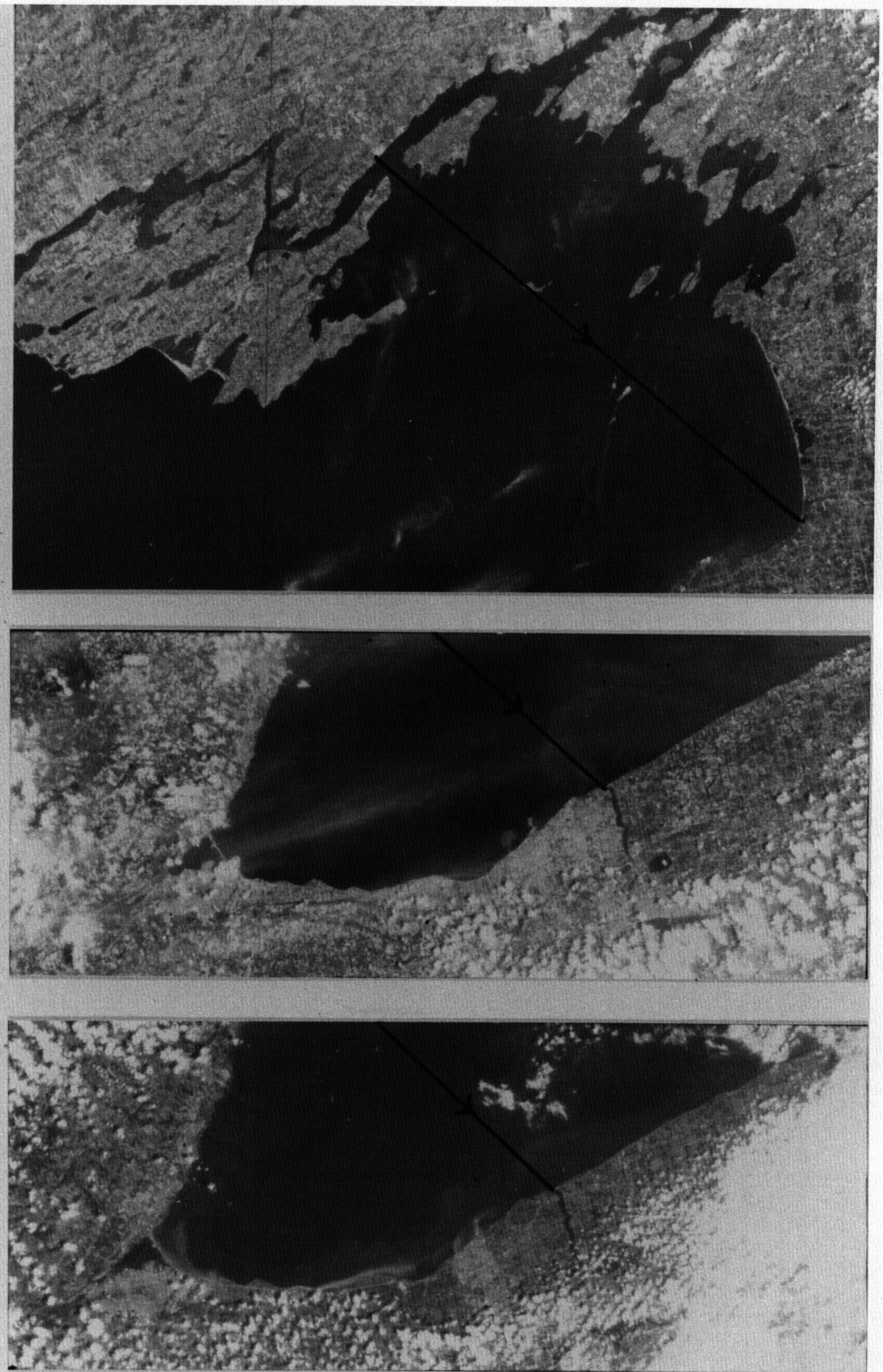

Figure (5.3) Landsat imagery from: a) line 001 (June 2,1975) b) part of line 006 (June 4,1975) c) Part of line 006 (Sept 2,1975) a and temperature data in Figures c); α coefficients derived from surface transmittance values in d), and the parameter $1/\alpha$ in e). The lake wide mean chlorophyll values, Secchi depths and transmittances have also been listed for reference in Figures c) and e).

In general, the value of these correlational data will be influenced both by sampling date and parameter equivalance. In many cases for example, line stations were sampled anywhere from two to six days after the actual flight had occurred. This will naturally diminish in some cases the value of correlational data comparisons. Parameter equivalence will also influence data comparison especially in comparison of scattering coefficient data with the parameter α and again with the comparison of photic depth with $1/\alpha$. Nevertheless, the controlling factors governing the behaviour of α (i.e. absorption, and scattering processes) are responsible for the similarities in the behaviours for photic depth and scattering coefficient parameters. There are therefore good physical reasons to expect similarities in these data comparisons:

As an aid both in the interpretation and the extraction of useful information from each of the five data product sets, we have summarized, in Table III several optical features which convey significant information on contrasting processes occuring in surface waters for each data product set.

The data in Table III has for each flight line, been normalized to

June 4/1975				June 10/1975				Aug 14/1975				Oct 6/1975				Oct 14/1975			
Dist	ch a	b	d	Dist	ch a	b	d	Dist	ch a	b	d	Dist	ch a	b	d	Dist	ch a	b	d
km	-	-	-	km	-	-	-	km	-	-	-	km	-	-	-	km	-	-	-
5	1.3	1.1	1.1	2.5	1.4	2.0	1.0	7.0	0.1	1.0	2.5	10	1.0	1.0	1.0	7	1.0	1.0	.97
20	1.3	1.2	0.6	20	1.0	1.0	1.0	9.5	.46	.87	3.0	18	0.3	2.0	1.3	9	1.3	2.7	.75
40	1.0	1.0	1.0	41	2.3	4.5	0.5	11	0.1	1.0	2.2	21	0.5	2.0	1.0	14	1.0	1.0	1.0
47	.95	1.1	.65	43	1.8	3.5	.83	18	1.9	1.2	0.5	25	2.3	10.0	0.5	31	.93	1.2	1.1
73	.59	.88	.75	45	3.0	7.5	.45	31	1.0	1.0	1.0	28	0.5	3.0	1.0	34	.88	1.2	.92
								47	.54	1.2	1.0	33	.25	3.0	1.5	37	1.1	2.0	.92
												50	1.1	1.3	.92	40	.95	1.2	1.0
																45	1.0	2.5	.95
																47	.90	2.0	1.0
																49	.75	2.5	.95

TABLE III Normalized parameter Values For Selected Optical Features unit value for the chlorophyll, scattering coefficient, and photic depth parameters. The normalization points have in each case been referenced to an optically benign or quiescent midlake feature (40 km for June 7th; 20 km for June 10th; 31 km for August 14th; 10 km for October 6th; and 7 km for October 14th). Utilizing this procedure we are able to examine relative variations in each of the derived data products sets to determine or extract interpretable information for each of the derived parameters.

An inspection of Table III reveals several informative data trends. First, significant variations in photic depth are seen to be invariably associated with significant variations in chlorophyll. Compare, for example, the data points for August 14th where small derived chlorophyll values occuring at 7, 9.5 and 11 km are seen to be associated with large relative photic depth values. The largest value for the chlorophyll a parameter, 1.9 at 18 km, is also reflected in a small (0.5 m) photic depth. This is an expected behaviour and one which reflects a consistant pattern for these two independently derived parameters. A second important observation on the interrelation of these parameters is the observation that photic depth appears to be relatively insensitive to large variations in the scattering coefficient. A likely explanation for this effect is that the sediment responsible for the large scattering coefficient values is largely inorganic or ditrital in origin rather than arising from the highly absorbing plytoplankton or organic phases. A striking example of this effect may be seen in several of the points from the October 14th data set where small variations in chlorophyll and photic depth parallel the associated larger variations (up to 270%) in the scattering coefficient.

These observations are consistant with the assertion that photic depth is controlled primarily by absorption processes;this therefore might enable discrimination between organic and inorganic materials.

With these general comments in mind we will briefly discuss each set of flight data products.

June 4th, 1975 Figure (5.4) a - e.

These data were obtained near solar noon in the presence of glitter within the sensor field of view. The effect of glitter is especially evident in a), as the surface features observed at 960 nm are very much pronounced and evident at all four sensor channels.

The corrected volume reflectance signals, in b), reveal the presence of several significant structural features indicated in the figure and summarized in Table III. Several of these features might appear to be associated with coastal zones in the vicinity of islands located near 25 and 47 km along the flight line (see Figure 5.3).

Both these observed and calculated parameters indicate little variation in data from shore to shore. At the southern extremity of the line

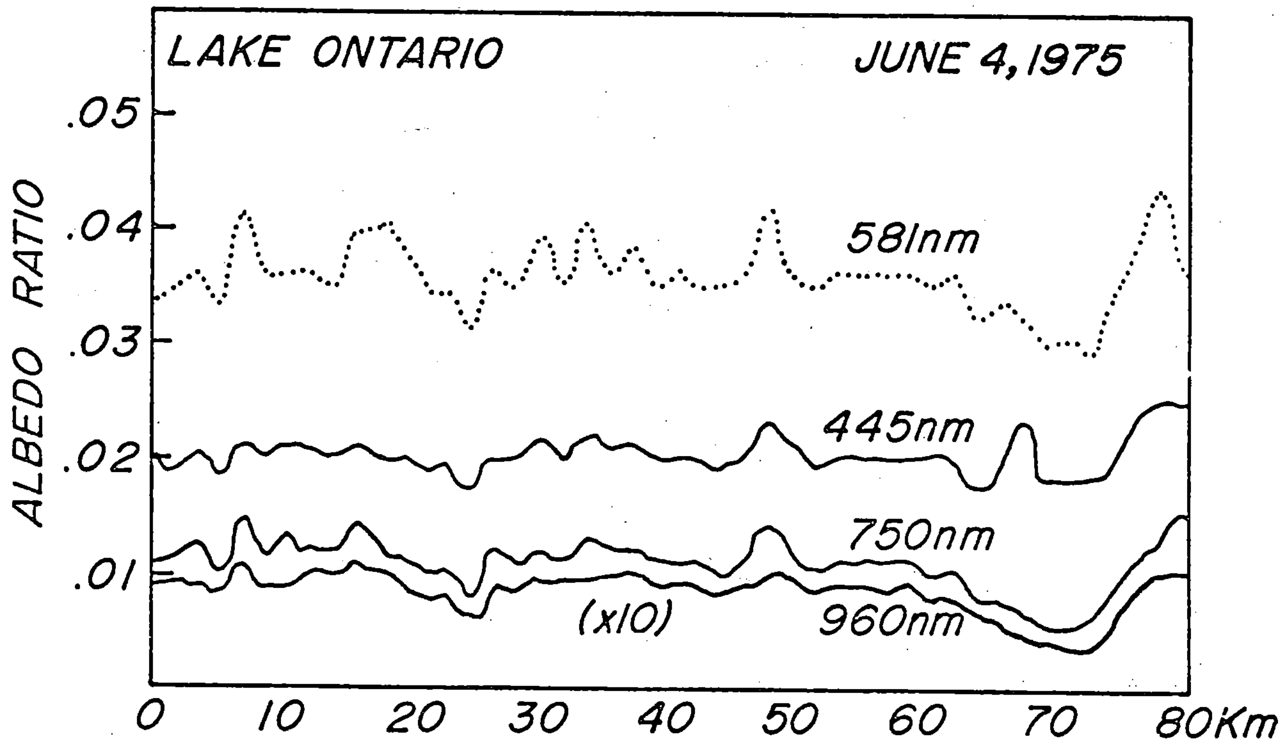

Figure (5.4)a) Albedo ratios (June 4,1975).

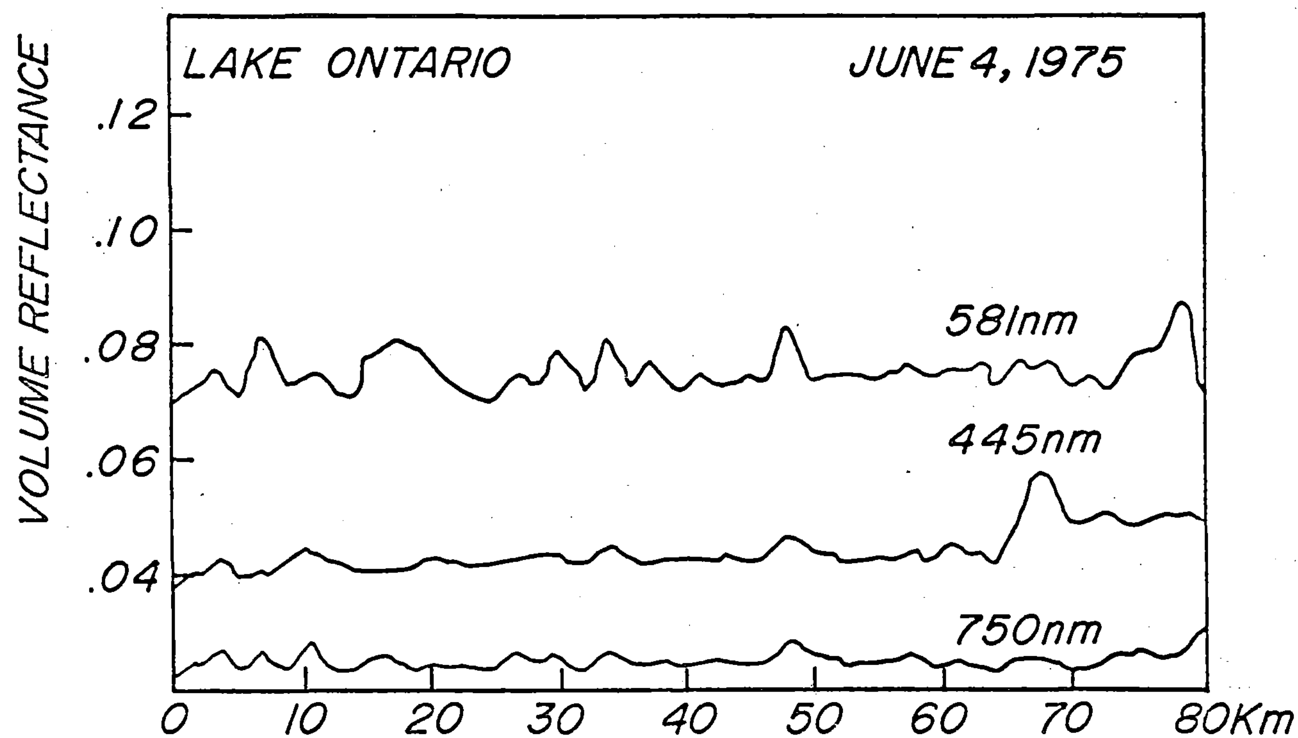

Figure (5.4)b) Volume Reflectances (June 4, 1975).

