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TESTS OF THE
DUAL DIFFERENTIAL RADIOMETER

WORKING PAPER No. 473

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Tests of the Dual Differential Radiometer

Working Paper No. 473

Environmental Monitoring and Support Laboratory
Las Vegas, Nevada

December 1975

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by

Robert W. Thomas
Water and Land Quality Branch
Monitoring Operations Division
Environmental Monitoring and Support Laboratory
Las Vegas, Nevada

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CONCLUSIONS

The differential radiometer was designed to provide real-time remote measurement of the near-surface chlorophyll *a* content of water bodies. It effectively spans the range 0.03 to 20.0 micrograms (μg) chlorophyll *a*/liter. Dual differential radiometers were tested on National Eutrophication Survey (NES) lakes in the Eastern United States to determine their applicability for the remote sensing of chlorophyll *a* content in U.S. surface waters. Output voltages obtained from the differential radiometers showed little correlation to chlorophyll *a* values determined from NES samples.

Although the NES tests were often compromised due to time, space, weather, and other considerations, sufficient data were collected to permit the following 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 have chlorophyll *a* contents above its effective range and/or have 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 nonquantitative "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 NES experience.

INTRODUCTION

Remote sensing of water quality parameters would allow rapid, cost-effective surveys and monitoring of surface waters. The dual differential radiometer is a two-channel instrument designed to remotely measure light in four spectral bands. Arveson, Weaver, and Millard (1971) selected filter pairs that allowed remote measurement of 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 is a research effort investigating the threat of accelerated eutrophication in freshwater lakes and reservoirs. Nationwide in scope, it is designed to develop, in conjunction with State environmental agencies, information on nutrient sources, concentrations, and impact on selected surface water bodies. Consequently, it was decided to test the differential radiometer as a possible vehicle to measure chlorophyll a on the NES lakes.

Two dual differential radiometers were obtained and installed aboard NES 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 from a few centimeters to over 7 meters. Although not quantitatively measured, suspended sediments were noted in many of the water bodies at the time of 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.

THEORY OF OPERATION

The dual differential radiometer measures 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 to reject or cancel the background.

The absorption spectra for a variety of phytoplankton have been determined (Yentsch, 1960; Friedman & 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 maximum transmission at 525 nm. This latter filter lies outside the major absorption region of phytoplankton. The two selected wavelengths lie near the absorption minimum for water, thus minimizing its effect on the returning radiation. Variations in upwelling light from a water body due to water surface roughness, scattering, or haze should have a similar effect on both wavelengths. Variations in the concentration of algae will primarily effect the intensity at the selected wavelengths. The resultant differential signal output can be calibrated by comparison with ground truth chlorophyll a values to yield chlorophyll a concentration (NASA/AMES, n.d.; Arveson et al., 1971).

