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TESTS OF THE DUAL DIFFERENTIAL RADIOMETER UNDER FIELD CONDITIONS

by

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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report assesses the use of the dual differential radiometer to remotely determine chlorophyll a values in United States lakes and reservoirs. The results obtained should be of value to prospective users of this and similar remote sensing instrumentation; many of the problems encountered are common in the use of spectral data for remote sensing. Raw data and further information can be obtained from the Water and Land Quality Branch, Monitoring Operations Division.

George B. Morgan
Director
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ABSTRACT

A dual differential radiometer was tested on numerous eastern United States lakes and reservoirs. Remotely sensed data were compared with ground-truth chlorophyll a values. Results indicate that the instrument has only limited application in the remote sensing of chlorophyll a in the nation's lakes. At its present state of development, its use should be confined to large, deep, relatively clear water bodies in conjunction with ground-truth and surface survey efforts.

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INTRODUCTION

Remote sensing of water quality parameters would allow rapid, cost-effective surveys and monitoring of surface waters. Arveson et al. (1971) utilized a dual differential radiometer to remotely measure chlorophyll a in Pacific Coast waters with fair precision. Their success led to interest in the instrument as a possible device to rapidly survey water bodies throughout the United States and to estimate their trophic state on the basis of observed chlorophyll a values.

The National Eutrophication Survey (NES) was a U.S. Environmental Protection Agency (U.S. EPA) research effort investigating the threat of accelerated eutrophication in freshwater lakes and reservoirs. Nationwide in scope, it was designed to develop, in conjunction with State environmental agencies, information on nutrient sources, concentrations, and impacts on selected surface water bodies. Consequently it was decided to test the differential radiometer as a possible vehicle to measure chlorophyll a levels in NES lakes.

Two dual differential radiometers were obtained from the National Aeronautics and Space Administration's Ames Laboratory (NASA/Ames) and installed aboard National Eutrophication Survey helicopters. These units were tested during the 1972 and 1973 field operations. Tests were conducted on lakes and reservoirs which varied in size, shape, depth, and water quality. Water colors ranged from red/brown to blue, and Secchi disc transparency ranged from a few centimeters to over seven meters. Although not quantitatively measured, suspended sediments were noted in many of the water bodies at the time of the sampling. These tests were conducted within the framework of the NES sampling effort. Therefore, testing was limited largely to obtaining spot readings when approaching or departing a lake sampling site. Few transects were obtained due to time restrictions.

The purpose of this report is to present the results of our experience in using the dual differential radiometer to measure chlorophyll a.

CONCLUSIONS

The concept of the dual differential radiometer is basically straightforward. The instrument is small, relatively inexpensive, and electronically simple. It may be readily installed in light aircraft without difficulty. Because of these considerations and the capabilities demonstrated by both Arveson et al. (1971) and NES tests on Lake Mead, it is felt that the instrument can be successfully utilized in some situations.

The radiometer could be of great value in contouring chlorophyll content in a lake of relatively low turbidity. However, it cannot be effectively employed without collection of simultaneous ground-truth data until the presence or absence of interferences is established. For successful utilization it should be operated by a well-trained individual and receive a high operational priority. Possible interferences should be known, considered, and compensated for if necessary.

Although the National Eutrophication Survey tests of the dual differential radiometer were often compromised by time, space, weather and other considerations, sufficient data were collected to permit the following specific conclusions:

1) The dual differential radiometer has limited application in the remote sensing of surface chlorophyll a.

2) A large proportion of U.S. surface waters has chlorophyll a levels above its effective range and/or has morphologic characteristics that preclude its use.

3) The dual differential radiometer could be a useful tool on large, relatively clear water bodies. It could provide adequate data for non-quantitative "survey" efforts, help define areas for most effective ground-truth sampling, and assist in extrapolating quantitative ground-truth data outside the immediate sampling area and interpolating between sample sites.

4) In spite of its basic simplicity, the instrument should be operated by a trained observer and close attention should be paid to the many possible interferences. Simultaneous ground-truth data should be collected.

5) Its use as a general field instrument on a broad range of lakes is not supported by the National Eutrophication experience.

RECOMMENDATIONS

The dual differential radiometer should not be considered a proven field instrument and used blindly without regard to the various possible interferences. As presently configured, it cannot be successfully utilized to measure chlorophyll a in areas of high turbidity. It is weather limited, requires a water body of substantial size and depth, cannot tolerate excessive boat wakes, and is subject to other interferences.

Based on the results of a literature review and the NES results, it is felt that calibration curves should be constructed for each different water body, and perhaps for the various seasons. (Typically, lacustrine phytoplankton populations shift from domination by diatoms in the spring to predominately blue-green or green algae in the summer. Suspended sediments would also typically be greater in the spring months than later in the year.) It also cannot be successfully used without considerable attention as to its operation. Frequent checks on solar zero, angle of view with respect to solar azimuth, elevation, and atmospheric conditions must be made.

Some ground tests of the dual differential radiometer should be conducted utilizing both channels simultaneously to attempt to separate out chlorophyll and non-chlorophyll effects. Immersion of the sensor bundle into the water would eliminate the reflection and skylight influences. Further field testing may allow for correction of many of the present interferences.

THEORY OF OPERATION

The dual differential radiometer is capable of measuring upwelling sunlight from bodies of water in four spectral bands. The system is designed for airborne operation and real time detection of small changes in spectral radiance. Its theory is based on a simple form of the correlation spectrometer. The instrument is configured to correlate the specific spectral characteristics unique to chlorophyll and reject or cancel the background.

The absorption spectra for a variety of phytoplankton have been determined (Yentsch 1960, Friedman and Hickman 1972, Grew 1973). These spectra indicate that for many species there is a maximum absorption in the blue region at about 440 nanometers (nm) due largely to chlorophyll, a relatively transparent region between 530 and 650 nm, and a secondary absorption maximum near the red at about 680 nm. These specific absorption bands modify upwelling sunlight from water at characteristic wavelengths corresponding to absorption maxima and minima.

