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The Blue-to-Green Reflectance Ratio and Lake Water Quality

Monitoring from aircraft or space considerably reduces the amount of *in situ* sampling required.

Introduction

One alternative to the enormous effort required for extensive sampling of water resources is the use of satellite and aircraft imagery. Such imagery cannot substitute completely for *in situ* measurements of physical, chemical, and biological variables; however, the data can provide substantial assistance in a synoptic evaluation of the water quality of lakes.

Abstract: *Correlations between the relative values of the blue and green reflectances of a lake and water quality indices, such as depth of photic zone, Secchi disk transparency, attenuation coefficient, and chlorophyll concentration, have been observed during an intensive satellite, aircraft, and surface vessel study of Lake Ontario and Conesus Lake. Determinations of blue and green reflectances from Skylab S190A color imagery are in excellent agreement with values obtained from small-scale color imagery from aircraft. Further, the accuracy of the satellite data appears within that required for extrapolation to the water quality indices. The study has also determined that changes in chlorophyll, lignin, and humic acid concentration can be discriminated by the behavior of the blue-to-green reflectance ratio and the reflectances of the green and red bands.*

The objective of this study was to evaluate satellite and aircraft measurements of lake reflectances, particularly the relative values of blue and green reflectances, as indices of water quality. Recent papers and extensive reviews (Graham, 1966; Fruh *et al.*, 1966; Stewart and Rochlich, 1967; Piech and Walker, 1971; Likens, 1972; Bukata *et al.*, 1974; Strong, 1974; Thomson *et al.*, 1974; Wrigley and Horne, 1974; Boland, 1976) have indicated that optical properties of lakes and related chlorophyll values are important in water quality and trophic assessments. Our investigation, involving remote sensing and field work, extends the relationship between trophic parameters and optical properties by comparing selected water quality indices and reflectance ratios for lakes of varying trophic character. The investigation has also developed a promising methodology for differentiating changes in chlorophyll, lignin, and humic acid concentrations.

The two lakes given the most attention during this study were Lake Ontario, the easternmost Great Lake, and Conesus Lake, the westernmost Finger Lake in New York State. Aircraft imagery were obtained for Lake Ontario in 1972 and 1973, and for Conesus Lake in 1973. Satellite imagery also was collected over Lake Ontario in 1973. *In situ* measurements of physical,

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chemical, and biological variables were obtained on both lakes. The Lake Ontario data were gathered in 1972 during the International Field Year on the Great Lakes (IFYGL), while the *in situ* data for Conesus Lake were obtained in 1973.

The primary technique for data analysis involved densitometry of color imagery and subsequent analyses to remove atmospheric and film processing effects from the photographic data. Accurate measurements of the ratios of broad band reflectances could then be obtained. The reflectance data were compared with *in situ* measurements of Secchi disk, irradiance, and chlorophyll in an attempt to derive relationships between changes in the optical and changes in the trophic variables.

Methods

Lake Data

The Secchi disk measurements were made with all-white disks (30 cm dia.) on Lake Ontario and black-and-white disks (20 cm dia.) on Conesus Lake. Irradiance measurements at depth in Lake Ontario were made with a Hydro Products Relative Irradiance meter equipped with a green filter (Wratten #58).

Water samples for chlorophyll(a) were collected at numerous stations in Lake Ontario by personnel of the Canada Centre for Inland Waters aboard vessels *Porte Dauphine*, *Limnos*, and *Martin Karlsen*. Chlorophyll values were determined by the spectrophotometric method of Strickland and Parsons (1968). Sample values from one and five metres were averaged and then a lake-wide average was determined.

Water samples for chlorophyll(a) from Conesus Lake were collected by boat from selected sites with an "integrated" open tube sampler (according to Lund, 1949) and analyzed by the spectrophotometric method of Lorenzen (1967). Chlorophyll(a) values from both lakes were corrected for pheopigments.