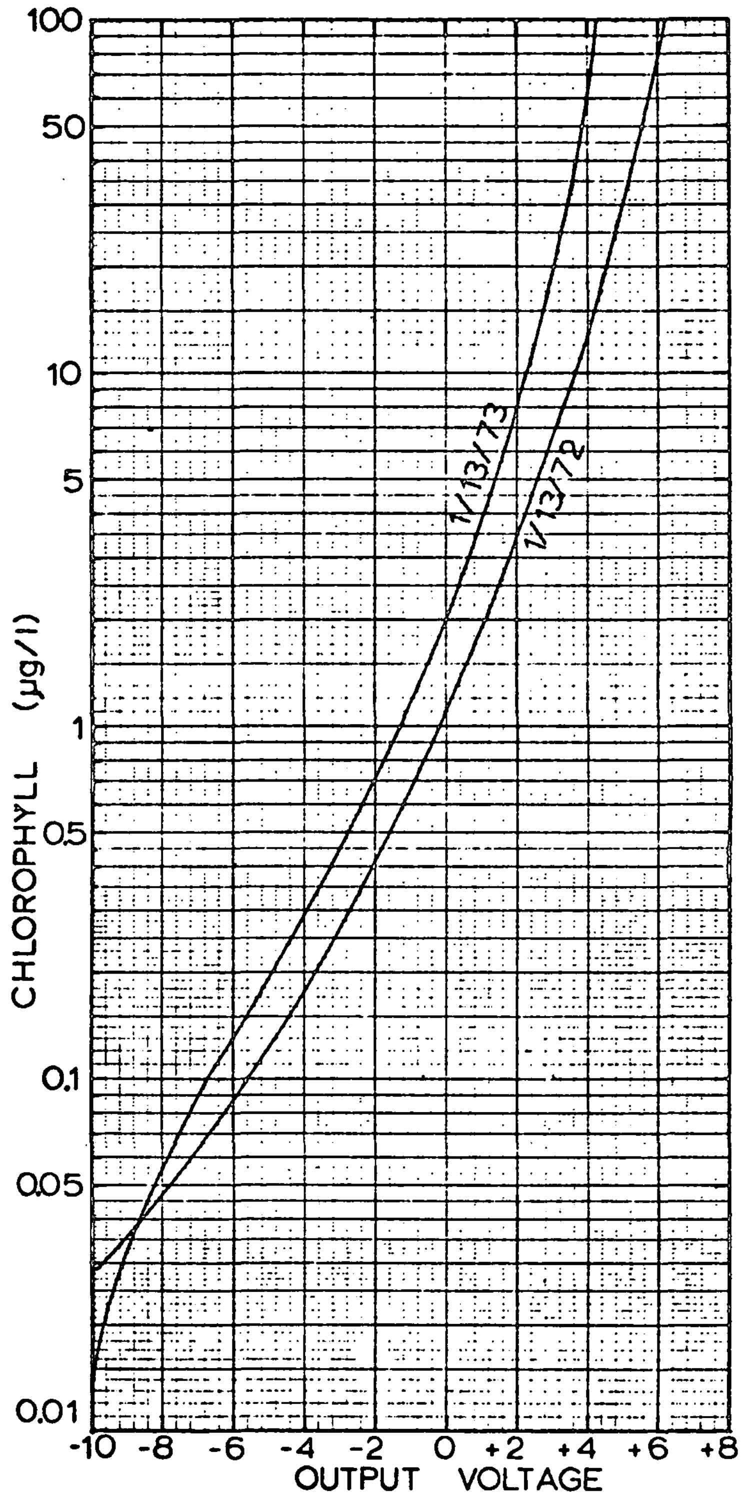
PROCEDURES

The dual differential radiometers were installed and tested aboard float-equipped Bell UH-1H "Huey" helicopters utilized by NES. 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 (EPA, 1974 and 1975). Samples for chlorophyll a analyses were collected at each station from water integrated from the surface to 4.6 meters or to the lower limit of the photic zone, whichever was greater. In waters less than 4.5 meters 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 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 compared to ground truth chlorophyll a levels showed little correlation. This, coupled with a high amount of down time, 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 NES personnel in the use and peculiarities of the instruments. He also provided a new calibration curve (Figure 1). 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 NES field season in the Eastern and Southeastern United States.

Figure 1. Radiometer calibration curve (after Arveson)



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

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 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 indicated that there was no appreciable effect on the calibration 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 meters 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.

