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Penetration Depth at Green Wavelengths in Turbid Waters

Laboratory results indicate that apparent penetration depth is influenced by mineral content and suspended sediments while field measurements show wide variation in penetration depth, even when suspended solids concentration is nearly constant.

Introduction

Many investigators are attempting to identify and/or quantify various constituents in suspension in coastal and inland water bodies from remote sensing data (Johnson and Bahn, 1977; Rogers *et al.*, 1976; Williamson and Grabau, 1973; Whitlock, 1977). As noted in Whitlock (1977), one critical factor in the interpretation process is whether or not bottom reflection affects the remote sensing data. When attempting to monitor water quality parameters for constituents in suspension, it is usually desirable that the data not include upwelled radiation from bottom reflection. To assess this problem, some knowledge of the water depth at which bottom reflection no longer influences upwelled radiation is necessary. This depth is known as the apparent remote sensing penetration depth.

Abstract: *A laboratory and field measurement program was conducted to determine apparent remote sensing penetration depths at a wavelength of 520 nm. Tests were made for various types of sediments under controlled conditions in a laboratory. Field tests were conducted in several different water bodies over a wide range of solar elevation angles.*

Laboratory results indicate that apparent penetration depth is significantly influenced by mineral content and/or size of suspended sediments. Field measurements show wide variation in apparent penetration depth, even when suspended solids concentration is nearly constant. Apparent penetration depth does not appear to be a strong function of solar elevation angle so long as the water mixture remains constant.

Gordon and McCluney (1975) gave considerable insight into the remote sensing penetration depth problem for various types of oceanic and coastal waters. In that publication, remote sensing penetration depth was defined as the depth above which 90 percent of the upwelled radiance originates and was referred to as Z_{90}. Z_{90} was expressed as a function of the diffuse attenuation coefficient for irradiance just beneath the surface, $K(0, -)$, or alternatively, in terms of the beam attenuation coefficient, c, the scattering coefficient, b, and the fraction of b in the forward direction, F, of the water mixture.

Unfortunately, all of the proceeding optical parameters except c and $k(0, -)$ are difficult to measure in the field and are not included in those parameters normally monitored by the environmental engineering and oceanographic communities.

In an attempt to relate Z_{90} to a parameter usually monitored in field experiments, Whitlock (1976) made estimates of Z_{90} as a function of suspended solids concentration for various types of coastal sediments. Experimental values of c and b from Ghovanlou *et al.* (1973) were combined with theoretical curves from Gordon and McCluney (1975) to produce the estimates. For water bodies with heavy sediment concentration, total suspended solids concentration is a dominant parameter, and penetration depth as a function of that sediment concentration parameter is useful information. Whitlock (1976) concluded that additional data are needed, particularly for turbid waters.

McCluney (1974) notes that the apparent remote sensing penetration depth may be much deeper than Z_{90} if bottom reflectance is high (greater than 20 percent). Frei and MacNeil (1973) shows that diffuse reflectance for various soil types may vary from only a few percent to as high as 80 percent. From these results, it was concluded that the bottom reflectance of coastal and inland water bodies may be quite variable. Calculations in McCluney (1974) indicate that the apparent remote sensing penetration depth for highly reflective bottoms is nearly identical for reflectances of 20 percent and 60 percent. Based on this information, a laboratory and field measurement program was conducted by the NASA Langley Research Center to determine apparent remote sensing penetration depth at 520 nm.

This article presents results of the laboratory and field investigation which measured apparent remote sensing penetration depths for a range of different sediment types and concentration levels typical of turbid water bodies. Spectral scans were performed using an underwater panel whose reflectance peaks rather strongly at 520 nm. Results are presented for various types of sediments investigated under controlled conditions in the laboratory. Field data obtained over a wide range of solar elevation angles for several different water bodies are presented. Finally, both laboratory and field results are compared with calculated values from Whitlock (1976).