To determine chlorophyll a, a sample filter with a maximum transmission at 443 nm, close to one of the absorption maxima of phytoplankton, is paralleled to a reference filter with a maximum transmission at 525 nm. This latter filter lies outside the major absorption region of the phytoplankton. The two selected wavelengths lie near the absorption minimum for water, thus minimizing its effect upon the returning radiation. Variations in upwelling light from a water body because of water surface roughness, scattering, or haze should have a similar effect on both wavelengths. Variations in the concentration of algae will primarily affect the intensity at the sample wavelength (443 nm). The resultant differential signal output can be calibrated by comparison with ground-truth chlorophyll a concentration (NASA/Ames n.d., Arveson et al. 1971). The rate of change of the differential signal obtained is such that the effective range of the radiometer is between 0.01 μg/l and 10 μg/l chlorophyll a. Above 10 μg/l the change in output voltage for a unit change in chlorophyll a is too small to be effective.

DESCRIPTION OF THE DUAL DIFFERENTIAL RADIOMETER

Two dual differential radiometers were obtained and labeled units A and B. Each radiometer consists of two main components, a sensor assembly and an electronics unit. The sensor assembly receives radiation through a fiber optics bundle. The bundle consists of randomly mixed fibers and is split into four sections. Behind each section is a bandpass filter to isolate the spectral region of interest. The passed radiation is detected by a silicon photodiode which produces an output voltage signal proportional to the incident radiation. The four output signals provide sample and reference signals to two channels, A and B.

The four output signals from the sensor assembly are further amplified within the electronics unit. The reference signals to channels A and B are amplified by fixed factors while the amplification factors to the sample signals are independently variable. This allows normalization of the signal pairs during solar standardization. The electronics unit also provides processing electronics to compute the algorithm:

$$SIG = \frac{10(I_r - I_s)}{I_r} \quad \text{Volts}$$

where I_r and I_s respectively represent the reference and sample signal levels in either channel A or B. In addition, the electronics unit contains precision voltage sources and null meters to provide signal offset over the range 110 volts to 10 volts and to determine the output voltage for each channel.

During the National Eutrophication Survey, only one channel was ever employed at any one time. Occasional changes from channel A to channel B were made, however this required internal switching of the filters and was not a frequent occurrence.

