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LABORATORY REQUIREMENTS FOR IN-SITU AND REMOTE SENSING OF SUSPENDED MATERIAL

By
Chin Y. Kuo
and
Robert Y.K. Cheng

Final Report

Prepared for the
National Aeronautics and Space Administration
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Under
Master Contract Agreement NAS1-11707
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LABORATORY REQUIREMENTS FOR IN-SITU AND REMOTE SENSING OF SUSPENDED MATERIAL

By

Chin Y. Kuo[1] and Robert Y.K. Cheng[2]

SUMMARY

Recommendations for laboratory and in-situ measurements required for remote sensing of suspended material are presented. This study investigates the properties of the suspended materials, factors influencing the upwelling radiance, and the various types of remote sensing techniques. Calibration and correlation procedures are given to obtain the accuracy necessary to quantify the suspended materials by remote sensing. In addition, the report presents a survey of the national need for sediment data, the agencies that deal with and require the data of suspended sediment, and a summary of some recent findings of sediment measurements.

1 Assistant Professor of Civil Engineering, School of Engineering, Old Dominion University, Norfolk, Virginia 23508.

2 Professor of Civil Engineering, School of Engineering, Old Dominion University, Norfolk, Virginia 23508.

CHAPTER I. NATIONAL NEEDS

1. Introduction

Annually, a great amount of sediment is carried down to rivers, lakes, estuaries, bays, coastal waters, and oceans. The soil disturbances are due to both natural phenomena and human activities. Soil is eroded due to rainfall and wind, resulting in tremendous sediment movement into water courses by flood and storm waters. Highway construction, tillage of cropland, housing, and urban development also yield a high volume of sediment transport. Other contributors are landfill, channel and harbor dredging, discharge of suspended solid contained in sewer and industrial wastes, and ocean dumping of solid wastes and sludge.

The impact of sediment erosion, transport, and deposition is very widespread. Deposition of coarse sediments may reduce the flow capacity and cause extensive disturbance to streams. Streams and lakes are damaged aesthetically. Reservoir storage and channel conveyance for water supply, irrigation, and navigation are lost. Water treatment costs for domestic and industrial uses are increased. Suspended sediment reduces water clarity and sunlight penetration, thereby affecting the biota. As the sediment settles to the bottom of lakes, bays, and marshes, it buries and kills vegetation, alters the benthic biota, and changes the ecosystem. All of this damage requires expensive remedial measures.

Sampling and measurement of suspended sediments is a tedious and expensive program for either in-situ or laboratory work. Since suspended sediment is an important environmental parameter used in determining the water quality, efforts have been directed towards a speedy and economical way for determination of suspended sediment. Measurement of suspended sediment is extremely useful for assessment and prediction of water quality. Turbid water can be detected though the use of optical methods. Fortunately, the turbid water can be seen from low altitude aircraft and high altitude spacecraft. Remote sensing techniques, offering data acquisition over a long time period and broad range, are therefore superior to any conventional method for field data collection. Efforts are currently underway at the National Aeronautics and Space Administration (NASA) and other government and private agencies are involved in activities to develop techniques for remotely sensing sediment distribution and transport patterns in riverine, estuarine, and coastal waters. Intepretation of data from photographic and spectral instruments is difficult due to the absence of sea truth and laboratory calibration data. The efforts necessary to obtain the sea truth data are currently known, but the type and content of the supporting laboratory effort is not known. The purpose of this study was to investigate:

a. Who are the agencies using sediment data and how will the data be used?

b. What are the problems related to monitoring sediment distribution and transport?

c. What further sediment related measurements are needed and how are these measurements tied in with remote sensing methods?

d. Previous and current work.

e. Laboratory program needed to be established to carry out the measurements and data collection required.

f. How should the laboratory effort be integrated with sea truth and remote sensing efforts?

2. Agencies Using Sediment Data

A study by the Environmental Protection Agency (EPA) (ref. 1) on methods for identifying and evaluating the nature and extent of non-point sources of pollutants shows that sediment is the major contributor among such types of pollutants as minerals, nutrient elements, pesticides, organic wastes, and thermal pollution. Cropland is the chief source of sediment on a total mass basis, accounting for 50 percent or more of the sediment deposited in streams and lakes. Construction and surface mining activities yield large quantities of sediment in relatively small regions of impact. The adverse impact is high on water quality, cost of water supply, and storm water management. Besides the sediment itself being a pollutant, the suspended material is a carrier for other types of pollutants, either from land erosion or dredging. Using sediment as a tracer is a good detection mechanism for non-point pollution sources.

Detection of high turbidity water would help the soil erosion control of land management, such as agricultural land practice and engineering sediment control methods. The Soil Conservation Service (SCS) of the Department of Agriculture has for a long time devoted effort to the study of soil erosion and control. As soil is eroded, sediment is washed by surface runoff, transported by streams, and finally deposited in lakes, storage reservoirs, and bays. The reservoir storage decreases as the result of high concentration suspended sediment inflow. Water treatment costs for domestic and industrial uses are increased for high turbidity water. Reservoirs and bays are damaged aesthetically. Recreation activities are hampered. The utility departments of municipalities are concerned with the water supply sources and ways to prevent storage reservoirs from deterioration due to sedimentary pollution. Park and recreation services from local governmental through federal levels are benefited in their management tasks if information on the concentration of suspended material is provided for their guidance.

As mentioned before, suspended sediment in streams is associated with the upstream activities in the watershed. The watershed could have been undergoing highway construction or urban housing development. District planning commissions, highway departments, and the U.S. Forest Service are among those agencies carrying out watershed management.

The U.S. Geological Survey (USGS) is the federal agency in charge of flow and sediment measurement including gaging, sampling, and data analysis. The USGS primarily deals with relatively coarse-size streambed sediment motion and high suspended sediment concentration; as a result, they are oriented towards sediment measurement in fresh water regions such as lakes and rivers. For estuaries where the flow is subjected to wave and tidal action, and the suspended sediment is more diluted and small in size, the USGS normally does not establish the sediment sampling program. Estuaries, bays, and coastal waters in general, are covered by the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce. Efforts in the direction of quantifying the suspended sediment, using remote sensing techniques, are extremely useful in aiding the sediment measurement program. Big savings are expected in terms of human and financial resources. In particular, the remote sensing program would help USGS during a period of big flood events whenever the sensing techniques could be applied and are permitted by atmospheric conditions.

The use of remote sensing techniques for detection and identification of municipal and industrial waste discharges with suspended solids is a promising area. It would help the agencies who monitor water quality, issue the permits, and enforce the water quality control laws and ordinances.

Annually, tremendous amounts of dredged material from streams, estuaries, and coastal waters are disposed of in the aquatic environment. The dredging operation involves the type of material to be dredged, location and method of dredging, methods and site selection for disposal, and the environmental impact of the dredged material. Particularly, the monitoring and prediction of the turbidity level near the dredging site is a very important step in assessing the environmental impact. The Office of Dredged Material Research of the U.S. Army Engineer Waterways Experiment Station (WES) devotes a large effort toward this type of study. In addition, the Environmental Characterization Branch of the Mobility and Environmental Systems Laboratory at the WES has also carried out studies on the suspended sediment mapping in waterways and lakes, using the remote sensing data from the Earth Resources Technology Satellite (ERTS). Remote sensing techniques would be extremely helpful in predicting the sediment settling rate by studying the spatial and temporal variations of suspended sediment concentration downstream of the dredging site.

The Coastal Engineering Research Center (CERC) of the Department of the Army for a long time has been studying the erosion and accretion of shoals and coastal areas such as beaches and inlets. Information on suspended sediment would identify the problem areas and transport patterns of the suspended sediment related to waves, currents, and man-made coastal structures.

The presence of suspended sediment in water bodies cuts down the light and thermal energy penetration depth. The energy and light source is essential to the biota dynamics (ecosystem). The turbidity level is a good indicator for fish and aquatic plant populations, the growth of algae as related to the dissolved oxygen level, and the reduction of nutrients associated with pollutant loadings. The Environmental Protection Agency (EPA), the state water control agencies, water resources planning and environmental conservation commissions at all levels of government have as their function the management of natural resources.

It has been suggested that turbidity variation might provide insights into the gross physical, chemical, and biological processes governing the estuary itself. The coastal and marine resources commissions at all government levels try to preserve the marshes and coastlines to avoid any adverse impact due to human activity. The Bureau of Wildlife and Refuge Management of the Department of the Interior has its major function in these areas.

A high concentration of suspended material might damage the shellfish population and benthic biota. The transport pattern of suspended materials is useful information to the Bureau of Sport Fisheries and Wildlife of the Department of the Interior, to the National Marine Fisheries Service of the Department of Commerce, and to local marine resources commissions.

Turbidity parameter yields a good indication of diurnal and seasonal variations of ecosystems such as plankton blooms, algae crop, and bottom fauna. Hence the mathematical model of an ecosystem can be calibrated and verified before the model can be used for the purpose of prediction.

NOAA has a broad interest in the environments of estuaries, bays, and coastal waters. Turbidity, of course, is a useful parameter for many purposes. Turbidity pattern, as a function of time, is able to deduce the current information since the suspended material is a good natural tracer. It also provides the information on water mass mapping such as convergence and divergence areas, upwelling, river plumes of sediment, and tides. NOAA is also interested in the assessment, monitoring, and prediction of continental shelf environments. The major item of interest is the estimation of coral reef activity as related to the ecosystem and pollutant loadings.

An underwater turbidity map is useful to scuba research efforts including the planning of television and camera studies of fish populations, underwater natural resources and geological explorations, and construction and inspection of offshore structures. The visibility of submarines is also studied by the U.S. Navy's Office of Naval Research and the National Oceanographic Instrumentation Center of NOAA. NOAA's primary effort on turbidity measurements is in the areas of in-situ measurement and development of instrumentation.

Both EPA and NOAA are joined by NASA in the task of ocean disposal of solid wastes, sludge, and other solid matter as dredged material. The task includes monitoring and prediction of the waste field, potential turbidity currents, and the selection of dumping sites.

The person engaged in research on the problems related to turbidity serves a large group of users of remote sensing data on suspended sediment concentration. These include universities, research institutions, and research and development groups of the industrial sector. Their interest covers all types of water bodies, all types of remote sensing methods and imagery, in-situ methods, laboratory methods, and all types of application.

3. Problems Related to Monitoring Sediment Distribution and Transport

Although turbidity is widely recognized as an important environmental parameter, the term "turbidity" is ill-defined and very ambiguous. Different users define this term in different ways according to their own application. Due to different methods of measurement, different locations of measurements, various measuring instruments, and varieties of scientists and engineers engaged in the measurements, there is much confusion in terms of units, standardization, correlation, and unit conversion.

NOAA's National Oceanographic Instrumentation Center (NOIC), in an attempt to clarify the problem, sponsored a workshop on turbidity in 1974. This was the most recent attempt to work out a general approach for wide recognition. The objectives of this workshop were to identify the various applications for turbidity, identify the basic information being sought by the measurement of turbidity, various types of instrumentation being used, and the capability, limitations, ranges, and areas of most beneficial application for these instruments (ref. 2).

It is the authors' opinion that the conclusions and recommendations drawn by a committee at the workshop are the most precise and relevant statements about turbidity and its measurement; they are quoted in the Appendix.

According to the classification of application for turbidity data in table 1, table 2 shows the relationship between the applications and agencies who use the data. Table 3 shows the primary use of the suspended sediment parameters.

From the literature surveys, visits, and communications with researchers at universities, and research institutions, the following topics for research have been devised and recommended for study. The goal of the proposed research is to achieve more accurate determination of suspended material in the field and laboratory.

a. A commonly-used list of terminology in the field of suspended material should be adopted. It should contain physical, geological, biological, chemical, and optical phases to completely describe the suspended material. For example, the glossary of optical oceanography in Jerlov's book (ref. 3) can be adopted by all researchers to ensure correct interpretation and communication of all reserach findings.

b. A standard procedure for measurements in field or laboratory should be established. Types of calibration for instruments, and correlation between the signal output and characteristics or conditions of suspended material should also be clarified and specified. It could include single or multi-parameter calibration or correlation.

c. For the purpose of optical measurements of suspended material, stating all units in terms of optical characteristics would yield more accurate descriptions of suspended material. However, development of one or more transfer functions to convert the optical units into commonly used units such as mg/l is also necessary. This would provide the accessibility of information by people other than scientists and engineers.

d. For the purposes of in-situ measurements, simultaneous monitoring of the micro-structures at the point where the samples are taken is recommended. For example, the temperature and salinity strongly govern the flocculation phenomena of suspended material in the ocean. Also, temporal variation of turbulent intensity level tends to influence the fall velocity of floc or discrete particles.

e. Particle shape and size distribution are very important parameters governing the concentration and optical characteristics of suspended material. No single method has been widely adopted by researchers to determine the small-size suspended material of the order of microns. Methods are particle counter TMC method, coulter counter, and microscopic observation. These will be described in more detail in a later chapter.

f. The percent of solid matter and organic matter significantly affect the optical characteristics of a mixture. Further investigations to quantitatively separate the solid and organic particles is strongly recommended. Moreover, identification of different types of organic matter or solid matter is also very important. Methods such as gas-liquid chromatography and spectrophotometry (ref. 4) can determine chlorophyll a and chlorophyll b. However, to separate different types of chlorophyll quantitatively needs more study. Using a parameter of refractive index to identify the clay mineral is currently available. However, quantitative determination of percent of different clay material in a mixture is necessary in the processes to correlate suspended material data to light scattering or attenuation, for example. Fundamentally, the importance of the parameters just mentioned depends on studies such as:

(1) How significantly does the individual constituent affect the overall optical characteristics of the entire mixture?

(2) Is it possible to measure the optical characteristics of the suspended material solely depending on the shape and size of the particle and not depending on the type of constituents?

Questions such as these need to be clarified.

g. There are so many different ways to indicate the optical characteristics of suspended material, which optical parameter to be used depends heavily upon the types of applciations for suspended material data. A type of correlation function and transfer function should be developed for a specific application. The procedures developed must be clearly stated so that comparison or conversion can be made with other instrumentation, parameters, and applications.

4. Factors Influencing Upwelling Radiance and Research Needs for Remote Sensing

Remote sensing techniques provide long-term and wide-area coverage data, making the data acquisition speedy and economical. NASA's efforts for obtaining photographic and/or spectral information and quantifying the suspended particulate is definitely needed and will be beneficial to all users. A considerable amount of work has been done on optical characteristics of suspended particulates. Most of it is tied in with the measurement instrumentation for gathering ground truth data. However, very little of it is related to the parametric studies in terms of factors influencing irradiance which is registered by sensors.

In order to investigate laboratory requirements for in-situ and remote sensing of suspended particulate, major factors influencing upwelling radiance must be known. In general, factors can be grouped as follows:

a. Source of electromagnetic radiation

b. Transmission of radiation between the source and the water body, the water and the sensor

c. Interaction of electromagnetic radiation and the water body

d. Remote sensors

e. Bottom effects.

Solar radiance is a commonly used radiation source for a given zenith angle. The length of the path through the atmosphere increases with increasing zenith angle. The attenuation of electromagnetic energy increases and less solar energy reaches the water body. Sensors which can be applied to the measurement of suspended particulate by remote techniques are (ref. 5):

a. Color film

b. Color infrared

c. Multispectral

d. Multichannel scanning radiometer

e. Correlation radiometer

f. Pulsed laser system

g. Polarimeter.

Instrumentation requirements for remote sensing of suspended particulate are listed below (ref. 5). An optimum value is given above the line and an acceptable value is given below the line in parentheses.

a. Spatial resolution $= \frac{20\text{ m}}{(500\text{ m})}$

b. Spectral resolution $= \frac{0.15\ \mu\text{m}}{(0.15\ \mu\text{m})}$

c. Spectral range $= \frac{350\text{ to }800\text{ nm}}{(400\text{ to }700\text{ nm})}$

d. Temporal resolution $= \frac{2\text{ hrs}}{(1\text{ day})}$

e. Solar elevation $= \frac{45°}{(30°\text{ to }60°)}$

f. Look low angle $= \frac{0° \sim 15°}{(-5° \sim 30°)}$

g. Area coverage $= \frac{200 \times 200\text{ km}}{(20 \times 20\text{ km})}$

The factors affecting the transmission of radiation from the source to water body and water body to the sensors are atmospheric conditions and sea states. Atmospheric conditions are described by clear, cloudy, and hazy in general terms. The transmission of radiation is a gross result of molecular and aerosol absorption, molecular and aerosol scattering, and profiles of basic gaseous and aerosol components of a variety of conditions. In other words, the transmission can be expressed in terms of profiles of pressures, temperature, density, water vapor concentration, and ozone concentration as a function of height above sea level. Of course, the atmospheric transmittance changes with geographic and seasonal variation. A computerized atmospheric transmission model, LOWTRAN I, developed by the U.S. Air Force, Cambridge Research Laboratories, can be used to calculate atmospheric transmittance (ref. 6). Sea state includes waves and currents.

The interaction of electromagnetic radiation and the water body with suspended material is of special interest. The interaction can be indicated by one or more optical characteristics:

a. Transmittance

b. Absorption

c. Scattering

d. Attenuation

e. Volume scattering function.

Naturally, these parameters vary according to the properties of suspension itself and the ambient fluid. The photographic or spectral image is therefore a strong function of the factors that influence the upwelling radiance. These factors are:

a. Concentration and distribution between organic, chemical, and solid matter in the water. (Concentration can be for an individual constituent or the whole mixture. A percentage of each constituent in the mixture is also an important parameter since the image would vary as the characteristics of a specific constituent.) Types of suspended material that may be present in water are:

(1) Organics and Chemicals
- (a) chlorophyll
- (b) phytoplankton
- (c) other micro-organisms
- (d) organic compounds - yellow body
- (e) heavy metals - lead, zinc, mercury
- (f) toxic chemicals - acids and others

(2) Solid Particles
- (a) sand
- (b) silt
- (c) clay

b. Variation of suspended material concentration with depth. (The depth of penetration for different wavelengths is directly related to the vertical concentration profile.)

c. Properties of solid matter including particle shape, size, distribution, color, and mineral types. Types of mineral can be represented by different parameters such as opacity, refractive index, and birefringence.

As described in part 3 of this chapter, the in-situ and laboratory measurements of suspended material are not fully understood. Measurement procedures, instrument calibration, standard units and their transfer functions require further study. All of these further complicate the remote sensing techniques and amplify the scope of the research. The combined effect of all the factors influencing the upwelling radiance can be investigated through the technique of parametric study. There exists a very serious lack of spectral and photographic data on:

a. Natural water body -- it gives the background information when no suspended material is presented.

b. Water body with the presence of suspended material.

Field tests should be conducted to quantitatively establish these relationships. The task to achieve this goal involves the following:

a. In-situ measurements of factors influencing the suspended material, such as sea states, in-situ optical characteristics, and properties of ambient water.

b. Samples taken back to laboratory for parametric identification and quantity determination, including properties of solid, organic, and chemical matter.

c. Remote sensing imagery obtained by aircraft or spacecraft.

d. Establishment of correlation between image and parameter. The procedures will be recommended in Chapter III and a detailed discussion presented.

The in-situ and laboratory measurements will establish a set of reference data, mainly the parameters influencing the upwelling radiance. With the imagery and the established reference data, information on the suspended material can be obtained via established correlation equations and/or figures. The entire process is indicated by a flow chart shown in figure 1.

This approach to studying suspended material distribution and transport has not been implemented. It requires intensive programs in the air, the field, and the laboratory, with extensive data processing and analysis. The currently available instruments for in-situ and laboratory measurements, together with the current state of research on parametric study and establishment of correlation, will be discussed in Chapter II. Additional laboratory programs needed to be integrated with sea truth and remote sensing efforts will be recommended in Chapter III.

CHAPTER II. METHODS FOR DETERMINING SUSPENDED MATERIAL

1. Turbidity Measurements

Turbidity is caused by the presence of suspended material such as clay, mud, algae, silica, rust, bacteria, calcium carbonate, etc. in water.

The oldest method for measuring turbidity is the Jackson Candle Turbidity Meter with the Jackson Turbidity Unit (JTU). This unit represents an arbitrary scale corresponding to the height of fluid for various suspended concentrations of a reference material required to cause the image of a candle flame to be lost. This method is no longer used by EPA or USGS because of the lack of accurate correlation with physical or chemical parameters of the suspension. However, the unit still appears in documents and is not yet phased out.

The Standard Methods (ref. 7) published by the American Public Health Association (APHA) suggests that the turbidity unit should be expressed in terms of optical properties of a sample which caused the light attenuation. A scattering meter (or nephelometer) has been developed along this line since the publication of APHA Standard Methods. The nephelometer is calibrated by means of a standard sample concentration of formazin and has a unit of Nephelometer Turbidity Unit (NTU) or Formazin Turbidity Unit (FTU). The correlation of suspended material (in mg/l) and turbidity (in NTU or FTU) can only be accomplished on an individual sample basis.

2. Attenuation Methods

a. Theory of light attenuation. To understand the method of light attenuation, a brief review is necessary of the optical phenomena of light passing through a medium with suspension. A fairly parallel light beam passing through a medium with sussion will cause scattering and absorption. The radiance of the beam is N_o at $X = 0$ and N_ℓ at $X = \ell$ for a path length of ℓ, where

$$N_\ell = N_o \, e^{-(a+s)\ell}$$

a = absorption coefficient of the medium

s = scattering coefficient of the medium

The transmittance T_ℓ for a path of ℓ is defined by

$$T_\ell = \frac{N_\ell}{N_o} = e^{-(a+s)\ell}$$

The transmittance is dependent on both absorption and scattering. The sum of a and s is called the volume attenuation coefficient, α, which can be expressed as a function of T_ℓ:

$$\alpha = a + s = \frac{1}{\ell} \ln \frac{1}{T_\ell}$$

All coefficients a, s, and α, are functions of wavelength λ.

Consider a radiance I_o incident on a small volume of dV which has a length $d\ell$ along the direction of propagation, and a projected area of dA normal to the direction of propagation. If the volume contains suspended material and is observed at a distance far away with respect to the dimension of the volume, the intensity $dI(\theta)$ is proportional to the incident radiance and the volume (see fig. 2). It follows that

$$dI(\theta) = \sigma(\theta) \cdot I_o \cdot dV$$

The constant of proportionality is called the volume scattering function $\sigma(\theta)$ which can be shown to be the fraction of the power scattered from a beam of light into a small solid Ω. The volume scattering coefficient S is defined as the total fraction of the power scattering away in any direction from the incident radiance.

$$S = 2\int_0^{\pi} \sigma(\theta) \sin\theta \, d\theta$$

Figures 3 and 4 illustrate the optical system of the transmissometer and scattering meter (or nephelometer) (ref. 2). A transmissometer measures light transmitted through a medium containing suspended material with a light-sensitive detector. Figure 3 shows a 1-meter water path length transmissometer development by the Visibility Laboratory of Scripps Institution of Oceanography (ref. 8). The transmittance values are converted to the volume attenuation coefficient. A scattering meter measures light scattering at various angles θ of an incident beam of light. For example, figure 4 shows the scattering meter to measure the volume scattering function in-situ at angles from 10 to 170 degrees, as described by Petzold (ref. 9) in Austin's paper (ref. 10). The output of the receiver can be converted into the volume scattering coefficient in absolute physical units.

In general, most of the instruments used by researchers or developed by commercial companies are in one of three categories: transmissometers, nephelometers, or a combination of these two.

b. Transmissometers

(1) In-situ transmissometer by Hydro Products, P.O. Box 2528, San Diego, CA 92112.

(2) In-situ transmissometer by Martek, Inc., 877 W. 16th Street, Newport Beach, CA 92660.