Aerial Data

The aerial data base consisted of color imagery from aircraft (Piper Aztec and B-26) and satellite (Skylab) overflights. The aircraft imagery utilized Ektachrome MS2448 color film from Hasselblad 500EL cameras with 80 mm focal length lenses. The Skylab imagery utilized SO242 film from the Skylab S190 camera package.

The three color film layers (red-, green-, and blue-sensitive) provided information on the color of the lakes in each photograph. A densitometer measurement of each film layer thus could provide a measurement of the brightness of the lake in the three color bands. Atmospheric and film processing effects, however, modify the color of the lake. Therefore, before the color information could be related to trophic indices, the atmospheric and film processing effects had to be removed from the density information in each film band.

A method to measure these effects and relate exposure values to reflectance values has been described previously (Piech and Schott, 1974; Piech and Walker, 1974; Piech *et al.*, 1975). The method uses densitometry of shadows within the image to establish the additive exposure caused by the atmosphere and the transmission loss through the atmosphere. Shadows cast (on land) by buildings near the shorelines of the lakes were used to calibrate the color imagery and thus relate film exposure to lake reflectance. Detailed analyses of the accuracy of the shadow calibration process have shown that reflectance ratios can be measured to an accuracy of ± 10 percent of the ratio value (Piech *et al.*, 1975). Such an accuracy appears sufficient to measure changes in chlorophyll concentration.

Laboratory Data

The lake sampling and aerial data were supplemented by a laboratory investigation of reflectance changes caused by varying amounts of chlorophyll, lignin, and humic acid.

The major difficulties associated with such a laboratory experiment are reproducing the geometry and illumination conditions of a large lake satisfactorily. The geometry of the problem is that of an infinite half space (an infinite half space approximates a large deep lake, i.e., a medium with x and y extent from $-\infty$ to $+\infty$ and z extent from 0 to $-\infty$). Constructing an approximation to the half space while retaining the ability to vary the parameters of the medium is difficult. Similarly, it is difficult to create satisfactory illumination over the half space approximation.

The above difficulties were resolved by the apparatus of Figure 1. A square tube, 0.07 metres on the side and 0.5 metres long, was lined with aluminum foil so that specular reflections from the foil would approximate a slab with infinite extent in directions perpendicular to the long axis of the tube. The tube was immersed in a vat of water, approximately 0.5 m^3 in volume, whose

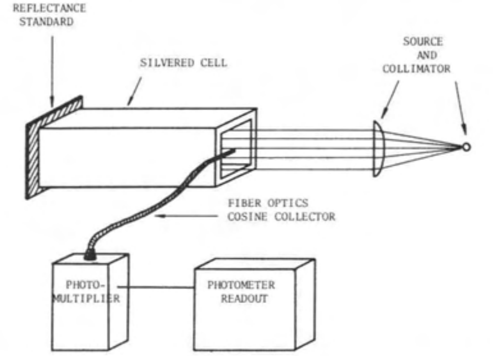

FIG. 1. Schematic of laboratory apparatus for reflectance measurement.

composition could be readily changed. A collimated tungsten source illuminated the tube at one end. The light reflected back from the tube was, in turn, collected by a fibre optics probe with a cosine collector head. The other end of the fibre optics bundle was integrated into the photomultiplier tube and electronics of the microdensitometer of the photointerpretation console described by Piech *et al.* (1975). Measurements were made in red, green, and blue spectral bands using Wratten 90 series filters.

The reflectance and transmission of the medium in the slab, r and t, were measured by monitoring the reflected signal from a set of known reflectance standards at the end of the slab. The reflectance of these standards ranged from 2 to 30 percent. The reflected signal, S, to first order consists of the signal reflected by the medium alone, $s(r)$, and that signal transmitted through the medium and reflected by the end reflector, i.e.,

$$S = at^2R + s(r) + c = mR + b \quad (1)$$

where R is the reflectance of the end reflector, and a and c are instrument constants. The correlation coefficient, r^2, for the linear fit between S and R was always in excess of 0.99 for all the test media. A set of six reflectance standards was used to establish the fit to Equation 1.