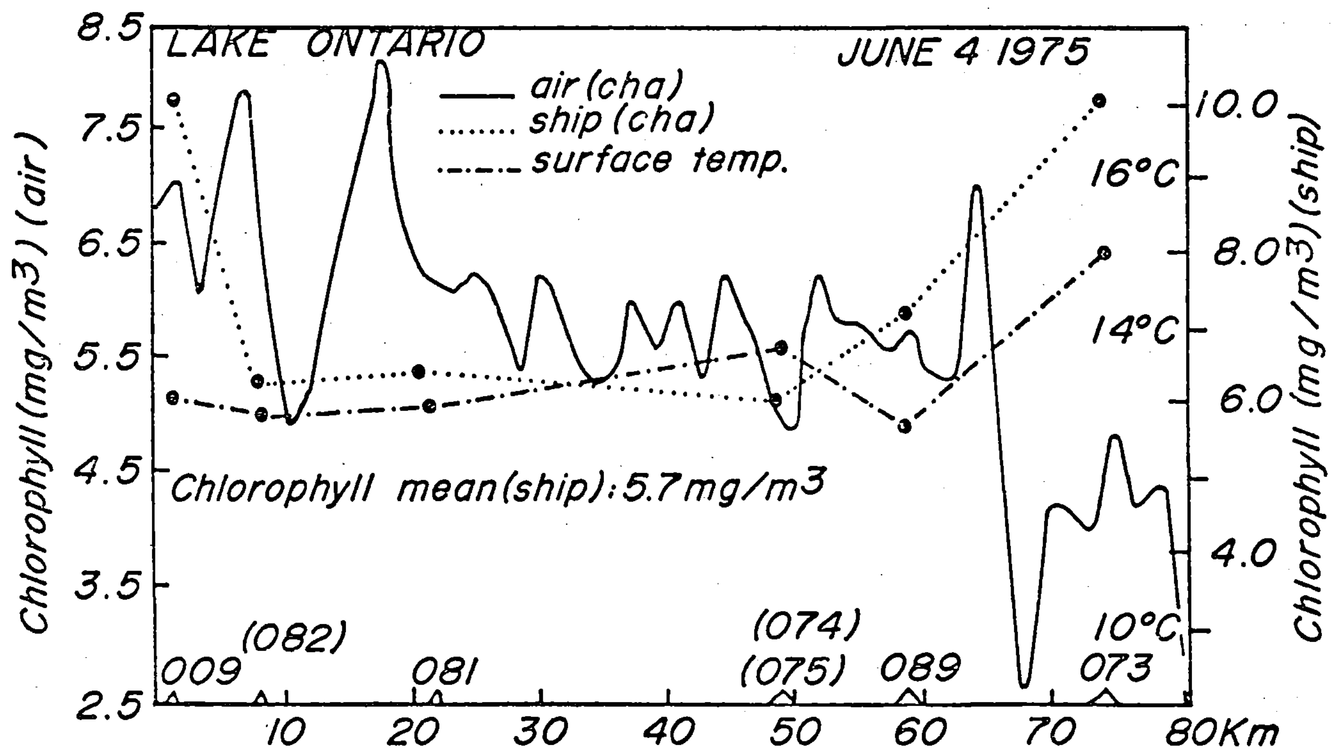

Figure (5.4)c) Chlorophyll concentrations (June 4, 1975).

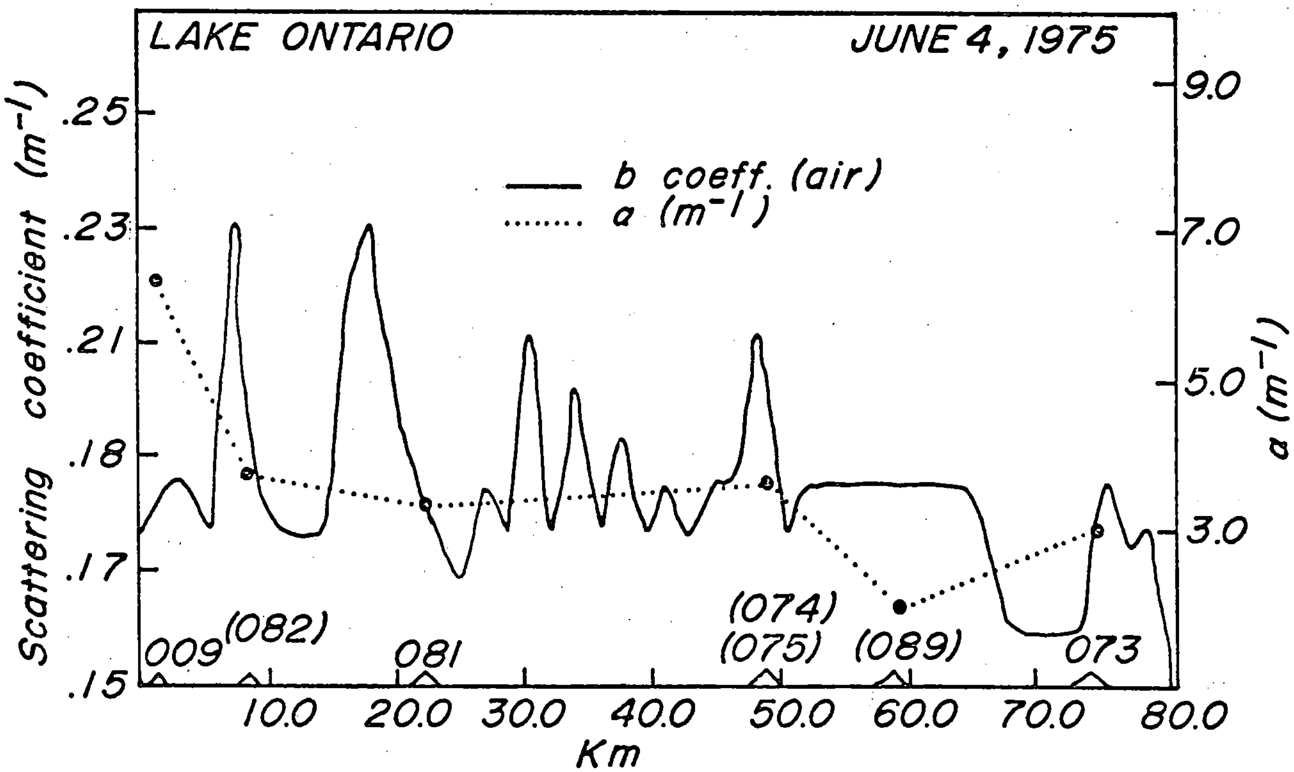

Figure (5.4)d) Scattering coefficient (June 4, 1974)

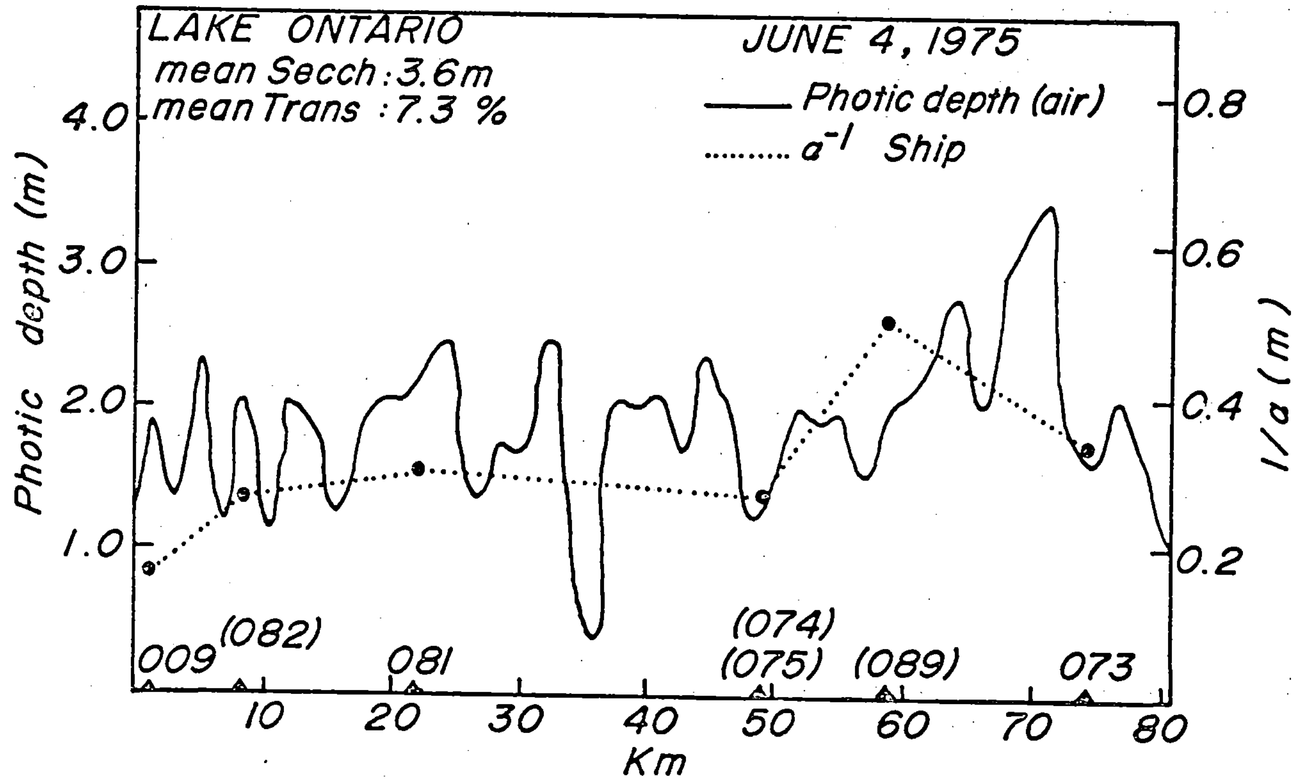

Figure (5.4)e)   Photic depth (June 4, 1975).

(from 60 - 80 km) there appears to be a band of clear coastal water with low chlorophyll and clearer than mid lake values - an effect which may be attributable to upwelling near shore (de Villiers, J.N.,(1976)).

The correlational data parameters α and $1 / \alpha$ in d) and e) confirm the presence of clearer waters in the 60 - 80 km region. The insitu chlorophyll observations do not appear to be in agreement with these observations.

June 10th, 1975 Figures (5.5) (a - e).

The data from June 10th 1975 dilineates three principal optical zones: 1) North near shore to 5 km; 2) Mid lake (5 to 35 km); and 3) South shore 35 to 50 km. These three zones are clearly demarcated in both the albedo ratio and volume reflectance curves a) and b).

The derived parameters reveal that the two coastal zones are higher in both sediment and chlorophyll a as one might expect. Compared to mid lake values, the North shore chlorophyll concentrations rise to values 40% greater than at mid lake while the total suspended load is nearly 100% larger. The South shore coastal zone is characterized by biomass concentrations ranging from 2.0 to 3.0 times larger than mid lake values. The South shore suspended load values rise as high as 7.5 times mid lake values.

It is interesting to compare the relative scatter to biomass ratio for various optical regions. This is an indicator which might reveal changes

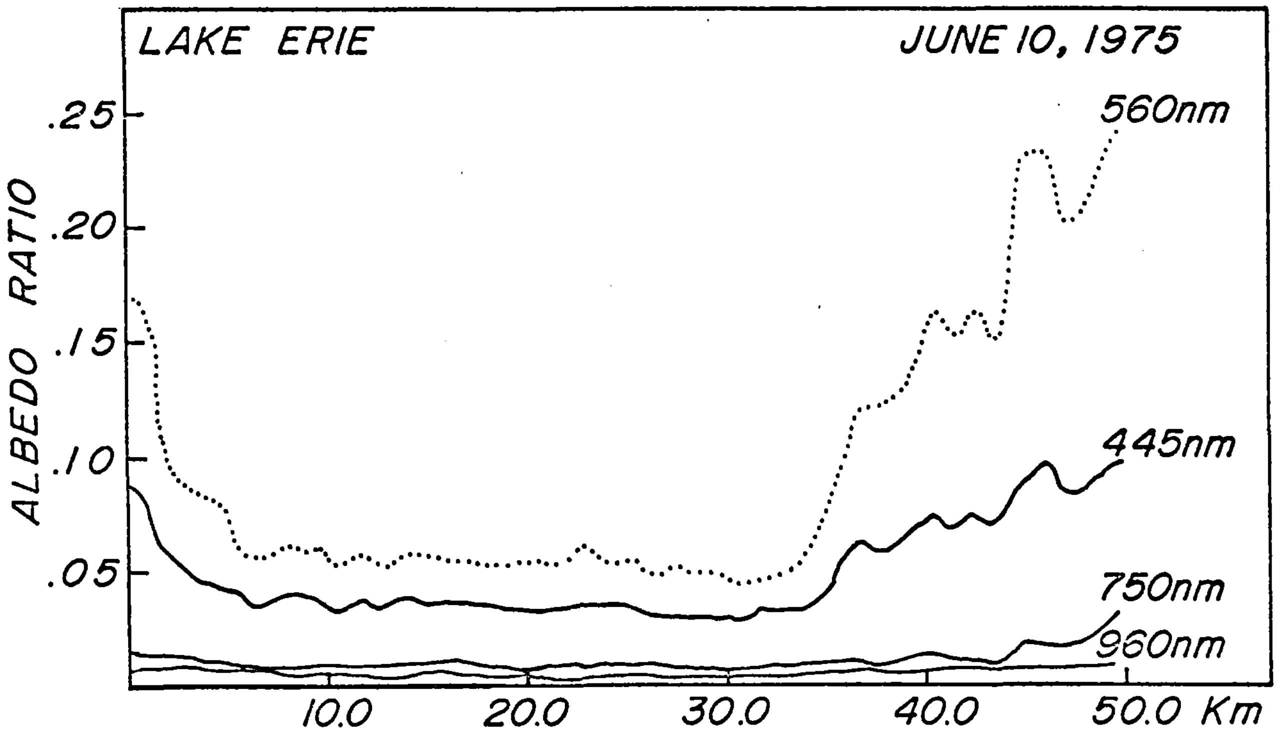

Figure (5.5)a) Albedo ratios (June 10, 1975).