(3) In-situ transmissometer by Montedoro-Whitney, P.O. Box 1401, San Luis Obispo, CA 93401.

(4) In-situ transmissometer developed by Visibility Laboratory, Scripps Institution of Oceanography, San Diego, CA.

(5) "Falling Stream" Turbidimeter by Hach Chemical Company, P.O. Box 907, Ames IA 50010. It measures the relative transparency of a gravity-induced smooth sample stream formed as the flow drops vertically from an orifice. The USGS has used this type of turbidimeter as a means for continuously measuring sediment concentration in streams (ref. 11).

(6) Iowa Sediment Concentration Measuring System, Iowa Institute of Hydraulic Research, University of Iowa, Iowa City, IA. This instrument is designed for in-situ measurement of the temporal variation in suspended sediment concentrations. A light source and light sensor are mounted in separate legs of a forked probe. The light is attenuated as the particles pass between the source and sensor. The output voltage

of the instrument is directly proportional to the concentration of suspended sediment for a uniform size distribution of particles. This instrument is still in the developmental stage. The limitations and improvements needed to suit it for field application are discussed in another report (ref. 12).

(7) Another type of beam transmissometer having an adjustable water path of 1/2 to 2 meters and a depth capability of 2000 meters was developed by the Scripps Institution of Oceanography (ref. 13) as shown in figure 5.

One major limitation to transmissometer use is the inaccuracy in measurement when the medium contains highly dissolved substances such as organic dyes. The dissolved organic material will absorb the light.

c. Scattering meter

(1) Hach Chemical Company, P.O. Box 907, Ames, IA 50010. The model of "Laboratory Turbidimeter" is for laboratory measurement. A light beam is sent upward, scattered at an angle of 90 degrees, and received by a sensor. The model of "Low Range Turbidimeter" is made to continuously monitor the suspended material. The 90-degree scattered light beam is measured by a photocell submerged in the sample. The model of the "Surface Scatter Turbidimeter" can be used for continuous monitoring in the field. A narrow beam of light is directed onto the smooth flowing surface of water at an angle of 15 degrees. The scattered light is recorded by the sensor at 75 degrees to the incident light beam. Figure 6 shows a general 90-degree side-scatter turbidimeter.

(2) Multiple-angle scattering meter. Gibbs (ref. 14) developed a scattering meter at adjustable low angles of forward scattering and at angles of 45, 90, and 130 degrees (see fig. 7).

(3) A general-angle scattering meter developed by the Visibility Laboratory, as described above (ref. 8). The angles are between the limit $\theta = 10$ degrees in the forward direction and $\theta = 170$ degrees in the backward direction.

(4) A narrow-angle scattering meter was used to measure the in-situ value of the volume scattering function (ref. 15). The angles used were

forward angles of 0.086, 0.172, and 0.344 degrees. Kullenberg (ref. 14) also used a very low angle scattering meter as shown in figure 8.

A single-angle scattering meter, such as 45 degrees, has been used during the past. The 45-degree angle was considered to be the optimum angle of measurement. It has been assumed that the volume scattering function correlates very well with the volume scattering coefficient at a single angle, and a 45-degree angle of measurement holds well for this assumption. Smith, et al. (ref. 15) discuss the limitation of the scattering meter. The volume scattering coefficient is not strictly proportional to particle concentration unless the relative particle-size distribution remains the same as the concentration changes. Also, the results of single-angle instruments are difficult to use for a direct comparison for different samples taken. Smith, et al. further state that the choice of 45 degrees as being the most nearly proportional to the volume scattering coefficient was based on early scattering data which did not include the result using a narrow-angle scattering meter. They concluded that an optimum angle for a single-angle instrument was between 1 degree and 2.5 degrees for the size distribution met in the upper layer of ocean used in their study.

In light of the above discussion, it seems that a general-angle scattering meter offers more complete information concerning the suspended material. As mentioned in Chapter I, optical properties of suspended material depend heavily upon the shape and size distributions of particles, and the percent and type of organic matter present in the water. Gordon (ref. 16) also indicated that the scattering is strongly dominated by the minerals present, and therefore, the size and refractive distribution should be available for the analysis. He also presented the fact that phytoplankton concentration can be monitored by simultaneous observation of small- and large-angle scattering. This further stresses the importance of more than a fixed-angle measurement on scattering.

d. Combination of transmission and scattering measurements

(1) The instrument used to obtain continuous measurement of in-situ turbidity by Eittreim and Ewing (ref. 17), Biscaye and Eittreim (ref. 18), Sternberg, et al. (ref. 19), and Feely, et al. (refs. 20, 21) is a moderately low-angle scattering meter shown in figures 9 and 10. This is an originally standard Lamont photographic nephelometer. It consists of a 35-mm camera with continuous film drive, a light source at a distance of 55 cm, and an intervening baffle-attenuator midway

between the light source and sensor to cut off scattering from angles less than 70 degrees. A direct beam of light source is allowed to reach to the camera, attenuated by a factor of about 10^3 by a combination of an opal glass and a gray filter whose transmittance is known. The film exposures produced by the scattered light E relative to that produced by the direct, yet attenuated light E_D can be found. The ratio E/E_D compensates for any change in intensity of the light source, film's transport speed, developing of the film, or film sensitivity. It is a function of scattering alone over a range of angles 7 ~ 30 degrees. Water depth can be also recorded on the film by deflection of a light spot through a bourdon-tube pressure sensing system. Thus, a nephelometer profile, E/E_D versus depth, can be plotted to get the concentration profile of the suspended material.

(2) A submersible forward-scatter turbidimeter was developed by Monitor Technology, Inc., Redwood City, CA. It provides turbidity readings which are linearly correlated with the JTU scale, and are insensitive to dissolved color, source aging and drift, and environmental factors. The turbidity measurement won't be affected by coating of the deposits on the immersed optical surfaces. Figure 11 shows the optical scheme of this instrument. The sensors are separated by a symmetrical fin which shadows each detector from the diametrically opposed light beam. The sources are sequentially energized. Each sensor receives either the direct light from the source or the scattered light from the suspension. The ratio of the scattered light signal to the direct light signal is computed with one source energized. The sensor functions are reversed when the other source is energized. The system output can be shown to be linearly proportional to the forward-scattering only.

(3) A laboratory model study was done by S. Klein (telephone communication) at Scripps Institution of Oceanography. He measured the ratio of transmission and 90-degree scattering signals using an infrared detector. The color caused by the dissolved substance becomes an irrelevant parameter.

e. Depolarization method using polarized light. An on-line, continuous suspended solids monitoring device was developed by Badger Meter, Inc., Tulsa, OK 74115. This is an instrument to measure the suspended solids in a wastewater stream that contains particles with a diameter exceeding 0.25 microns. The principle is based on the depolarization of light in the back-scattered portion of an initially polarized light beam. Figure 12 shows the schematic diagram of the instrumental arrangement. There are two components of the back-scattered light. One portion consists of singly-scattered waves which are still oscillating in phase (and parallel) with those in the emitted light beam. The remaining portion represents light which has been depolarized by multiple scattering. The two components are measured by splitting the back-scattered light and sending the two resulting beams through analyzer lenses to photodiode detectors. The depolarization was used to measure the concentration of suspended solids in sewage. Experimental results from Liskowitz and Franey (ref. 22), using the instrument shown in figure 13, indicated that the relationship between the degree of depolarization and suspended solid concentration was unaffected by the following parameters. They are particle size of the suspended solids, solids' density, color of the samples, refractive index of the medium, sample flow, the build-up of solids on the optical surface, and the ambient light. Under laboratory conditions, a single prototype sensor has operated over the range of 10 to 1,000,000 ppm.

f. Acoustic method. Acoustic observations of a low-density sediment flow, appearing at the onset of the shallow thermocline and at greater depth, and originating with a dredge operation in the main Miami, FL shipping channel, have been made by Proni, et al. (ref. 23). The acoustic system transmitted a 1-kW, 2-millisecond-long, sinusoidal pulse of energy with a center frequency of 20 kHz. The transducer was towed in a "teardrop" shaped tow body. The transducer beam width was 12 degrees in the fore-aft direction and 18 degrees in the orthogonal direction. They stated that, for the range of traditionally used frequency (e.g., 5 to 200 kHz), biological scattering is the most logical candidate. The acoustic results have not been compared with the traditional transmissometer data. The basic principle of this method is that attenuation of reflected sound waves is affected by the suspended material.

g. Upwelling radiance measurement. Using solar radiance as a source, the reflected solar radiance is a function of the type and concentration of the suspended material.

In-situ measurements were made of the incident and reflected solar radiation from the surface water of reservoirs (ref. 24). Solar radiation was measured by spectroradiometer at intervals from 400 to 1550 nm. The Sun angle was found to be an important parameter affecting the reflectance measurement. The total suspended solids in the surface water had a greater effect on the amount of reflected solar radiation than the Sun angle.

Secchi Disk depth is another method to estimate the water clarity. For example, Clark (ref. 25) used this method to have a useful rough index of visibility. A 20-cm-diameter disk, divided into alternating black and white quadrants, is lowered by an observer. The average of two readings, for the depth at which the plate disappears during descending and at which the plate reappears during lifting, is adopted. The depth can be compared with the concentration of suspended material or the microdensitometer readings from a multispectral scanner on board an airplane or satellite (ref. 26). A spectral attenuation board is similar to a Secchi disk. The depth of penetration for different wavelengths can be obtained by placing the spectral attenuation board at different depths. The concentration of suspended material can be compared with the depth of penetration.

A multispectral scanner (MSS) has been widely sued in the measurement of suspended material (refs. 26, 27, 28, 29, 30, 31, and 32). Basically, the concentration of suspended material is correlated with the data obtained from the scanner for the different spectral bands. Types of MSS are as follows:

(1) NASA's Earth Resources Technology Satellite (ERTS-1), contains four spectral bands ranging from 0.5 microns to 1.1 microns.

(2) NASA's Skylab/EREP Satellite includes 13 spectral bands ranging from 0.4 microns to 12.5 microns.

(3) Bendix Modular Multispectral Scanner (M2S) has 10 bands of spectral range, 380 to 1060 nm.

(4) NASA's 24-channel scanner ranges from 0.34 microns to 13 microns.

(5) Multichannel Ocean Color Scanner (MOCS) had a spectral range of 400 nm ~ 700 nm; used by Grew (ref. 33).

Aerial photography also offers the capability for remote sensing of the upwelling radiance of the sunlight. Ruff, et al. (ref. 34) studied the Clark Fork Yellowstone River sediment problem, using color infrared film, which is sensitive to electromagnetic energy having a wavelength from 0.4 microns to 0.9 microns and thermal infrared imagery with a spectrum from 8 to 14 microns. Remote measurement of turbidity and chlorophyll through aerial photography was made by Schwebel, et al. (ref. 35). Studies were conducted utilizing six different film and filter combinations to quantitatively detect chlorophyll and turbidity in six farm ponds.

Schenk and Davis (ref. 36) did a survey on turbidity in Narragansett Bay. They made optical measurements by lowering an upward-facing photocell to known depths and comparing its output through a bridge circuit to an identical cell mounted in gimbals on the research vessel deck. With Hd as the cell output at depth D, and Hs as the surface output of the deck cell, K is found from the equation

$$\frac{Hd}{Hs} = e^{-KD}$$

in which K is the attenuation function for scalar irradiance which is correlated with the suspended sediment load.

h. Lidar Systems. The lidar system is another kind of attenuation method. It consists of a laser source, telescopic receiver, and a photo-detector. The system is operated by transmitting a light pulse from a platform to and through some depth of water. The return signal is collected and detected. From the wavelength of the return signal, or from the time difference of the signals received from the ocean surface and bottom, the turbidity is measured. This system has been used by researchers at Texas A & M University.

3. Radiometric Methods

In-situ determination of suspended sediment by measuring the absorption of radioactive energy has been proven to be a useful method. This method is satisfactory for studying high concentrations of suspended material such as that found in estuarine water and the surf zone of beaches, and where the mass absorption of the sediment to radiation does not vary with time. The concentration of suspended sediment has been studied using monoenergetic gamma radiation as a source and observing the absorption (ref. 37). By knowing the mass absorption coefficient, absorber thickness, incident radiation intensity, and intensity of radiation passed by the absorber, the density of the absorber can be calculated. The concentration of the suspended material, therefore, can be known. Figure 14 shows the field installation. As pointed out by Gibbs (ref. 14), this method has also been adopted using the radioactive isotopes Am^{241} and Cd^{109} as energy sources, and placed in a fish-like probe for use in rivers and estuaries. He points out that this system is not very sensitive to the variation of sediment concentration. However, the effect of compositional changes of the suspended material on the absorption is sensitive.

4. Gravimetric Methods

This method is basically to measure the quantity of suspended material in terms of the ratio of the dry weight of the material to the total weight of the mixture in units of mg/l. This unit has been used very frequently. For very small concentrations in open ocean water, it becomes more difficult to get reasonable accuracy when using this unit. Samples are collected at the surface or at a given depth, using Niskin bottles, depending upon the information needed. The volume needed for each sample depends upon the concentration of the suspended material. For in-situ point sampling, a pump system can be adopted. In-situ évaporation or filtering can reduce the volume of the samples being stored on board and brought to the laboratory. Evaporation methods can be used for samples with high concentrations of suspended material to desiccate the material before it is weighed. For low concentration samples (500 ppm or less), the filtration method seems to be more satisfactory The rate of filtration can be increased by vacuum pumping or centrifuging. Centrifuging, even at high speeds, presents a disadvantage for samples having fine-grained or neutrally buoyant particles such as organic material. The filter used for filtration has different specified pore sizes. Commercially available filters are glass fiber, Millipore and Gelman-brand filters which resemble an intricate cellular network, and Nucleopore-brand filters of thin plastic with holes punched in specific sizes. If the concentration is extremely low, a smaller weight filter tends to give better accuracy. Glass fiber filters, frequently used by the USGS, are suitable for larger suspended sediments and higher concentrations in rivers and estuaries. The other types will give satisfactory results for the case of open ocean, provided that the salt is first washed away.

Biscaye and Eittreim (ref. 18) discussed some of the advantages in using Nucleopore-brand filters over the other types:

a. Nucleopore filters weigh less than an equivalent Millipore filter.

b. Millipore filters are coated with a wetting agent which can be washed out upon use.

c. Due to a lower surface area and possibly the lack of a wetting agent, Nucleopore filters achieve relative humidity equilibrium much more rapidly and therefore are not so sensitive to the humidity control in the weighing room.

d. The surface of Millipore filters has enormously more visual texture than Nucleopore filters. A small particle can be distinguished easier on the Nucleopore filter for scanning electron microscopy work at a given magnification.

e. If any analytical work on trace elements is to be done on the samples, Nucleopore filters have a significantly lower blank for a number of elements than has the Millipore filter.

For fresh water, the laboratory procedures for the determination of suspended sediment concentrations are specified in the series of "Techniques of Water-Resources Investigations of the U.S. Geological Survey" (ref. 38). Both the evaporation method and the filtration method are presented. Field methods for collecting suspended sediment are also documented (ref. 39). They include depth-integrating samplers and single-stage samplers. The standard samplers and methods were developed by the Federal Inter-Agency Sedimentation Project.

5. Methods To Determine Particle-size Distribution

Particle shape and size distribution are important parameters for suspended material. The size of suspended material varies from place to place. For example, submicron material is found at a depth in the open ocean, material measured in tens of microns in surface ocean water, and in millimeters in rivers and estuaries. The number of particles, their shape, and size distribution are necessary data to calculate the concentration of suspended material at extremely low concentrations such as the case of open ocean water. Of course, the absorption and scattering of the light or radiance are strongly affected by the size distribution (ref. 40). It appears that the particle shape is an influential factor.

For rivers and lakes, the USGS has detailed information about the methods to determine particle size distribution of suspended sediment (ref. 38). Selection of method, procedures and set-ups for each method, limitation of each method, and discussions on organic material and dissolved solids are all specified. Methods to determine the size include sieve analysis for size range of 0.062 to 32 mm, pipet for size range of 0.002 to 0.062 mm, Bottom Withdraw Method for size range of 0.002 to 0.062 mm, and visual accumulation tube method for size range of 0.062 to 0.2 mm.

Particles to 4 µm could be resolved with standard microscopy; however, size measurement could be done with confidence only on grains greater than 10 µm (ref. 41).

The Coulter Counter has been widely used to determine particle size distribution (refs. 25, 30, and 42). The diluted suspension containing small size particulate in microns is passed through different sizes of apertures, where the volume of the particle is detected in the electromagnetic field. The choice of aperture diameter depends upon the size range of the particles in the sample. Dual apertures can be used to cover and overlap the desired range, utilizing the most effective area of each aperture tube. Detailed information on the use of the Coulter Counter is described by Sheldon and Parsons (ref. 43). The Coulter Counter gives the output of size distribution in terms of a particle size histogram representing the frequency distribution. Particle volume measured by the Coulter Counter is converted to an equivalent diameter of a sphere. This up-to-date method is widely adopted and is considered to be satisfactory. This method can be applied only to collected samples; further development is needed to extend the application of the Coulter Counter for in-situ measurements.

The other type of particle counter is the Millipore Particle Measurement Computer (πMC). The sample is filtered by means of the Millipore brand filter. The filter is dried and mounted on a slide which is then placed under the microscope for observation. With careful adjustment of focal length, the contrasted picture of particles remains on the filter and is shown in the TV screen. Each particle is identified and recorded. The output of the computer shows the number of particles greater than a specific size of particle by the comparison of projected area. The output is then expressed in terms of a figure with particles per liter versus particle diameter in microns. Particles less than 0.5 μm seem to be difficult to identify. Since the computer counts the number of particles by comparing the projected area of the particles, the shape and orientation of the particles becomes an important factor. Inaccurate focusing on the picture may produce error in measurement. Particles sticking together may be mistaken for big particles. Organic particles which are transparent might not give a good contrast on the screen. This method has been used by Bowker and Witte (ref. 27). However, there do not seem to be as many users of the πMC method as of the Coulter Counter.

Both πMC and the Coulter Counter may have difficulty in converting the number of particles into the unit mg/l. Since the unit mg/l is the weight ratio of suspended material to the mixture, the specific gravity of the suspended material must be known in order to compute the weight of an individual particle. Neither method, however, is capable of isolating suspended solids from organic matter. The type of particle cannot be differentiated by simply counting numbers of particles.

6. Measurement of Organic Matter

Suspended organic matter such as algae, phytoplankton, and chlorophyll present in the water sample would affect the optical properties of the suspended material. As mentioned in Chapter I, there are many important problems to be concerned with: isolation of organic matter from inorganic matter, identification and quantification of different species, and optical characteristics of each individual constituent or mixture. A common chlorophyll measurement is made by the acetone extraction method of Strickland and Parsons (ref. 44). The chlorophyll a, for example, can be calculated in mg/M^3 using trichromatic equation. Schultz and Quinn (ref. 4) suggested that unsaturated isoprenoid alcohol phytol is a constituent of the major chlorophylls a and b. They used the gas-liquid chromatography method and the spectrophotometric method to analyze phyto. There are other methods to measure organic matter, but there is not a major emphasis in this study.

7. Clay Minerals and Identification by X-ray Diffraction Patterns

The constituent particles of solids suspended in water are of various sizes and soil types. The size of suspended particles varies in diameter from smaller than .001 mm to larger than the colloidal size of 10^{-6} mm. Clay particles usually fall within this range.

The term clay has various meanings. It is used to describe particle size less than .002 mm effective diameter. These clay-size particles will include noncrystalline, amorphous materials, as well as crystalline minerals known as clay minerals. The clay size fraction of most soils contains clay minerals which are the result of chemical weathering of rocks. All soils of clay size fractions consisting of a high amount of clay minerals will have the property of high plasticity and cohesion.

The many varieties of clay minerals have been classified on the basis of the nature and arrangement of their atoms. The most abundant and important clay minerals are silicate minerals, which may be divided into three major groups known as kaolinite, illite, and montimorillonite. Because of the layer-latticed structure, the clay mineral particles are plate-shaped. The thickness and size of the plates will vary according to the types of mineral. An edge-view showing the relative size and shape of the clay particles is given in figure 15. Variation of size of each type of clay mineral is related to the degree of crystallinity of the clay mineral. Although a well-crystallized kaolinite clay particle will be large, a poorly crystalline particle may be no larger than those of montimorillonite clay.

An important property of the clay mineral is the negative electric charge on the surface of the clay particle. The negative charge will attract the cations of the water to the particles to maintain electroneutrality. The amount of negative charge per unit weight or per unit surface area of the clay is described by the ion-exchange capacity which is usually expressed in milliequivalents per gram of clay. Figure 16 shows that the ion-exchange capacity of montimorillonite is much higher than kaolinite mineral. If strong charges exist between two advancing particles, a repulsive force will keep them apart. In addition to a repulsive force, there is also an attractive force which acts between all adjacent pieces of matter. This attractive force is the van der Waals force which is inversely proportional to the seventh power of distance. If the clay particles are suspended in water, the repulsive force between particles will be suppressed when the temperature and electrolyte concentration is high. The net effect of forces between two particles becomes attractive; the two particles will tend to attach to each other or to flocculate. A thick flocculation of the clay particles will form a hazy cloud suspended in water. If the net effect of force is repulsive, the particles will move away from one another. The particles will be suspended or settled in a dispersed state.

The most widely used method for clay mineral identification is the interpretation of an x-ray diffraction pattern of a powdered sample of clay-size material. The diffraction patterns only indicate the types of minerals present. Many researchers have attempted, without success, to use these patterns to quantify the portions of each mineral in the sample. A quantitative identification of the amounts of each type of mineral may require several methods applied to the same sample.

Since the clay minerals are crystalline, the basic structure of a crystal can be considered to be made up of identical unit cells. The unit cell is the smallest repeating unit and the stacking of these cells by means of atomic bonds form the lattice plane structure of a crystal. The thickness of the unit cell forms the lattice plane or interplanar spacing and it varies with the type of mineral. The x-ray diffraction patterns are used to interpret the interplanar spacing which is given as the "d" value used in the identification of clays.

Although x rays are not necessarily monochromatic, a finite part of their energy is transmitted by a monochromatic wave having a wavelength of λ. Figure 17 shows that, as a beam of parallel x rays passes through a set of lattice planes, the diffracted and refracted rays from successive planes will form constructive interferences, which depend on the angle of incidence θ, the plane spacing, and the wavelength. The Bragg equation

$$n\lambda = 2\ d \sin \theta$$

where n is an integer defining the order of reflection, relates the planes spacing, d, to the monochromatic x-ray wavelength, λ, at a known angle of incidence, θ. Constructive interferences will occur as successful peaks in the x-ray pattern when the angle of inclination satisfies Bragg's equation.

Figure 18 shows a schematic diagram of an x-ray diffraction spectrometer. A motor rotates the specimen and Geiger-Müller counting tube to vary the angle of incidence of the x rays. The Geiger-Müller counter measures the intensity of the reflected x rays and records it as a function of twice the angle of incidence. A typical x-ray diffraction pattern is given in figure 19, and the d values for various clay minerals can be seen in figure 20. It is evident that experience and a knowledge of the relative intensity of different peaks are required to identify complex mixtures of minerals. Typical x-ray diffraction patterns of pure kaolinite, illite, and montmorillonite are given in figure 20.