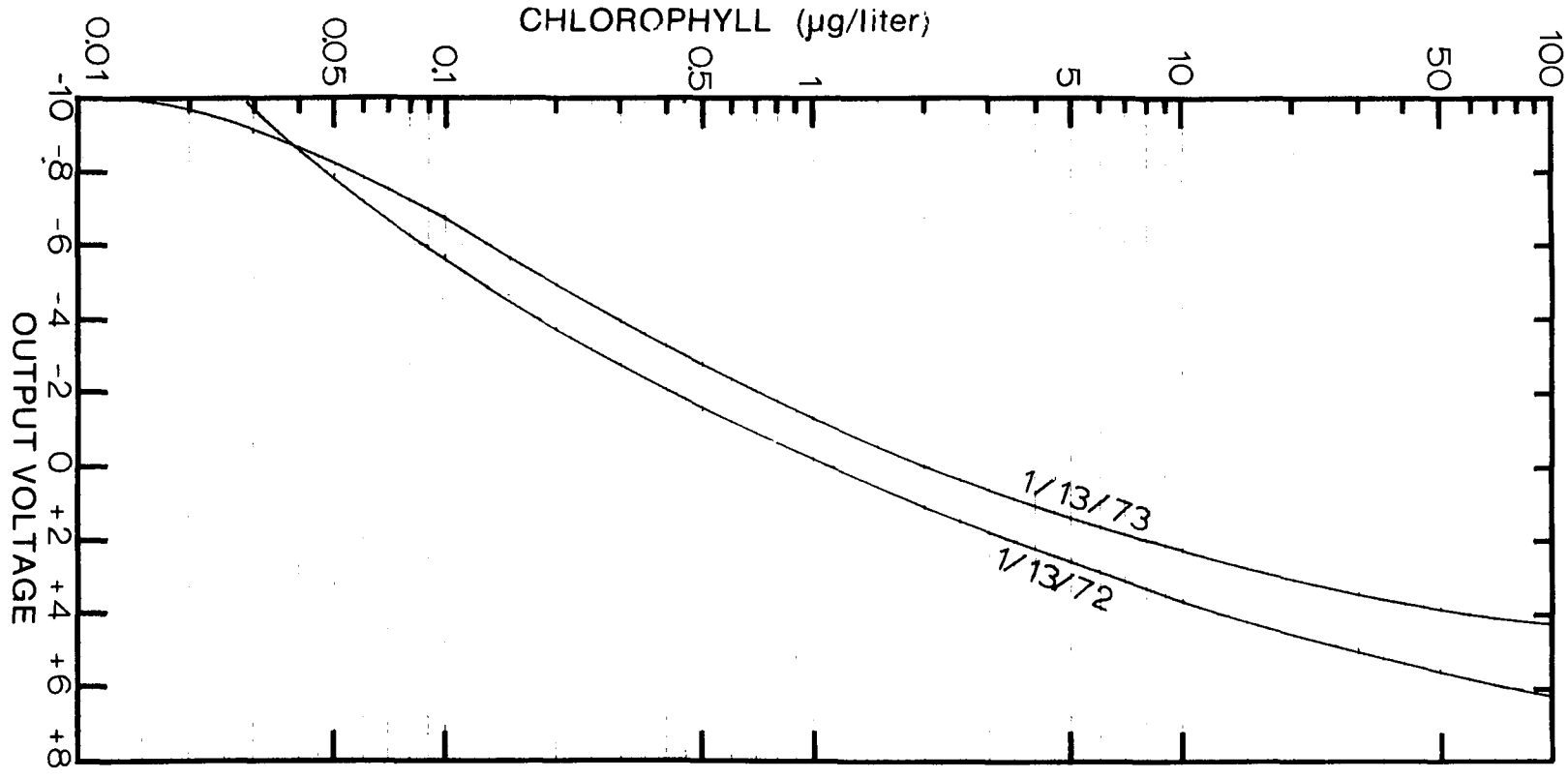
PROCEDURES

The dual differential radiometers were installed and tested aboard float-equipped Bell UH-1H "Huey" helicopters which were utilized in the National Eutrophication Survey. Voltage readings were obtained from the instruments while either approaching or departing an NES sampling station. At each site the helicopter would land on the water, perform in situ measurements, and collect water samples for later analysis (U.S. EPA 1974 and 1975). Samples for chlorophyll a analyses were collected at each station from water integrated from the surface to 4.6 meters (m) or to the lower limit of the photic zone, whichever was greater. In waters less than 4.6 m deep, the lower limit of the integration was a point just off the bottom. Samples were collected in unused polyethylene bottles and stored in an icebox aboard the helicopter. At day's end, they were removed and analyzed using a modification of the fluorometer procedure described by Yentsch and Menzel (1963). In addition, in 1973 surface samples were collected at specific sites for the specific purpose of comparing surface chlorophyll a values with the radiometer data.

During the 1972 field year, use of the dual differential radiometer was attempted utilizing an aligning yoke (located in the helicopter rotor well) which directed the sensor bundle's field of view 20° from the vertical in any selected quadrant. This configuration made calibration of the instrument a tedious, torturous process and exposed the sensor assembly to damage. Radiometer data showed little correlation with ground-truth chlorophyll a levels. This, coupled with a high amount of downtime, inadequate instructions in its use, and a work schedule demanding 10- to 12-hour days, 7 days a week, resulted in field researchers viewing the radiometer largely as a hindrance to more important work. Consequently, it received minimal attention and effort.

John Arveson of NASA/Ames Research Center visited the Environmental Monitoring and Support Laboratory-Las Vegas during the 1972-73 winter. He assisted in repairs and calibration, advised as to methods of installation, and instructed National Eutrophication Survey personnel in the use and peculiarities of the instruments. He also provided a new calibration curve (Figure 1) which incorporated additional data collected during 1972. Subsequently, the instrument was tested over Lake Mead, Nevada. The remotely obtained data compared very favorably with simultaneous ground-truth chlorophyll a data (Figure 2). It was therefore decided to continue testing the instrument during the 1973 National Eutrophication Survey field season in the Eastern and Southeastern United States.

The instrument was relocated such that the limnologist could aim the sensor bundle through an open window of the helicopter. The dual differential radiometer was calibrated daily (and often before each use) by aiming it at



1/13/72 - Original Curve 1/13/73 - Modified Curve

Figure 1. Radiometer calibration curve (after Arveson personal communication, 1973).

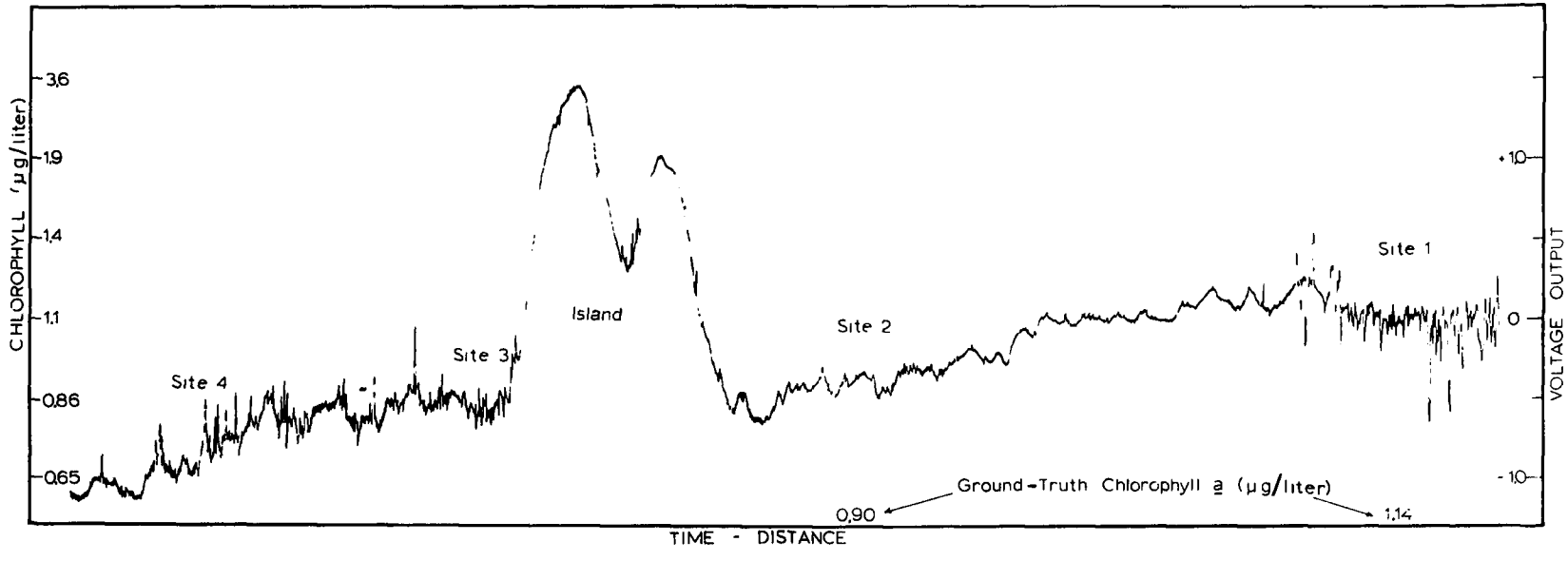


Figure 2. Radiometer strip chart record, Lake Mead (December 1972). Horizontal distance is approximately 10 kilometers and the chlorophyll scale is from the 1972 calibration curve.

the sun with a Teflon diffuser over the optic bundle. Since this was often done while airborne, concern as to the effect of the rotor shadow was expressed. Several simple experiments using the radiometer and several photometers were conducted. Measurements were made before and after starting the helicopter (i.e., with the rotors motionless and up to speed) and simultaneously inside and outside the rotor shadow. No appreciable effect on the calibration was observed, although a 5% light loss was encountered. Whenever possible, calibration was performed prior to takeoff with the rotor still or by banking the helicopter while in flight to allow a direct line to the sun.