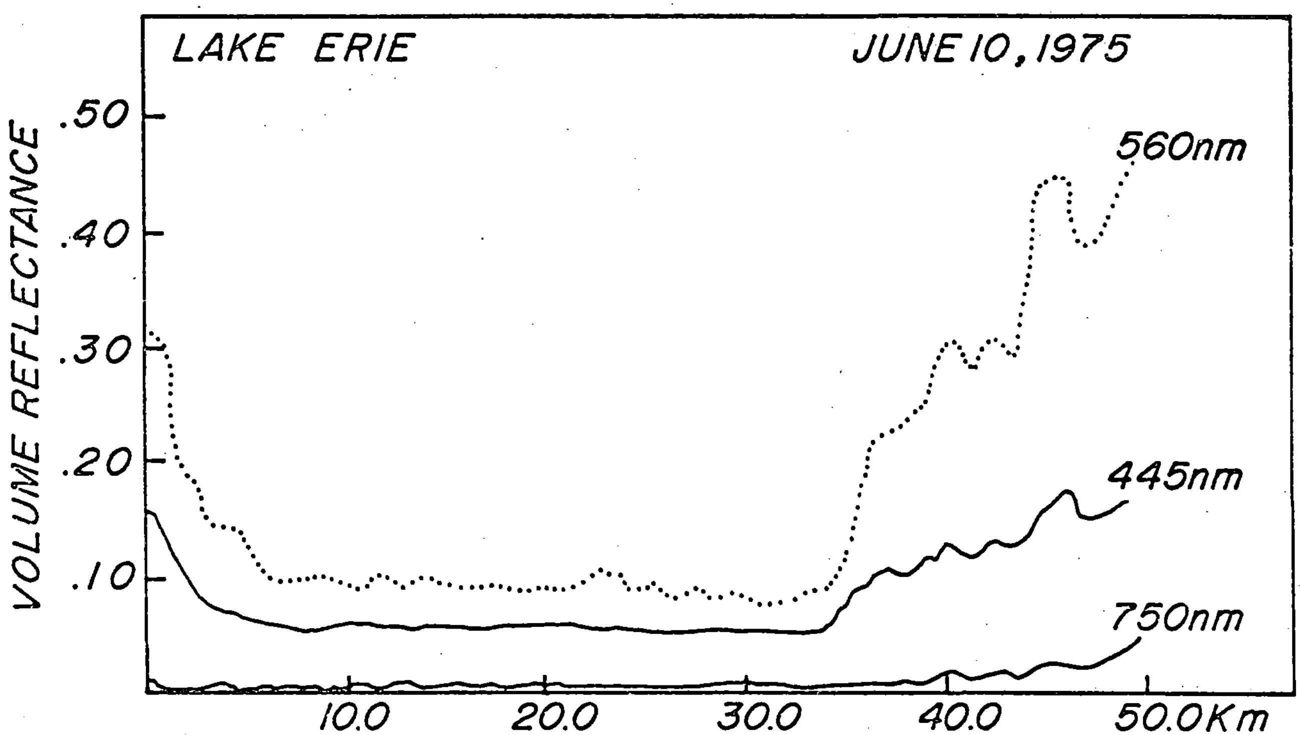

Figure (5.5)b) Volume Reflectances (June 10, 1975).

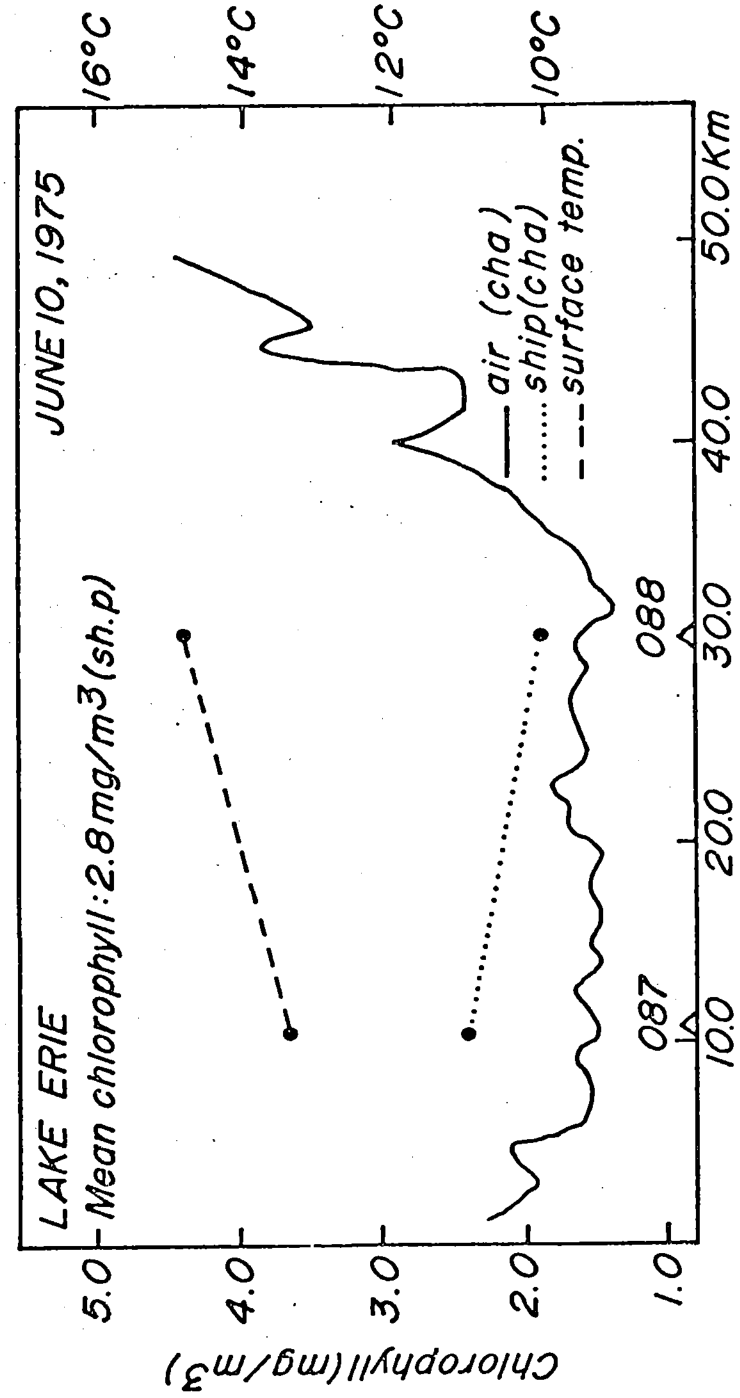

Figure (5.5)c) Chlorophyll conce.trations (June 10, 1975).

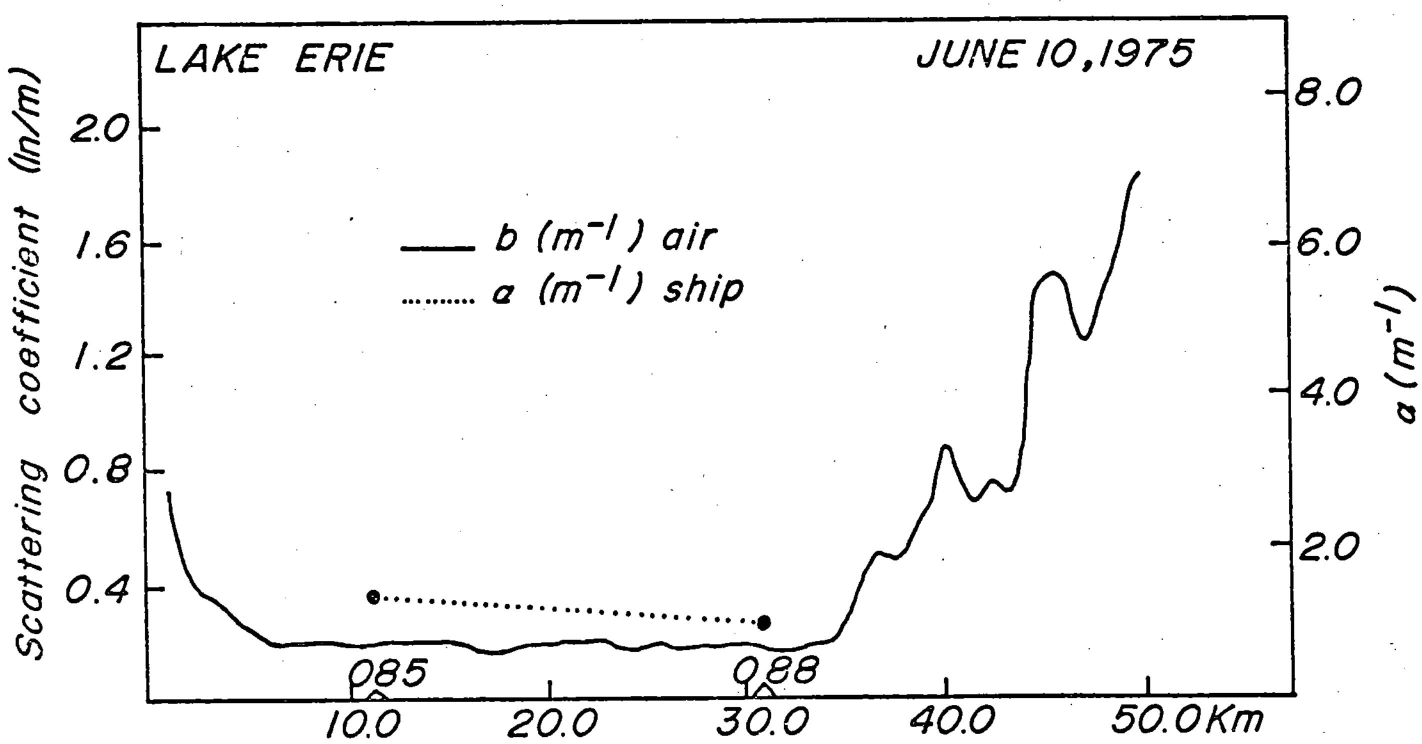

Figure (5.5)d) Scattering coefficient (June 10, 1975).

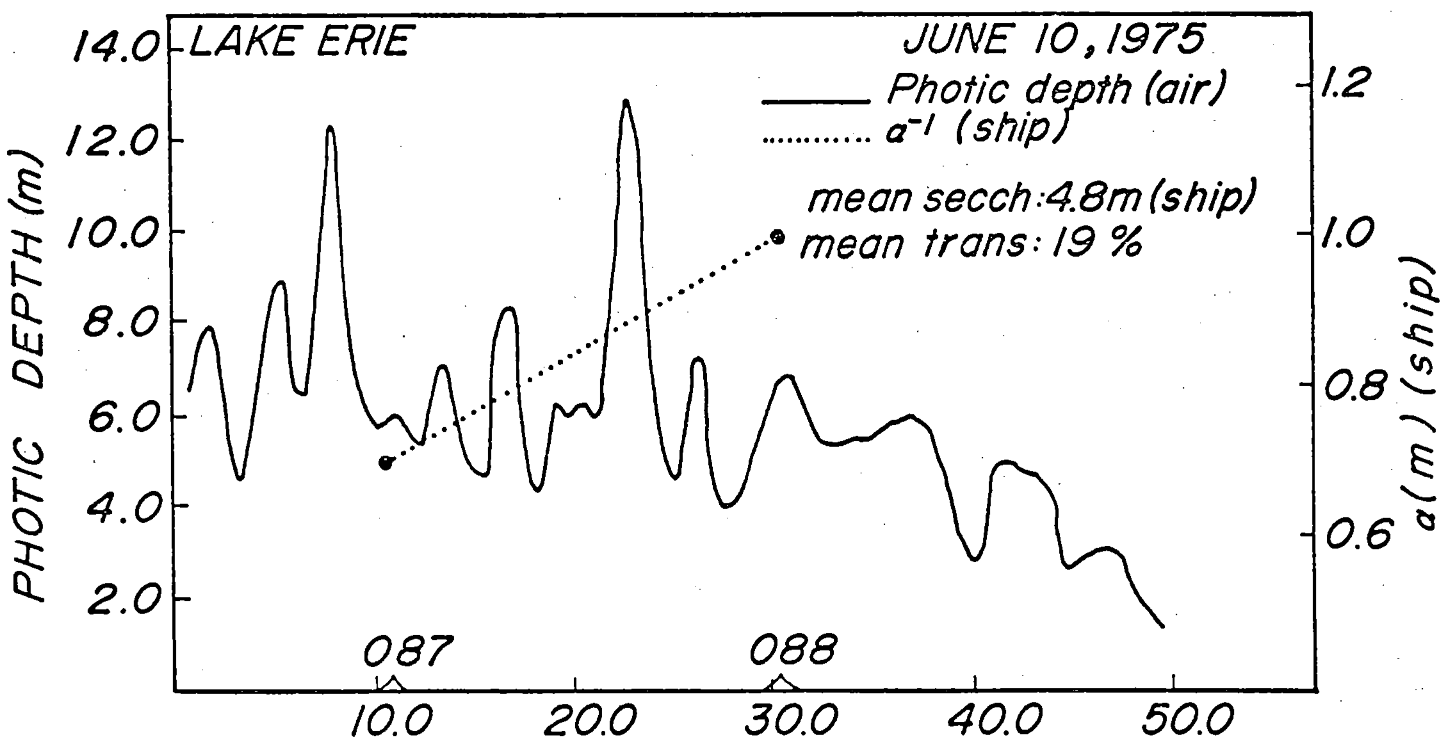

Figure (5.5)e) Photic depth (June 10, 1975).