8. A Summary of Some Recent Findings

Gibbs (ref. 40) indicated that all optical instruments measure not only the concentration, but also the effects due to size, shape, index of refraction, and color of the suspended material. Figures 21 and 22 clearly show the influence of particle size on the transmission of light, and on the intensity of light scattering. Zaneveld (ref. 45) proposed a procedure for use of the index of refraction of suspended particles as a tracer of water masses and for analysis of the composition of particulate matter. Organic matters generally have low indices of refraction, whereas inorganic particles have higher indices of refraction. Using the ratio of light scattered at 45 degrees for two wavelengths to the particle size distribution, the index of refraction of suspended particles can be evaluated. Figure 23 shows a study of the spatial distribution of the index of refraction near the Galapagos Islands in relation to ocean dynamics and to the nature of the suspended material. In varying the angle of scattering, Brown and Gordon (ref. 46) showed the relationship of the volume scattering function and the size fractions for various refractive indices (see fig. 24). To improve the optical measurement techniques and instrumentation, Austin (ref. 10) presented the volume attenuation coefficients as a function of wavelength computed from transmission measurements in the upper 3 to 5 meters at five wavelengths on each station (see fig. 25). There is a definite need for using a spectral transmissometer, capable of rapidly shifting wavelengths, for in-situ measurements for various types of water. Since a small variation of scattering coefficient is highly desirable, Austin recommended (see fig. 26) the small range of angle between 5 and 10 degrees for light scattering measurements. The conventional measurement angles of 45, 90, and 135 degrees resulted in a larger variation of the scattering coefficient. Using a single wavelength of 520 nanometers, Austin, as shown in figure 27, indicated the influence of the relative magnitude of scattering and absorption coefficients on the volume attenuation coefficient. The relative amounts of scattering and absorption vary according to the nature of the suspension (such as coastal or oceanic). Any correlation between the optical measurements and the suspended material would require the reference data (mentioned in Chapter I) of the region. Figures 28, 29, and 30 clearly indicate the need for regional reference data to interpret any observations. Baker, et al. (ref. 46), Feely (ref. 20), and Drake (ref. 28) have indicated as shown in figures 31, 32, and 33, respectively, that a linear correlation may be established between various optical measurements and the quantity of suspended solids.

Irradiance measurement of sunlight reflected from the water can be developed as an effective and economical method for wide area monitoring. However, in addition to the issues discussed for optical measurements, other major factors that will influence the upwelling radiance will have to included. Scherz (ref. 48) has indicated (see fig. 34) that influential factors such as surface reflection of the Sun, atmospheric scatter, surface reflection of the sky, and bottom effects be incorporated in the analysis of volume attenuation measurements, although the laboratory measurement of light reflectance of water varied proportionally with the logarithm of turbidity (in JTU units) and also with the logarithm of Secchi disk readings in inches (see fig. 35). The relationship among reflected solar radiation, wavelength, and concentration of total suspended solids in surface water given by Ritchie (ref. 24) indicated that the range of wavelength between 550 to 600 nm provided the optimum sensitivity for irradiance measurements (see fig. 36). However, Neefus (ref. 49) indicated (see fig. 37) that the optimum sensitivity occurred for a wavelength of 490 nm. The influence of Sun angle on the relationship between radiance reflectance and the suspended solid concentration was also given by Ritchie (see figs. 38 and 39). McCluney (ref. 50) studied the sunlight penetration for clear water and turbid water, as shown in figures 40 and 41. The significance of depth of penetration of sunlight as given by Clark (ref.

25) is shown in figure 42. When such highly irregular variation of light transmission with depth is present, these variations must be an important consideration for interpreting the irradiance measurement for this case.

It is apparent that the sea truth data must be collected simultaneously with irradiance measurements taken by aircraft or by satellite. Nichols (ref. 30) presented (see fig. 43) the variation of relative magnitude of reflectance with time. The variations are related to changes in temperature, in tides, and in season.

Correlation studies of the irradiance measurements with ground truth data from in-situ and laboratory measurements have been made by many engineers and scientists. Some of these are Klemas (ref. 26) (see fig. 44), Williamson (ref. 32) (see fig. 45), Link (ref. 6), Johnson (ref. 29) (see fig. 46), and Bowker (ref. 27) (see fig. 47).

CHAPTER III. RECOMMENDATIONS FOR LABORATORY AND IN-SITU RESEARCH RELATED TO REMOTE SENSING

The available in-situ and laboratory suspended material measurement techniques are described in Chapter II. Factors affecting the optical properties and concentration of the suspended material are discussed in Chapter I. Since no standard procedures have been established for the measurements in the field or in the laboratory, the effort to resolve these problems is logically the first task. Recommendations for research related to these priority problems and instrumentation is outlined in Chapter I. Unless a widely recognized specification for suspended material measurement is adopted by all researchers, research related to the remote sensing of suspended material can only be done based upon the current available procedures and instrumentation.

The main discussion and recommendations in this chapter are the laboratory and in-situ measurements required for remote sensing of suspended material, and the integration of laboratory programs with sea truth and remote sensing efforts.

The major issue is the calibration and correlation efforts needed to quantify suspended material through the remote sensing technique. As described at the end of Chapter I, information on suspended material can be obtained if an established reference (including in-situ conditions and parametric identification), a correlation between parameters and imagery, and the remote sensing image are known. Figure 48 shows the flow chart for the work of calibration and correlation between parameters and image. This is an essential effort in the process of quantifying the suspended material. The research program requires an outdoor test set-up as shown in figure 49. The effort includes in-situ measurements, laboratory measurements, sample preparation for simulation, and imagery taken as indicated in figure 48. All the tests would be performed outdoors in an aboveground or underground pool. The size and depth of the pool would depend upon the available space, concentration of the suspended material, and the depth of penetration for different wavelengths related to their spectral bands. One or more pumps would be provided to be able to empty or fill the pool in a short time, as the parameter of the Sun angle should be kept constant while other parameters are under investigation. The advantages of outdoor tests are the ease of including Sun angle, atmospheric conditions, and possibly the sea states into the study. A full spectrum radiometer or multiple channel scanner would be placed on board a helicopter or platform so that the height above the water surface could be adjusted.

Prepared samples should include the following information:

1. particle size and distribution

2. particle shape

3. type of particle (organic or inorganic matter)

4. specific gravity of constituent present in the suspension

5. percent of organic and inorganic matter, or percent of different type or size of particle

6. concentration of the mixture

7. dissolved substance in the mixture

8. pH value of the water

9. water temperature

10. salinity level of water

The in-situ and laboratory measurements serve as a monitoring process to check if the sample placed in the pool under the outdoor condition is indeed the same as originally prescribed. This is a very desirable step to ensure that little error will be involved in the correlation procedures. The in-situ measurements keep track of water composition in the outdoor condition, atmospheric conditions, and sea state, and more importantly, the in-situ measurements of all the optical properties of the suspension. This step exactly simulates the same processes as the in-situ measurement in the natural water bodies. The in-situ measurements include the following:

1. location and time for computing solar radiance

2. measurement of solar radiance

3. atmospheric condition between the radiance source and the pool, and the pool to the sensor

4. sea state including wind, wind induced or artificially introduced wave, water surface roughness, current or velocity in the pool

5. salinity measurement at different depths (or measuring conductivity)

6. temperature measurement at different depths

7. total water depth

8. acoustic signal

9. laser attenuation measurement using lidar system

10. transmissometer measurement at different depths

11. scattering meter measurement at different depths

12. batch or continuous sampling at different depths for laboratory use.

This test set-up involves simultaneous measurements using different types of instrumentation. Measurements can be recorded individually or by a multiple channel recorder. The basic idea is to obtain all different types of optical property measurements so that the image from the sensor can be correlated with a single or multiple parameter. It is still unknown, at this point, what kind of correlation can be achieved to give the best result for quantifying the suspended material. Therefore, simultaneous measurements of optical properties would yield more flexibility and advantages in the process of searching for the best correlation function, linear or non-linear, single variable or multi-variable.

The samples collected in the last step of the in-situ measurement need to be analyzed as stated below. Although the sample is prescribed, the properties of samples collected at different depths might give slight deviations from the prescribed formula.

1. Determine size distribution and number of particles using Coulter counter, TMC method, microscope observation, pipet, visual-accumulation tube, bottom withdraw method, hydrometer, or sieve analysis, whichever can be applied best.

2. Perform microscopic observation on particle shape and texture, and possible identification of types of particle in the mixture for a specific sample.

3. Determine the dry weight using filter, oven, and balance.

4. Determine percentage of organic and solid particles in the samples.

5. Determine dissolved substance which may give color to the sample and affect the transmissometer measurements.

6. Determine mineral composition or type of clay which can be identified using the parameters such as zeta-potential, opacity, refractive index, and birefringence.

7. Determine possible chemical or biological changes for the particles under the ambient pool condition.

Depending upon the type of instrument used, some of the measurements, like absorption and scattering, can only be measured in the laboratory with the samples collected from the pool. Hence, the laboratory or in-situ measurements just described are not an absolute matter. The researcher should set up his own experiment and keep in mind the principal philosophy recommended in this study.

Based on the above recommended set-up and all types of measurements, a series of experiments is recommended for the study of correlation in order to quantify the suspended sediment through remote sensing techniques. The proposed tests may be performed individually or in combination. However, they will be discussed individually according to the factors influencing the upwelling radiance.

Test 1. Variation of Type of Clay, Percent of Clay Mixture, and Concentration

The purpose of this test is to establish the relationship of upwelling radiance as a function of types of clay or their mixtures while keeping the concentrations constant. It also provides the relationship between the upwelling radiance and the concentration of the mixture with types of clay varied. These two relationships are shown in figure 50. The mixing method of three different types of clay, kaolinite, illite, montmorillonite is illustrated by figure 51. The pool is divided into six compartments with each being filled with a specified type of clay of known concentration as shown in the figure. Spectral information is taken for this arrangement. Then, for the second step, the partitions are removed to achieve an arrangement with only three compartments where a mixture of A+B, B+C, C+A are contained in each compartment. Finally, all partitions are removed to obtain a mixture of all three types of clay in the pool. This arrangement gives a complete experiment within a manageable short time period. The mixing method for one type of clay with different concentrations is shown in figure 51. Seven different concentrations of suspension can be correlated with their corresponding spectral images. The big tank should be painted in a flat black color. Reference data should be obtained for upwelling radiance to take into consideration the reflection from the tank's bottom and side wall. The reference data would be for the case of an empty tank and for the case of a tank filled with clean water. A different percentage of clay in the mixture can be arranged by means of a "Feret Triangle". A point inside the triangle represents the percent of A, B, and C. If upwelling radiance is measured for a specific mixture and indicated beside that point, contour lines of equal upwelling radiance can be drawn. Figure 52 shows expected equal upwelling radiance lines, which is another kind of correlation curve to be used in quantifying suspended material. The same type of graphical representation can be adopted for other types of study, such as the mixture of silt, clay, and organic matter. Mixing should be done in a short time period so that the other parameters such as solar radiance, zenith angle, atmospheric conditions, water surface conditions, etc., can be kept constant during the experiment for parametric studies.

Test 2. Variation of Type of Organics, Percent of Clay, Silt, and Organics in Mixture

Test 2 is an extension of Test 1. The interaction effect is examined through the preparation of samples of increasing complexity in the sequence, as shown in figure 53.

Test 3. Water Composition

In order to understand the colloid agglomeration, water composition is an important parameter to consider. Tests 1 and 2 can be combined with Test 3 in the following ways:

a. variation of pH values

b. variation of water temperature

c. variation of salinity in water column by creating salt concentration gradient.

The salinity profile over the depth of water can be simulated using salt concentration with different types listed below:

a. homogeneous media

b. two-layered system to simulate the thermocline in the ocean with elevation of the interface varied

c. multi-layered system with suspended material introduced in a particular layer of given depth and thickness in order to simulate "sediment cloud"

d. linear salinity gradient over the water depth.

Experiments should be carried out prior to this test concerning the proper kind of suspended material to be used in terms of different types of mixtures stated in Test 2, density and concentration of the mixture. Neutral buoyant particulates would be used for "sediment cloud". If flocculation and sedimentation occur, the unsteady phenomena present in the test will be studied as follows:

a. sequential measurement of upwelling radiance

b. continuous operation of all the in-situ measurements and sampling of the suspended material at different elevations.

The particle concentration or size gradient generated in this test can be used in conjunction with Test 4 on the penetration depth study.

Test 4. Penetration Depth

A spectral board is installed at various depths to study the penetration depth of each band for various types of suspended material and water composition. This test can be combined with other tests. The effect of the bottom at shallow water areas can be studied in this test.

Test 5. Sea States

Different sea states, such as wind, waves, are created in conjunction with other tests.

Test 6. Atmospheric Conditions

Various solar radiance and zenith angle and conditions of haze and clouds are studied. This can be combined with other tests.

The tests recommended are primarily outdoor experiments on the ground and in the air, in conjunction with some of the parametric measurements indoors. All of them are considered as laboratory study. There are certain experiments which do not need to be involved with solar radiance to simulate the "real world". They can be performed in an indoor laboratory. For example, the following studies (not limited to) can be investigated for feasibility study and estimation of order of magnitude.

a. Study the unsteady nature of suspended material under chemical or biological reaction. For example, the flocculation phenomena of clay particles with respect to the temperature, salinity, pH value of the water.

b. Estimate the sensitivity of parameters affecting the upwelling radiance. For example, the depth of penetration can be studied under artificial light to see how sensitively the concentration gradient is affected by the upwelling radiance.

c. Test the theory for differentiating constituents present in the water. If the theory is valid for indoor tests under artificial light, the theory can then be directly tested or modified for natural sunlight.

d. Study the limit of particle size above which the upwelling radiance is independent of the particle size as far as light absorption and scattering are concerned.

e. Test the effect of surface roughness compared with the concentration of suspended material on the upwelling radiance.

In general, fundamental questions can be studied and answered inside the indoor laboratory first and then tested outdoors for a "double check". In certain instances, it may turn out to be more simple and economical since a lot of other parameters can be held constant during the study of a particular parameter. However, a few things have to be carefully handled.

a. Simulation of collimated light and diffuse light.

b. Bottom and sidewall effects of the container on the scattering light.

c. Adequate depth and surface area of the container related to the depth of penetration.

d. Circulation pattern inside the container.

e. Strength, size, and parallelism of artificial light.

f. Properties of the constituents in the water as well as water composition should be frequently monitored in terms of spatial and temporal variations.

If an attempt is made, using the indoor laboratory results, to predict the phenomena in the field, a careful study on the similitude should be done. Like all the hydraulic models for the study of circulation patterns, scaling effect is an important factor. All the quantities must necessarily be expressed in non-dimensional terms and a relation established to convert the model results into the prototype conditions for the purpose of prediction. The modeling technique being applied to the remote sensing of suspended material in an indoor laboratory needs further study.

APPENDIX

NOAA NATIONAL OCEANOGRAPHIC INSTRUMENTATION CENTER

PROCEEDINGS OF TURBIDITY WORKSHOP, MAY 1974 (REF. 10)

The concept of turbidity is optical; however, the use of the term "turbidity" was found to be ambiguous, and the practice of calibrating the various instruments for its measurement in JTU, FTU, NTU, or ppm was found to be misleading and in fact incorrect. There was general agreement that the optical instruments in current use provide an inferred and not a direct measurement of suspended solids. Their use for this purpose must be supported by ancillary measurements which demonstrate that the optical measurand is correlated with the concentrations of the specific material to be monitored. It must be recognized that any such correlation may be invalidated by variations in the particle shape, size distribution or the index of refraction of the material normally found in natural waters.

Instrument-to-instrument comparisons may be possible if the necessary optical characteristics of the instruments are known and a scattering transfer standard or standards can be defined together with appropriate calibration procedures. For scattering instruments, the angles of measurement together with the size and shape of the optical beams and the scattering volume need to be specified, as well as the spectral distribution of the energy utilized in the measurement.

Scattering instruments using different scattering angles and polarizations may each have individual advantages in specific particle size and/or concentration ranges.

Application of transmissometers may be advantageous where the role of absorption is of special concern, and their use is particularly valuable in investigating the spatial distribution of the total attenuation coefficient.

Calibration of instrument dials in terms of grams per liter, ppm or other mass concentration units are not direct optical measurements, and are the result of calibration techniques producing a specific transfer function for that instrument. It must be pointed out that a transfer function is required and not a single point calibration.

The special requirements of the biologists for optical measurements related to the study of particulate matter and primary productivity, as irradiance, have been thoroughly covered by the WORKING GROUP 15 of the SCIENTIFIC COMMITTEE FOR OCEANOGRAPHIC RESEARCH OF THE INTERNATIONAL ASSOCIATION OF PHYSICAL OCEANOGRAPHY.

Scientists and engineers who require relatively complete information on the nature of a particulate suspension will probably need to perform a multi-parameter measurement; simple scattering measurements are unlikely to be satisfactory. This subject was addressed recently at the ONR meeting on Suspended Solids in Water; the proceedings will be published in the summer of 1974.

RECOMMENDATIONS

1. The term "TURBIDITY" shall be used only as a non-technical appearance descriptor. It is a qualitative and relative term to the same manner as warmth. One does not measure warmth; one measures temperature.

2. The measurements shall be labeled to accepted scientifically identifiable terminology.

3. The instruments shall be named in accordance with the physical parameters measured.

4. The requirements for scattering standards in terms of size and shape distributions, refractive index, concentration, stability, and reproducibility should be carefully examined in view of their potential use in widely varying contexts; and appropriate systems should be selected.

5. A phased conversion from existing ambiguous standards must be executed.

6. NOIC shall encourage the formation of professional multi-disciplinary committees, drawn from concerned agencies, industries, and institutions, who shall establish standard procedures for calibration, test and evaluation of commercially available scattering instruments and publish recommended means of transition from present practice to the new standards.

Table 1. Applications for "turbidity" data.

Application	Particle Size	Medium Characteristics	Concentration Range	Basic Information Desired	Secondary Information Desired	Parameters To Be Measured	Remarks
Biological	0.5 to 200 microns (Mean value usually adequate)			Light extinction at various wavelengths	Cause & origin of material producing the light extinction	Diffuse attenuation coefficient	For complete reference on solar illum...Vol. 10 SCOR Proceedings (Scientific Committee on Oceanic Research) Working Group 15
Geological	1. Geological: up to 2000 microns 2. Dredged Materials: <10 microns plate shaped >10 microns spheres or cubes	Refractive Index 1.1 to 1.2	2 to 5000,000 mgm/l (Extremes of most interest)	a. Amount of sediment & identification of source b. Asthetic value		Particle size distribution - concentration of suspended material a) organic b) mineral composition	
Wastewater	1. Municipal: <1 to 1000 microns (variable shapes) 2. Industrial: in general, size is not important (variable shapes) 3. Combined: Storm, Sewer: for specific processes, size may be important (variable shapes)	Refractive Index 1.0 to 1.2	10 - 10,000 mgm/l	a. Particulate composition b. Asthetic value c. Foam	Organics & hazardous inorganics Color		

(cont'd.)

Table 1. Applications for "turbidity" data (concluded).

Application	Particle Size	Medium Characteristics	Concentration Range	Basic Information Desired	Secondary Information Desired	Parameters to Be Measured	Remarks
Oceanographic	0.5 to 50 microns	Refractive Index 1.0 to 1.2	.005 to 200 mgm/l	Composition and concentration of particulate matter		a. Absorption coefficient, scattering coefficient, volume scattering function b. Color	
Monitoring				Asthetic value		Qualitative and usually a result of complaints	
Drinking Water						Refer to USPHS Standards 1962 where specific parameters and methods are listed.	

Table 2. Users and applications of data on suspended particulates.

	Agency	Biological	Geological	Wastewater	Oceanographic	Monitoring	Drinking Water
1.	EPA	X	X	X	X	X	X
2.	USGS		X			X	
3.	USACE						
	WES						
	CERC	X	X			X	
4.	USDA (SCS)		X				
5.	NOAA				X	X	
6.	Bureau of Sport Fisheries and Wildlife (Dept. of Interior)	X					
7.	Division of Wildlife Refuges (Dept. of Interior)	X					
8.	National Marine Fisheries (Dept. of Commerce)	X					
9.	U.S. Forest Service	X	X				
10.	Federal and State Highway Depts.		X				
11.	State Water Control Agency	X	X	X	X	X	X

(cont'd.)

Table 2. Users and applications of data on suspended particulates (concluded).

Agency	Biological	Geological	Wastewater	Oceanographic	Monitoring	Drinking Water
12. District water resources planning agencies	X	X	X		X	X
13. Marine resources commissions	X	X	X	X	X	
14. Utility departments of local governments	X	X	X			X
15. U.S. Navy		X		X		
16. Federal and State parks & recreation services	X	X				
17. Environmental conservation groups at all levels of government, and private citizens	X	X	X	X		X
18. Researchers from universities, research institutions, industrial R&D	X	X	X	X	X	X

Table 3. Primary use of suspended solids parameters.

	Shape	mg/l	Total Particles	Particle Size Distribution	Clay Type	Mineral Composition	Optical Characteristics
1. Circulation pattern analysis		X	X				X
2. Indication of environmental change (Ecosystem, shellfish)		X	X				X
3. Flocculation reactions	X				X	X	X
4. Calculation of particle settling	X	X	X	X			X
5. Chemical reaction	X			X	X	X	X
6. Erosion from cropland, surface mining, and urban development		X		X			X
7. Monitoring non-point pollution sources		X				X	X

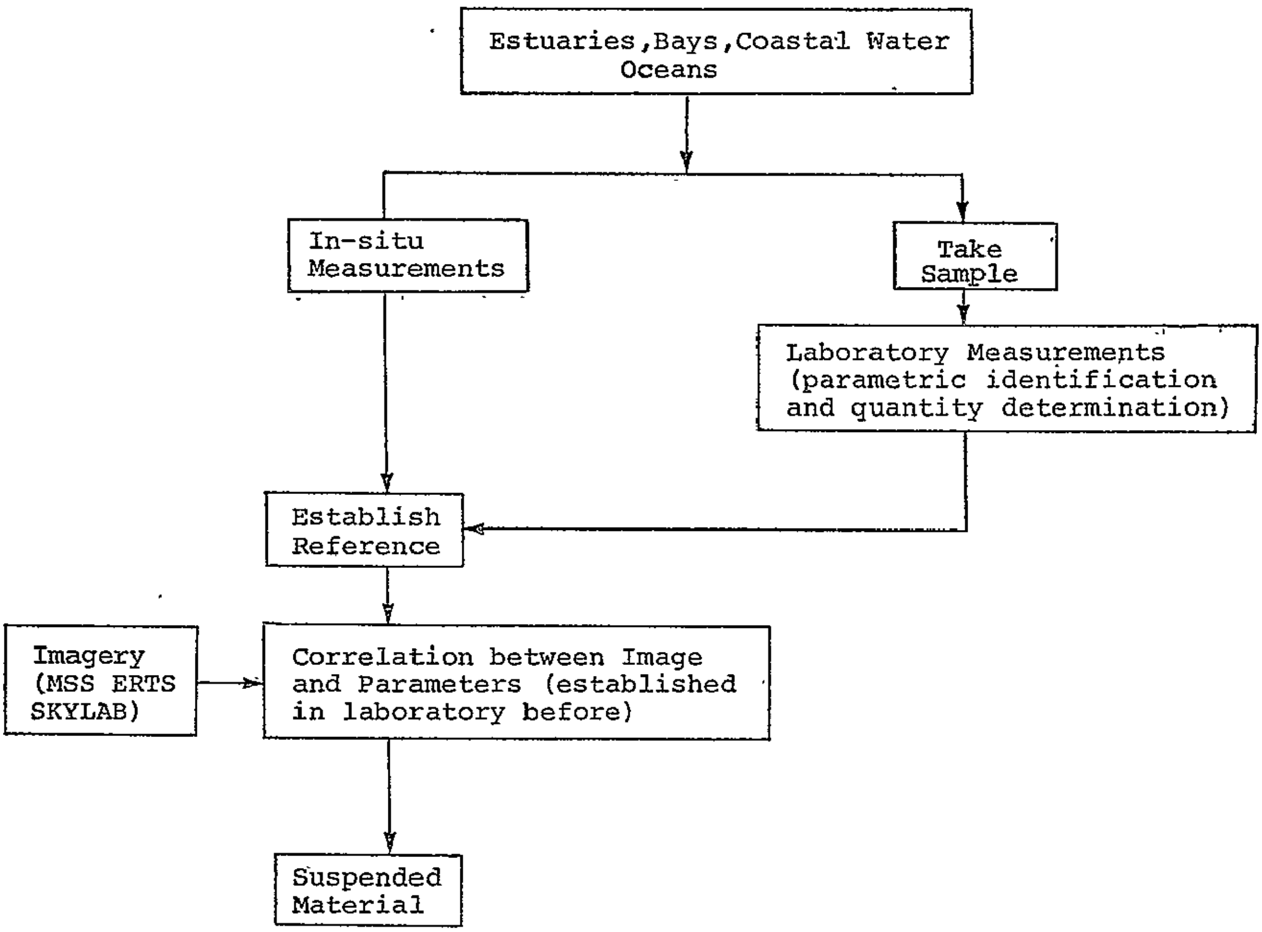


Figure 1. Flow Chart for Normal Operation.