Voltage readings were taken by pointing the sensor bundle at the water surface in a direction away from the sun. Measurements were taken at elevations from 60 to 150 m above the lake level during acceptable weather conditions.* Care was exercised to avoid including the helicopter's shadow, the float bag, or portions of the shoreline within the 30° field of view. Throughout these tests only one channel and filter pair per instrument were employed at one time. Changes from channel A to channel B were made periodically with no noticeable effect on the voltages obtained.

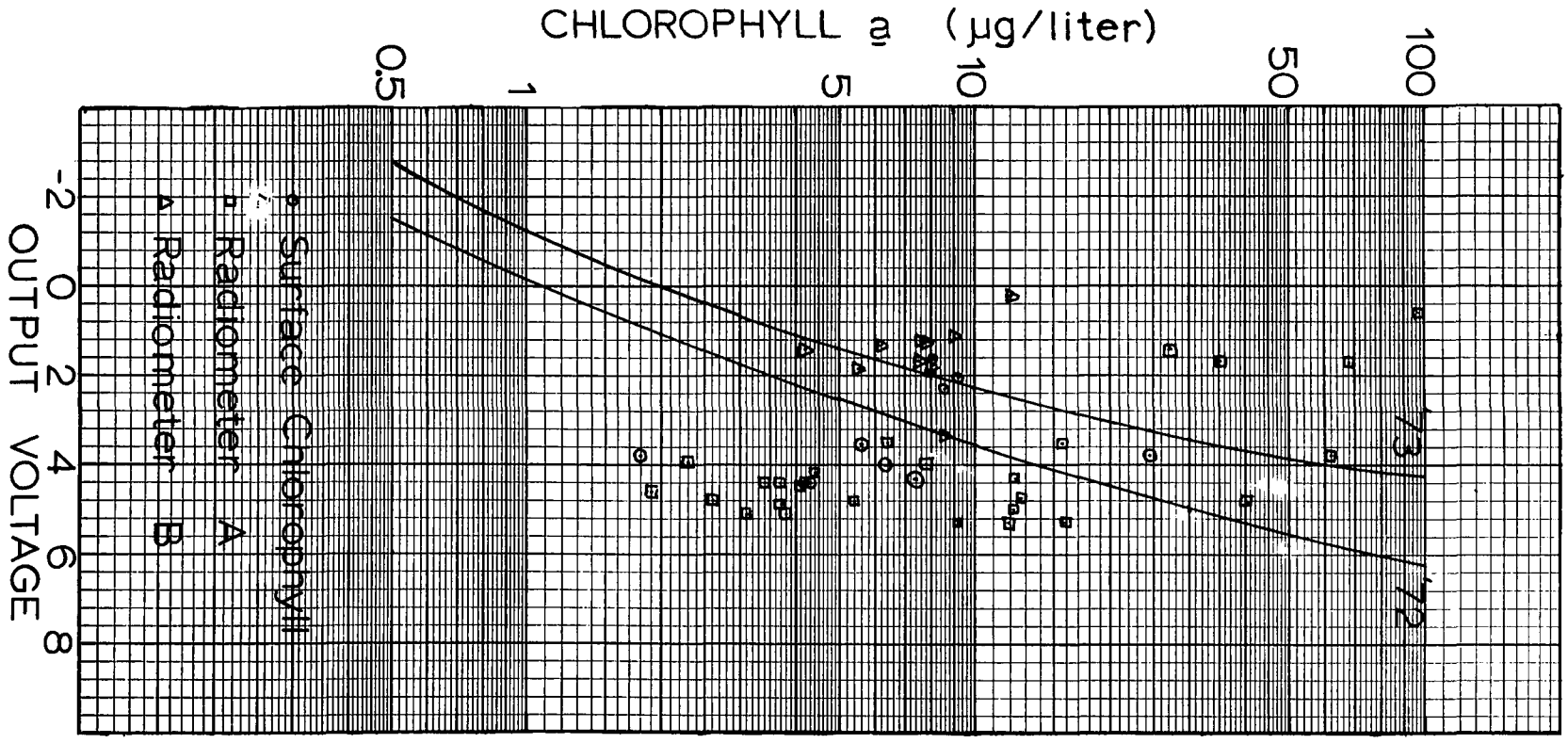
*Acceptable weather conditions are defined as enough available light existing to throw a readily visible shadow, when neither the water body nor the helicopter is in a cloud shadow, and water surface roughness does not exceed 10% whitecaps.

RESULTS

In the early spring of 1973, test flights dedicated to testing the dual differential radiometer were made on transects down Las Vegas Bay into Lake Mead proper. The area was selected for its proximity and because chlorophyll a levels were known to decrease from the upper end of the bay toward the main lake body. Figure 2 presents a reproduction of the strip chart record obtained from the radiometer on a transect flown about 150 m above lake level. Ground-truth data collected at sites 1 and 2 compare quite favorably. Because of rapidly deteriorating weather conditions, ground-truth data at sites 3 and 4 were not obtained.

During the 1973 NES field sampling in the Eastern and Southeastern United States, use of the radiometer was attempted when weather permitted. Voltage readings were obtained by directing the sensor bundle toward the sampling site upon approach or departure from an elevation which varied from 60 to 150 m above the lake. The lakes visited varied in size, morphology, trophic state, phytoplankton assemblage, and chlorophyll a level. Data collected are presented in Figure 3. It is readily apparent that the correlation between the output voltage and chlorophyll a levels is poor.

Mr. Arveson visited the NES team in the field and checked the calibration of the internal filters. He also performed some minor maintenance and again instructed personnel in the use of the instruments. Following this visit, several more tests of the differential radiometer were conducted. The results, utilizing the integrated chlorophyll a value, are presented in Figure 4. Data obtained were also reviewed on an individual lake basis (Figure 5). Again, no consistent relationship was apparent in either case.