June 4		June 10		Aug 14		Oct 6		Oct 14	
Dist	b/c	Dist	b/c	Dist	b/c	Dist	b/c	Dist	b/c
km	-	km	-	km	-	km	-	km	-
5	0.4	2.5	2.4	7	37	10	1.0	7	1.5
20	0.4	20	1.7	9.5	5.5	18	6.7	9.0	3.2
40	0.5	41	3.2	11	39	21	4.0	14	1.5
47	0.5	43	3.2	18	1.8	25	4.4	31	1.9
73	0.7	45	4.2	31	2.9	28	6.0	34	1.9
				47	6.4	33	12	37	2.7
						50	1.1	40	1.8
								45	3.7
								47	3.3
								49	4.3

TABLE IV Scattering Coefficient to chlorophyll Ratio for Optical features listed in TABLE III in the relative composition of surface waters. High values of this ratio will indicate high relative concentrations of inorganic sediments while in the primarily organic mid lake regions this parameter is expected to be low. Table IV summarizes these parameter values for the five flight lines of the series. As might be expected, parameter values within the coastal zones are 1.4 to 2.4 times larger than within the mid lake zones. The correlational data from the June 10th flight was unfortunately limited as surface vessels were unable to complete their sampling due to weather constraints. What correlational data was collected does however show reasonable agreement for chlorophyll secchi depth and α.

August 14th, 1975 Figures (5.6) (a - e).

Analysis of data from the August 14th overflights reveals widely varying values for all indicative parameters. The North shore coastal zone (out to 10 km) is extremely chlorophyll poor but high in sediment. As the values in Table IV reveal; this region is marked by the highest scatter to chlorophyll ratios for the entire series. Mid Lake chlorophyll values are also high and vary over a large range as illustrated in Figure c).

The South shore region extending from 35 km to 50 km, lying within the Niagara plume(see Figure (5.3)), is characterized by high chlorophyll, high sediment, high scatter to chlorophyll ratios (Table IV) and low photic depths.

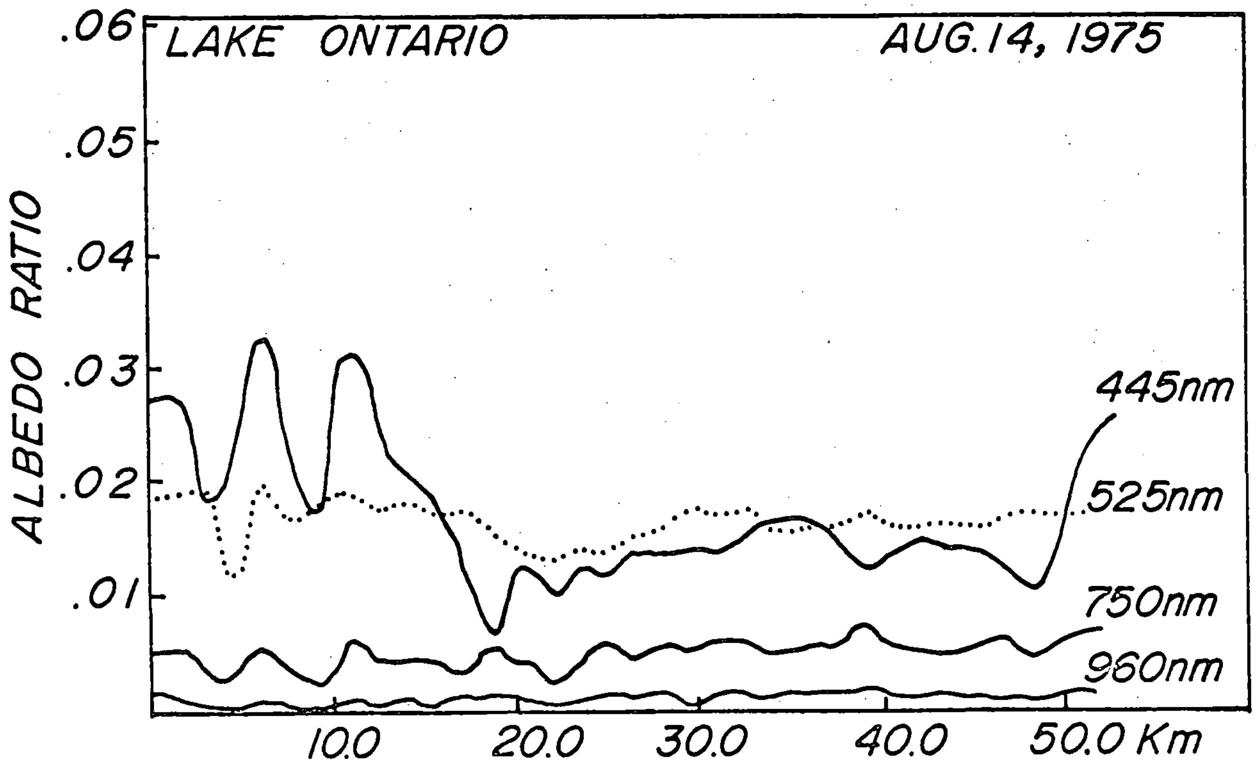

Figure (5.6)a) Albedo ratios (August 14, 1975).

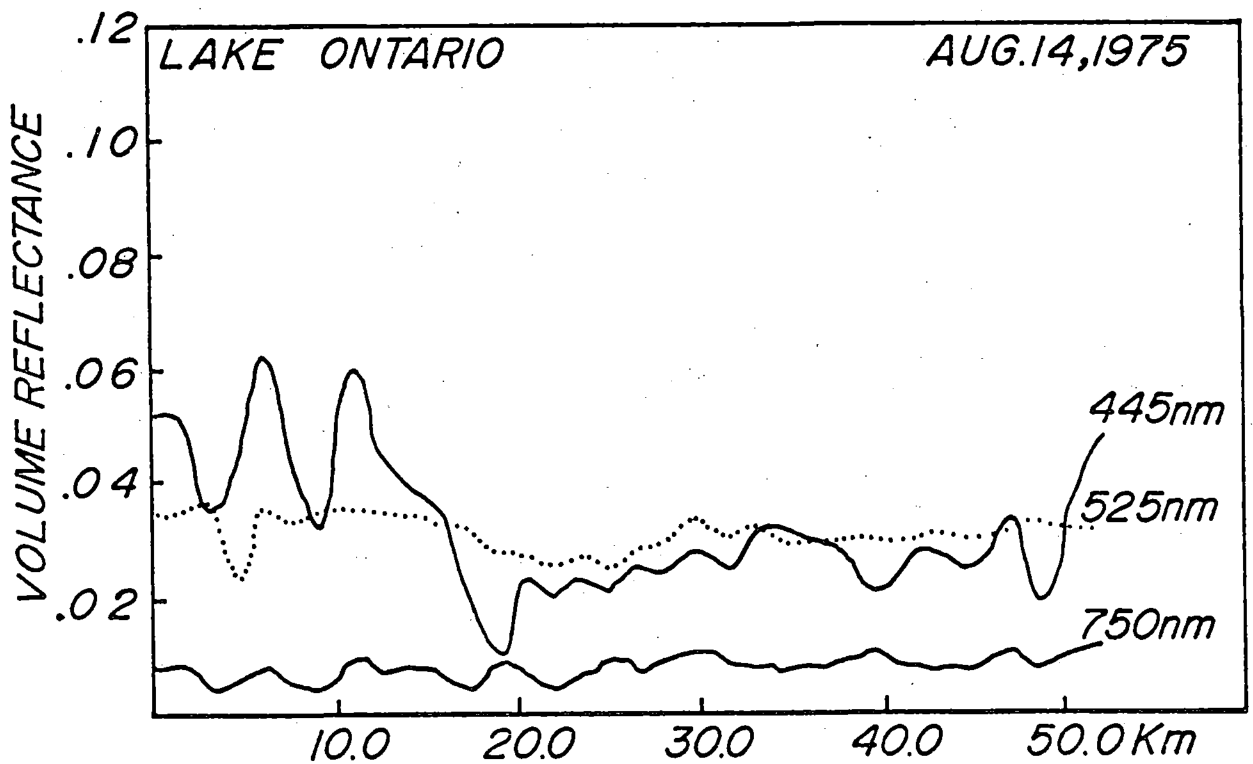

Figure (5.6)b) Volume Reflectance (August 14, 1975).

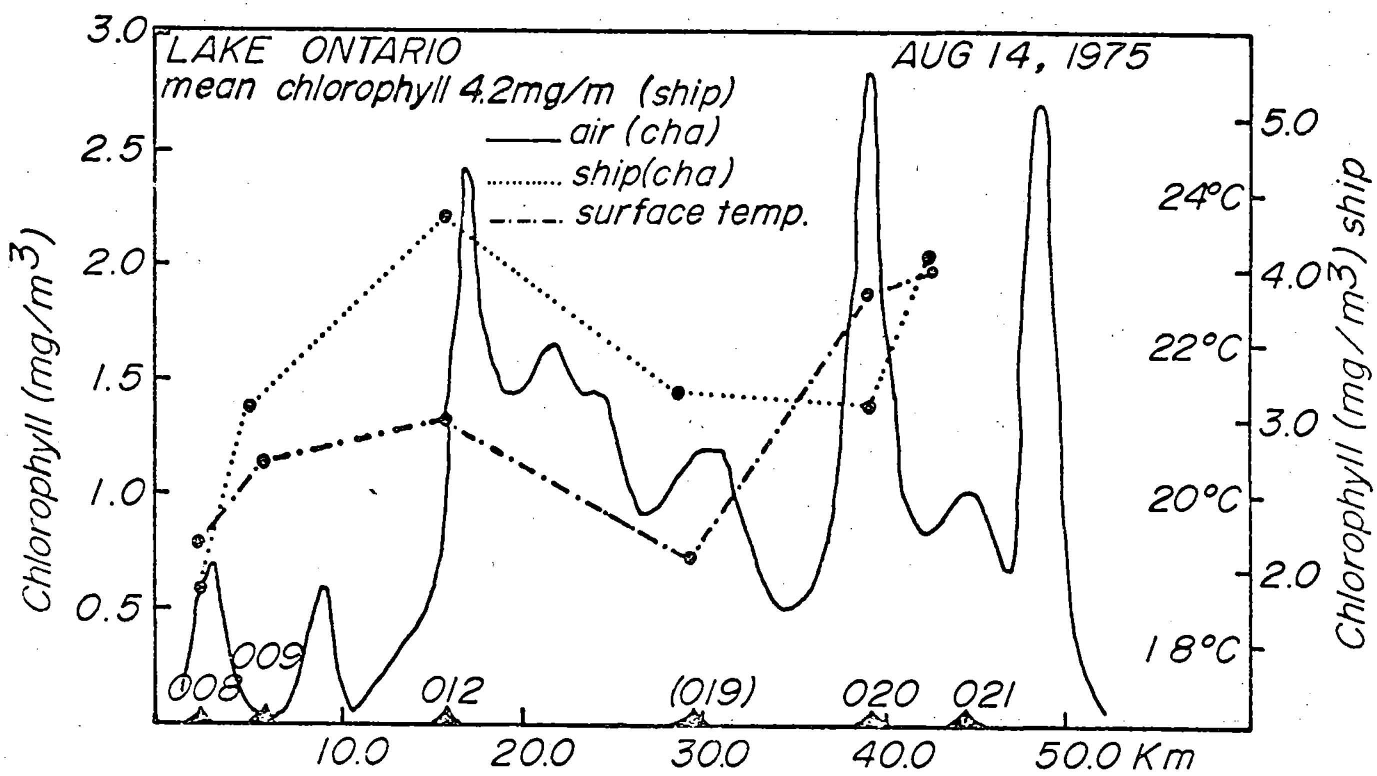

Figure (5.6)c) Chlorophyll concentrations (August 14, 1975).

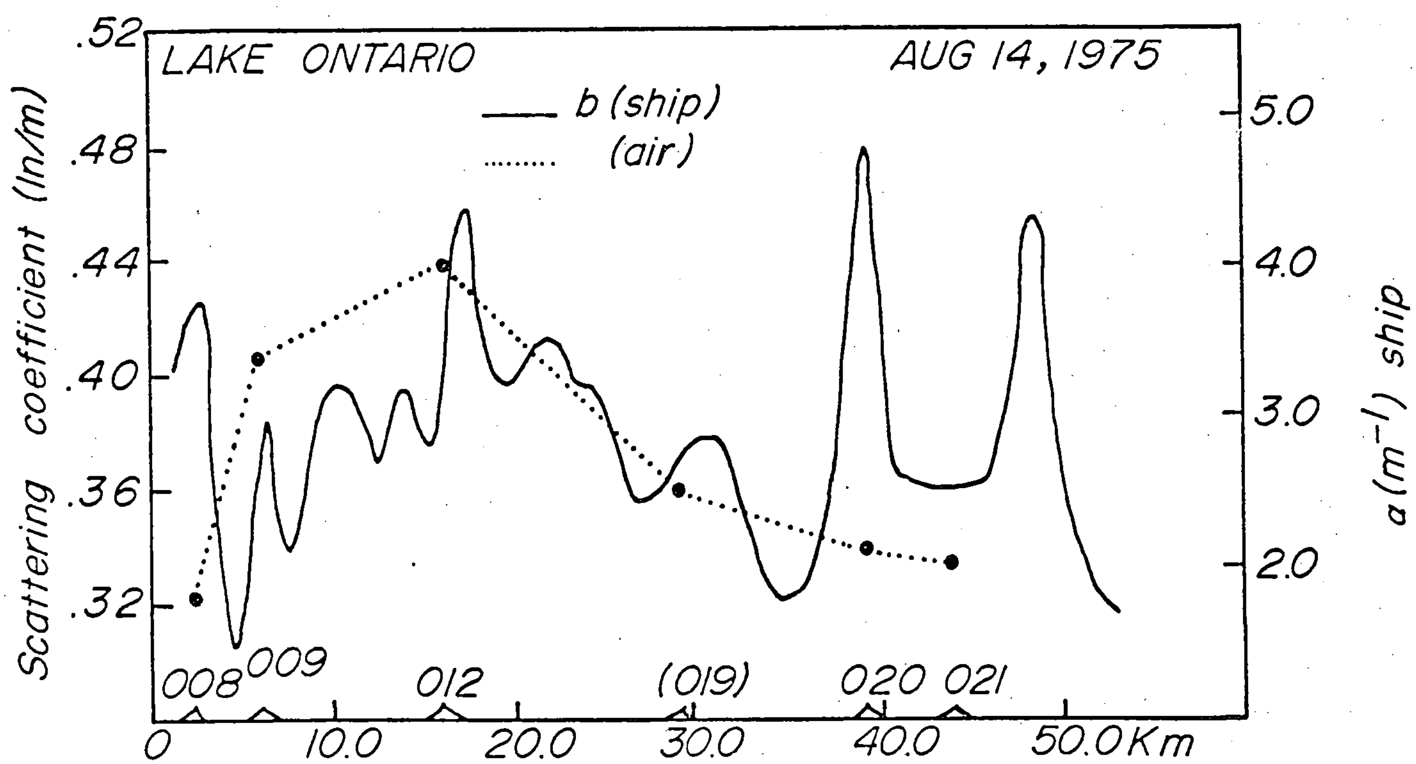

Figure (5.6)d) Scattering coefficient (August 14, 1975).