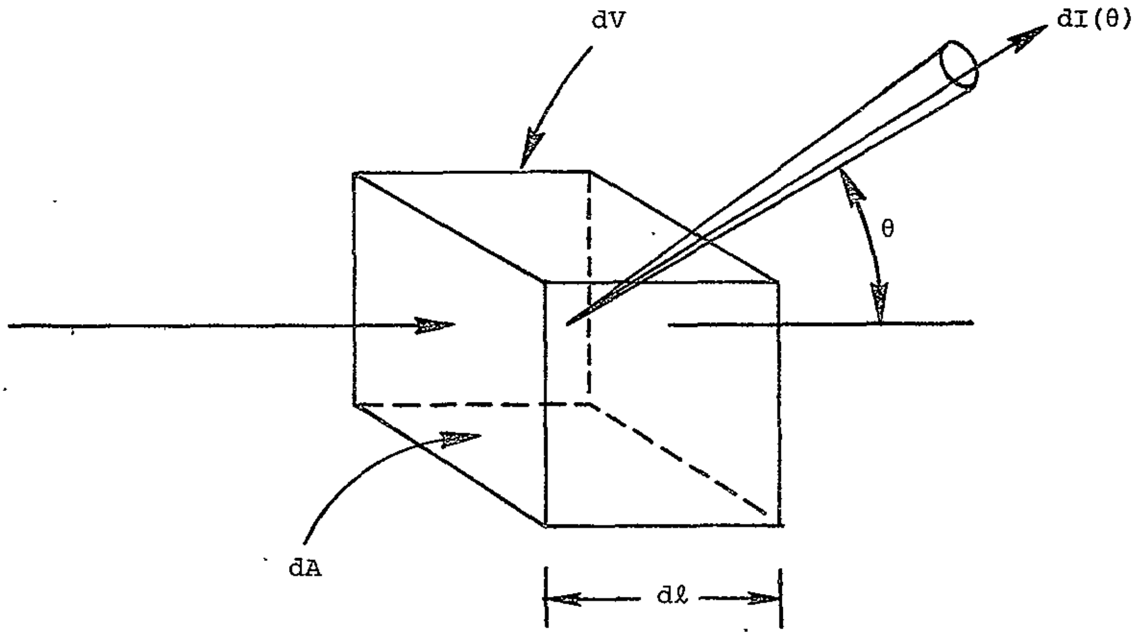


Figure 2. Scattering Measurement (ref. 10).

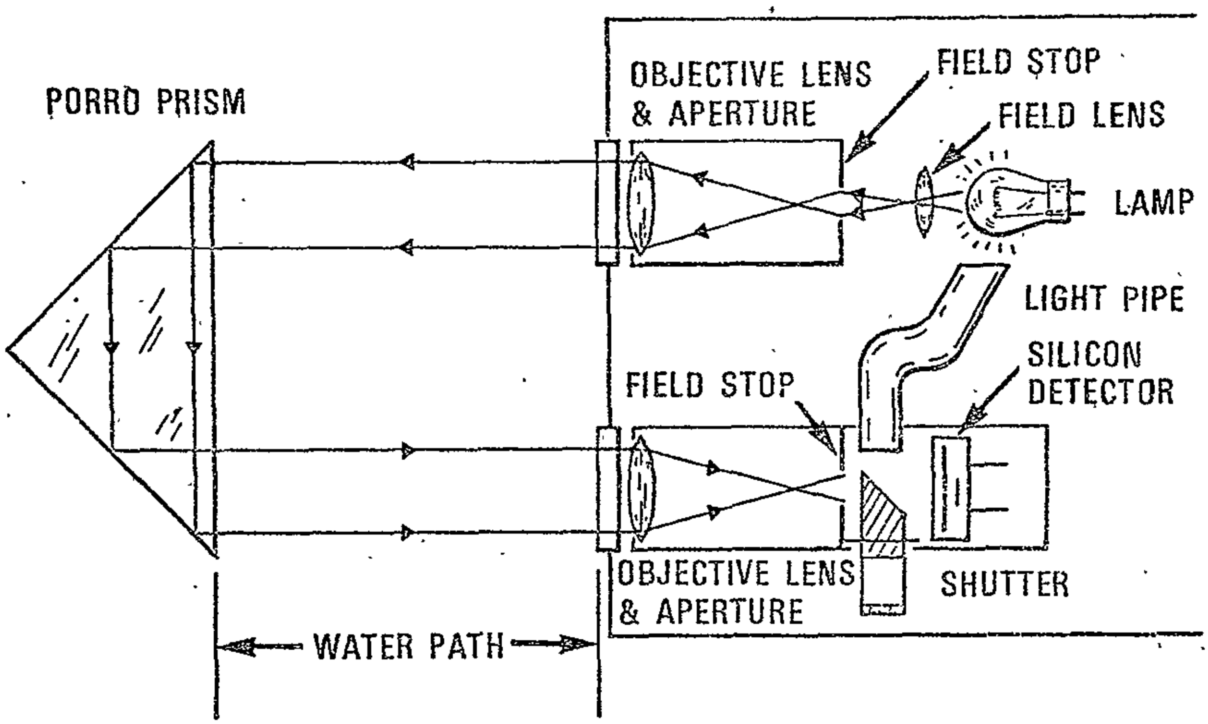


Figure 3. Transmissometer Optical Schematic (ref. 10).

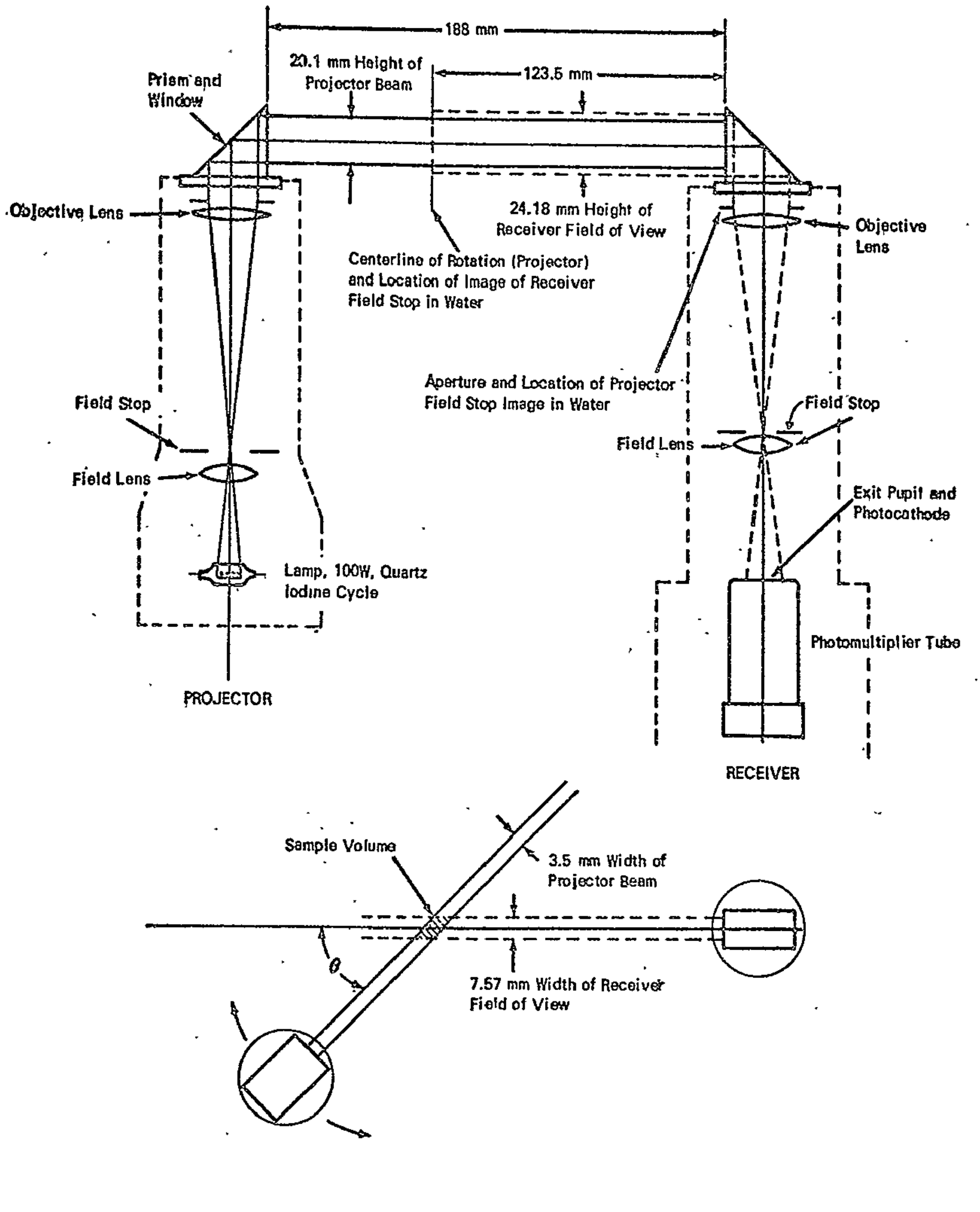


Figure 4. General Angle Scattering Meter Optical System (Ref. 10).

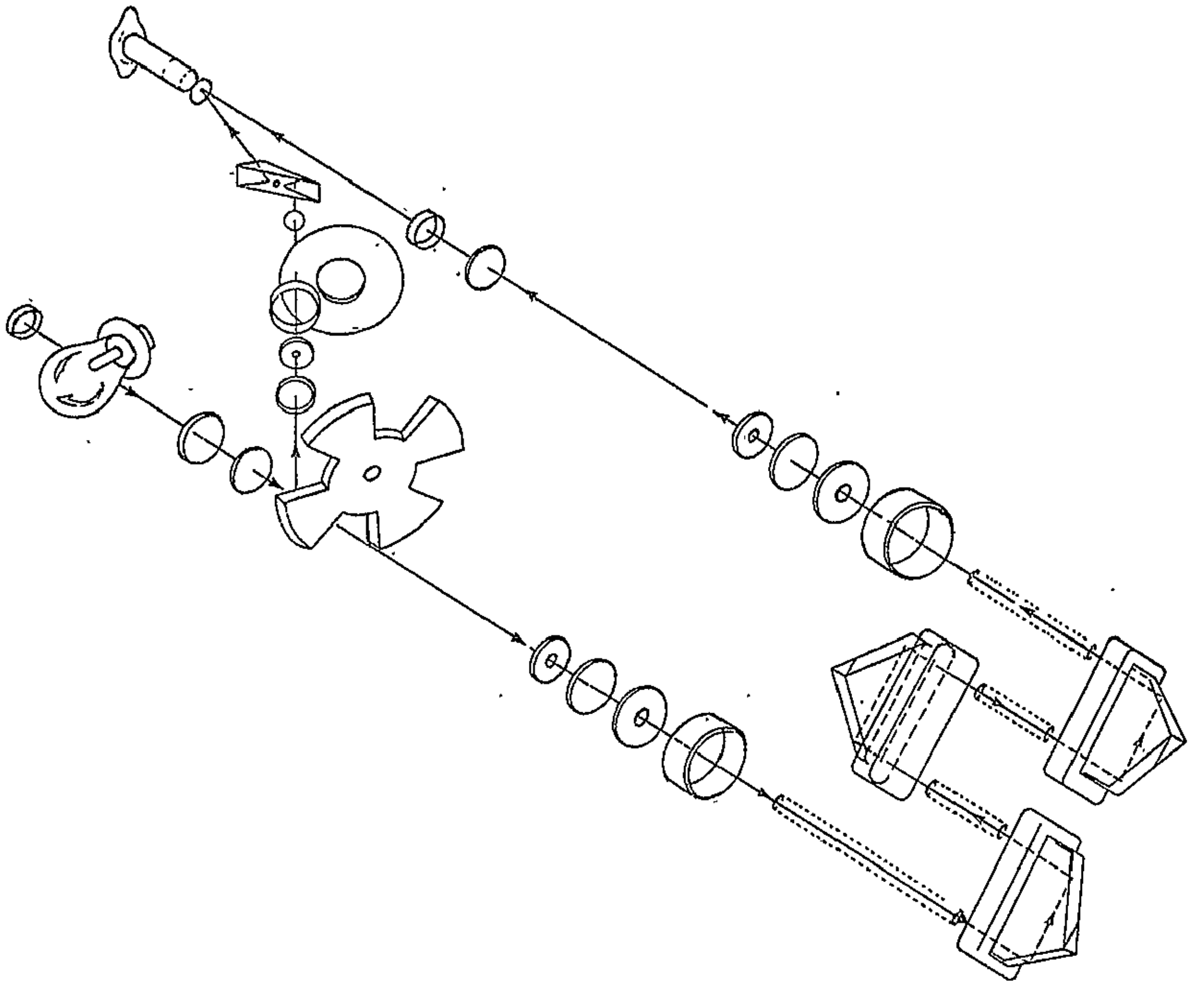


Figure 5. Schematic optical system of the null-balance beam transmissometer of *Hughes and Dustin* [1965]. (1)-(8) comprise its projection system; (9)= housing windows; (10)= the prism system for folding the path length; (11)-(16)= the detector optical system; (17)= a rotating sector disc which, by means of (3), (18), (19), (20), (22), and (23) intermittently images the field stop (4) on the photodetector (25); (24)= a spectral filter; (21)= a neutral density wedge which, by means of a servo mechanism, equates the two signals, one via the water path and the other via the air part within the instrument housing (Ref. 13).

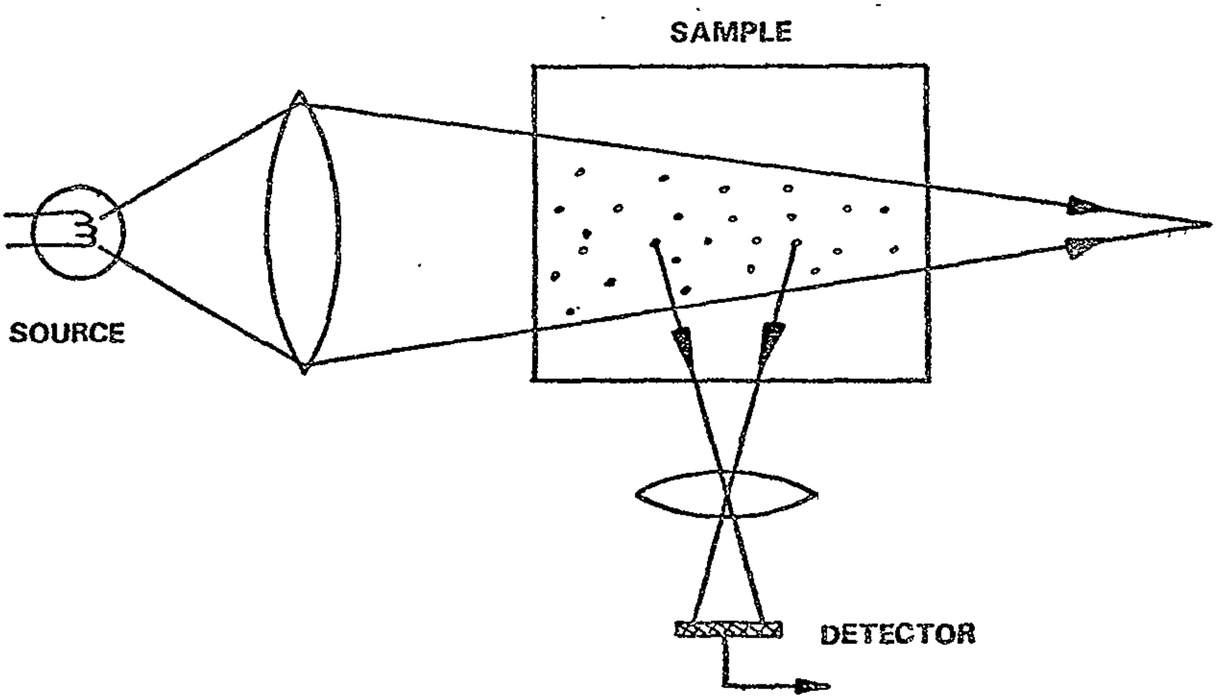


Figure 6. Side-Scatter Turbidimeter Design (ref. 51).

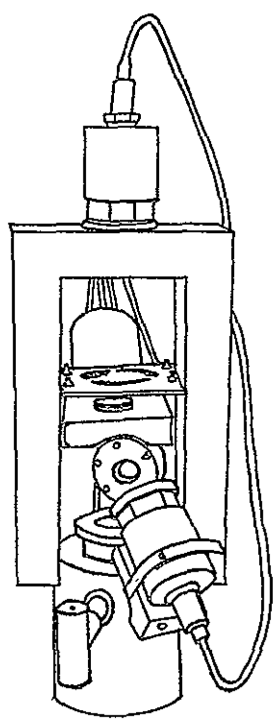


Figure 7. Multi-angle Scattering Meter Developed by Gibbs (ref. 14).

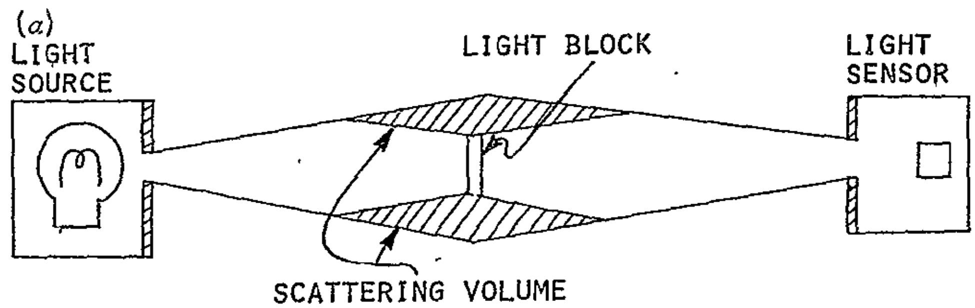


Figure 8. Drawing of an Extremely Low-Angle Scattering Meter After Kullenberg (ref. 14).

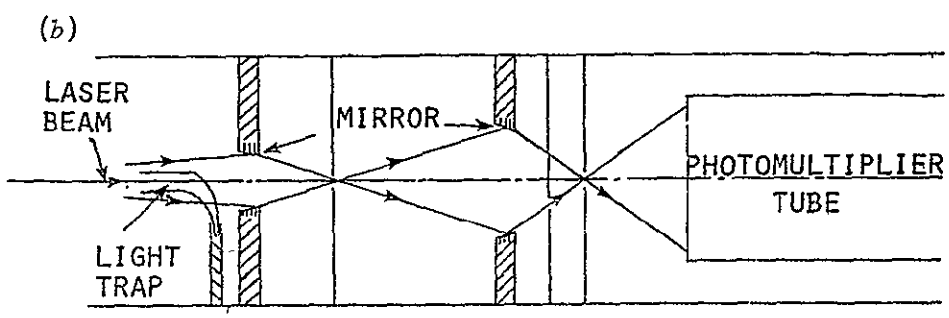


Figure 9. Drawing of a Moderately Low-Angle Scattering Meter after the design of Thorndike and Ewing (ref. 14).

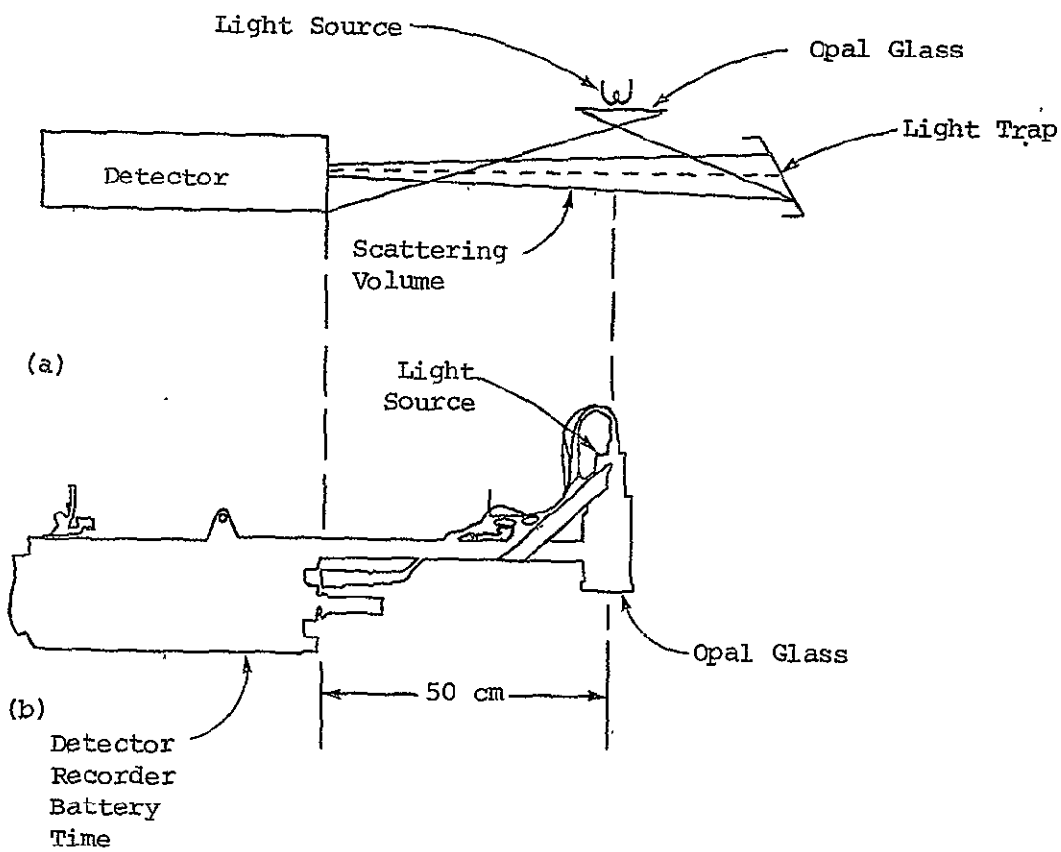


Figure 10. (a) Geometry of the Scatterance Meter of Beutell and Brewer [1949]. (b) The Nephelometer Used in this Study (ref. 47).