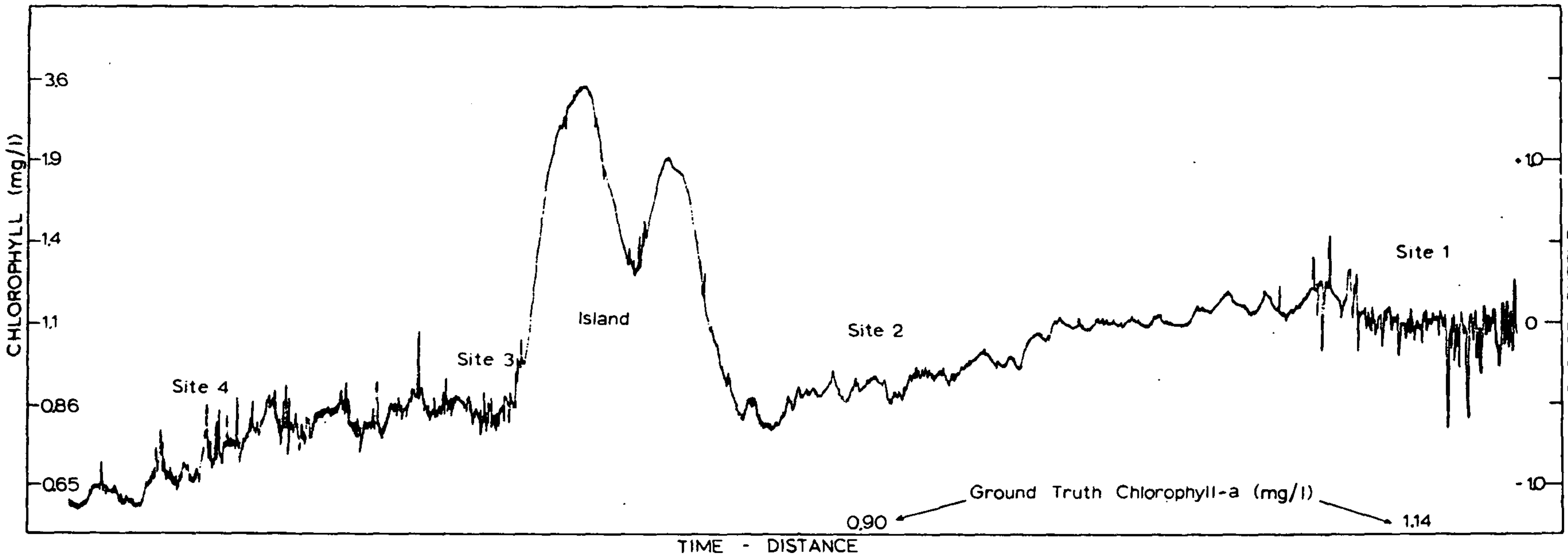
RESULTS

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. Chlorophyll a levels decreased 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 meters 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 meters above the lake. 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.

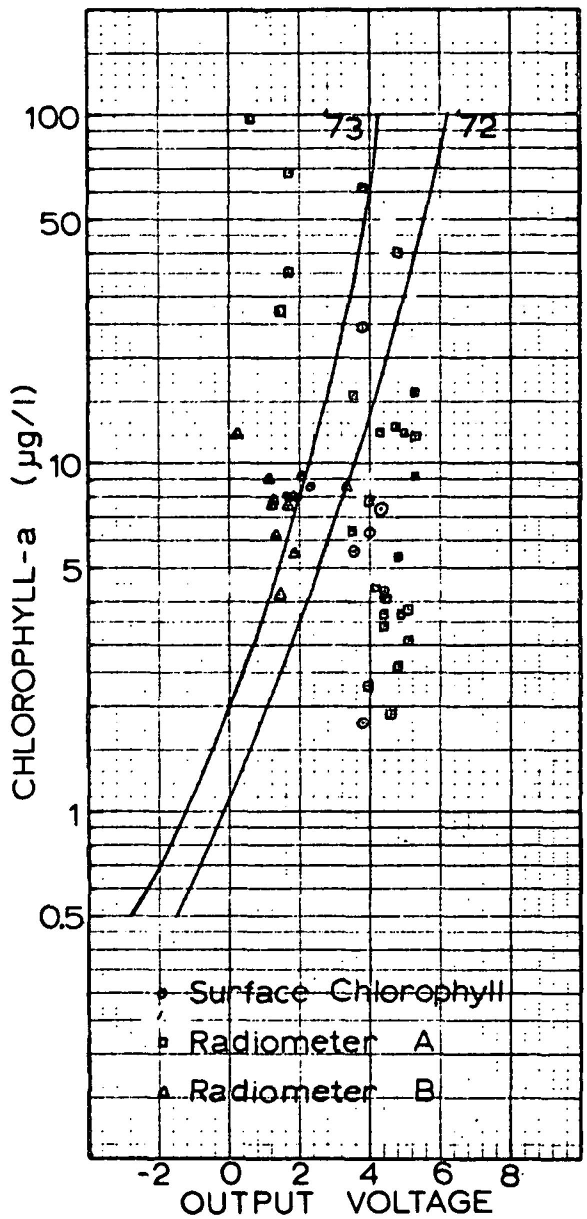
Mr. Arveson visited the NES team in the field and checked the calibration of the internal filters. He also performed some minor maintenance and again instructed personnel in the use of the instruments. Following this visit, several more tests of the differential radiometer were conducted. The results 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.

Figure 2. Radiometer strip chart record, Lake Mead
(December 1972.)