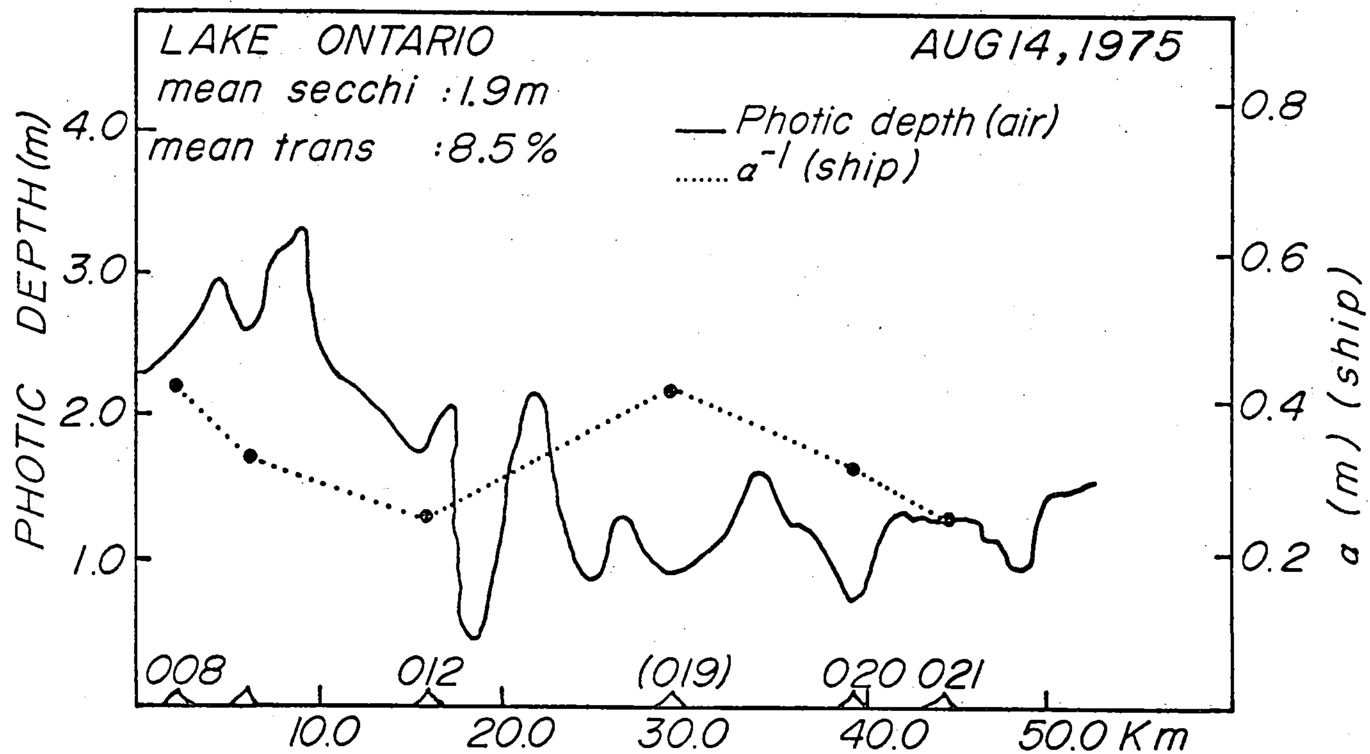

Figure (5.6)e) Photic depth (August 14,1975).

The correlational data for this set is in good agreement with α , Secchi depth, and curve shape for all three derived parameters. The absolute magnitude of the shipborne chlorophyll a data are about 2.5 times larger than that predicted from the airborne data. This may however be attributable to an atmospheric effect.

October 6th, 1975 Figure (5.7) (a - e)

The data from October 6th again reveals three optical regimes: 1) North shore (0 - 15 km), 2) Long point plume (15 to 35 km) and 3) South shore zone (35 - 65 km). Each of these regions is described below.

The North shore region is characterized by the lowest chlorophyll values, lowest sediment values, lowest scatter to chlorophyll ratios and high photic depths.

The long point plume, which is an extention or transport zone of near shore phenomena into the middle of Lake Erie created by complex radial currents (Bukata, (1976)),is optically structured in an interesting fashion.

While the entire region within the plume is charaterized by high sediment and high sediment to chlorophyll ratios, in certain regions the observed chlorophyll values are actually quite low. In fact the lowest chlorophyll a values for the entire line are found within a region centered at 33 km. These predicted values are nearly nine

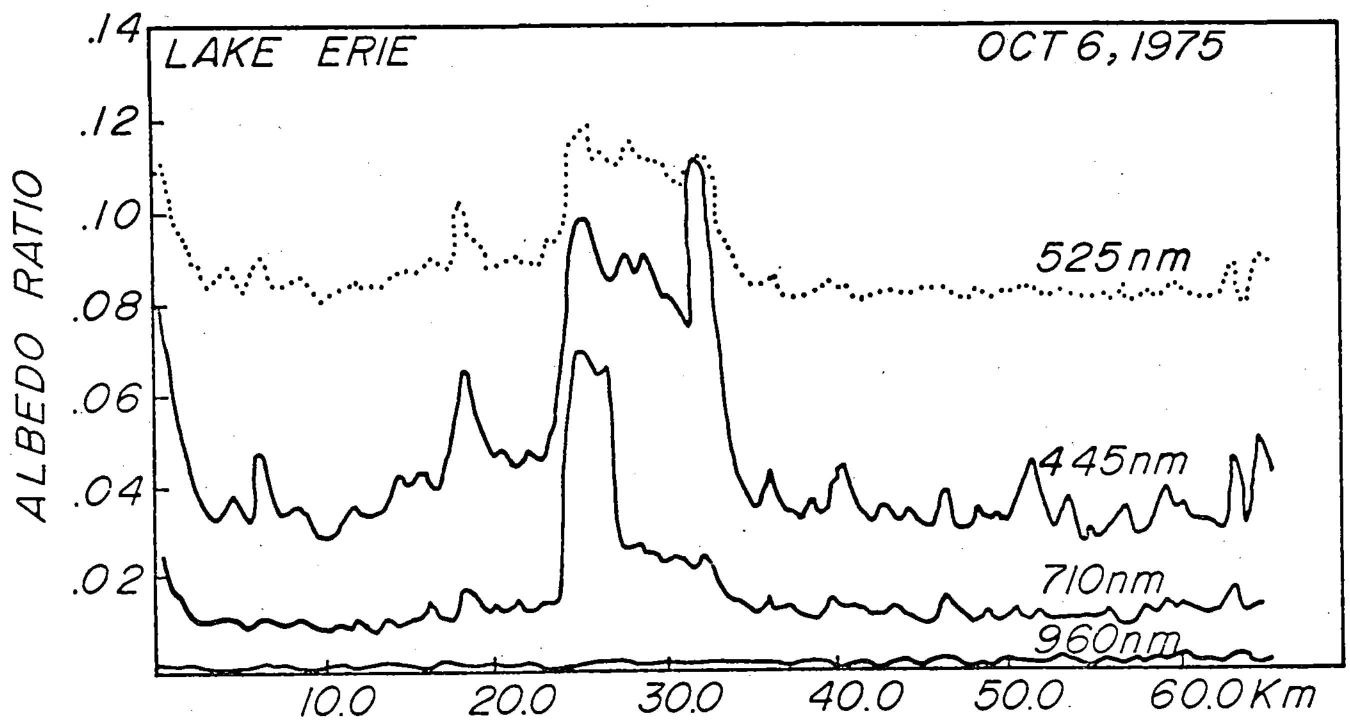

Figure (5.7)a) Albedo ratios (Oct 6, 1975).

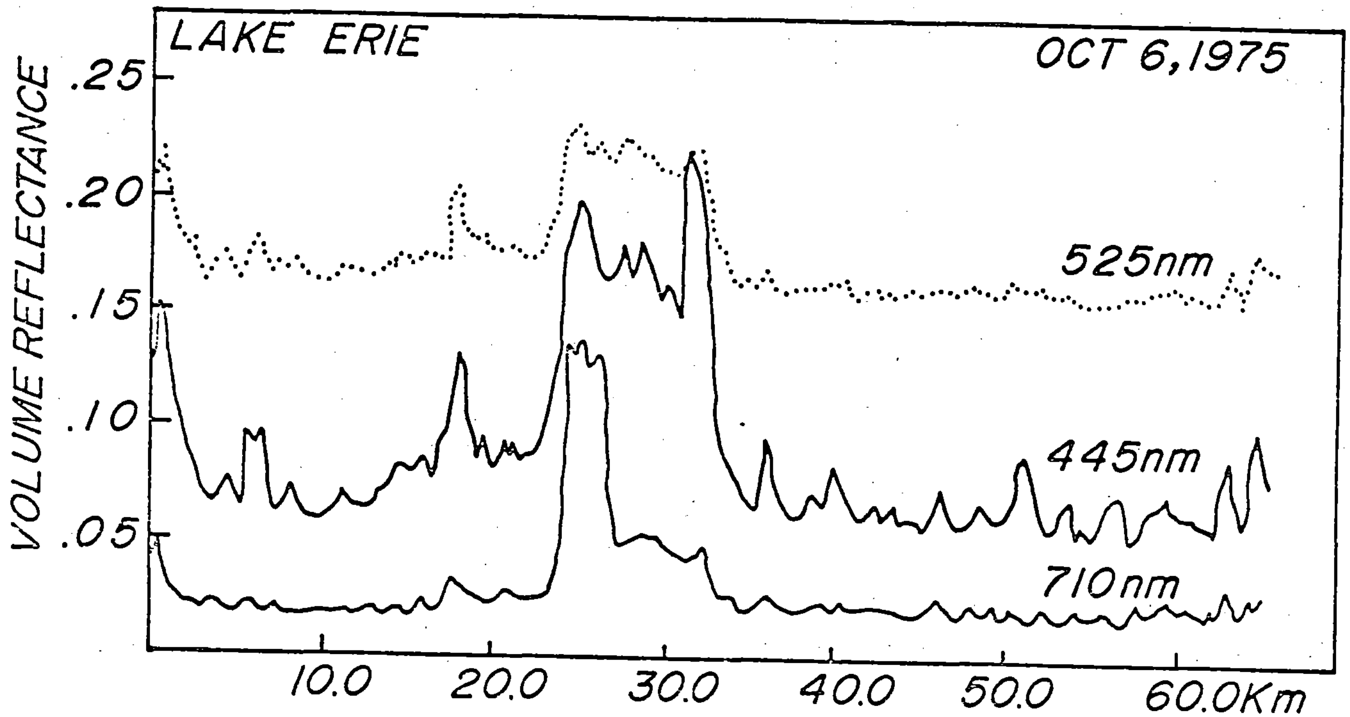

Figure (5.7)b) Volume reflectance (Oct 6, 1975).