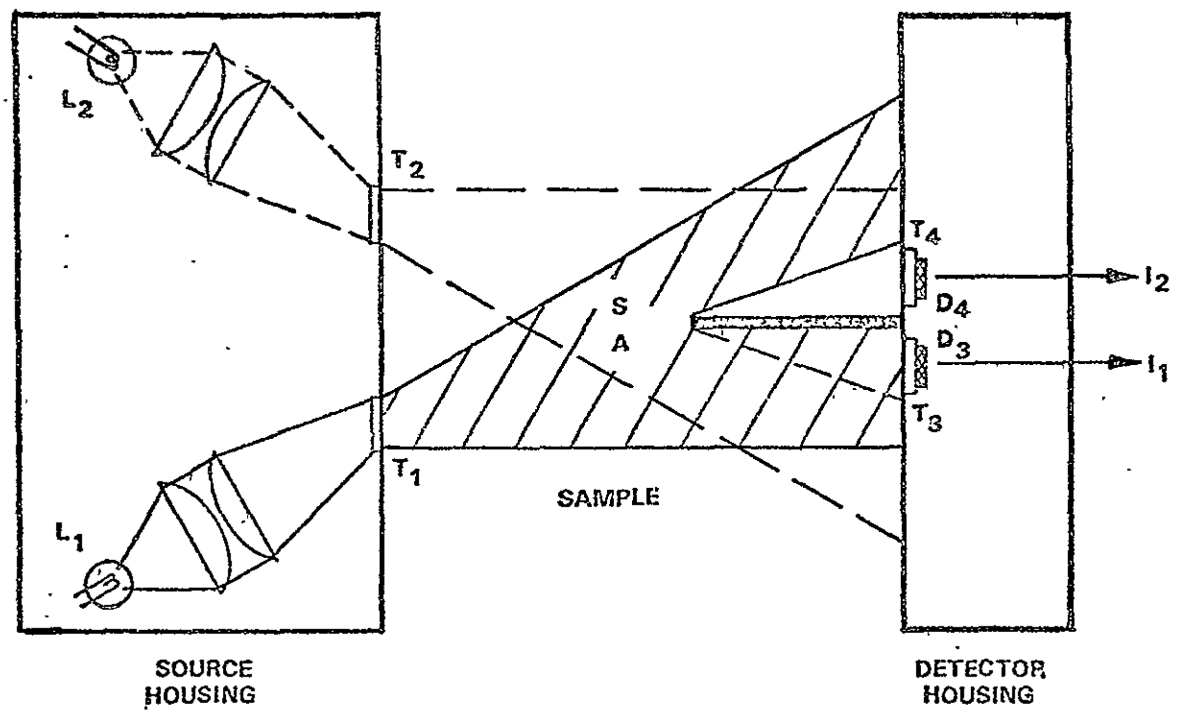


Figure 11. Submersible Turbidimeter by Monitor Technology, Inc. (ref. 51).

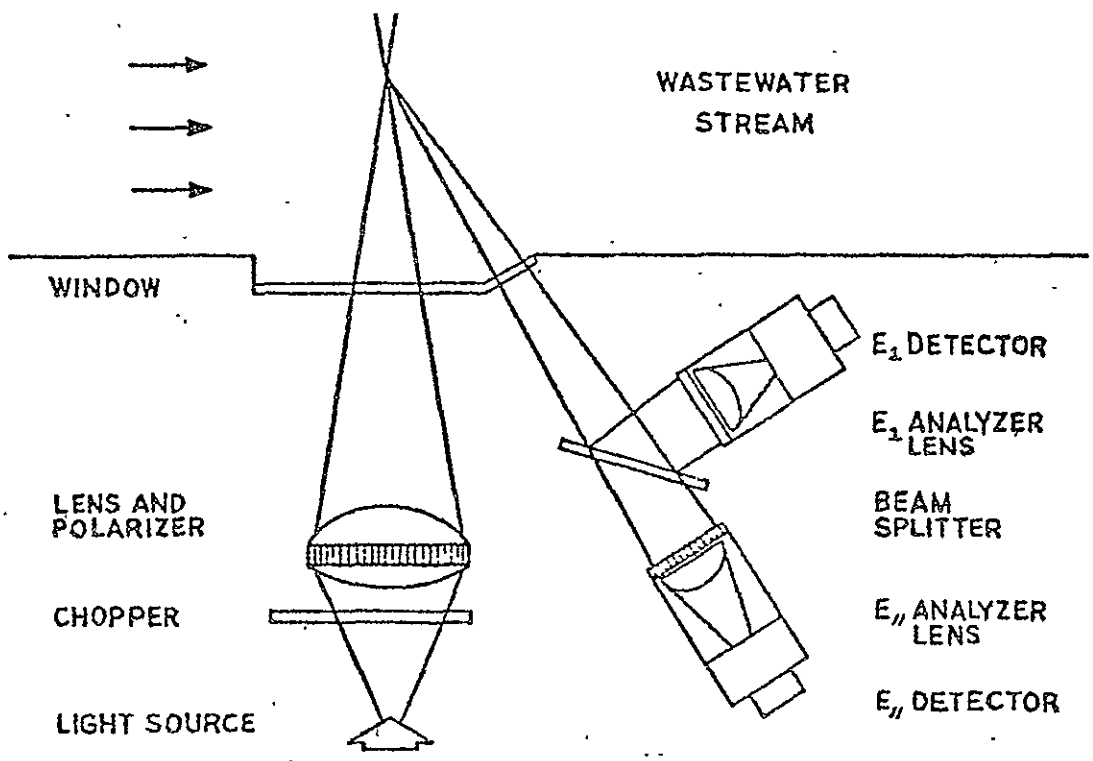
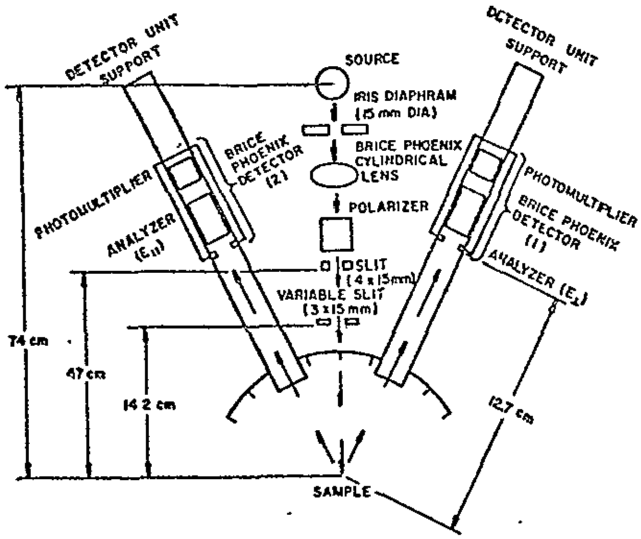
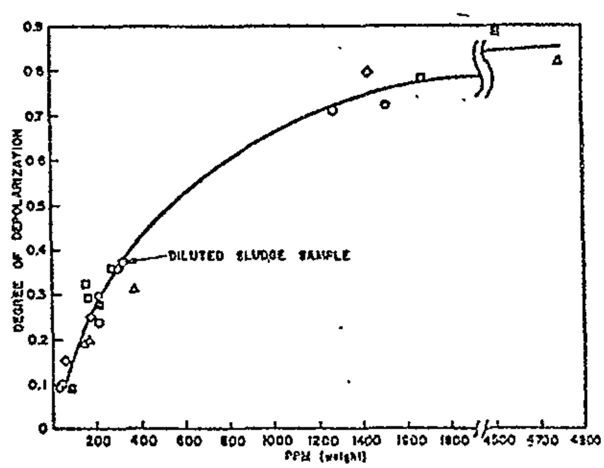


Figure 12. Badger Meter by Badger Meter, Inc. (ref. 52).



Schematic of instrumental arrangement for depolarization measurements at a back-scattering angle of 170°

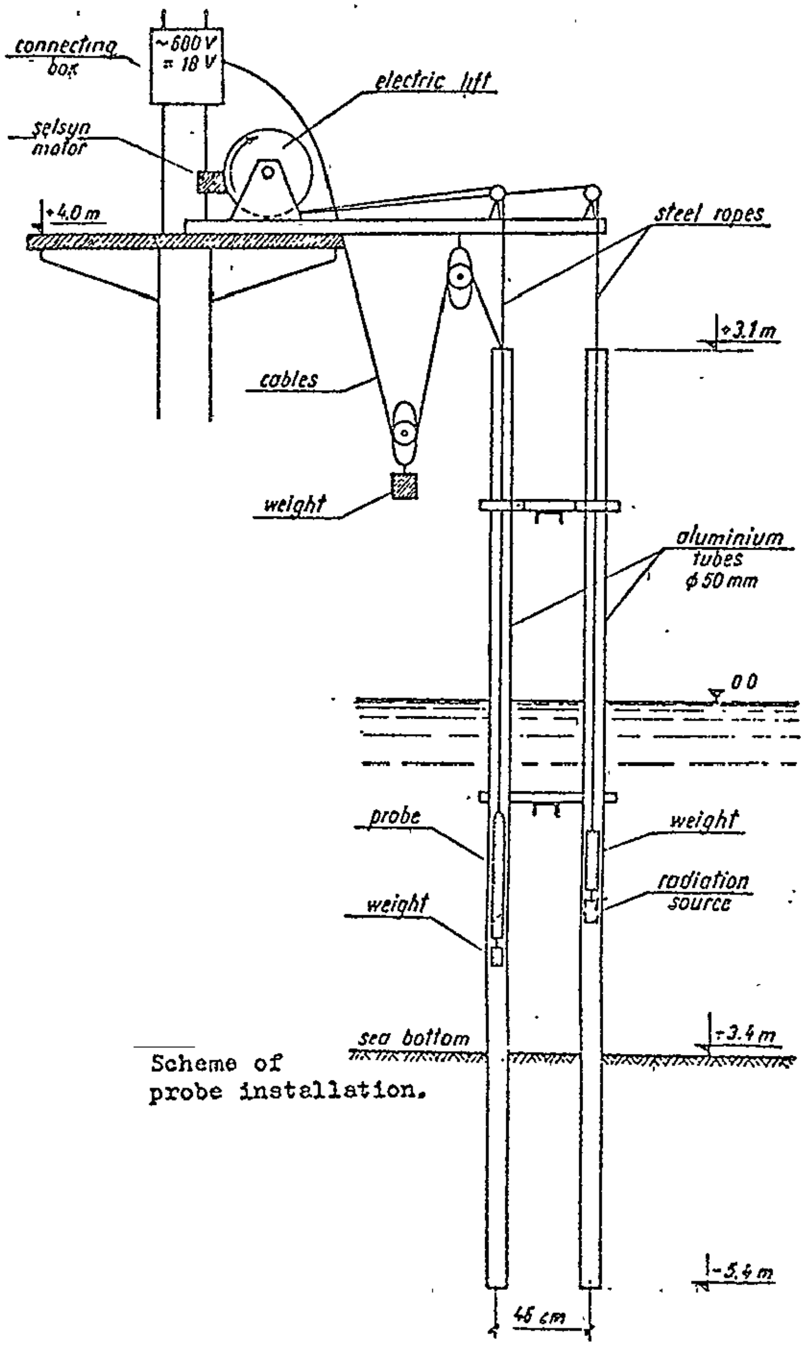


Degree of depolarization as a function of suspended solids. Wavelength of incident radiation = polychromatic light

Scattering angle = 170°

- □ Middlesex samples collected 5/23/69
- ◊ Middlesex samples collected 5/27/69
- o Bernardsville samples collected 6/10/69
- O Bernardsville samples collected 6/13/69
- Δ Middlesex samples collected 6/17/69
- ⊠ Bernardsville samples collected 6/20/69

Figure 13. Depolarization Method (Ref. 22).



Scheme of probe installation.

Figure 14. Radiometric Method (ref. 37).

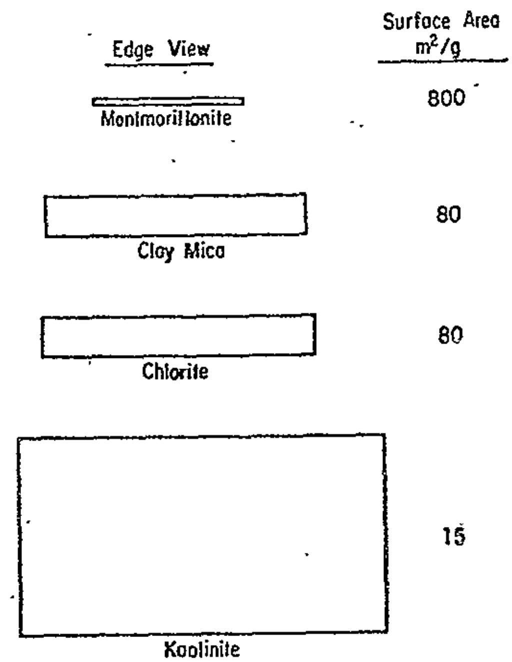


Figure 15. Edge-View Sketches to Show Relative Size and Shape of Clay Particles; Dimension Not Shown is Equal to Length (ref. 53).

Clay mineral	*Exchange capacity, meq/100 g*
Kaolinite	3–15
Illite	10–40
Montmorillonite	80–150

Figure 16. Values of Ion-Exchange Capacities (ref. 54).

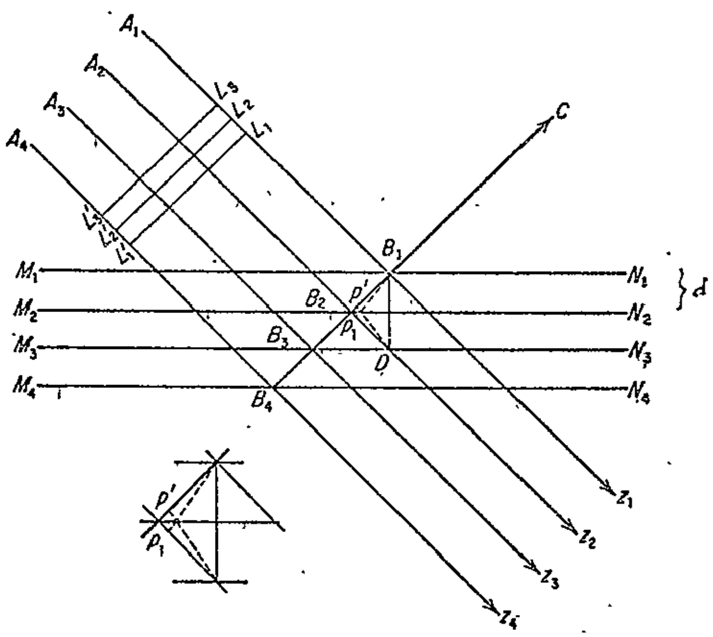


Figure 17. Representation of a Set of Planes in a Crystal and a Beam of Parallel X rays (ref. 53).

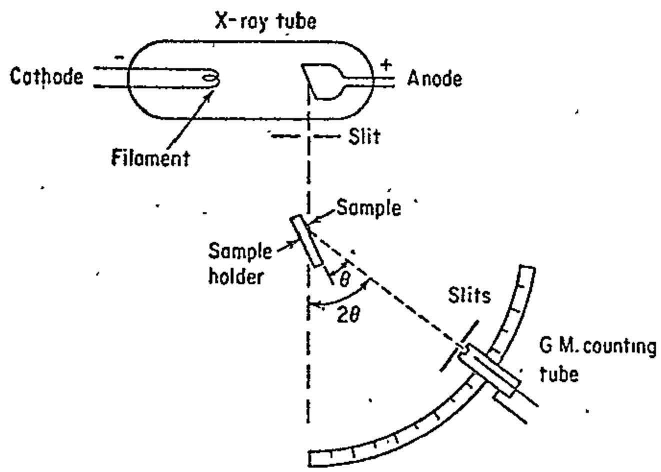
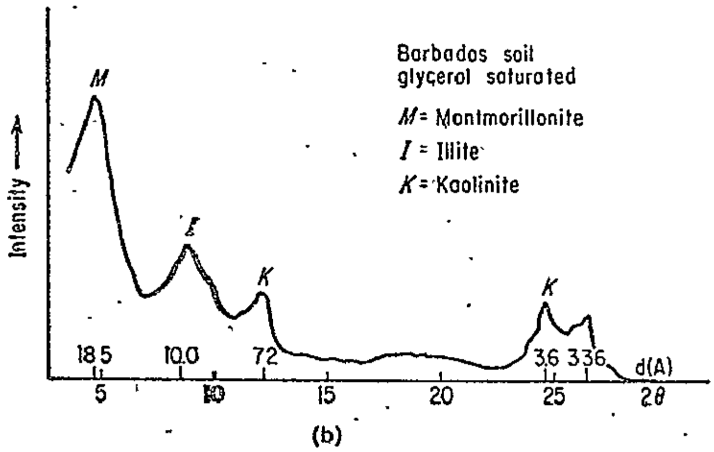
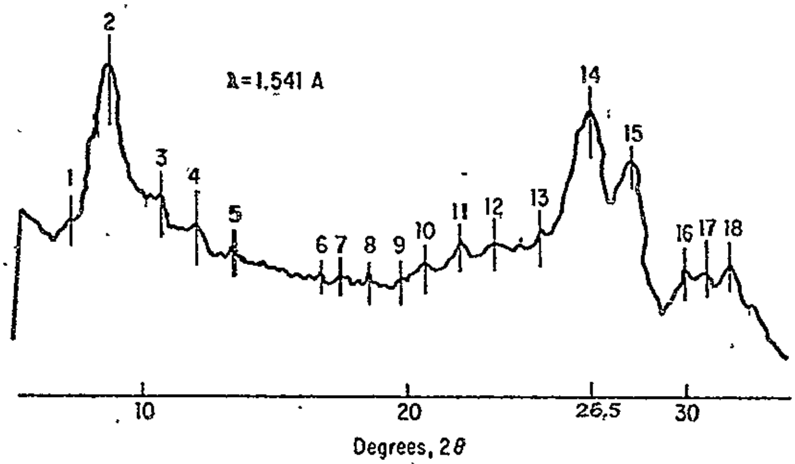


Figure 18. Schematic Diagram of X-ray Diffraction Unit for Crystal Identification. The Sample Holder Rotates Through 0 Degrees While the Geiger-Muller Counting Tube Rotates Through 20 Degrees. The X rays are Diffracted by the Crystalline Sample and When 0 is Such that the Refracted Rays Are in Phase, a Higher Intensity is Recorded by the G.M. Tube (ref. 53).

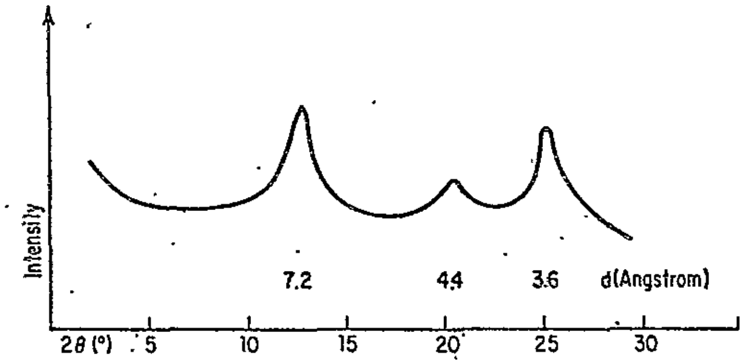


X-Ray Diffraction Patterns for Three Soil Samples and Identification of Minerals from Diffraction Peaks (Samples in (a) from Linell and Shea, 1960)

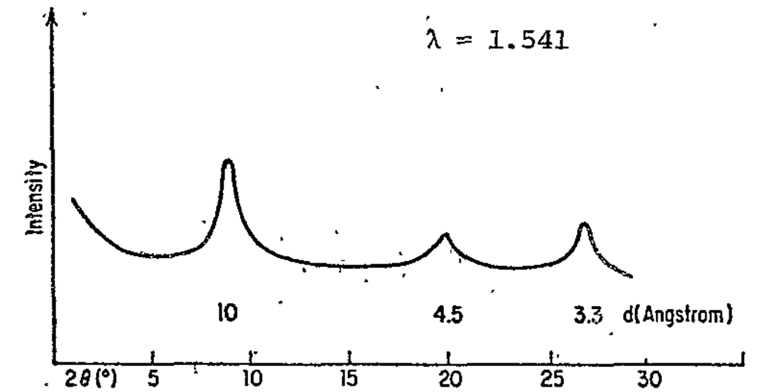


X-Ray Diffraction Pattern for "Seven Islands" Clay

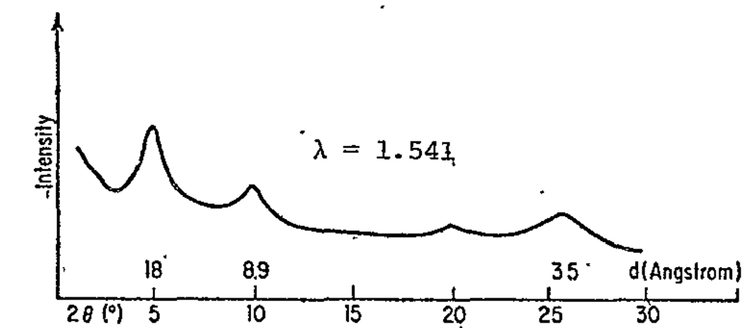
Figure 19. X-Ray Diffraction Pattern (ref. 53).



Typical X-Ray Diffraction Pattern of Kaolinite Mineral (Oriented particles using CuKα radiation)



Typical X-Ray Diffraction Pattern of Illite (Oriented particles using CuKα radiation)



Typical X-Ray Diffraction Pattern of Montmorillonite with Glycerol (Oriented particles using CuKα radiation)

Figure 20. Typical X-Ray Diffraction (Ref. 53).

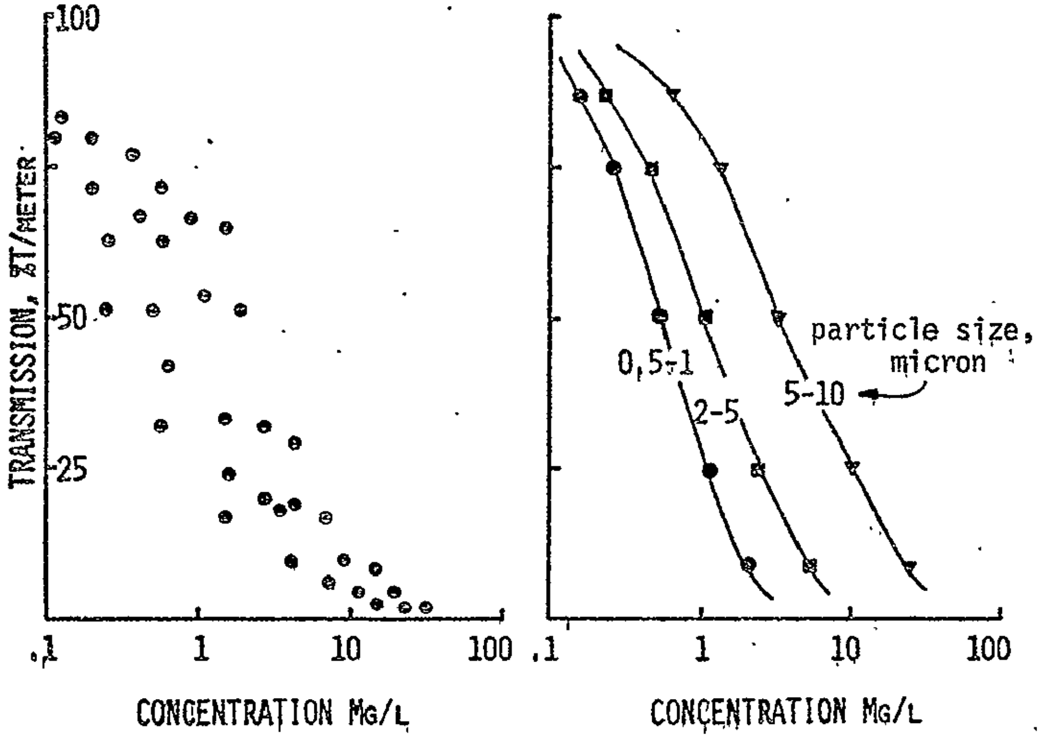


Figure 21. Transmission Calibration Curve for Absorption Studies of Suspended Solids in Water. (a) Calibration Curve for Suspended Natural Sediment Obtained In-situ From Molecular Filter Sample at the Same Place and Time as the Instrument Reading; (b) Calibration Curves Prepared with Distilled Water and a Known Amount of Sized Natural Sediments (ref. 40).