○ Output voltage vs. chlorophyll a content of surface dipped water samples.

□ Output voltage from Unit A vs. chlorophyll a content of integrated water sample.

△ Output voltage from Unit B vs. chlorophyll a content of integrated water sample.

(calibration curves superimposed)

Figure 3. Radiometer output vs. chlorophyll a (Spring 1973 data).

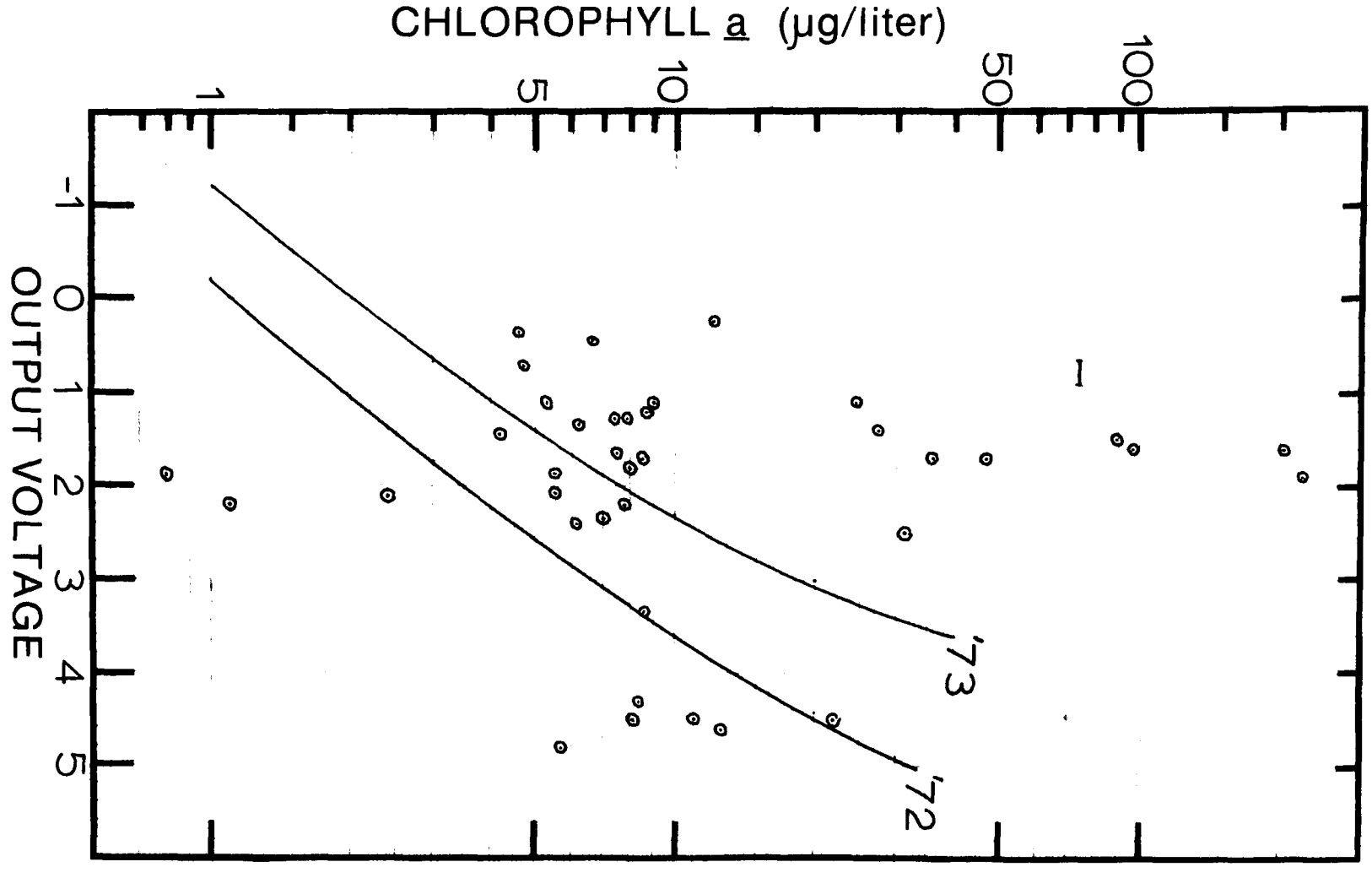
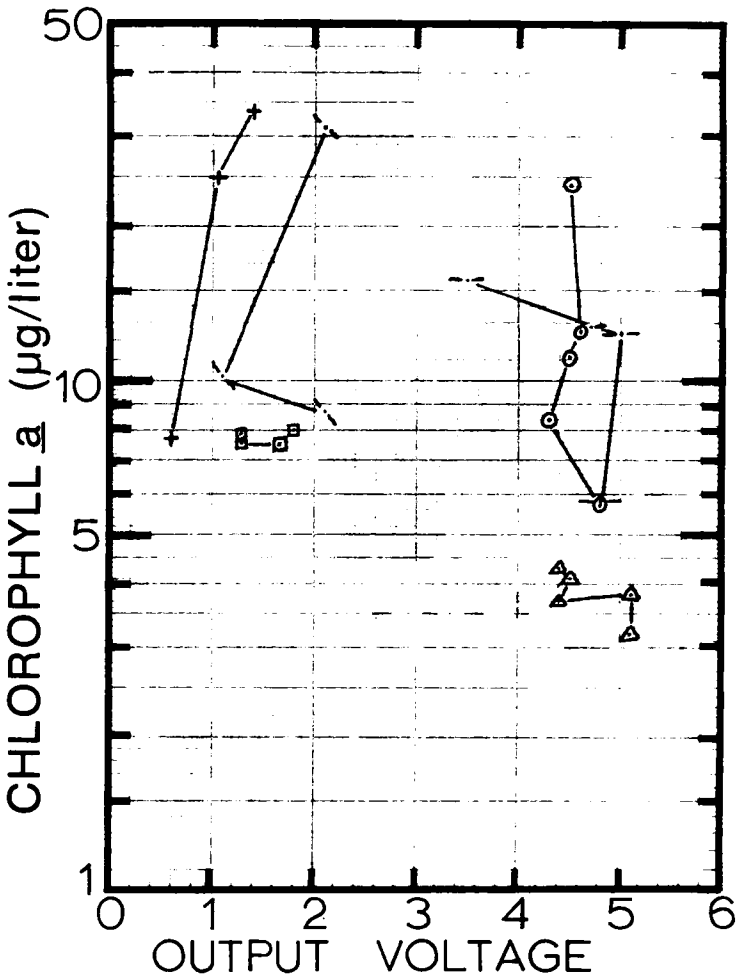


Figure 4. Radiometer output vs. integrated chlorophyll a, August 1973 data (calibration curves superimposed).