Experimental Technique

Laboratory measurements were made with the equipment setup shown in Figure 1. A xenon lamp beam was projected to a tank which contained 11,600 litres of water. The elevation angle (from the horizon) of the light incident on the water surface was 77°. The tank was filled with tap water which had been processed through a filtration-deionization system which achieved purities of less than 0.5 ppm suspended solids and 2.0 ppm dissolved substances. Various weights of the test sediments were then sequentially added to the filtered-deionized base water to achieve mixtures with increased concentration. Each mixture was circulated to keep the sediments in suspension. A spectrometer was used to obtain upwelled reflectance spectra over the wavelength range from 380 to 980 nm for each water mixture. A green plate with 57 percent diffuse reflectance at 520 nm was then lowered into the water. The depth at which the signal reflected from the plate could no longer be seen on the spectrometer was considered to be the apparent remote sensing penetration depth at 520 nm for the particular water mixture being observed. Measurements were made at a green wavelength for two reasons: Gordon and McCluney (1975) indicates that maximum penetration depths for coastal waters occur in the green range, and Whitlock (1976) presents calculated values for penetration depth based on optical coefficients at 540 nm. Additional information on the laboratory setup can be found in Whitlock (1977) and Whitlock *et al.* (1977).

The equipment setup for the field measurement program is shown in Figure 2. The same spectrometer was used for the field tests as was used for the laboratory measurements. As in the laboratory tests, the instrument was located 2.44 metres above the water surface, pointed toward nadir. Optics of the spectrometer-lens system were such

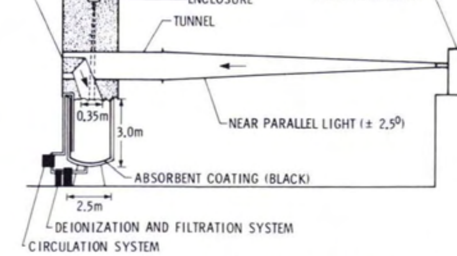

FIG. 1. Sketch of laboratory set-up.

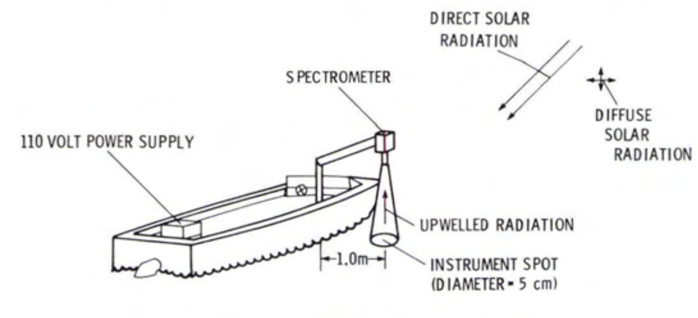

FIG. 2. Sketch of field experiment set-up.

that the spot being monitored on the water surface was 5 cm in diameter. As in the laboratory experiments, the green plate was lowered into the water until the reflected signal disappeared on the spectrometer. Spectral reflectance characteristics of the green plate during a typical field test in the Back River at Hampton, Virginia, are shown in Figure 3. Reflectance magnitude is based on measured upwelled radiance values from the water divided by the upwelled radiance from a 99 percent diffuse reflector.

RESULTS AND DISCUSSION

Apparent remote sensing penetration depth values from both the laboratory and field tests are summarized in Figure 4. Shaded symbols denote values obtained in the laboratory. Tests were made over a range of concentration values from 4 to 173 ppm for Jordan clay, Calvert clay, and Feldspar soil sediments. Upwelled radiance and reflectance spectra for these sediments are presented in Whitlock *et al.* (1977), and beam attenuation coefficients are given in Ghovanlou (1977). Mineral content and particle size distribution are described in Chapman (1977). The clay sediments are very fine, with the majority of their particles (by weight) smaller than one micrometre. The Feldspar sediment is a mixture of quartz and feldspar and has an average particle size of 20 μm. From the laboratory results shown in Figure 4, it is concluded that sediment type and/or size has an effect on the apparent remote sensing penetration depth in turbid waters.