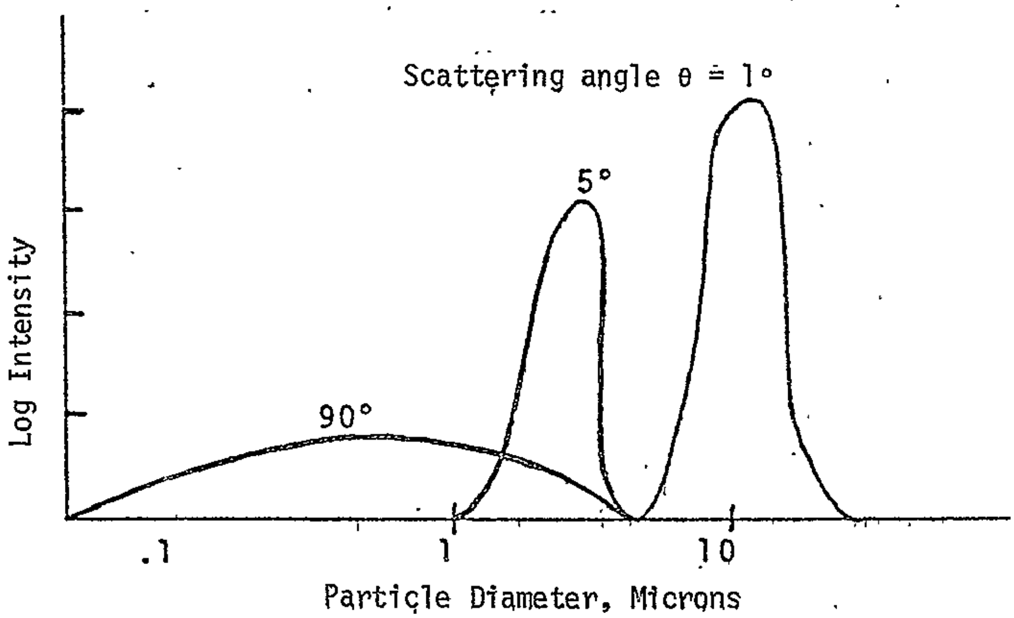


Figure 22. Scattering Response at 1 Degree, 5 Degrees, and 90 Degrees, from the Receptive Sizes Originating Response (ref. 40).

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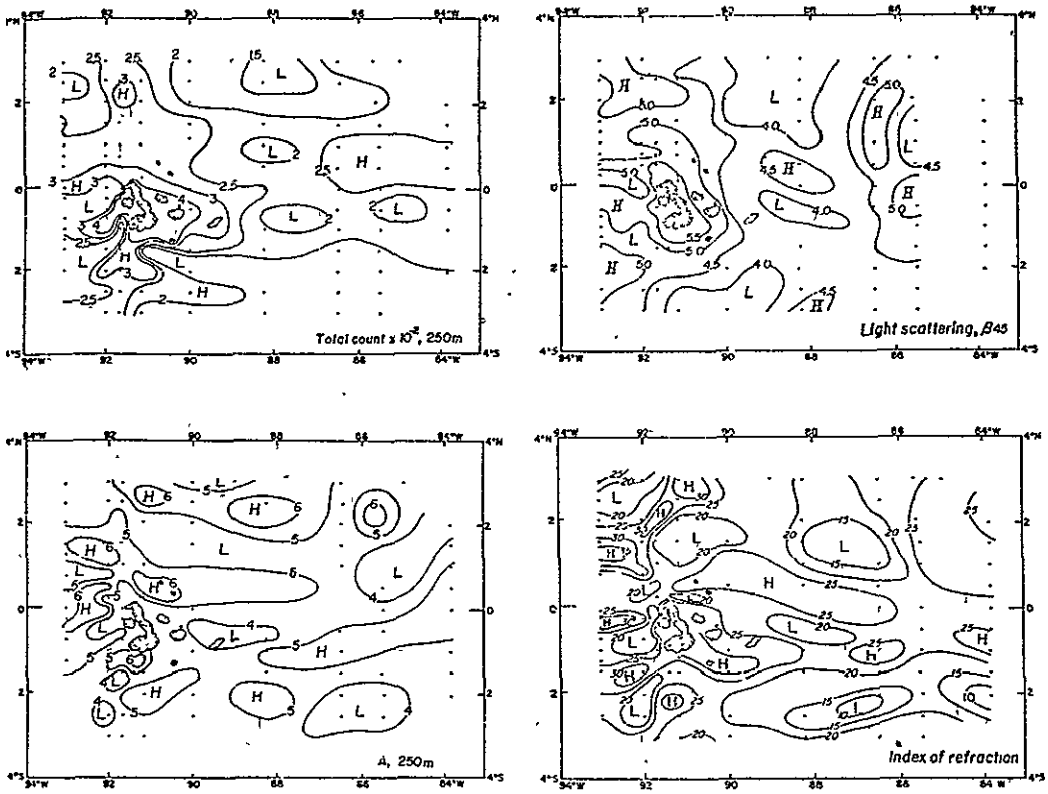


Figure 23. (a) Total Particle Count × 10^{-2} (μm)^3/cm^2; (b) Light Scattering at 45 Degrees × 10^{-4} m^{-1}-ster^{-1} Particle-size Distribution Parameter A × 10^{-1} m^{-1} and the Difference Between the (c) Particle, and (d) Water Indices-of-Refraction × 10^{-3} + 1 at 250 m Depth near the Galapagos Islands (ref. 45).

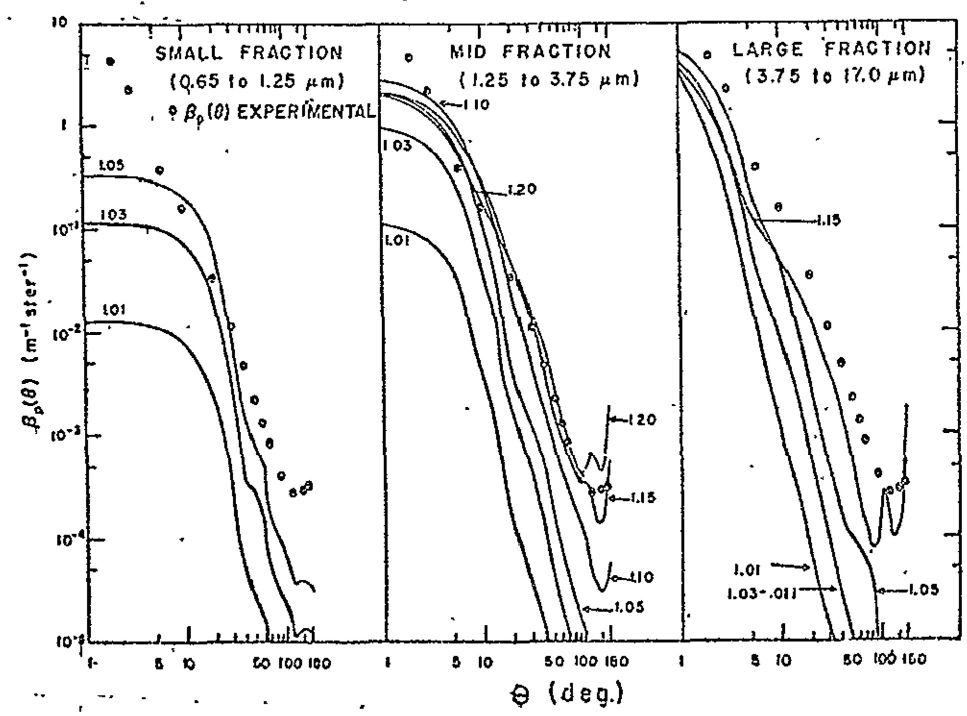


Figure 24. Particle Scattering Functions of the Small, Mid, and Large Fractions for Various Refractive Indices (ref. 46).

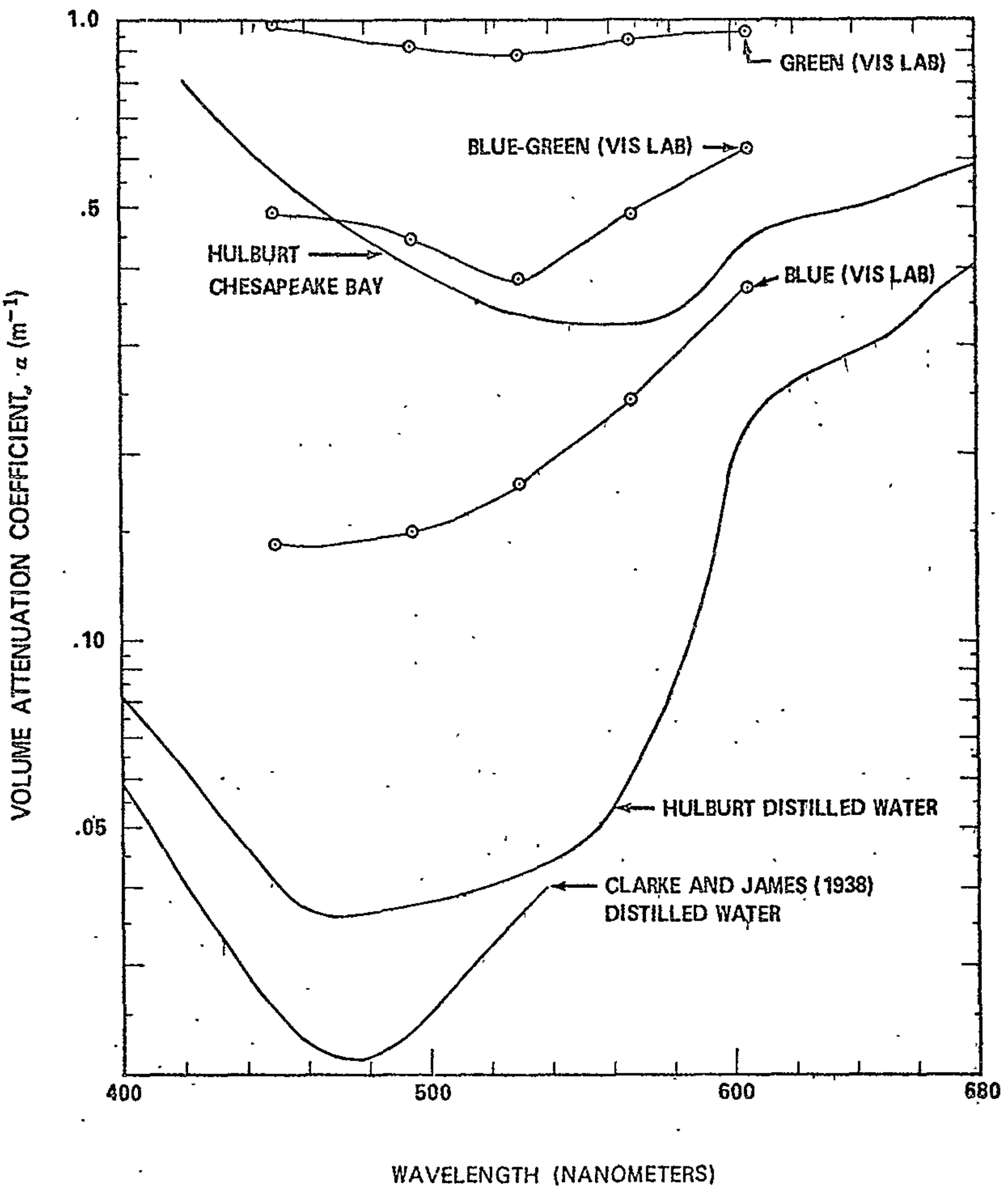


Figure 25. Volume Attenuation Coefficient as a Function of Wavelength for Various Waters (Ref. 10).

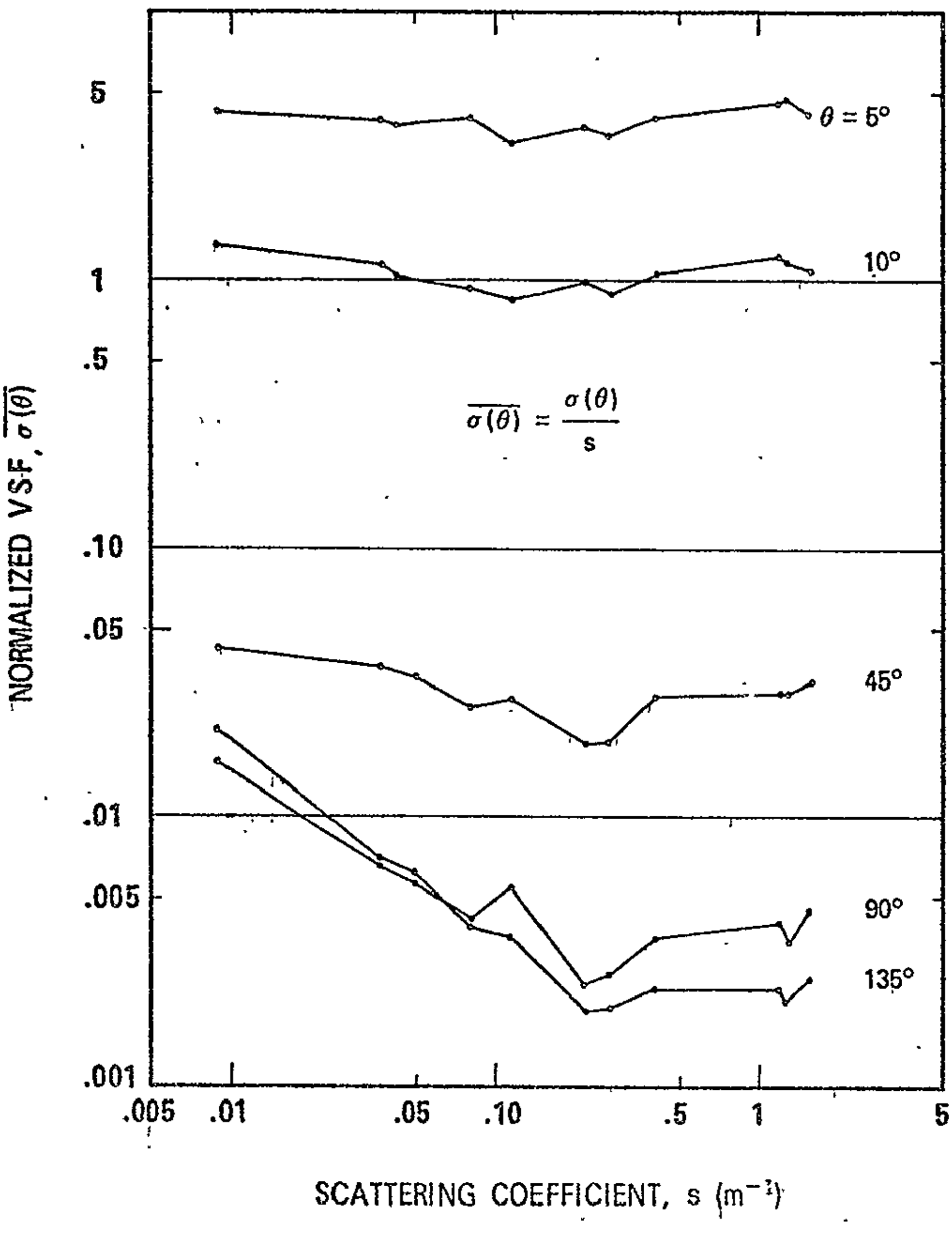


Figure 26. Normalized Volume Scattering Function $\sigma(\theta)$ As a Function of Scattering Coefficient, s. (Note the much smaller variation of (θ) with s for angles of 5 and 10 degrees than for the more conventional measurement angles of 45, 90, and 135 degrees.) (Ref. 10).

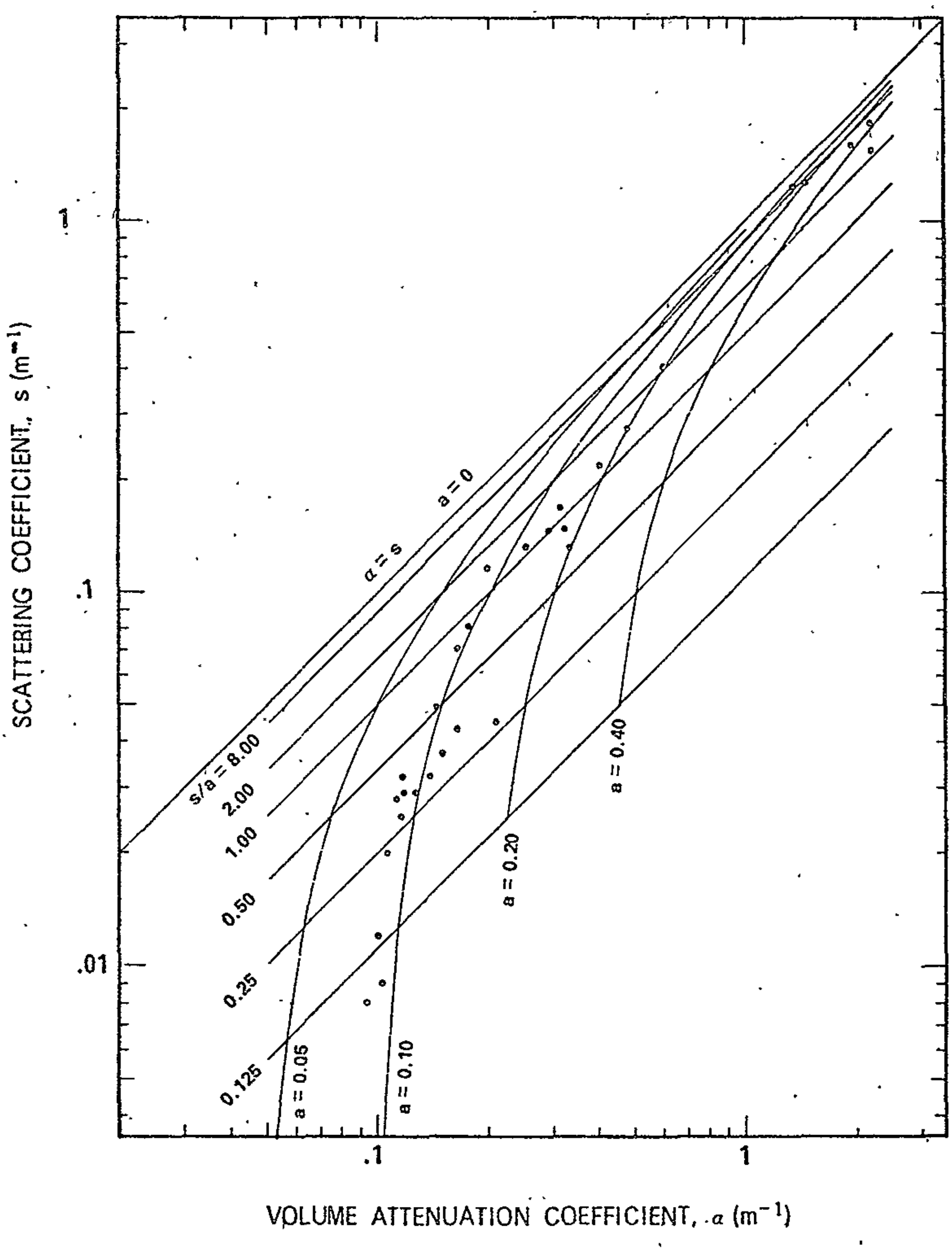


Figure 27. Plot of Scattering Coefficient Data Against Volume Attenuation Coefficient Measured Contemporaneously for a Variety of Waters. All data obtained at a wavelength of 520 nanometers (Ref. 10).

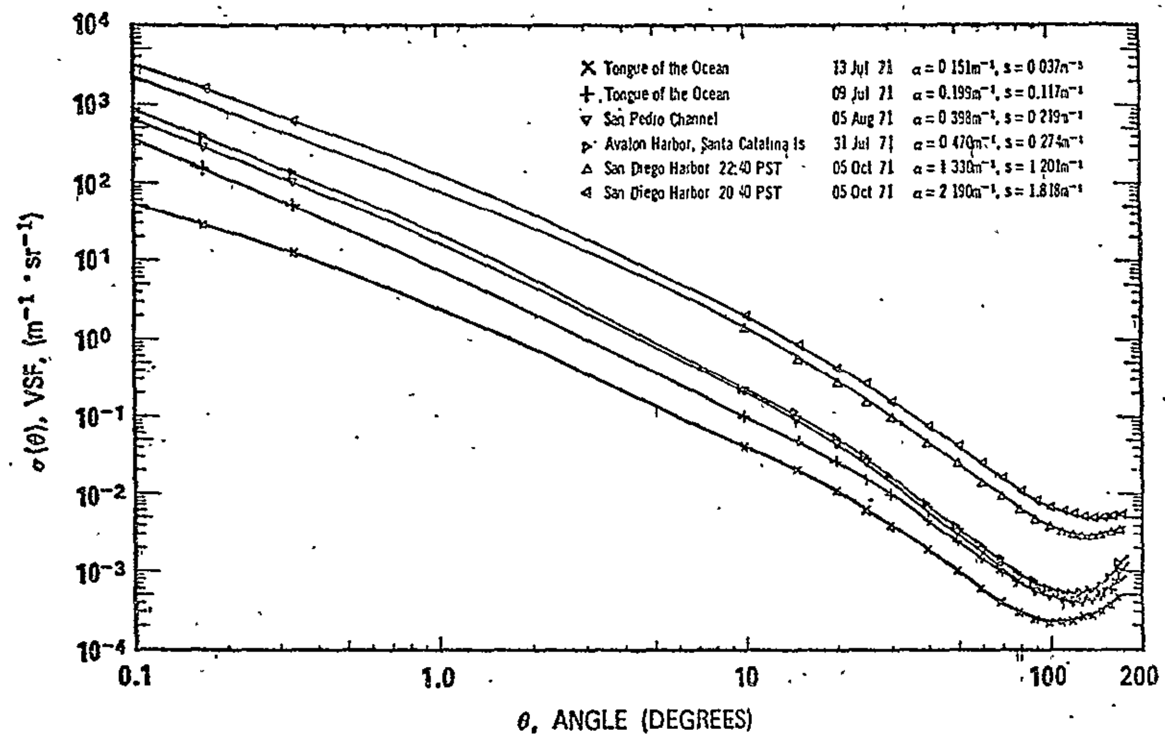


Figure 28. Volume Scattering Function of Sea Water for Various Locations (ref. 10).