The apparatus was calibrated using distilled water as a standard. Letting the subscript o denote distilled water,

$$S_o = at_o^2R + s(r_o) + c = m_oR + b_o \quad (2)$$

The values adopted for distilled water transmission in the red, green, and blue spectral bands were 75.0, 93.3, and 98.1 percent per metre, respectively, or t_o = 86.9 percent, 96.6 percent, and 99.0 percent.

Comparison of the slopes of the test and standard media then yields t through

$$t = t_o \sqrt{\frac{m}{m_o}}. \quad (3)$$

The difference between the intercepts of the test and standard media curves yields r through

$$b - b_o = s(r) - s(r_o) \approx s(r), \text{ and} \quad (4)$$

$$r = \frac{s(r)t_o^2}{m_o}. \quad (5)$$

The reflectance for infinite depth was obtained from the diffuse reflectance, r, and transmission, t, of the tube or slab by consecutive computation of the reflectance, r_2, and transmission, t_2, of slabs with double thickness. The necessary equations are

$$r_2 = r + \frac{t^2 r}{1-r^2}, \quad (6)$$

$$t_2 = \frac{t^2}{1-r^2}. \quad (7)$$

The doubling was continued until no change in the reflectance was obtained.

The properties of the medium were varied by additions of chlorophyll, lignin, and humic acid. The chlorophyll was added in the form of water-soluble chlorophyll; the lignin was in the form of bleached hardwood paper pulp. Since the chlorophyll was on a soap substrate, the weight of water-soluble chlorophyll necessary to simulate a given concentration of *in vivo* chlorophyll was determined by matching spectral responses on the standard spectrometer method for measuring chlorophyll concentration. The chlorophyll concentrations were varied from 0 to 7 μg/L while lignin concentration ranged from 0 to 70 mg/L and humic acid from 0.5 to 1.8 mg/L.

A major difficulty with the experiment proved to be the soap substrate of the water-soluble chlorophyll. The original intent was to modify the chlorophyll concentration while keeping the scattering turbidity constant so that a model could be developed for chlorophyll concentration at varying degrees of background turbidity. Unfortunately, the soap substrate modified the background turbidity by contributing a spectrally uniform scattering as chlorophyll concentration was changed. The net effect of this background turbidity was to dampen changes in the reflectance ratios.

Reflectance change with addition of both chlorophyll and lignin was linear. As the amount of chlorophyll was increased, the increased scattering by the substrate effectively cancelled the increasing absorption of the chlorophyll in the blue. The blue reflectance thus remained a uniform 4 percent from 0 to 7 μg/L. The green reflectance varied from 2.7 to 7.2 percent over this concentration range, while the red reflectance changed from 1.1 to 2.9 percent. The corresponding variation in the blue-to-green reflectance ratio was from 1.5 to 0.6, with the variation being approximately linear. Reflectance of the medium with lignin variation was 4 percent to 11 percent in the blue, 2.7 percent to 8.5 percent in green, and 1.1 percent to 5.7 percent in red.

The data obtained by individual variation of the three components were supplemented by joint variation of the components. As a result, it was possible to develop a set of discriminators for determining whether a turbidity change is caused by a variation in lignin, chlorophyll, or humic acid.

Results

RATIOS

The study of Lake Ontario during 1972 established the feasibility of monitoring selected water quality indices using aircraft imagery at scales as small as 1:50,000. The study demonstrated that indices such as depth of photic zone (1 percent relative irradiance in green spectral region), Secchi disk transparency, total attenuation coefficient, and chlorophyll concentration could be related to the ratio of blue lake reflectance to green lake reflectance as measured from the color film imagery. Figure 2 illustrates these relationships using lake-wide averages, i.e., averages over all lake stations occupied. Although station by station comparisons are more complex, the data of Figure 2 generally indicate a surprising seasonal relationship between the various parameters. The ratio of blue-to-green reflectance is inversely proportional to chlorophyll concentration and coefficient of total attenuation and directly proportional to photic zone depth and Secchi disk transparency.