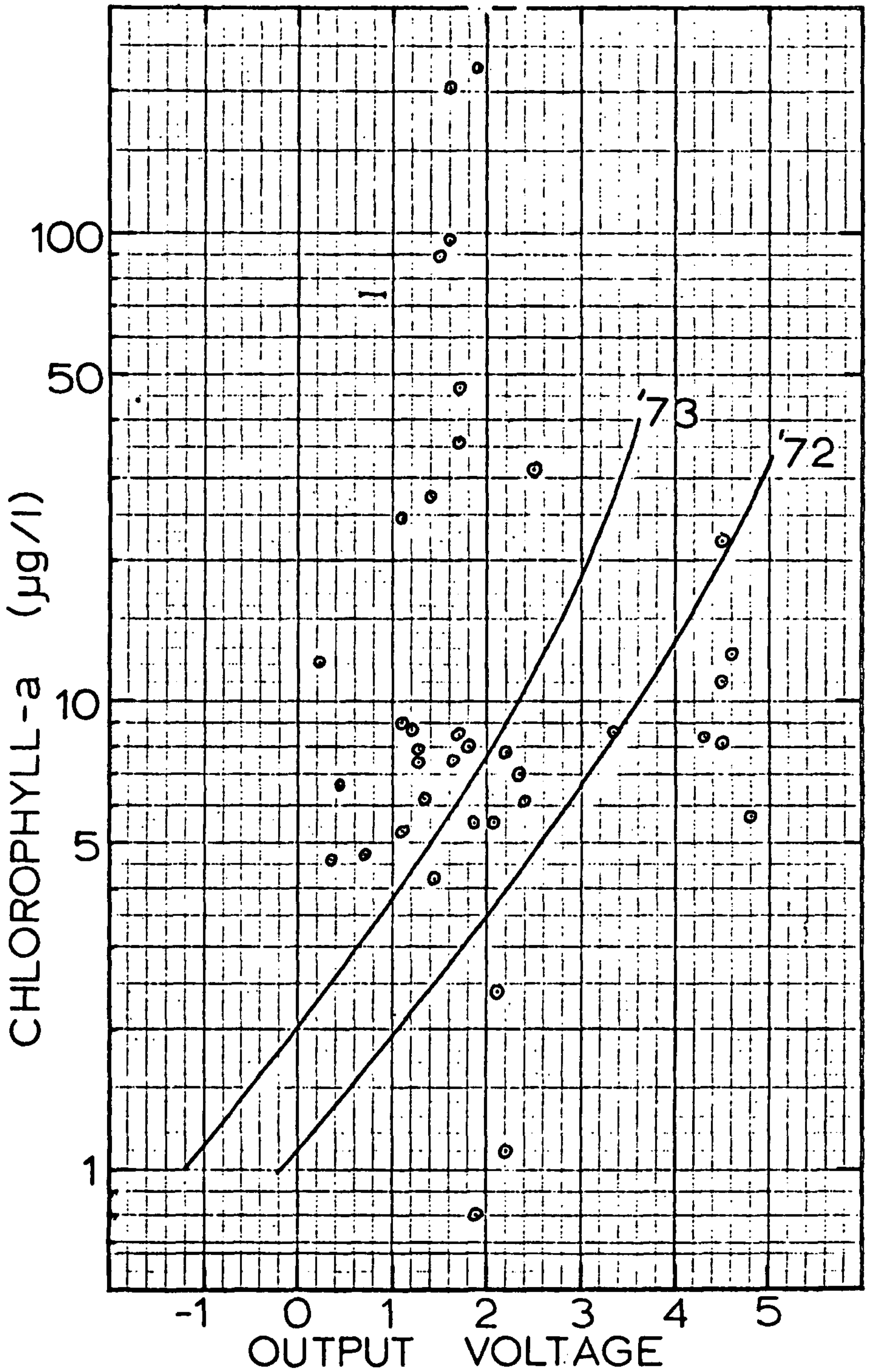
Horizontal distance approximately 10 kilometers
(Chlorophyll scale from 1972 calibration curve)