A single laboratory measurement (the shaded triangle) was also made using actual Back River water which had been pumped into the tank (April 7, 1977). The laboratory-measured penetration depth for that "real world" water was in the same range as values for the clay soil sediments.

Field results are shown by the open symbols in Figure 4. Both the James River and Appomattox River tests were conducted near Hopewell, Virginia, in May 1977. The Wabash River value is taken from Bartolucci *et al.* (1977). Back River tests (at Hampton, Virginia) were conducted over a series of solar elevation angles on two separate days, June 22, 1977, and August 26, 1977. In general, values for remote sensing penetration depth from the field tests are in the same range as laboratory measured values. However, there is a wide spread in the Back River values which does not appear to be a function of total suspended solids.

A simplified analysis was conducted in an attempt to explain the wide variability in the Back River data. First the June 22 total suspended solids, penetration depth, and chlorophyll *a* values were plotted as a function of solar elevation angle as shown in Figure 5. (Water samples from which the suspended solids and chlorophyll values were measured were taken from a depth of 0.5 metre.) Penetration depth values were then adjusted to simulate what might be expected if total suspended solids had been constant over the experiment period (an incoming tide in the morning). Considering the 19 ppm point in the upper chart as an example,

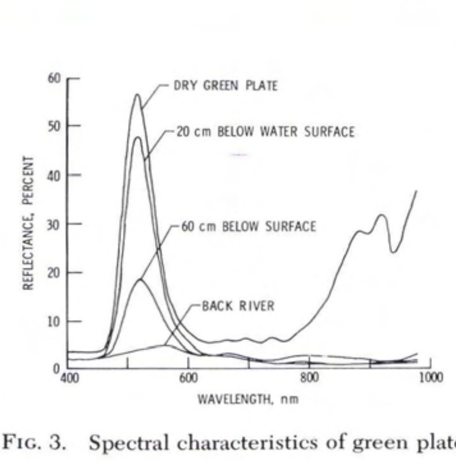

FIG. 3. Spectral characteristics of green plate.

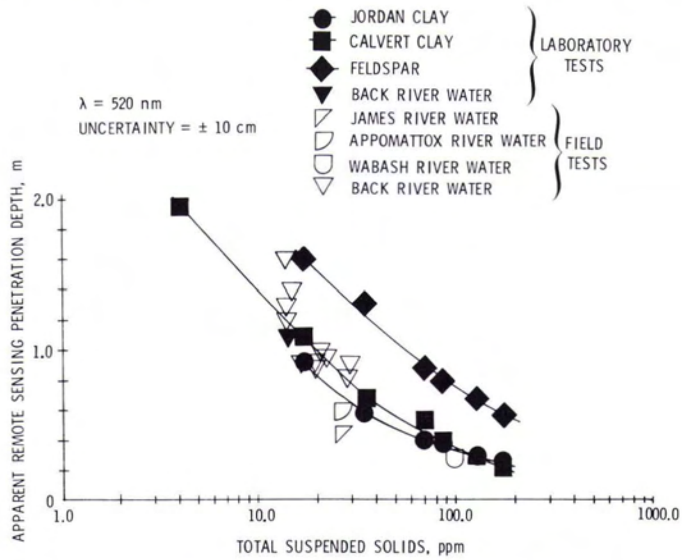

FIG. 4. Apparent remote sensing penetration depth.

it was assumed that if the concentration had been 14 ppm, then the penetration depth would have been 1.1 metres instead of 0.9 metre based on trends of the laboratory clay sediments data in Figure 4. The penetration depth associated with the 15 ppm solids concentration value was adjusted in the same manner. Dashed lines were then used to examine trends based on the assumption of a constant total suspended solids concentration of 14 ppm. Remote sensing penetration depth tended to increase with solar elevation angle on June 22, 1977, in the Back River. However, algae concentration tended to decrease that day as solar elevation angle increased. Thus, it cannot be determined from the June 22 data whether the increase in penetration depth was caused by the increase in solar elevation angle, the decrease in algae concentration, or unknown changes in dissolved substances or sediment composition.