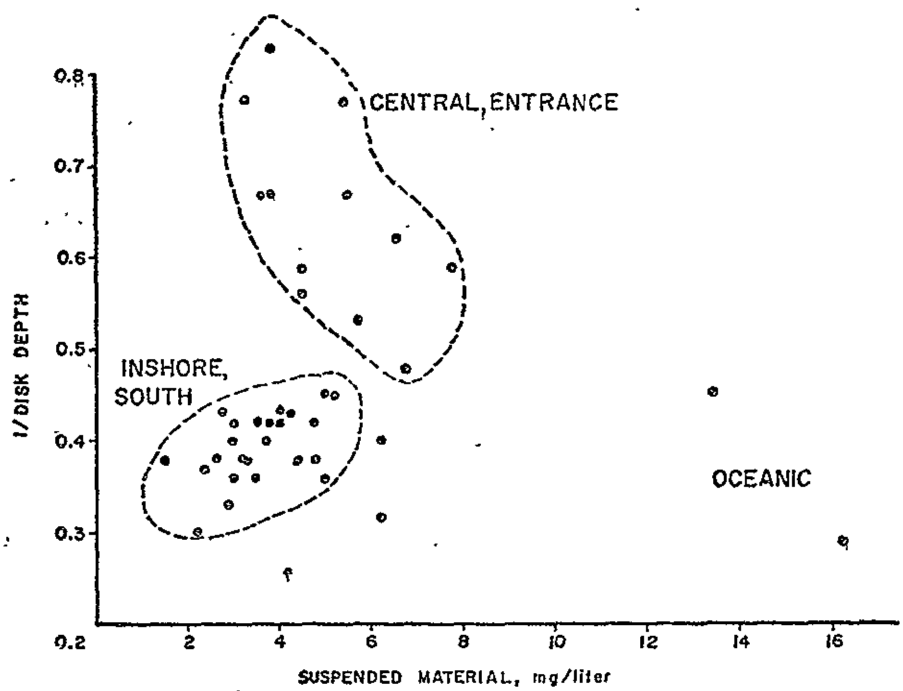


Figure 29. Scatter Diagram of 1/Disk Depth versus Concentrations of Total Suspended Material for Stations in Lower Chesapeake Bay, May 31, 1973. Clusters Define Different Water Masses (ref. 30).

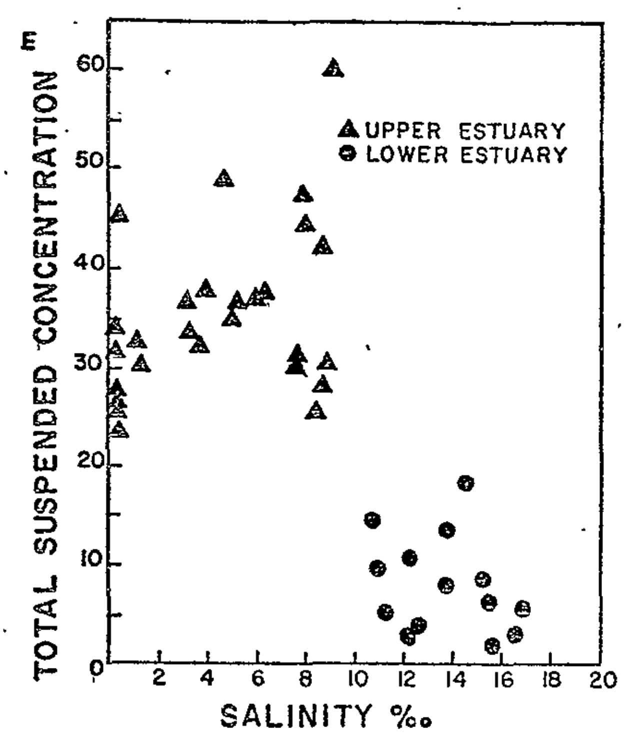


Figure 30. Scatter Plot of Total Suspended Material (Sediment) versus Salinity. From Surface Truth Observations, Sept. 12, 1973 (Rappahannock Estuary) (ref. 5).

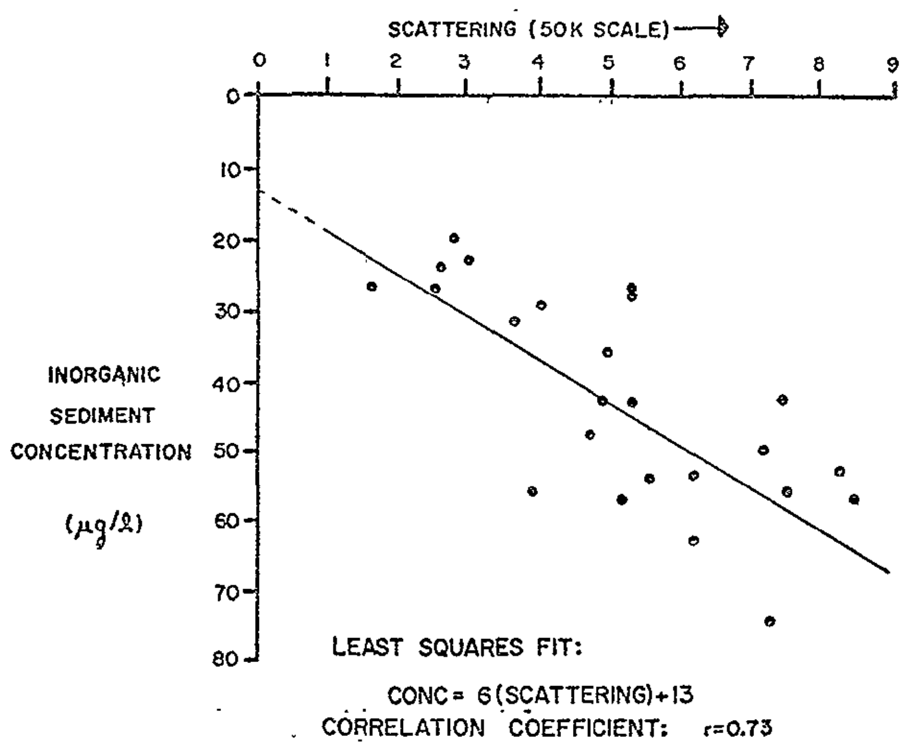


Figure 31. Concentration of Inorganic Suspended Sediment versus Light Scattering for Samples from Cruise TT68 Within the BNL and the Overlying Clearer Water. Note that the Curve is Not Defined for Concentration Values Below About 20 µg/ℓ or Above 80 µg/ℓ (ref. 47).

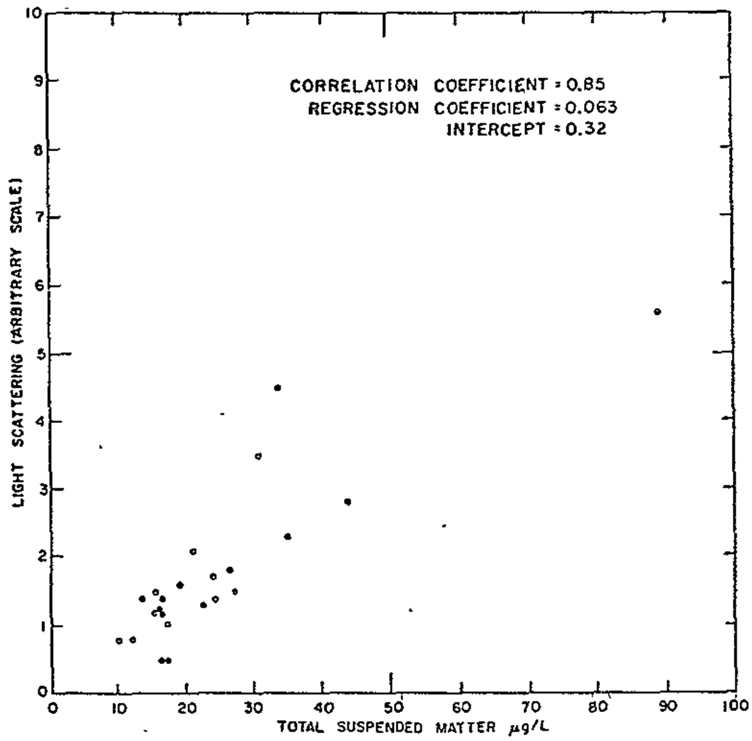


Figure 32. Relationship Between Light Scattering as an Arbitrary Scalė and Total Suspended Matter for 23 Samples from Cruise 73 A-3 (ref. 20).

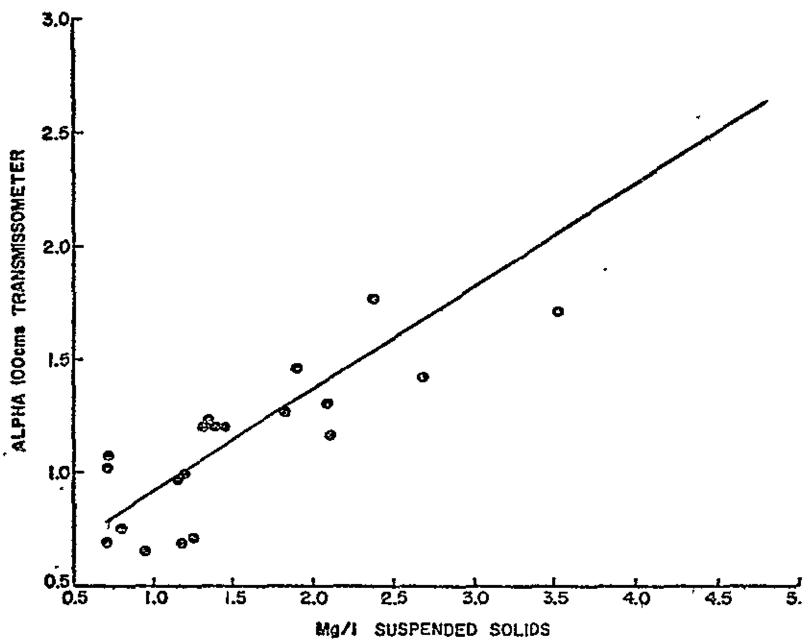
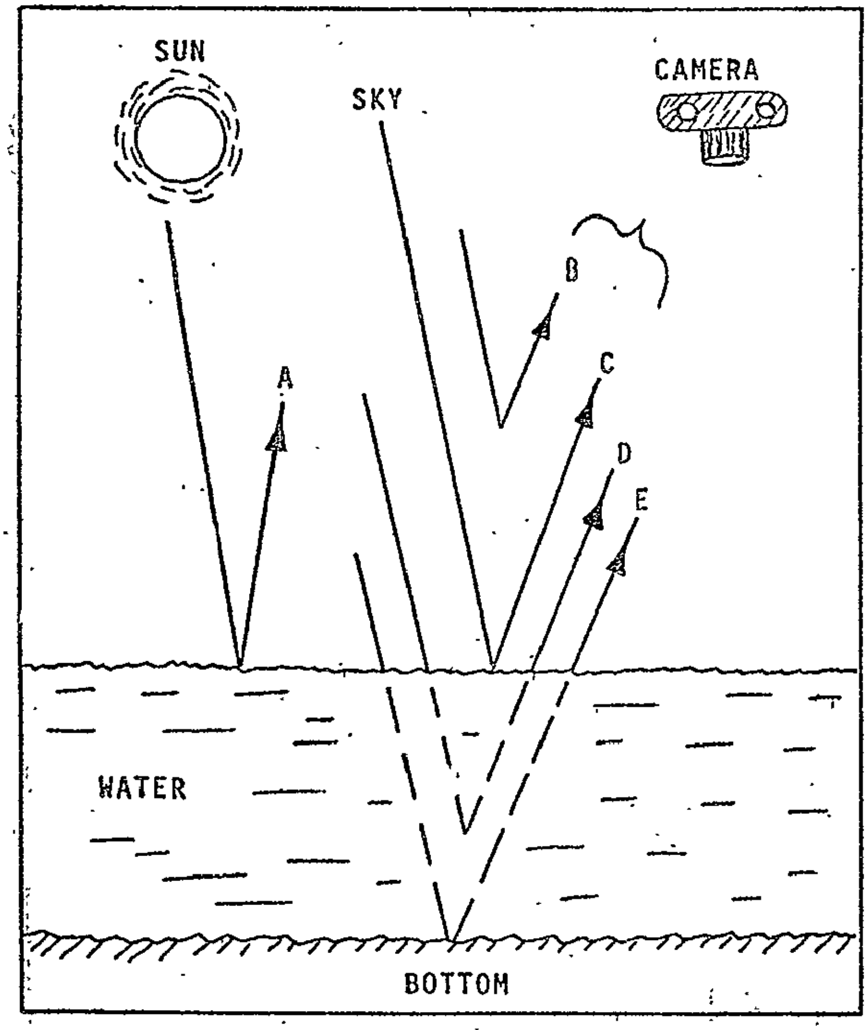


Figure 33. Correlation of Transmissometer Solids (ref. 41).



A = Surface Reflection of the Sun
B = Atmospheric Scatter
C = Surface Reflection of the Sky
D = Volume Reflectance of the Water
E = Bottom Effects

Note: Both Atmospheric Scatter, B, and Surface Reflection of the Sky, C, cause the apparent reflectance of an aerial photo to be higher than the laboratory analysis, which measures only volume reflectance, D. It must be assured that bottom effects, E, are insignificant and that there is no sun reflection, A, in the area of the photo being analyzed.

Figure 34. Components of Light Showing on an Aerial Image Caused by Various Interactions of Light In, On, and Through the Water (ref. 48).

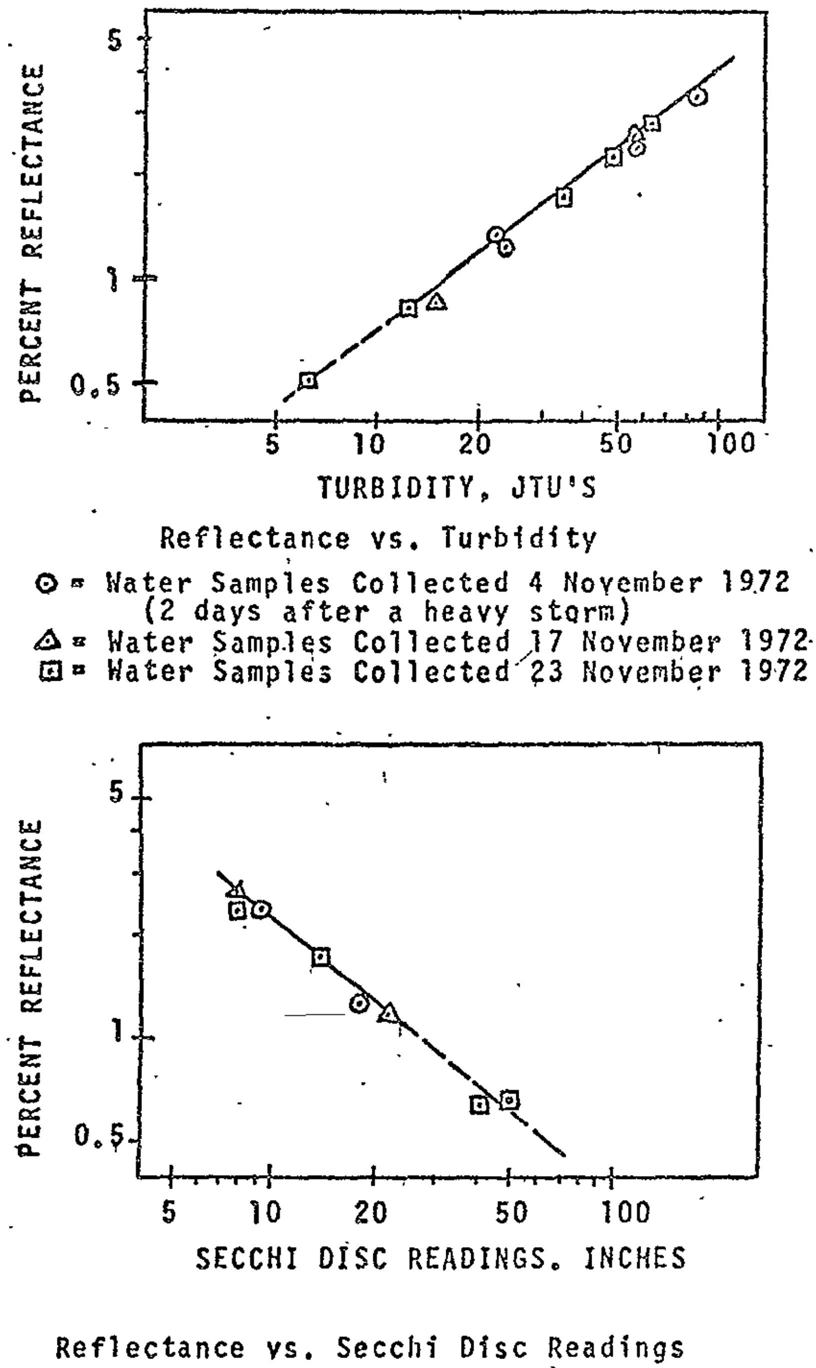


Figure 35. Laboratory Reflectance versus Turbidity and Secchi Disc Readings for all of the water samples collected during the 3 days in November, 1972. The location is dirty water in Lake Superior near Duluth. (Ref. 48).

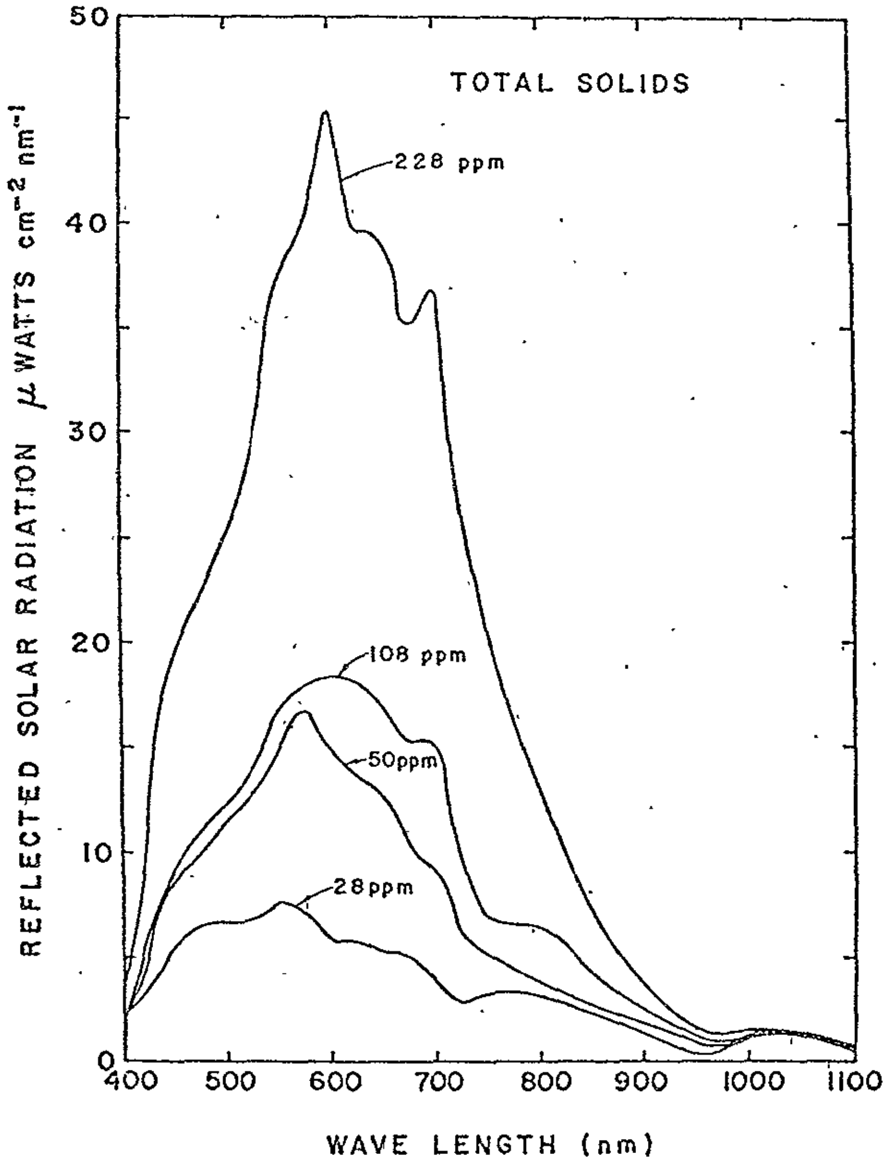


Figure 36. Relationship Among Reflected Solar Radiation, Wavelength, and the Concentration of Total Solids in Surface Waters (ref. 24).

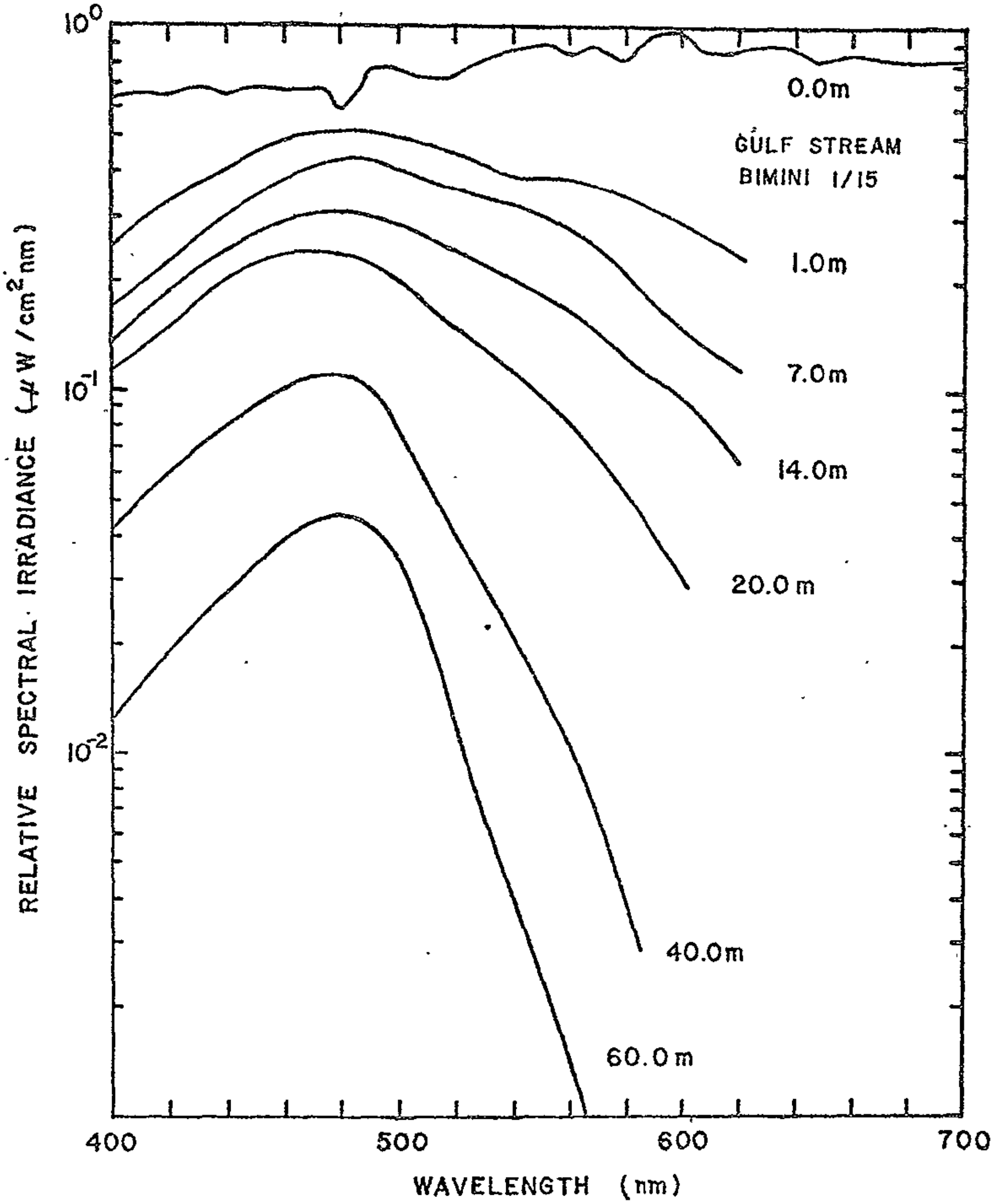


Figure 37. Relative Spectral Irradiance vs. Wavelength for Gulf Stream (ref. 49).