A key aid in water quality evaluation of lakes from optical data would be the use of satellite imagery. A test was therefore conducted to determine if lake reflectances could be measured to sufficient accuracy for such assessments from Skylab imagery.

Figure 3 is a Skylab S190A image (from an altitude of ~435 km) of Lake Ontario in which the Skylab satellite track and two aircraft tracks are indicated. The simultaneous aircraft underflights were at an altitude of 3 km on two north-south tracks separated by approximately 50 km.

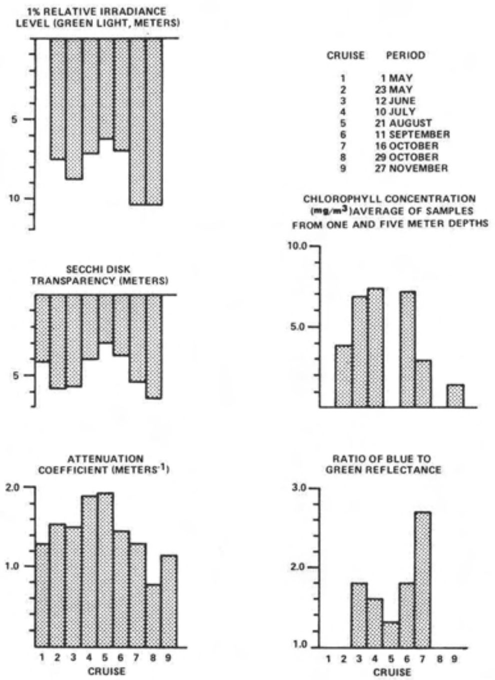

FIG. 2. Comparison of optical and biological data obtained from surface vessel and aircraft measurements during the International Field Year on the Great Lakes (1972). Data represent lake-wide averages. Chlorophyll data supplied by Canada Centre for Inland Waters.

The S190A image of Lake Ontario was processed to remove atmospheric effects in order to yield a color encoded display of the blue-to-green reflectance ratio, and the data from this display were compared to the aircraft data at a scale of 1:40,000. About 15 photographs were obtained on each aircraft track, with each photograph covering an area of about 6.6 km^2.

The ground resolution of the Skylab imagery was only 15 to 30 metres, insufficient for the shadow calibration mentioned earlier. The Skylab imagery was calibrated using reflectances of objects measured on previous flights, e.g., coal piles and aircraft runways (Piech *et al.*, 1975). The aircraft imagery was calibrated using shadow analyses at the ends of the aircraft tracks.

Figure 4 compares the satellite and aircraft data obtained on the two tracks. The aircraft points include error bars corresponding to ± 12 percent of the blue-to-green reflectance ratio and ± 1.6 km in aircraft position. The statistical correlation between reflectance ratios of the satellite and aircraft is excellent (correlation coefficient = 0.87 in Olcott to Gold Point flight and 0.98 in the Troutberg to Chub Point flight, highly