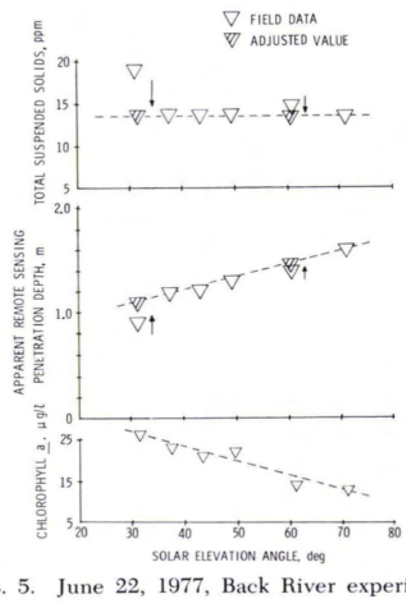

FIG. 5. June 22, 1977, Back River experiment data.

A second Back River experiment was conducted on August 26, 1977. That day was somewhat windy and water properties were more erratic as the morning progressed (an outgoing tide). As shown by the open symbols on the top chart in Figure 6, total suspended solids ranged from 15 to 30 ppm. Penetration depth values were between 0.8 and 1.0 metres, even after adjustment to a constant total solids concentration of 20 ppm. Most important, remote sensing penetration depth did not show a significant trend with solar elevation angle. Chlorophyll *a* concentration was also erratic with no significant trend. It is thus concluded that the penetration depth trend observed on June 22 was probably caused by changes in water constituents rather than by increases in solar elevation angle. The limited number of field measurements in this investigation suggest that apparent remote sensing penetration depth is not a strong function of solar eleva-

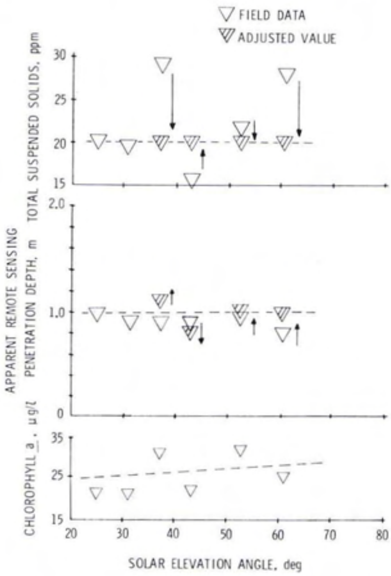

Fig. 6. August 26, 1977, Back River data.

tion angle in turbid waters if the mixture remains constant.

Comparison of measured apparent penetration depth values with calculated Z_{90} trends from Whitlock (1976) are shown in Figure 7. It must be noted that the sediments used in the Whitlock (1976) calculations were not of the same composition as those tested in the experimental program. The trend of the experimental data follows that of the calculated Z_{90} values. As would be expected from the McCluney (1974) discussion, apparent penetration depth values taken with a 57 percent diffuse green plate tend to be higher than calculated Z_{90} values. Both laboratory measurements and calculations appear useful for estimating the general range of remote sensing penetration depth, but field measurements are required to obtain accurate values.

Concluding Remarks

From the results of this investigation, the following conclusions are made:

(1) Laboratory results obtained under controlled conditions indicate that apparent remote sensing penetration depth is significantly influenced by mineral content and/or size of suspended sediments.

(2) Field measurements show wide variation in apparent penetration depth, even when suspended solids concentration is nearly constant.

(3) Apparent penetration depth does not appear to be a strong function of Sun angle, based on a limited number of field tests over a wide range of solar elevation angles.

(4) Laboratory measurements appear useful for estimating the general range and trends of penetration depths, but field measurements are required to obtain accurate values. Additional field and laboratory tests are recommended to assess penetration depth values at red and infrared wavelengths. Measurements at these wavelengths may have promise for remote monitoring of marine pollutants in shallow waters.