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



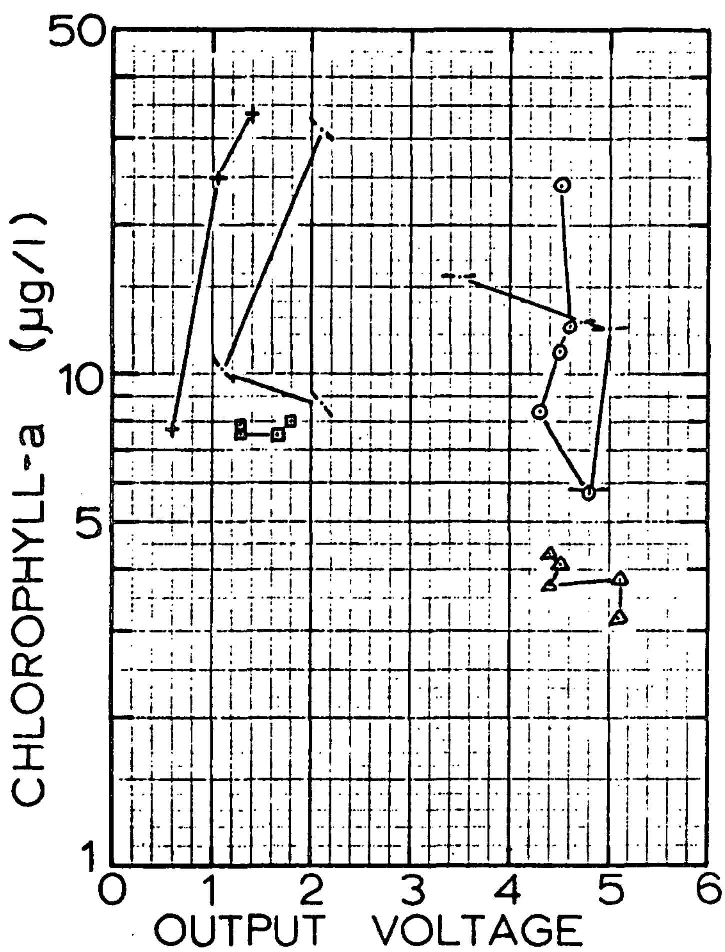
(1) Output voltage vs. chlorophyll a content of surface dipped water samples.
(2) Output voltage from Unit A vs. chlorophyll a content of integrated water sample.
(3) Output voltage from Unit B vs. chlorophyll a content of integrated water sample.
(calibration curves superimposed)

Figure 4. August 1973 radiometer data.



RADIOMETER OUTPUT vs. CHLOROPHYLL a, AUGUST 1973 DATA
(Calibration Curves Superimposed)

Figure 5. Data for selected large reservoirs



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)

DISCUSSION

Results of testing the dual differential radiometer by NES personnel 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.

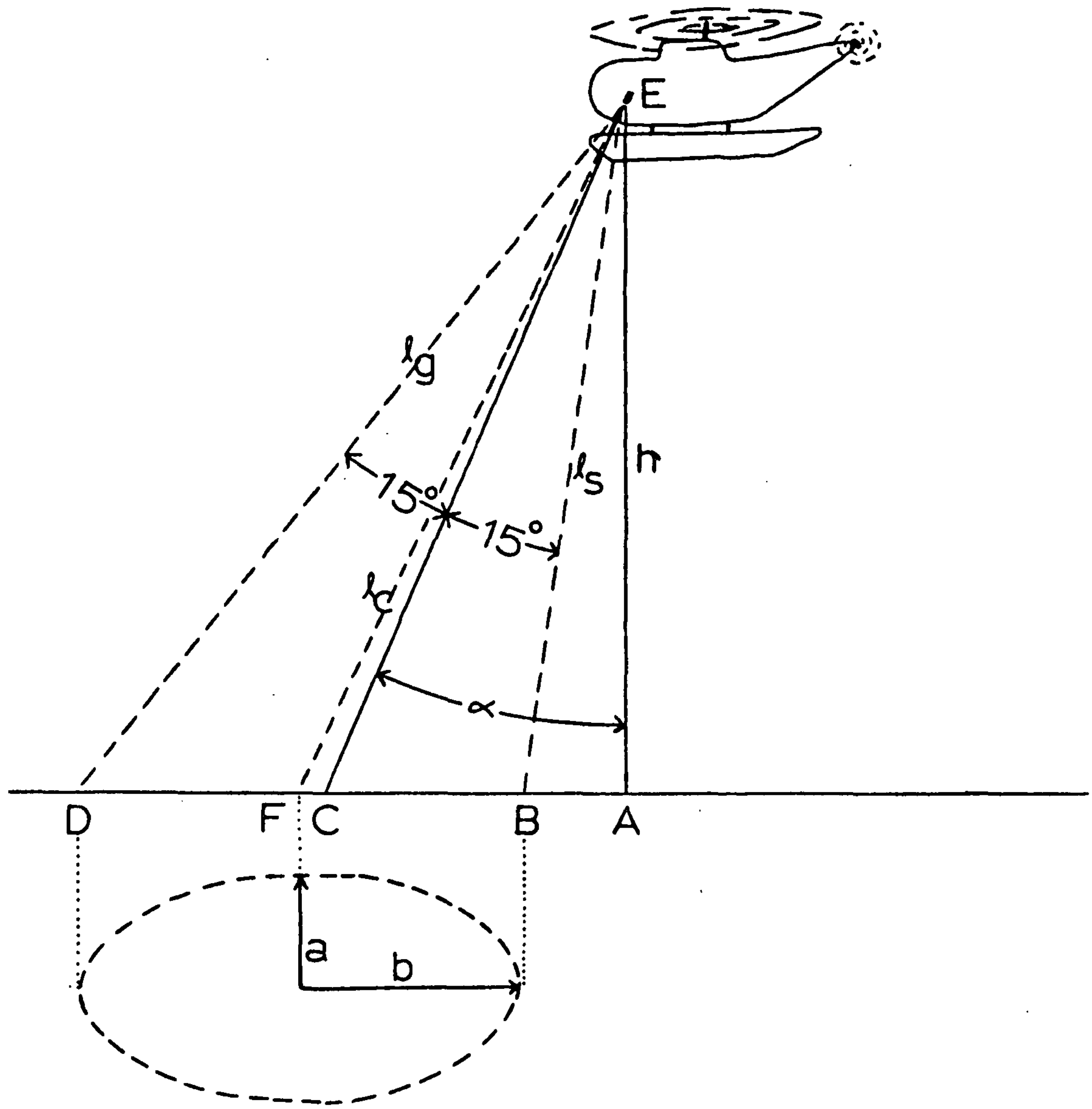
As an example of this last consideration, the geometry of the system was not thoroughly investigated at the time of use. Figure 6 presents the geometry of the radiometer as it was used in 1973. Table 1 presents the major and minor axes and area of the field of view of the sensor bundle at several elevations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