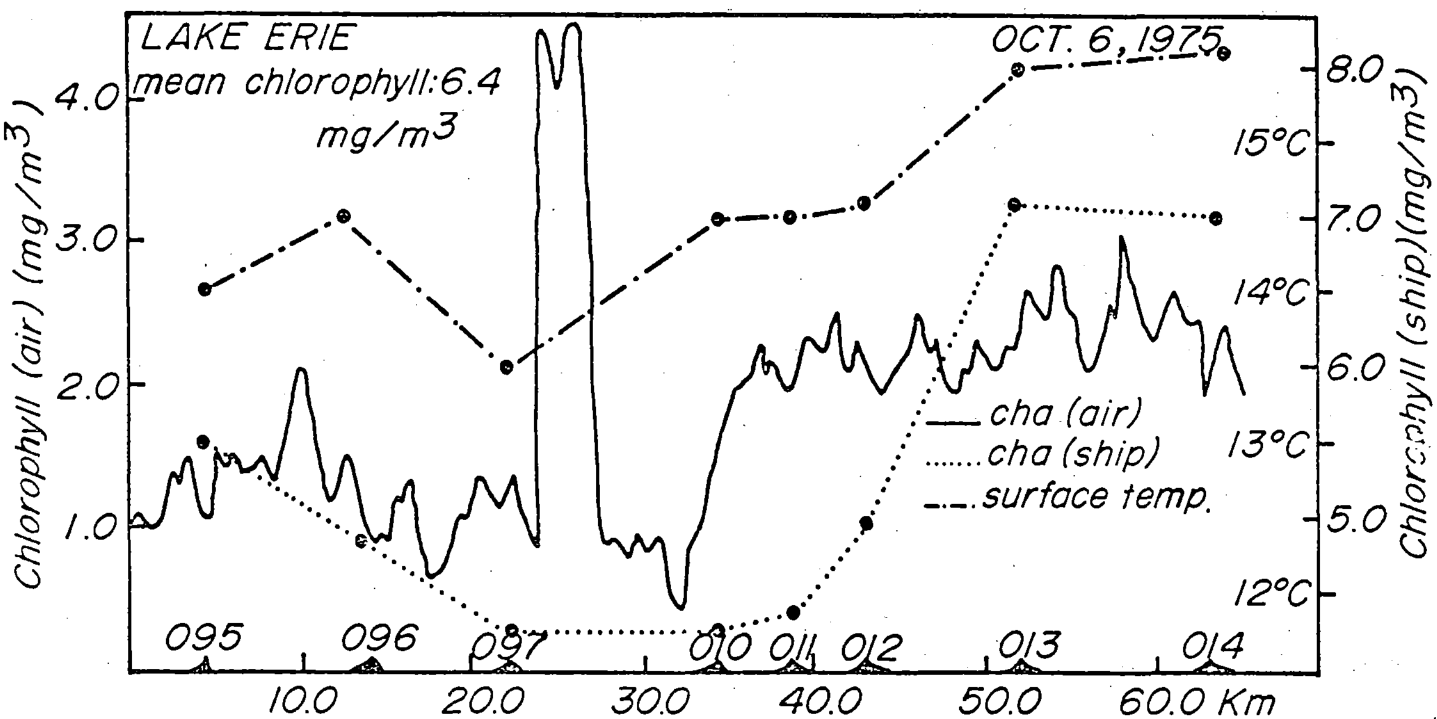

Figure (5.7)c) Chlorophyll concentrations (Oct 6, 1975).

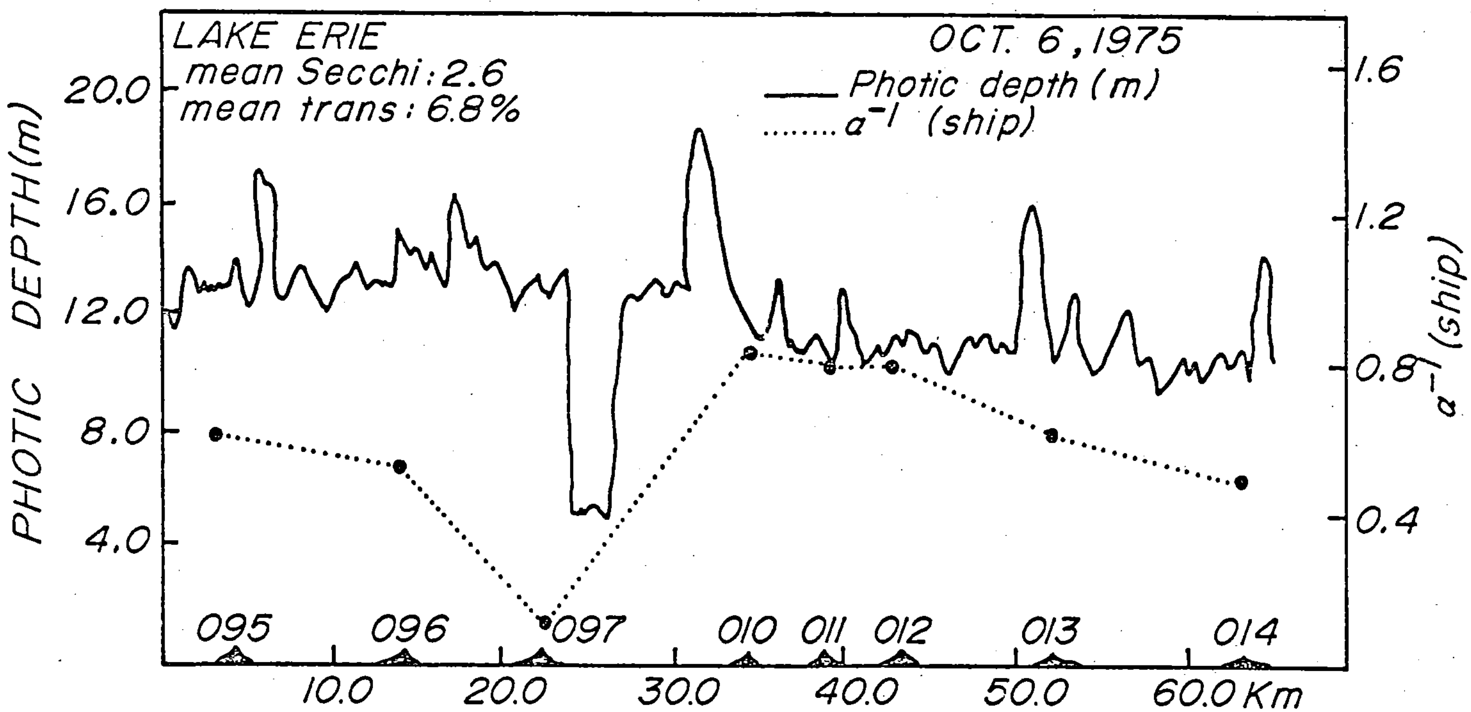

Figure (5.7)e) Photic depth (Oct 6, 1975).

times smaller than those found near the plume edge at 25 km. These two optical regimes (25 km and 33 km) are moreover nearly identical at 445 nm and 525 nm - an observation which underscores the need for complete spectral resolution. The chlorophyll and photic depth curves in c) and e) clearly illustrate the contrast between these two regions, both within the long point plume.

The South shore zone, extending from the southern boundary of the long point plume to the South shore, is optically similar to the North shore zone except that the predicted chlorophyll values are in the mean about 2.0 times greater. This is seen to also be the case for the scattering coefficient. The scatter to chlorophyll ratios on either side of the central plume (see Table IV) are however nearly identical in value. This might suggest similar particulate mixtures for both coastal zones. An inverse relationship between the chlorophyll and photic depth parameters is both observed and expected (Figures d) and e)).

The theoretical insensitivity of photic depth to increases in scattering coefficient values (but not chlorophyll), is especially evident where figures d) and e) are contrasted at 33 km. While the region near 33 km is high in chlorophyll, higher in fact than either coastal region, the photic depth is also high. This is an important consequence of the physical observation that photic depth is controlled by absorption, and reveals the likely presence of inorganic materials probably arising from near shore processes.

Correlational data from shipborne measurements is in good qualitative agreement for this flight date for chlorophyll, photic depth and scattering coefficient. The airborne measurements are in substantial disagreement as to absolute values for both chlorophyll and photic depth (the actual comparison is with Secchi depth).

<u>October 14th, 1975 Figure (5.8) (a - e)</u>

Our analysis of data from this flight again reveals three principal zones of interest:

1) North shore to 10 km
2) Mid lake, to 30 km
3) South shore, or Niagara plume, 30 - 50 km. This zone possesses three sub regions: 30 - 38 km, 38 - 43 km, and 43 to 52 km (see Figure (5.3)):

Each of these regions is discussed in turn:

The North shore zone is high in chlorophyll, although there are a number of structural features evident; the region is also high in sediment and displays large scatter to chlorophyll ratios. These higher chlorophyll values are also reflected in lower than average photic depth values for the line in this zone.

The mid lake zone exhibits slowly decreasing chlorophyll <u>a</u> values, constant sediment concentrations and slowly increasing scatter to chlorophyll ratios. Photic depth increases slightly throughout this regime - again in an inverse relation to the chlorophyll trends. Within the plume, or South shore coastal zone, there appears to be two distinct sediment laden bands, one extending

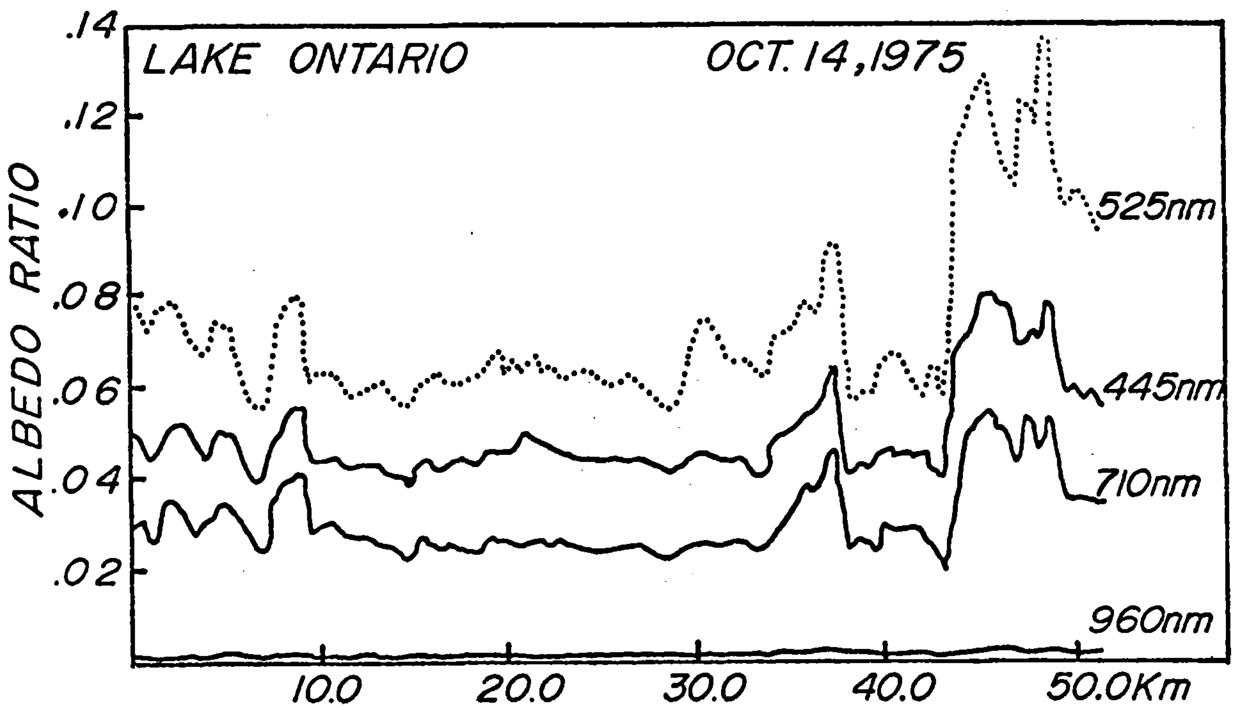

Figure (5.8)a) Albedo ratios (Oct 14, 1975).

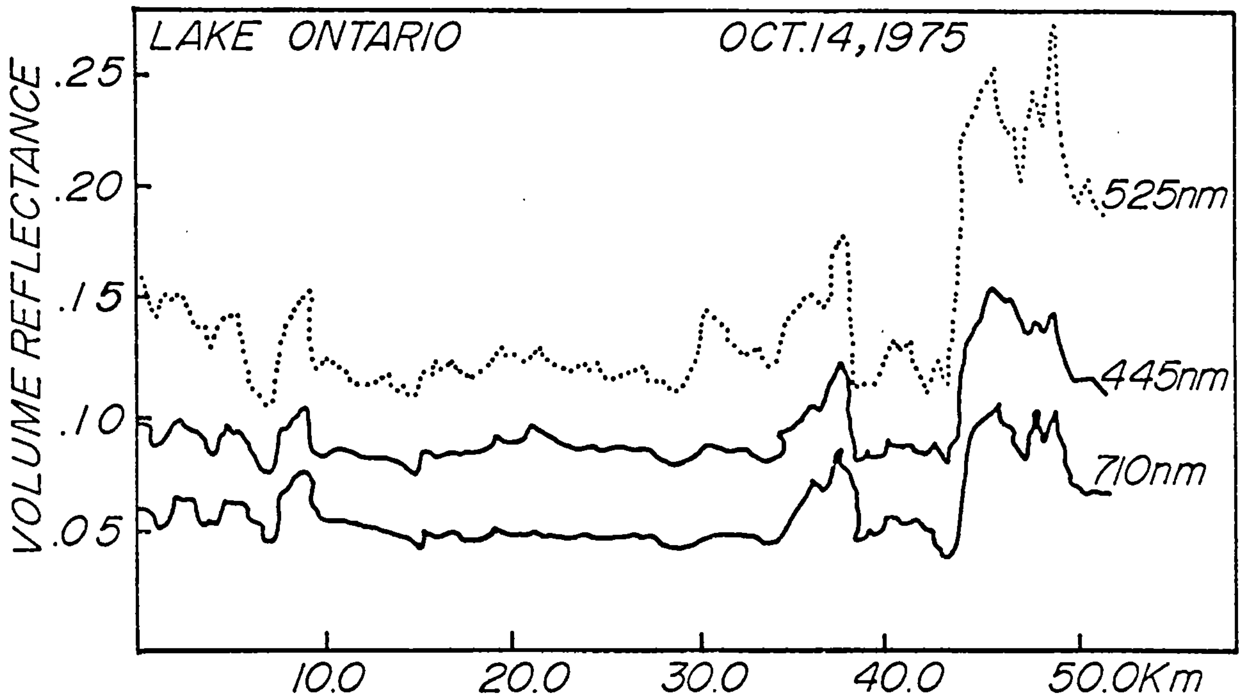

Figure (5.8)b) Volume reflectance (Oct 14, 1975).