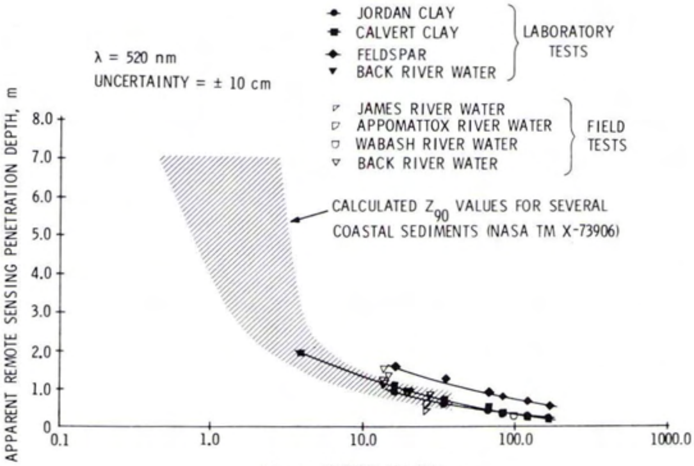

Fig. 7. Comparison of measured and calculated values.

REFERENCES

Bartolucci, L. A., B. F. Robinson, and L. F. Silva. 1977. Field Measurements of the Spectral Response of Natural Waters. *Photogrammetric Engineering and Remote Sensing*, vol. XLIII, no. 5, May 1977, pp. 595-598.

Chapman, R. S. 1977. *Particle Size and X-Ray Analysis of Feldspar, Calvert, Ball, and Jordan Soils*. NASA TM X-73941.

Frei, R. W., and J. D. MacNeil. 1973. Diffuse Reflectance Spectroscopy in Environmental Problem Solving. CRC Press, Cleveland, Ohio.

Ghovanlou, A. 1977. Radiative Transfer Model for Remote Sensing of Suspended Sediments in Water. NASA CR-145145.

Ghovanlou, A. H., G. F. Hickman, and J. E. Hogg. 1973. *Laser Transmission Studies of East Coast Waters*. Sparcom Inc. Technical Report No. 2, March 1973.

Gordon, H. R., and W. R. McCluney. 1975. Estimation of the Depth of Sunlight Penetration in the Sea for Remote Sensing. *Applied Optics*, vol. 14, no. 2, February 1975, pp. 413-416.

Johnson, R. W., and G. S. Bahn. 1977. *Quantitative Analysis of Aircraft Multispectral Scanner Data and Mapping of Water Quality Parameters in the James River, Virginia*. NASA TP 1021.

McCluney, W. R. 1974. *Estimation of Sunlight Penetration in the Sea for Remote Sensing*. NASA TM X-70643.

Rogers, R. H., N. J. Shah, J. B. McKeon, and V. E. Smith. 1976. Computer Mapping of Water Quality in Saginaw Bay with LANDSAT Digital Data. *Proceedings of the ACSM-ASP Convention*. Washington, D. C., February 1976.

Whitlock, C. H. 1976. *An Estimate of the Influence of Sediment Concentration and Type on Remote Sensing Penetration Depth for Various Coastal Waters*. NASA TM X-73906.

——— 1977. *Fundamental Analysis of the Linear Multiple Regression Technique for Quantification of Water Quality Parameters From Remote Sensing Data*. NASA TM X-74600.

Whitlock, C. H., J. W. Usry, W. G. Witte, and E. A. Gurganus. 1977. *Laboratory Measurements of Upwelled Radiance and Reflectance Spectra of Calvert, Ball, Jordan, and Feldspar Soil Sediments*. NASA TP 1039.

Williamson, A. N., and W. E. Grabau. 1973. Sediment Concentration Mapping in Tidal Estuaries. *Proceedings of Third Earth Resources Technology Satellite-1 Symposium*. Washington, D. C., December 1973.

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