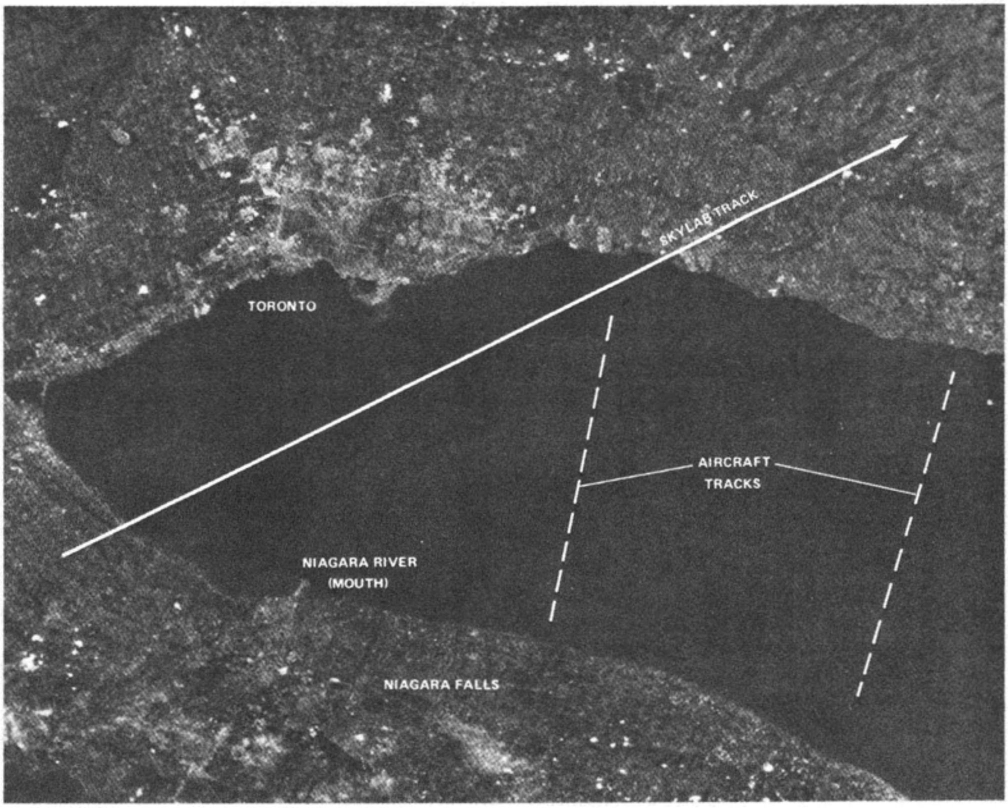

FIG. 3. Black-and-white copy of a Skylab S190A color image of the western half of Lake Ontario, 9 Sept. 1973. Two frames of imagery covered the lake on this Skylab pass. The large urban complex on the north shore is Toronto. The discharge on the south shore just west of the Niagara River is the Welland Canal. The Niagara Falls and the white water of the lower Niagara River can be observed just to the south of the two power station reservoirs which straddle the Niagara River. The altitude from which this image was taken was ~435 km. Resolution on the original transparency is superior to this copy.

significant in both cases). This indicates that either S190 imagery or aircraft imagery may be utilized for defining the optical properties of the lake using relationships similar to those obtained on the IFYGL program.

The relationship between the optical and trophic parameters is dependent on the physical properties of the lake being studied. For example, Figure 5 contains the relationship between blue-to-green reflectance ratio and chlorophyll concentration for Conesus Lake, as obtained on the Skylab effort. Again, a strong dependency is evidenced with a marked blue-green minimum occurring at maximum chlorophyll concentration, although the specific relationship of chlorophyll concentration and ratio level differs from the Ontario values. The variation occurs because Conesus and Ontario are quite different in physical character. For example, Conesus is darker than Ontario, having a green reflectance of about 2 percent com-

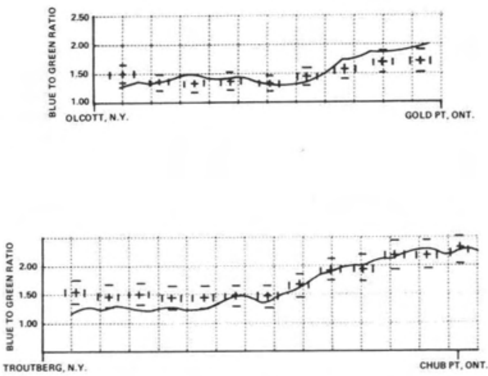

FIG. 4. Comparison of S190 measurements of blue-to-green reflectance ratio along the aircraft tracks (solid line) with the aircraft measurements (crosses and error bars). Each division on the horizontal axis represents 4.8 km. Correlation coefficient between blue-to-green ratio measurements by S190A satellite and small aircraft is 0.87 for the upper plot and 0.98 for the lower plot, statistically highly significant in both cases.

pared to a reflectance of 3 percent for Lake Ontario. The darker the lake, the greater the effect chlorophyll absorption can be expected to have on the blue-green ratio. The actual situation is, of course, more complicated than this simple model.