○ Old Hickory Reservoir, TN; 8/16/73
□ Cumberland Reservoir, KY; 8/21/73
△ Chickamauga Reservoir, TN; 8/23/73
+ Rend Lake, IL; 8/8/73
—— Berlin Reservoir, OH; 7/30/73
\ Lake Carlyle, IL; 8/10/73

(lines between points for clarity only)

Figure 5. Data for selected large reservoirs.

DISCUSSION

The results of testing the dual differential radiometer by NES personnal were generally poor. Little correlation between radiometer output voltages and chlorophyll a was evidenced. There are several probable reasons why this is so. Not the least of these is the fact that the instrument had a low priority among NES objectives and personnel commitment to its use was correspondingly low. The extremely hectic schedule of the NES field team left little opportunity for involved personnel to review data in detail, perform side experiments, and fully investigate the instrument and all its nuances.

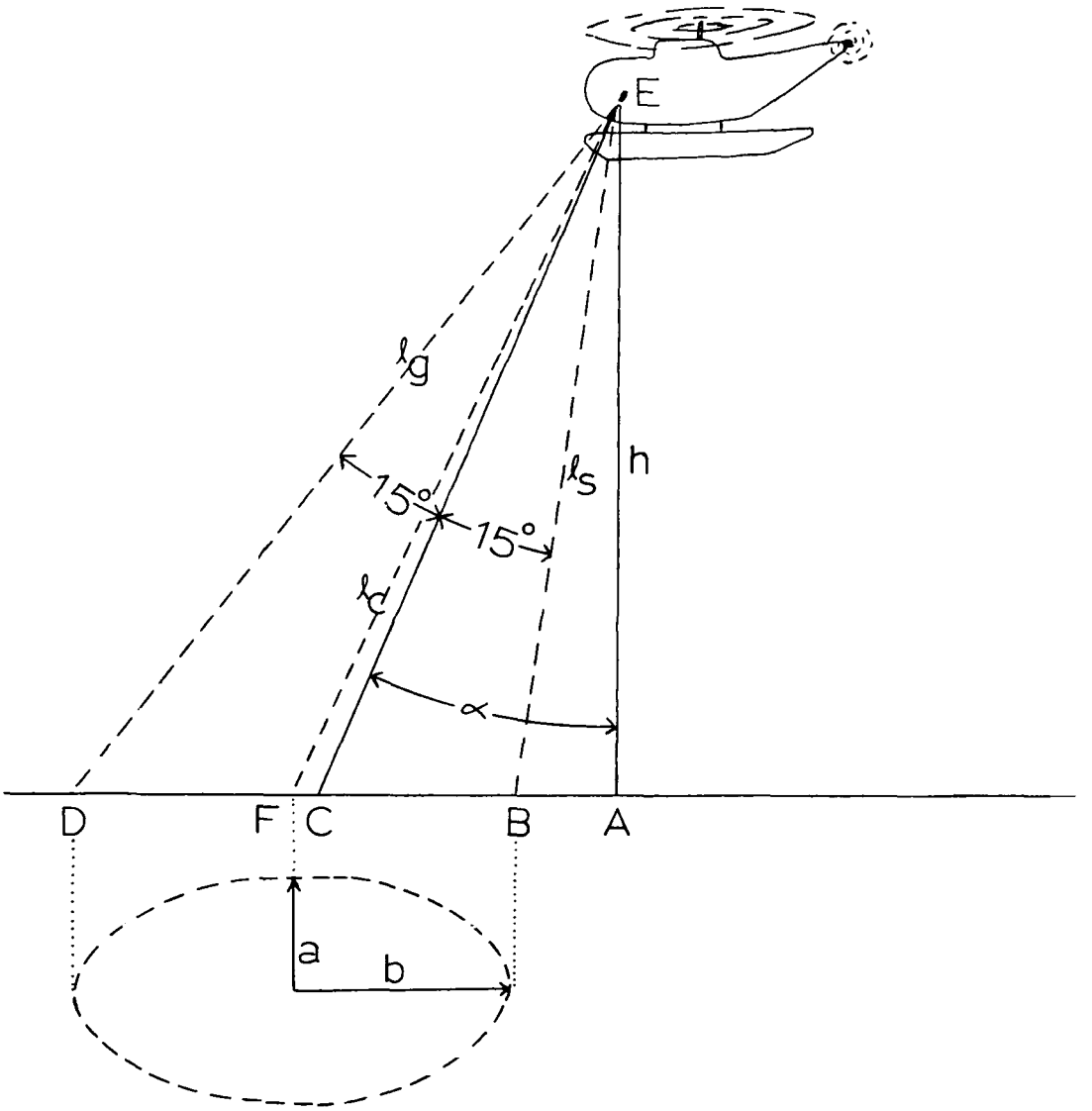
As an example of this last consideration, the geometry of the system was not thoroughly investigated at the time of use. Figure 6 presents the geometry of the radiometer as it was in 1973. Table 1 presents the major and minor axes and area of the field-of-view of the sensor bundle at several elevations and angles from the vertical.

As can be seen, the sensor bundle views an ellipse on the ground and integrates over this area. The area of the ellipse defining the field-of-view is much larger than most of the NES team members realized. Consequently the inclusion of shorelines, visible lake bottom, or other objects that would affect the reflected light differentially probably occurred occasionally.