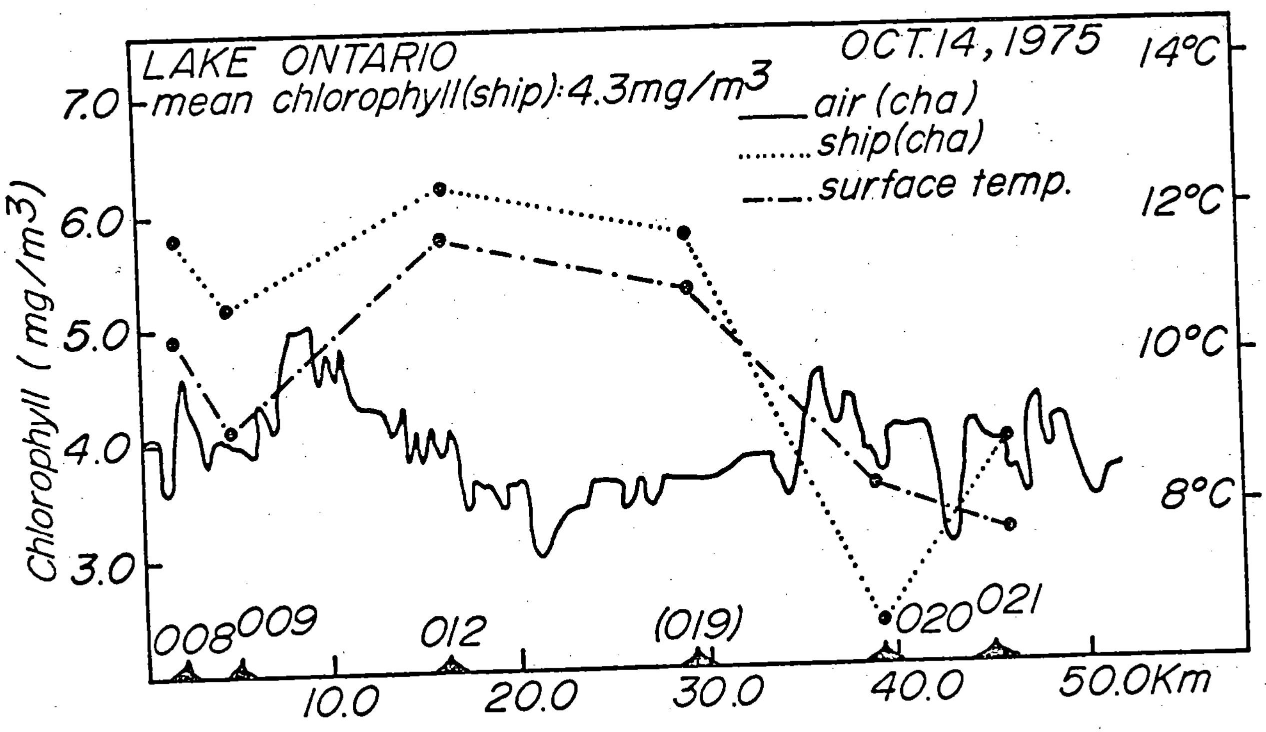

Figure (5.8)c) Chlorophyll concentrations (Oct 14, 1975).

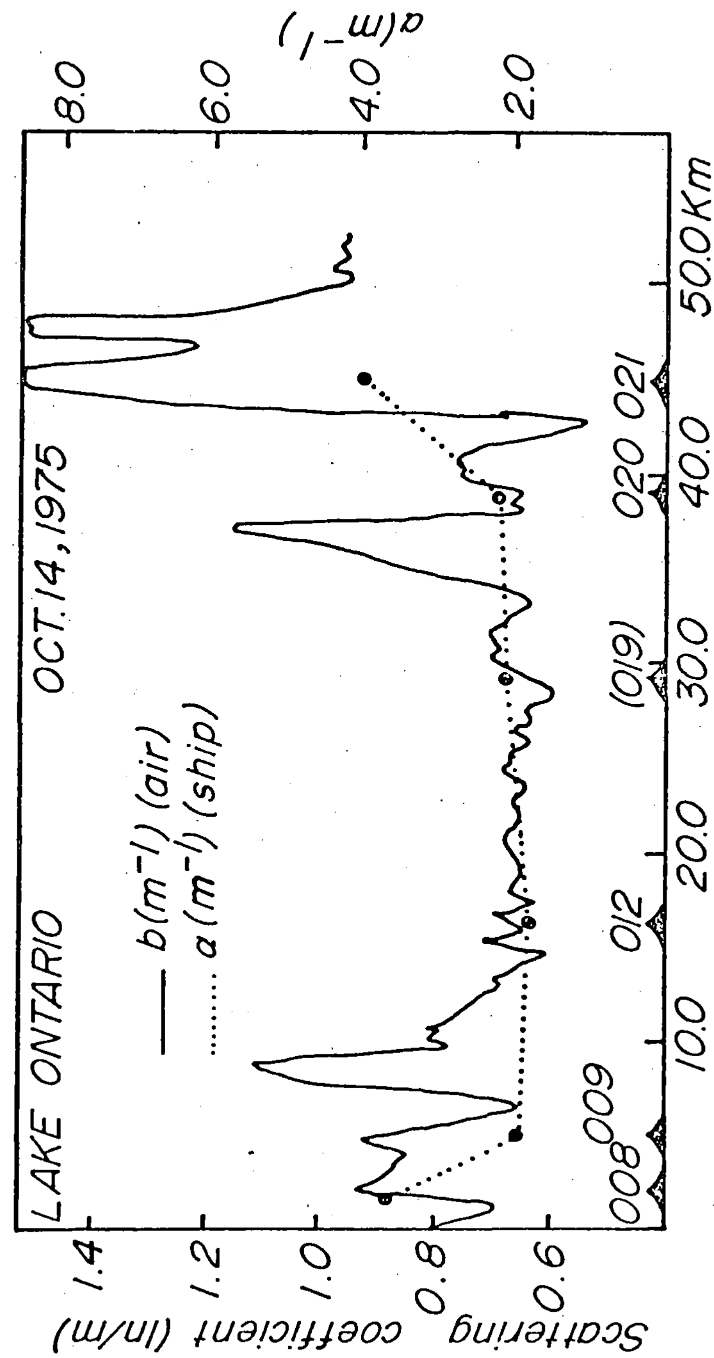

Figure (5.8) d) Scattering coefficient (Oct 14, 1975).

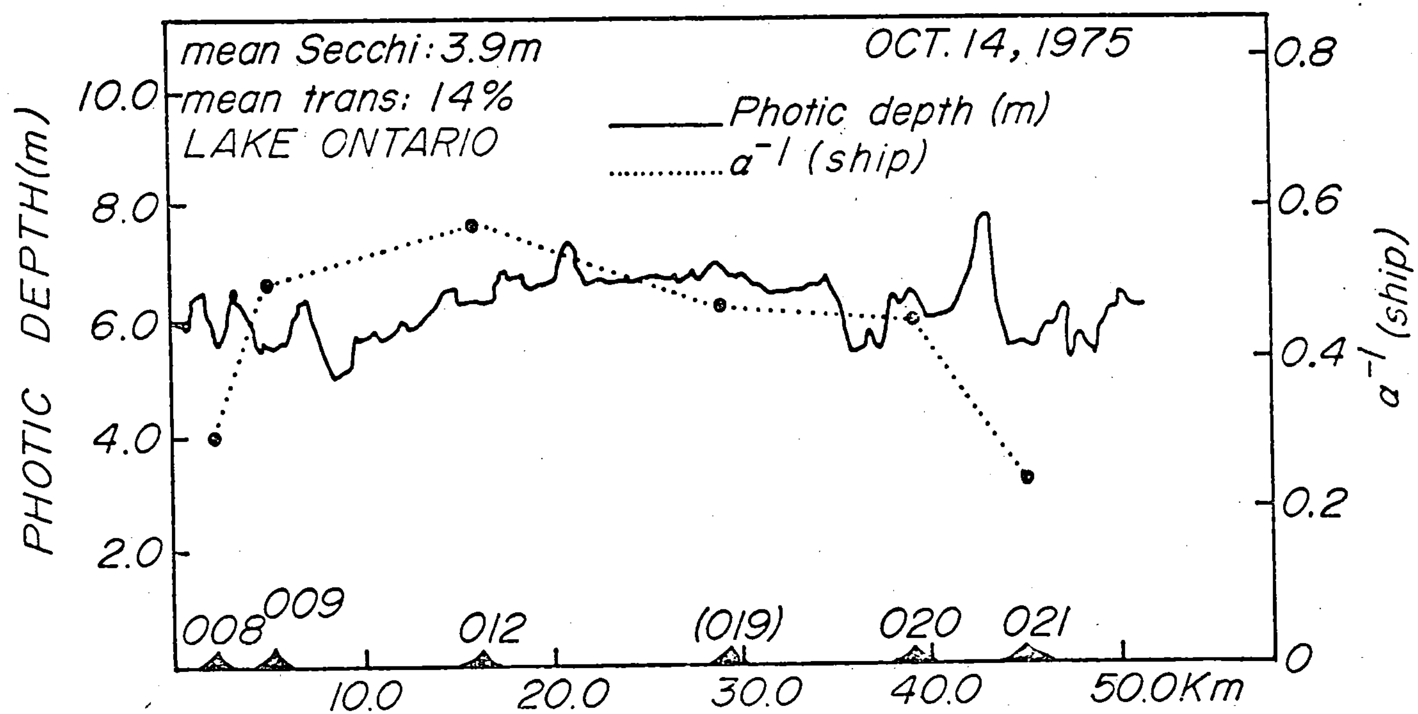

Figure (5.8) e) Photic depth (Oct 14, 1975).

from about 33 to 38 km, a second from 43 to the vicinity of 50 km. An intermediate clear band, stretching from about 38 km to 43 km appears to possess mid lake optical characteristics.

Unlike examples from previous lines, these sediment laden coastal bands do not reflect in significantly higher chlorophyll concentrations. This would appear to indicate a mixing of the sediment rich river outflow with the Lake Ontario waters.

The clear band within the South coastal zone possesses a feature near the boundary of the second plume band at 43 km which is reminiscent of the 33 km feature for the October 6th Lake Erie feature discussed earlier. The chlorophyll values within this narrow minima are the lowest for the line - this is mirrored in e) as a region possessing high photic depths.

The correlational values for the October 14th flight are in better agreement in magnitude than with shape. The lack of curve shape agreement is likely due to the late lake sampling dates. As the information in Table II summarizes, the South shore stations were sampled nearly a week after the actual overflight date.

5.1 Temperature and Chlorophyll

It has long been known that a quantitative inverse correlation between temperature and transparency can be deduced from lake line profiles. Low transparency may moreover be attributable to either organic or inorganic materials (Rodgers, 1968). The ship supplied correlative data obtained from the lines corresponding to the June 4th, August 14th, October 6th, and October 14th overflights appear to confirm chlorophyll and α as illustrated with inspection of figures (5.4) - (5.8). However, these data also reveal a marked direct correlation between chlorophyll and temperature as illustrated. The correlation in fact would appear to be consistently more convincing than that already known to exist for α and temperature.

Although this observed temperature - chlorophyll relation may be a non-linear effect and seasonal in nature, its existance may have substantial implication for remote sensing applications.

By combining thermal and photometric techniques it might in fact be possible to extend the photometric techniques into a two dimension regime. In effect, one might be able to minimize the non-linear chlorophyll/thermal relation by regular normalization of photometric line data along track. In this way, it might be feasible to generate chlorophyll maps utilizing a suitable combination of non-imaging photometric and imaging thermal instrumentation.

5.2 Yellow Substances?

As noted in the presentation of data, there is an inverse relationship between chlorophyll and photic depth - alternatively the observation is expected as photic depth is a function of absorption as is chlorophyll. However, the linear relationship exhibits itself in different functional

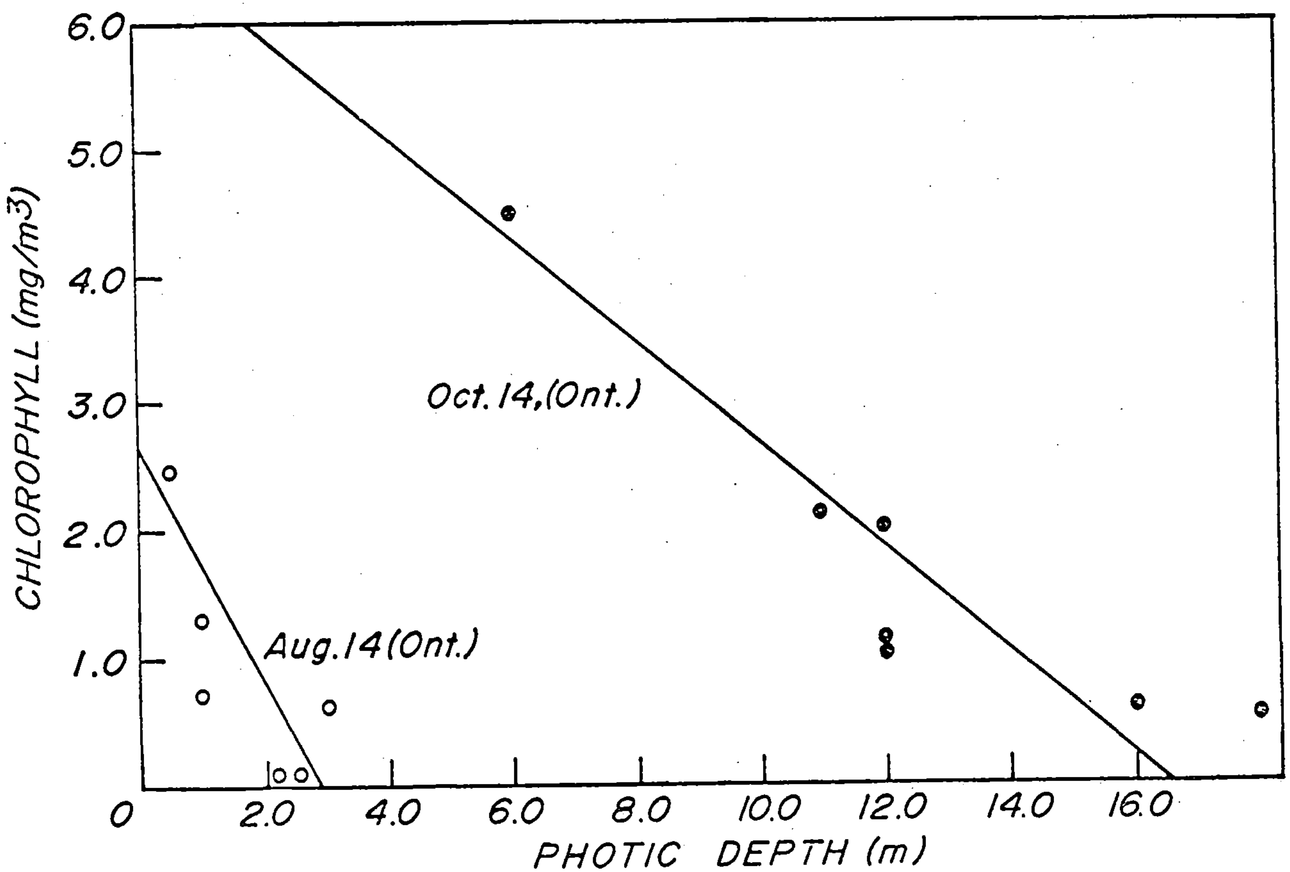

Figure (5.9) Relationship between chlorophyll and photic depth along Lake Ontario line 001 on Aug 14 and Oct 14, 1975.

forms for differing dates. Figure (5.9) contains a plot of the chlorophyll/ photic depth data from the Toronto to Niagara lines obtained on August 14th, and two months later on October 14th. The linear relations for the two dates are as follows:

$$ch\ \underline{a} = -\ 1.1d + 2.7 \quad (Aug\ 14/75) \tag{8}$$

$$ch\ \underline{a} = -\ 0.4d + 6.5 \quad (Oct\ 14/75) \tag{9}$$

Extrapolation of both cases to zero chlorophyll yields differing residual photic depths of 2.5 and 16.3 m for August and October respectively.