A major area of further research therefore involves generalizing the relationships between aerial and surface data. By way of example, Conesus and Canadice Lakes (the latter of which is a shorter but deeper Finger Lake near Conesus Lake) had approximately the same range of chlorophyll and Secchi disk values at the time these measurements were made. The Canadice blue-to-green ratio values which correspond to the Conesus values of Figure 6 are: 7 May, 1.5; 19 June, 0.3; 13 August, no data; and 9 September, 1.4. The close correspondence between the blue-green ratios of Conesus and Canadice, even though specific chlorophyll data for Canadice are not available on these dates, is encouraging. This correspondence, coupled with the correlation of the aerial and surface data for both Conesus Lake and Lake Ontario, leads us

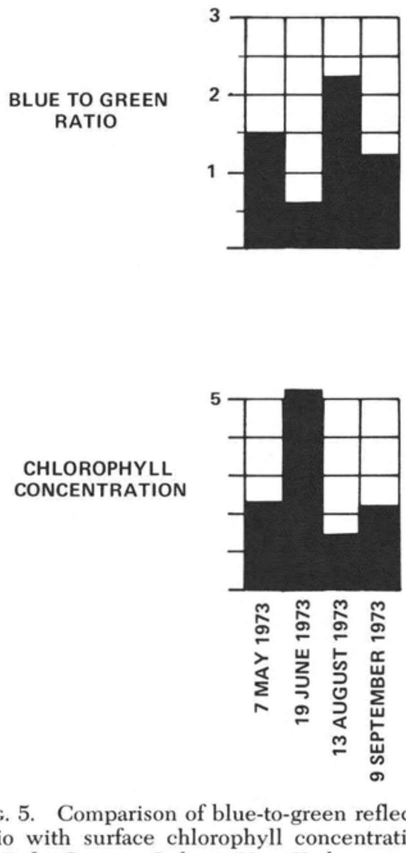

FIG. 5. Comparison of blue-to-green reflectance ratio with surface chlorophyll concentration in mg/L for Conesus Lake in New York.

to believe that general relationships valid for lakes of a given trophic classification can be developed, and that such understanding will serve to significantly broaden the scope of application of sophisticated satellite photography.

LIGNIN AND HUMIC ACID

The laboratory measurements of reflectance versus chlorophyll, lignin, and humic acid concentration attempted to broaden this understanding. The laboratory data also provided a method for relating color or turbidity changes to changes in concentrations of chlorophyll, lignin, or humic acid.

The discriminators for changes in chlorophyll, lignin and humic acid are listed in Table 1. In essence, the data indicate that changes in any of the three components can be discriminated by the blue-to-green reflectance ratio and reflectances of the green and red bands. The blue-to-green ratio is inversely proportional to chlorophyll concentration, does not vary with humic acid, and is directly proportional to the amount of lignin. The green and red reflectances are directly proportional to both chlorophyll and lignin, while the green reflectance is inversely proportional to humic acid and red reflectance is unchanged by humic acid. Measurements of the blue-to-green reflectance ratio and green and red band reflectances thus appear sufficient to specify variations in chlorophyll, lignin, and humic acid concentration. Use of Table 1 in studying the Skylab image of Figure 3 indicates that major turbidity changes may be caused by changes in chlorophyll concentration. However, it is also apparent from investigations of Dobson *et al.* (1974) and Bukata *et al.* (1974) that some variations in turbidity may also be related to particulate matter and suspended sediment.

Application of the discrimination rules of Table 1 would facilitate investigations such as studies of the effects of power plant discharges on neighboring water quality, evaluation of the impact of chlorination of power plant discharges on algal concentration, and a study of the effects of sewage treatment outfalls on stream or river conditions.