Light reflected from the water surface could mask the backscatter signals. Since the sensor bundle was always directed away from the sun, this effect was minimized. However, experiments by both the National Aeronautics and Space Administration's Langley Laboratory (NASA/Langley) (NASA 1973) and NES personnel indicate that a slight increase in voltage with increasing angle is experienced utilizing the 443- and 525-nm filters.

These considerations, however, do not explain all the scatter observed. Results obtained by researchers at NASA/Langley utilizing the dual differential radiometer were also disappointing (NASA 1973, Witte 1975). They noticed that, among other problems, atmospheric haze affected the solar standardization zero; boat wakes could cause up to a 15 percent of full-scale deflection in the radiometer output; and the geometry of the system with respect to viewing angle, solar orientation, and stream flow affected the results.

Many of the difficulties encountered apparently stem from one basic assumption, that "changes in light intensity, variations in water surface roughness, or scattering within the water body have similar effects on the intensity of both wavelengths and are automatically corrected" (Arveson et al. 1971). Although not stated, the implication is that the only significant variation in signal between the two wavelengths is due to chlorophyll absorption. This is definitely not the case. Clarke et al. (1970) showed that as the altitude of the



The distance $\underline{DA} = h \tan(\alpha + 15°)$

The distance $\underline{BA} = h \tan(\alpha - 15°)$

The minor radius $a = (\tan 15°)\ell_c$

The major radius $b = (\underline{DA} - \underline{BA})/2$

where: $\ell_c = \sqrt{\underline{FA}^2 + h^2}$

$\underline{FA} = \underline{BA} + b$

and the area of the ellipse $= \pi ab$

$$\ell_g = \frac{h}{\cos(\alpha + 15°)}$$

$$\ell_s = \frac{h}{\cos(\alpha + 15°)}$$

Figure 6. Sensor bundle field-of-view geometry.

TABLE 1. SENSOR FIELD-OF-VIEW FOR VARYING HEIGHT, ANGLE*

h meters	α	a meters	b meters	Area meters^2
60	20°	17.3	18.4	997.8
	30°	19.0	22.0	1,313.6
80	20°	23.0	24.5	1,774.1
	30°	25.4	29.3	2,334.6
100	20°	28.8	30.6	2,772.2
	30°	31.7	36.6	3,648.4
150	20°	43.2	45.0	6,236.2
	30°	47.6	54.9	8,208.0
300	20°	86.4	91.9	24,944.6
	30°	95.2	109.8	32,835.0

*See Appendix for English units.

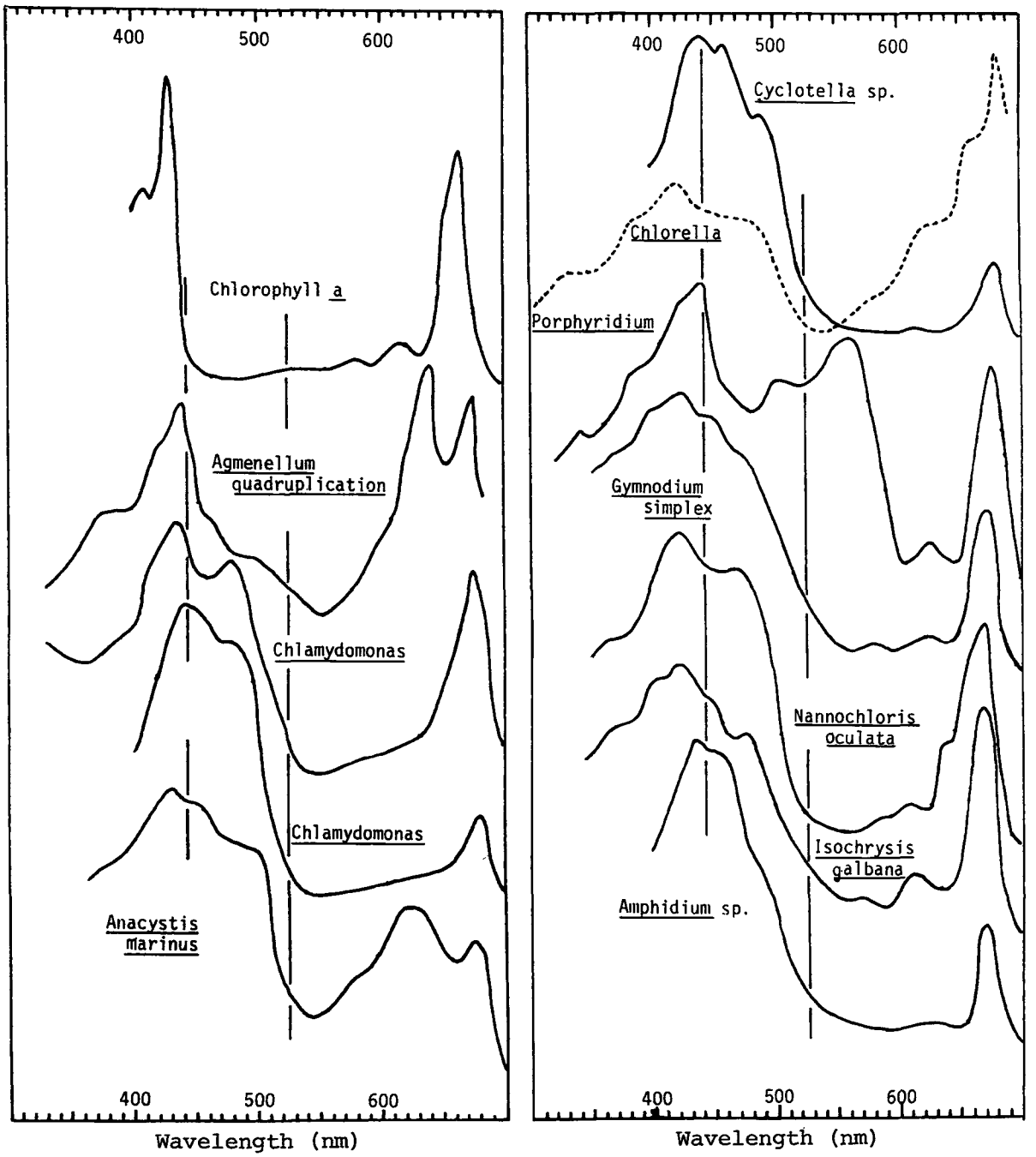
the sensor above the water body increased, there was a differential increase in the percent of incident light upwelled with the larger increase occurring at shorter wavelengths. Considering the elevations encountered during the NES study this effect would probably be negligible. However, since it is largely attributed to "air light" (light backscattered by the atmosphere) the presence or absence of haze or smog, differences in humidity, and the increasing influence of "air light" as the bundle is increasingly directed off-nadir, would differentially affect the two measured spectra.