As can be seen, the sensor bundle scans 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. Because light intensity varies as a square function with respect to distance, it is apparent that the portion of the ellipse nearer to the vertical has more effect than that further from the helicopter.

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

These considerations, however, do not explain all the scatter observed. Results obtained by researchers at NASA Langley Research Center 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% of full-scale deflection in the radiometer output; and that the geometry of the system with respect to viewing angle, solar orientation, and stream flow affected the results.

Figure 6. Sensor bundle field of view geometry.



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

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

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

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

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

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

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	1313.6
80	20°	23.0	24.5	1774.1
	30°	25.4	29.3	2334.6
100	20°	28.8	30.6	2772.2
	30°	31.7	36.6	3648.4
150	20°	43.2	45.0	6236.2
	30°	47.6	54.9	8208.0
300	20°	86.4	91.9	24,944.6
	30°	95.2	109.8	32,835.0

*See Appendix A for English Units

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 at both wavelengths and are automatically corrected" (Arveson, 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 sensor above the water body increased there was a differential increase in the percent of incident light upwelled with the larger increase occurring at lower wavelengths. Considering the elevations encountered during the NES study this effect would probably be negligible. However, since it is largely attributable to "air light" (light back-scattered by the atmosphere) the presence or absence of haze or smog, differences in humidity, etc., would differentially affect the two measured spectra.

Prewett et al. (1973) found that the relative reflectances from four ponds of differing suspended solid 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 influence of the various dominant pigments changes. The absorption curves presented by Friedman and Hickman (1972) demonstrate this nicely. Not only does the magnitude of the absorption for differing genera vary, but for a terrestrial red algae, there is a secondary maximum at about 560 nm, and the absorption at 525 nm is about three-fourths that at 443 nm. Similarly, in the data presented by Grew (1973), the 525-nm filter value is significantly up the absorption curve as it passes from its maximum to its minimum values for two of the species. On the spectral signature Grew obtained for Clear Lake, California, the signal strength at 525 nm is nearly one-half that at 443 nm. Clearly, one cannot expect chlorophyll _a_ measurements based on spectral characteristics of 443 and 525 nm to be the same in each of these cases.

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 possiblity 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 microemter. 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.

SUMMARY

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 the 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 *a* content in a lake of relatively low turbidity. However, it cannot be effectively employed without collection of simultaneous ground truth data, at least 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 operations priority. Possible interferences should be known, considered, and allowed for.

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* on 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. From the NES data and literature review, 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 diatom domination in the spring to blue-green or green algae predominance in the summer. Suspended sediments would also typically be greater in the spring months than later in the year.) Also, it 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.

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APPENDIX

SENSOR BUNDLE FIELD OF VIEW GEOMETRIC VALUES FOR VARYING h, α.

Sensor Bundle Field of View Geometric Values for Varying h, α.

h ft	α °	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	14,678
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