These discrimination rules have been applied to aerial imagery of power plant discharges into the Hudson River (Schott and Gaucher, 1977). Comparison of the aerial predictions based on Table 1 were verified by surface data collected simultaneously with the aerial overflights. The validity of the general behavior between

TABLE 1. DISCRIMINATORS FOR CHANGES IN CHLOROPHYLL, LIGNIN AND HUMIC ACID*

Variable	Change	Discrimination Equation
chlorophyll	increase	if $\frac{B}{G} < \frac{B1}{G1}$ and $G \geq G1$ and $\frac{B}{R} < \frac{B1}{R1}$
chlorophyll	decrease	if $\frac{B}{G} > \frac{B1}{G1}$ and $G < G1$ and $\frac{B}{R} > \frac{B1}{R1}$
lignin	increase	if $R \geq R1$ and $G \geq G1$ and $\frac{B}{G} \geq \frac{B1}{G1}$ and $\frac{G}{R} < \frac{G1}{R1}$
lignin	decrease	if $R \leq R1$ and $G \leq G1$ and $\frac{B}{G} \leq \frac{B1}{G1}$ and $\frac{G}{R} > \frac{G1}{R1}$
humic acid	increase	if $\frac{B}{R} < \frac{B1}{R1}$ and $G < G1$ and $\frac{B}{G} < \frac{B1}{G1}$
humic acid	decrease	if $\frac{B}{R} > \frac{B1}{R1}$ and $G > G1$ and $\frac{B}{G} > \frac{B1}{G1}$

* R1, G1, and B1 are the red, green and blue reflectances respectively at some arbitrary reference level and R, G, and B are the reflectances at the sample points.

chlorophyll concentration and the blue-to-green reflectance ratio observed on Lake Ontario and Conesus Lake for the very turbid waters of the Hudson River is quite encouraging.

SIGNIFICANCE

Our results indicate that relative chlorophyll concentrations can be monitored using blue-to-green reflectance ratios. Because the chlorophyll/reflectance relationship may vary between lakes of different trophic character and even within a lake, a general relationship between chlorophyll and reflectance data cannot have uniform application to all lakes. The *in situ* sampling requirements are, however, significantly reduced by aerial monitoring while at the same time a more complete description of lake behavior is obtained.

ACKNOWLEDGMENTS

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Optical Science and Engineering Short Course

The course will be given at the Doubletree Inn in Tucson, Arizona, by members of the faculty of the Optical Sciences Center, the University of Arizona, 2 to 12 January 1979. The purpose of the course is to acquaint both the specialist and the nonspecialist engineer or scientist with the latest techniques in the design and engineering of optical systems. The course comprises 17 three-hour lectures; detailed notes will be supplied.

The wide range of topics that will be covered includes geometrical and physical optics, optical system layout and design, Fourier methods, polarized light, radiometry and photometry, image quality, adaptive optics, optical testing, photodetectors, infrared systems, photographic and CCD systems, low light level television systems, lasers, and sampled imagery and digital image processing.

Address inquiries to Professor Philip N. Slater, Optical Systems & Engineering Short Courses, Inc., P.O. Box 18667, Tucson, Arizona 85731, or telephone 602-626-4242.

Inventory of Programs in Science, Mathematics, and Engineering for Women and Girls

The National Science Foundation has asked the American Association for the Advancement of Science to survey programs in science for women and girls. The results will appear in a publication that describes all efforts made between 1966 and the present to improve the science, mathematics, and engineering education of girls and women in the United States and to increase their participation in science related careers.

Programs directed at any age level will be eligible for inclusion, as will work conducted by any type of organization or agency. Projects of direct benefit to women and girls and research on the topic will be surveyed.

Persons who know of projects which might be within the scope of this inventory are asked to contact Dr. Michele L. Aldrich, OOS-AAAS, 1776 Massachusetts Avenue N.W., Washington, DC 20036, 202/467-5431.