Prewett et al. (1973) found that the relative reflectances from four ponds of differing suspended solids concentrations changed differentially. Ritchie et al. (1974) were able to correlate these changes with suspended sediments. In both studies reflectances were greater at 525 nm than at 440 nm. This would result in an increased difference in the signals received and give higher than true chlorophyll a values. This was indeed evidenced in NES data. Although NES did not measure suspended sediments, their presence was observed in many of the reservoirs, particularly in the Southeast.

Another consideration is the composition of the phytoplankton population. Spectral absorption curves for different algae can be expected to vary as the various dominant pigments change. Figure 7 presents absorption curves redrawn from data presented in Freidman and Hickman (1972), Grew (1973), and NASA/Ames (n.d.) for chlorophyll a and various algae species. The absorption maximum for each curve was arbitrarily assigned a unit value and the remainder of the curve adjusted proportionally. The curves are therefore not quantitative.

The sample filter central wavelength, interestingly, is generally near the maximum phytoplankton absorption, but is well off the peak for chlorophyll a. The sample wavelength does occur well up the absorption maximum curves (not shown) for other chlorophyll species, however. In addition, the width of the filter transmission curve (NASA/Ames, n.d.) would permit significant transmission at the chlorophyll a maximum wavelength absorption. The shapes of curves for the marine genera Cyclotella, Amphidium, and Chlamydomonas are remarkably similar while a fourth, Isochrysis, is reasonably close. Freshwater species show more variation; in two cases (Chlorella and Agmenellus) the larger maximum occurs at 630-680 nm. The most distinct form, Porphyridium, is a terrestrial red algae. It should also be noted that curves obtained by different researchers for Chlamydomonas, although similar, differ distinctly. Although quantitative data are not illustrated, the magnitude of the absorption varies by a factor of 2 to 4 between different genera.

The reference wavelength is seen to be subject to more variation than the sample wavelength. In several cases the reference wavelength intersects the algae-absorption curves significantly up the slope toward the maximum absorption. On a spectral signature obtained by Grew (1973) over Clear Lake, California, (not shown) the signal strength at 525 nm is nearly one-half that at 443 nm. Clearly, one should not expect chlorophyll a measurements based on spectral characteristics centered at 443 nm and 525 nm to be the same in each of these cases.



Vertical lines denote center of sample (443nm) and reference (525nm) filters.
Vertical scale is arbitrary--curves adjusted on basis of maximum absorption.

Figure 7. Absorption spectra for various algae.
(Adapted from cited references)

Grew (1973) also discusses the results of multispectral analyses along a flight line over the New York Bight. Changes were observed in spectral bands centered at 468 nm and at 543 nm, indicating that the 525-nm reference band is affected by other parameters. He suggests that one possibility for these changes is due to particle size. In the atmosphere and in clear water, backscattered light is predominantly due to Rayleigh scattering which occurs when the size of the scatterers is much smaller than the light wavelengths. The amount of scatter is inversely proportional to the fourth power of the wavelength. A second type of scattering, Mie scattering, becomes important as particle size approaches 1 micrometer. Mie scattering is predominantly in the forward direction and nonselective as to wavelength. The result is a differential change in the radiometer output signal due to particle size alone.

Other factors could also affect the values differentially. The presence of large amounts of pollens, dyes, or other colored substances could be expected to result in a differential output. Surface films of oils would greatly reduce the upwelled signal from the water and probably increase the reflected light. Since none of these factors which may differentially affect the sensor channels were allowed for during the testing, the poor results are not surprising.

A final consideration in the poor success of the dual differential radiometer was that many of the NES lakes sampled in 1973 had chlorophyll a concentrations greater than 10 μg/liter. These are above the effective range of the radiometer. However, as can be seen in Figures 3-5, output signals from water bodies with high chlorophyll a concentrations were usually significantly offset from the calibration curves. These offsets are indicative of the presence of interfering factors other than excessive concentration alone.

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Appendix:
Sensor Bundle Field-of-View Geometric Values for Varying Height (h) + Off-Nadir Angle (α)

h ft	α o	a ft	b ft	ℓ_s ft	ℓ_g ft	ℓ_c ft	Area ft^2
200	20°	58	62	201	244	215	11,206
	30°	64	73	207	283	237	14,478
300	20°	86	92	301	366	322	24,856
	30°	95	110	311	424	355	32,830
400	20°	115	122	402	488	430	44,257
	30°	126	146	414	566	473	57,991
500	20°	144	153	502	610	537	69,215
	30°	159	183	518	707	592	91,410
1,000	20°	288	306	1,004	1,220	1,075	276,862
	30°	317	366	1,035	1,414	1,184	364,494

Symbols are those defined in Figure 6. Values of ℓ_s, ℓ_g, and ℓ_c are included for comparison with h.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

A dual differential radiometer was tested on numerous eastern United States lakes and reservoirs. Remotely sensed data were compared with ground-truth chlorophyll a values. Results indicate that the instrument has only limited application in the remote sensing of chlorophyll a in the nation's lakes. At its present state of development, its use should be confined to large, deep, relatively clear water bodies in conjunction with ground-truth and surface survey efforts.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
* Radiometer * Chlorophylls Field tests Remote sensing		7C 20F

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