Data from other flights yielded intermediate values for these residual depths (9.0 for June 10th and 13.4 for October 6th). This variation in intercept could be indicative of dissolved substance variations on a lake wide or seasonal basis and consequently might offer potential as an important water quality indicator.

6.0 CONCLUSIONS

The 1975 CCIW volume reflectance series has demonstrated that a reliable set of quantitative and reproducible water colour data products can be provided to suit a number of research and operational requirements.

While the absolute values of several of the derived data products are in some instances displaced in value from the shipborne measurements, the relative variations of the derived data products convey significant information on a number of hydro-optical features.

While it is recognized that no reliable general correlations have been shown to exist between volume scattering characteristics and water quality parameters in the past (Kruus, J., (1974)), we strongly feel that these techniques, designed to overcome for the first time impediments imposed by a number of environmental factors, represent a new standard in remote water quality diagnostics.

7.0 RECOMMENDATIONS

Serious consideration should be given to incorporation of a cost-effective airborne programme, utilizing both photometric and imaging thermal techniques, as part of a regular CCIW operational programme. Any proposed scheme should include as part of its planning, synoptic inputs from both thermal IR and multi-spectral satellite sources.

A proposed approach would allow some flexibility in surveillance cruise timing in order to allow for synchronization of satellite, airborne and shipborne measurements. Airborne data should be obtained along stragically selected flight lines in close liaison with the shipborne measurements.

APPENDIX A: HARDWARE AND SOFTWARE MODIFICATIONS

A.1 HARDWARE (Miller J., (1976)

(1) The photometer presently permits manual insertion of 0 and 5 volt calibration levels on the four analog signal outputs so that data recorded on the MINCOM tape recorder may be referenced to an absolute voltage scale. However, this facility was not provided for the 4 analog range outputs with the result that data interpretation ambiguities may arise that can be resolved through careful examination of the data. It has been proposed that modifications be incorporated to permit the insertion of 0 and 5 volt calibration levels on the 4 analog range outputs.

(2) With the present design, the MPPH photometer provides the photometer output signals in a digital form every 40 msec, with each analog signal digitized by its own A/D converter and clock driver. It has been proposed to modify the A/D conversion systems so as to be driven by the same clock and therefore provide 4 signals which can be considered truly simultaneous.

(3) It has been proposed that a brake be installed on the solar calibration stepper to remove the overshoot problems presently evident in the servo-controlled calibration system.

(4) A mechanical design should be done and implemented to provide a mechanically secure mounting of the 4 fibre optic bundles in the photometer frame.

(5) Provision should be made in the detector heads for the location of desicant material to reduce the probability of system malfunction in humid conditions.

(6) A consistant and standardized recalibration procedure should be established to monitor changes in its performance and to re-establish the solar calibration factors - these are imperative for quantitative analysis and interpretation of MPPH data.

A.2 SOFTWARE

A software routine has been developed by CCRS to convert MINCOM recorded in flight data to
formats compatable for analysis on either 7 track or 9 track systems (Adel, H., (1976). A software package developed by York University has been demonstrated in use to compute up-welling radiance, downwelling irradiance and apparent reflectances in the four wavelength bands of the York/Cress photometer (Miller J., Jain S., (1976).

With the demonstrated success of the interpretive techniques described herein, it is recommended that consideration be given for inclusion of sub-routine software packages to calculate the following set of parameters:

1) Chlorophyll *a*
2) Scattering coefficient
3) Volume reflectance

(and)

4) Photic depth

The first two parameters would be based upon modifications of the optimization scheme described by Jain and Miller (1976). The volume reflectance and photic depth parameters can be adapted for inclusion in the present CCIW software package with a minimum of effort using algorithms described in Sections 1.0 & 4.0 of this report (Equations 5 & 7).

APPENDIX B: OPERATIONAL METHODS

The operational methods outlined herein are intended as a guide for both CCIW users and CCRS service personnel who are engaged in application of techniques for quantitative determinations of water colour parameters.

B.1 OPERATING PROCEDURES

The following set of operating procedures has been adapted from those presented by Pieau & Miller (1975) and summarized here for convenience:

B.2 PRE-FLIGHT SENSOR PREPARATION AND SYSTEM CHECKS

The following set of instructions constitutes what is envisaged as a required sequence of pre-flight system checks and adjustments.

Sensor:

(1) The filters requested by the user (see Table B.1) should be mounted in the appropriate photometer units (each photometer unit is stamped with a number on the rear end plate). The sensor units can be unscrewed to expose the filters which are mounted in aluminum cells and are secured by 3 screws. The 3

protruding screws on the filter cells provide the manual grip necessary to pull the cell from the photometer optics housing.

(2) Check that the 4 fibre optic bundles are properly seated in (i) the sensor head and (ii) the fibre bundle mount in the airplane roof. Also ensure that the fibre bundle number (1,2 3, or 4) corresponds to the photometer channel number which is stamped on the sensor rear mounting plate.

(3) The field of view (FOV) requested by the user (Table B.1) should be manually selected at each sensor head by rotating the aperture wheel until the appropriate number appears on the wheel perimeter.

TABLE B.1 Sample User's Photometer Specification Request

YORK/CRESS PHOTOMETER SPECIFICATION

PHOTOMER UNIT #	FILTER WAVELENGTH (nm)	FOV (milliradians)
1	445	100
2	581	100
3	750	100
4	960	100

SCENE TIME (sec) : 3
SOLAR CALIBRATION TIME (sec) : 2
PHOTOMETER RANGING: Automatic ______ Manual _____
DATA RECORDING: Mincom _____ ADAS _____

The following table specifies the relationship between the aperture wheel number, the FOV setting number displayed on the control unit,and the user requested FOV in milliradians.

Aperture Wheel Number	Control Unit FOV Number	FOV (mr)
10	5	100
5	4	50
2	3	20
1	2	10
0	1	0

<u>Control Unit</u>:

(4) Set the user-requested scene time and solar calibration time by setting the thumbwheel switches on the control panel.

(5) Master power ON. The motor control begins in a search mode in order to initialize the solar calibration mask in the proper position. With the solar calibration system on AUTO the "scene on" indicator light should alternate betwwen ON and OFF (with the above setting 3 seconds ON and 2 seconds OFF). In the event that the ON state is not maintained for the full set time, the system has not been properly initialized. Then turn master power OFF, ensure that scene time and solar cal. time are each set at 2 seconds or greater and repeat step (5).

(6) Power ON for photometer channels 1, 2, 3, and 4. The displays of filter wavelength and FOV which should now be illuminated permit verification of photometer parameters with the user-requested specs.

(7) Verification of satisfactory operation of the 4 photometer units is performed by observing the SIGNAL/RANGE* during a number of checks: (i) an observable signal level change is expected as the photometer is switching from scene to solar cal. state; (ii) if the FOV aperture wheel on the sensor is set to 0 the detector dark current level is displayed and expected to be between 0 and 2 volts with Range = 1.

(8) Verification of the operation of the A/D signal conversion and signal display is performed by depressing the 5 VOLT CAL. switch to give 5.00 volt signals on all 4 photometer signal displays followed by depressing the 0 VOLT CAL. switch to give 0.00 volts.

(9) The data recording devices connect to the photometer output signals at the rear panel of the control unit. For digital recording of data with ADAS, only the ELCO connector in the upper right side of the panel need by connected. For recording of analog data 9 BNC connectors are provided for connection to MINCOM. The interconnection data should be logged on the field sheet (see Table B.2)

B.3 DATA COLLECTION

With the system airborne, the following steps are suggested for the data collection:

---

* The SIGNAL/RANGE display for each photometer unit has the format S.SS.R where the signal voltage output is S.SS (0 to 5 volts) and R is the range or gain factor (R = 1, 2, 3, or 4).

(10) Bring sensor to fully operative state.

(11) Verify the user-requested photometer specifications

TABLE B.2 Sample Operator's Field Record Sheet

SENSOR - YORK/CRESS PHOTOMETER (MPPH)

DATE: ____________________

PROJECT ID (up to 10 characters): ______________________________

FLIGHT LINE # (up to 10 characters: ______________________________

RECORDING: MINCOM __________________ ADAS ____________________

MINCOM ROLL # ____________

Photometer Output	Mincom Track #
Cal. State Monitor	________
Signal 1	________
Range 1	________
Signal 2	________
Range 2	________
Signal 3	________
Range 3	________
Signal 4	________
Range 4	________

PHOTOMETER PARAMETERS:

	PHOTOMETER UNIT #			
	#1	#2	#3	#4
WAVELENGTH (nm)	________	________	________	________
FOV (Control Unit #)	________	________	________	________
5 VOLT CAL	________	________	________	________
0 VOLT CAL	________	________	________	________

SOLAR CAL. TIME (sec): ______________________________

SCENE TIME (sec): ______________________________

START TIME (DDD HH MM SSS): ______________________________

STOP TIME (DDD HH MM SSS): ______________________________

with the control unit display and record this information in the operator's field sheet (Table B.2).

(12) About 1 minute prior to the start of the flight line (i) press 5 VOLT CAL.; (ii) start data recording, and (iii) record the data start time on the field sheet. This calibration signal should be maintained for about 30 seconds at which time simultaneously release 5 VOLT CAL and depress 0 VOLT CAL. At the beginning of the flight line release 0 VOLT CAL permitting the photometer data to be recorded.

(13) At the end of the flight line (i) depress 5 VOLT CAL for about 30 seconds, then release 5 VOLT CAL and (ii) depress 0 VOLT CAL for 30 seconds after which (iii) stop recording and note the data stop time on the field sheet.

(14) Repeat steps 11, 12, and 13 for each flight line. The purpose of the 5 volt - 0 volt signal segments around each block of flight line data is to aid in the data processing.

B.4 SUPPLEMENTAL CONDITIONS

In addition to the operational procedures outlined above, users interested in obtaining reliable quantitative data should confirm prior to each flight each of the following experimental conditions:

1) Data interpreters from each user agency (i.e. CCIW or its agent) should accompany each flight to record a variety of environmental conditions related to data correction - these should include:

   i) Surface conditions
   ii) Glint patterns
   iii) Qualitative assessment of water colour
   iv) Cloud cover
   v) Haze or fog conditions
   iv) Visibility

2) Operators should ensure and verify recalibration checks before each flight or series of flights.

3) Verify that sensor angle is truly vertical. It is important for interpretive purposes that data be collected normal to the water surface.

4) Flight line flexibility might be encouraged. During the June 10 lake Erie overflight, a substantial oil slick apparently associated with a nearby ship was visually sighted near the mid point of the line. In such instances a line diversion to obtain data from such violations should be encouraged.

REFERENCES

Adel, H., (1976), Canada Centre for Remote Sensing, Ottawa, personal communication

Bukata, R., (1976), Canada Centre for Inland Waters, Burlington, Remote Sensing Section, personal communication

de Villiers, J.N., (1976), Canada Centre for Remote Sensing, Ottawa, personal communication

Hulburt, E.O., (1943), J.O.S.A., 33, 42

Jain, S.C., Miller, J.R., McNeil, W.R., (1975), "An Evaluation of a Mathematical Model for Water Colour Spectral Analysis", Proc. 3rd Cdn. Symp. on Remote Sensing, Edmonton, Alberta

Jain, S.C., Miller, J.R., (1976), "An Optimization Approach to the Determination of Subsurface Water Parameters from Remotely Sensed Water Colour Data", Applied Optics, to be published

Kruus, J., (1974), "Remote Sensing of Sedimentation and Water Quality", Report to Hydrology Working Group of CACRS, Dec.,

McNeil, W.R., (1975), "Study and Evaluation of Remote Spectral Measurements in Water Quality Surveillance", Final Report to CCIW, DSS Contract 12SQ.KL347-4-0082

McNeil,W.R., Thomson, K.P.B., Jerome, J., (1976), "The Application of Remote Spectral Measurements in Water Quality Monitoring", Can. J. Rem. Sensing, April, to be published

Miller, J.R., Jain, S.C., (1976), "Software Development for the Analysis and Interpretation of the CCRS YORK/CRESS Photometer Data", Final report to CCIW, Jan.

Miller, J.R., (1976), York University, Centre for Research in Experimental Space Science, personal communication

Pieau. J., Miller, J., (1975),"YORK/CRESS Silicon-Photodiode Photometer Model MPPH/75," CCRS Sensors Section, Ottawa

Ramsey, R.C., (1968), "Study of Remote Measurements of Ocean Color", NASW -1650, TRW Report to NASA

Rodgers, G.K., (1968), "Heat Advection within Lake Ontario in Spring and Surface Water Transparency Associated with the Thermal Bar", Proc. 11 Conf. Great Lakes Res., 480-486