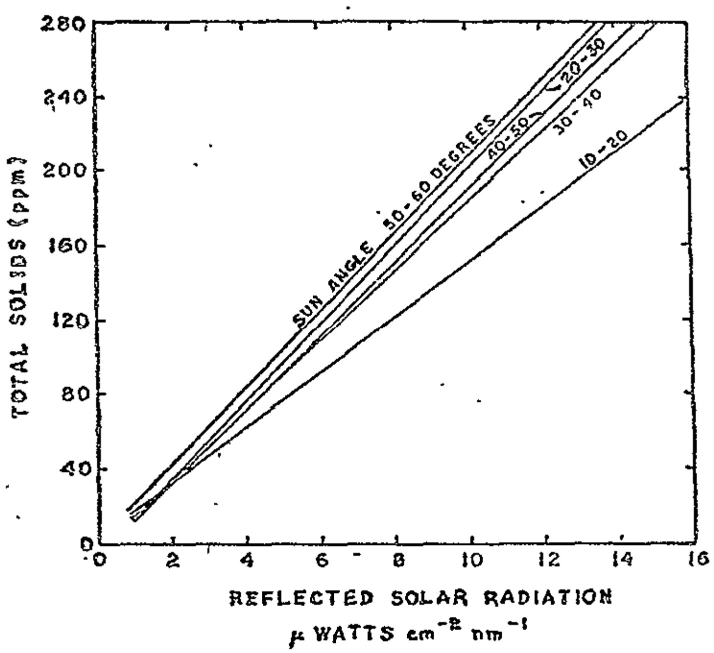


Figure 38. Reflected Solar Radiation versus Total Solid at 750 nm for Different Sun Angle Groupings (ref. 24).

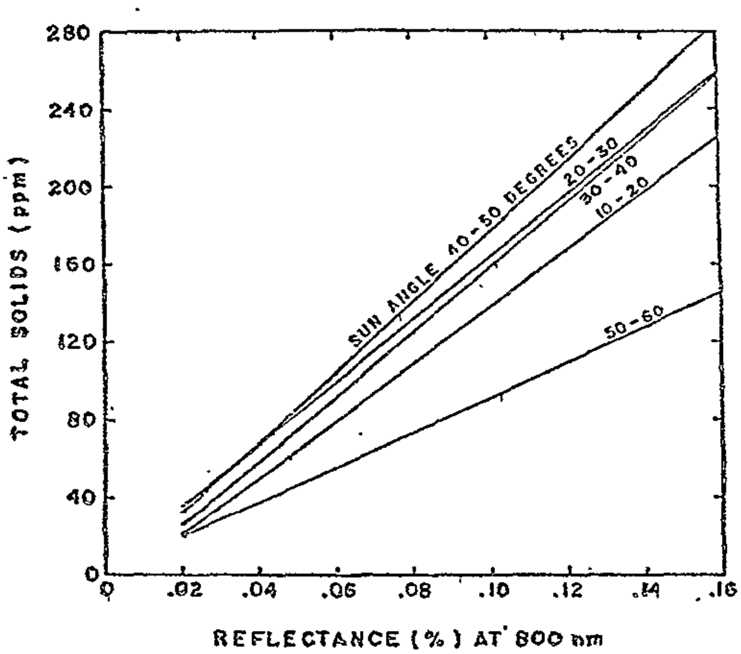


Figure 39. Reflectance versus Total Solids at 800 nm for Different Sun Angle Groupings (ref. 24).

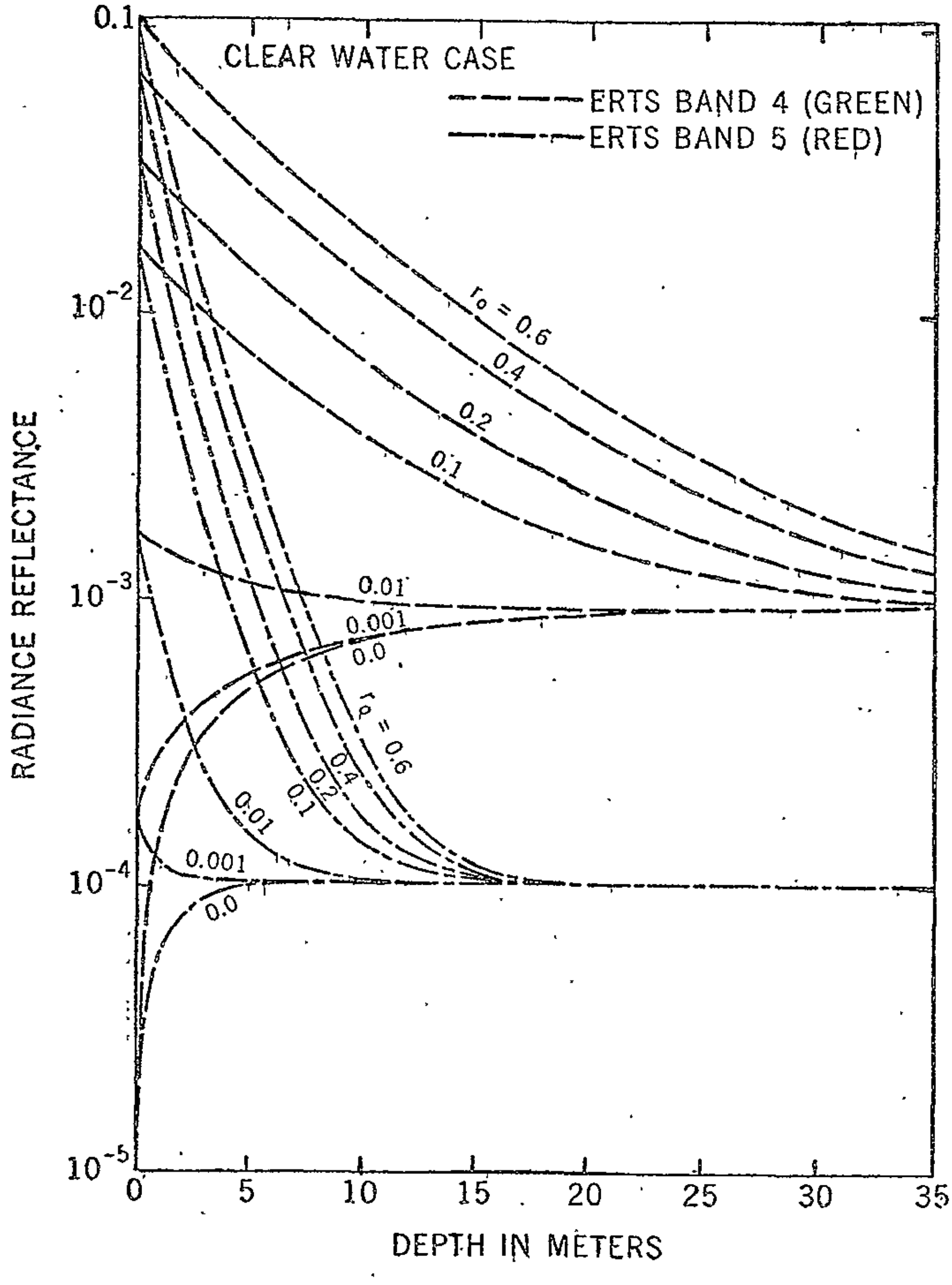


Figure 40. QSS Model Radiance Reflectances Versus Layer Depth Averaged Over the ERTS-1 MSS Bands for Clear Water and Several Different Bottom Albedos r_o (Ref. 50).

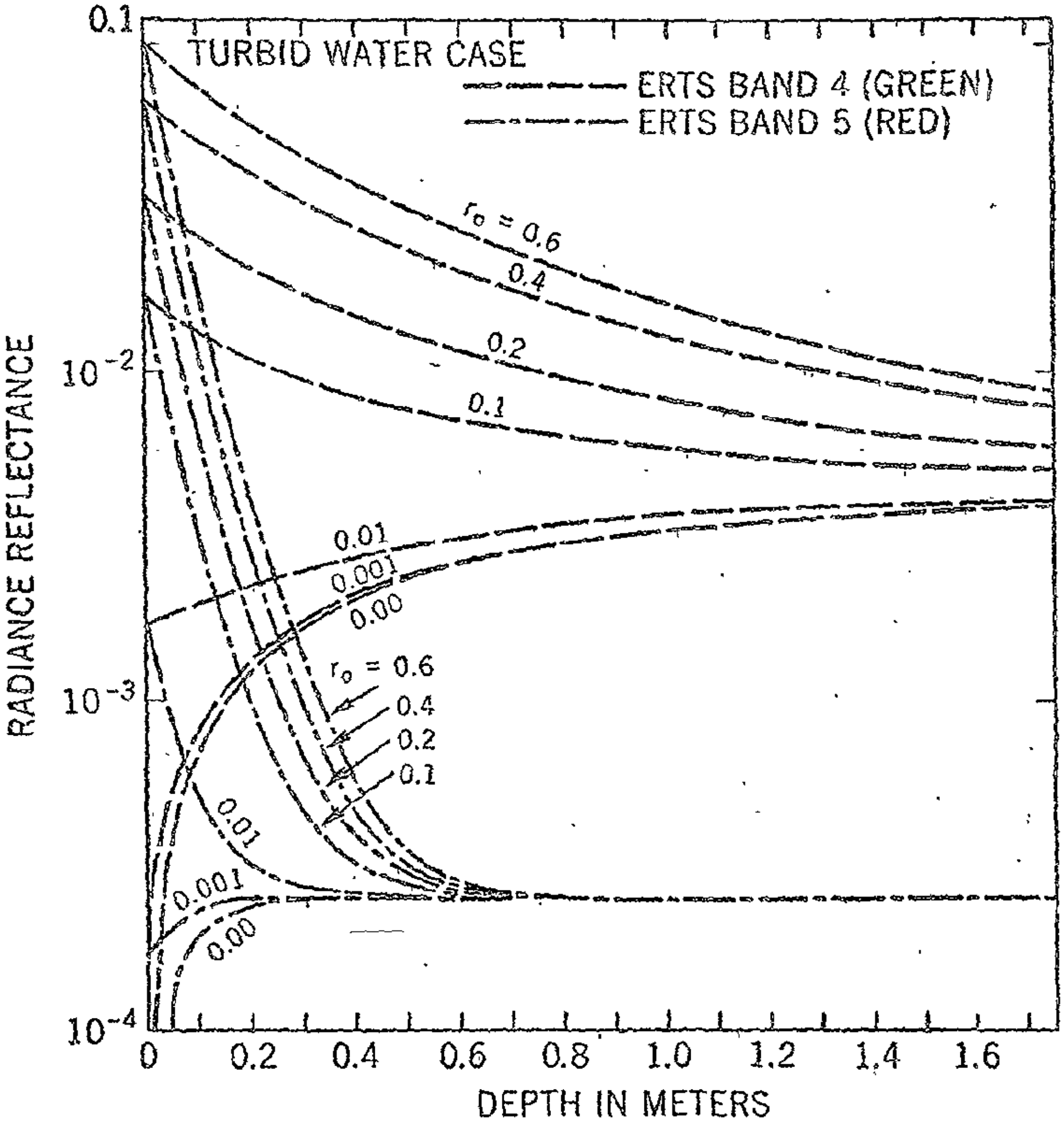


Figure 41. QSS Model Radiance Reflectances Versus Layer Depth Averaged Over the ERTS-1 MSS Bands for Turbid Water and Several Different Bottom Albedos r_o (Ref. 50).

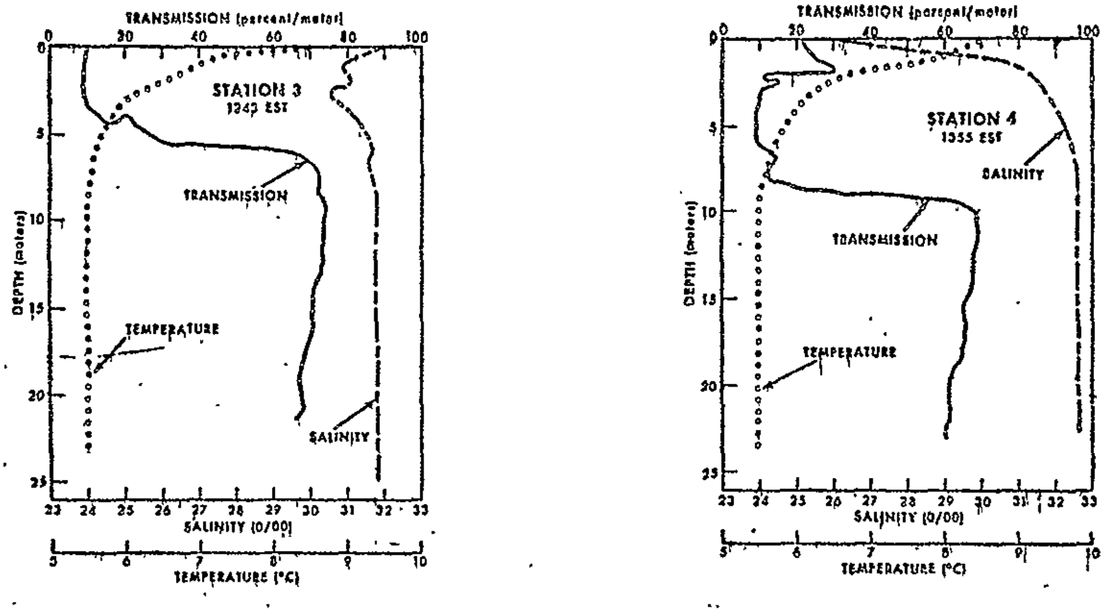


Figure 42. Typical Spectral Signatures in Coastal Water (ref. 25).

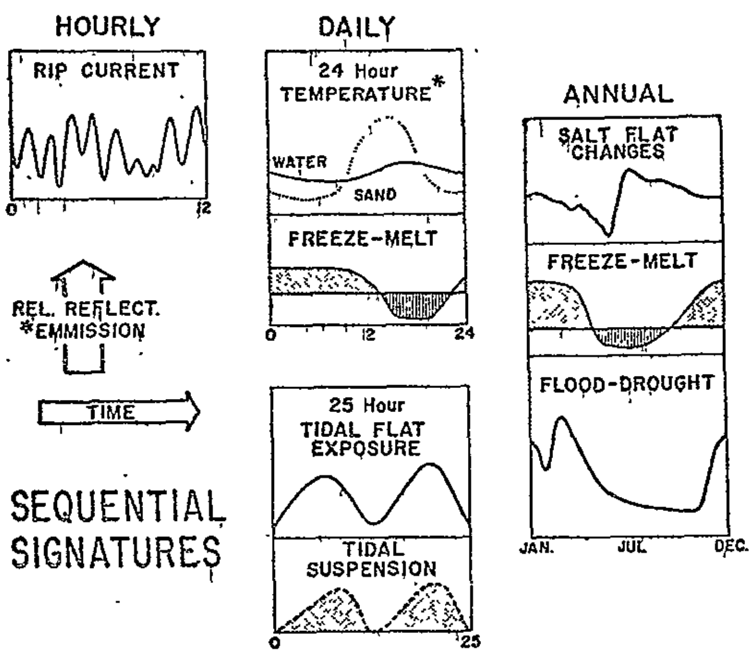


Figure 43. Examples of Some Prospective Sequential Signatures at Different Time Scales: Hourly, Solar Day (24-hour), Lunar Day (25-hour), and Annual. Relative Magnitude of Reflectance (or Emission) is Directed Along Ordinate, Time on Abscissa (ref. 55).

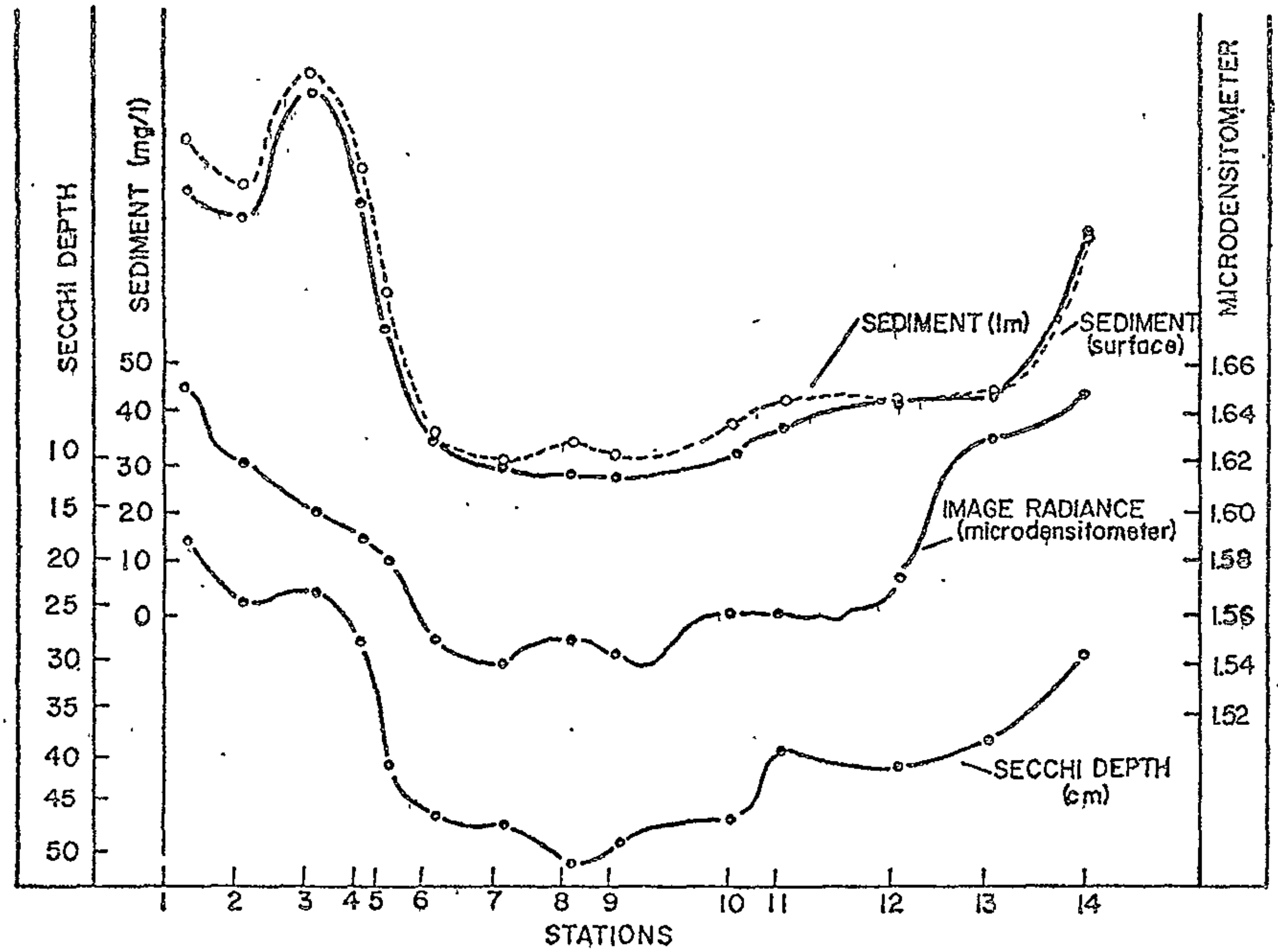


Figure 44. Correlation of ERTS-1 MSS Band 5 Image Radiance (Microdensitometer Scan) with Suspended Sediment Concentration and Secchi Depth (ref. 26).

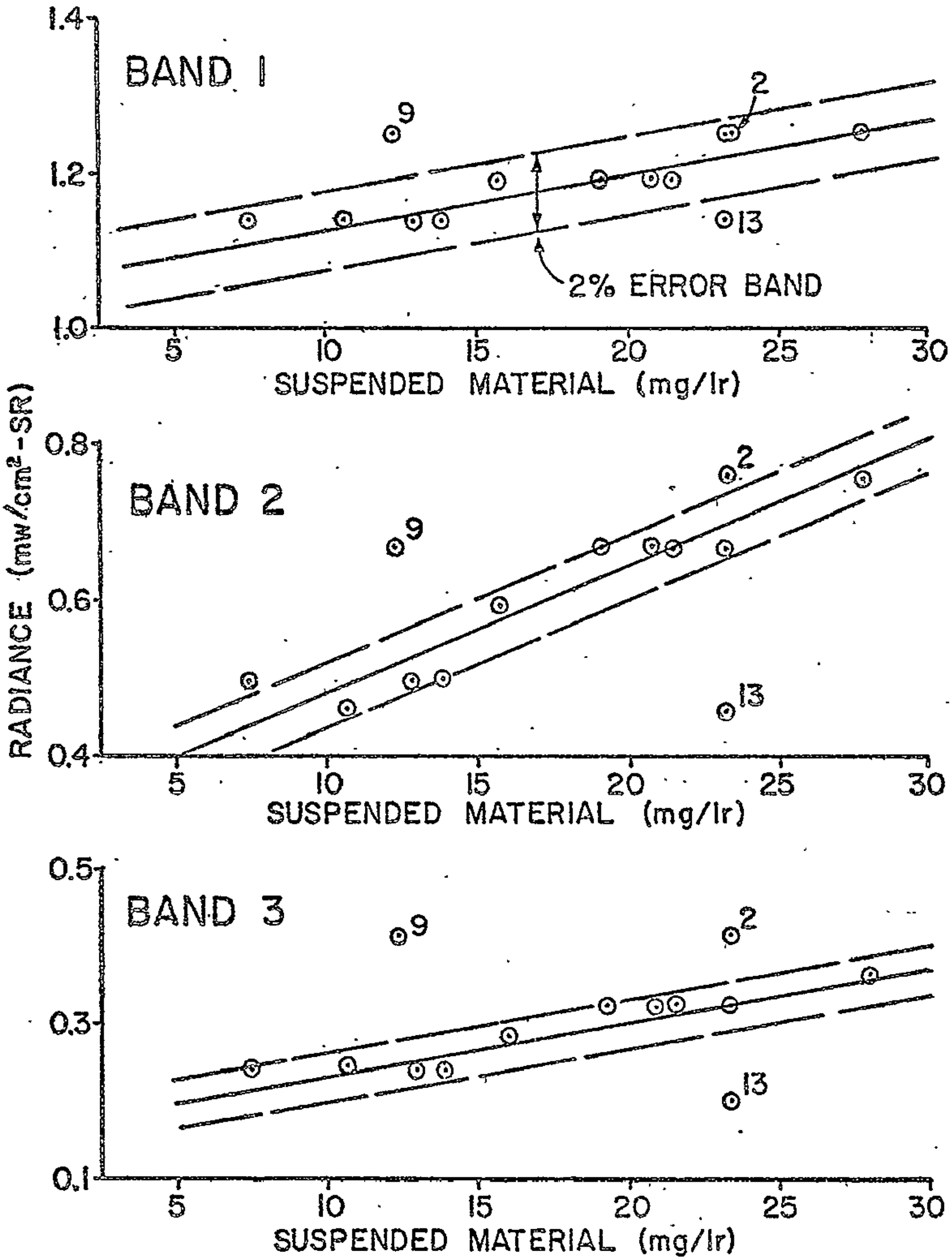


Figure 45. Radiance vs. Suspended Material - York River Estuary (Ref. 32).

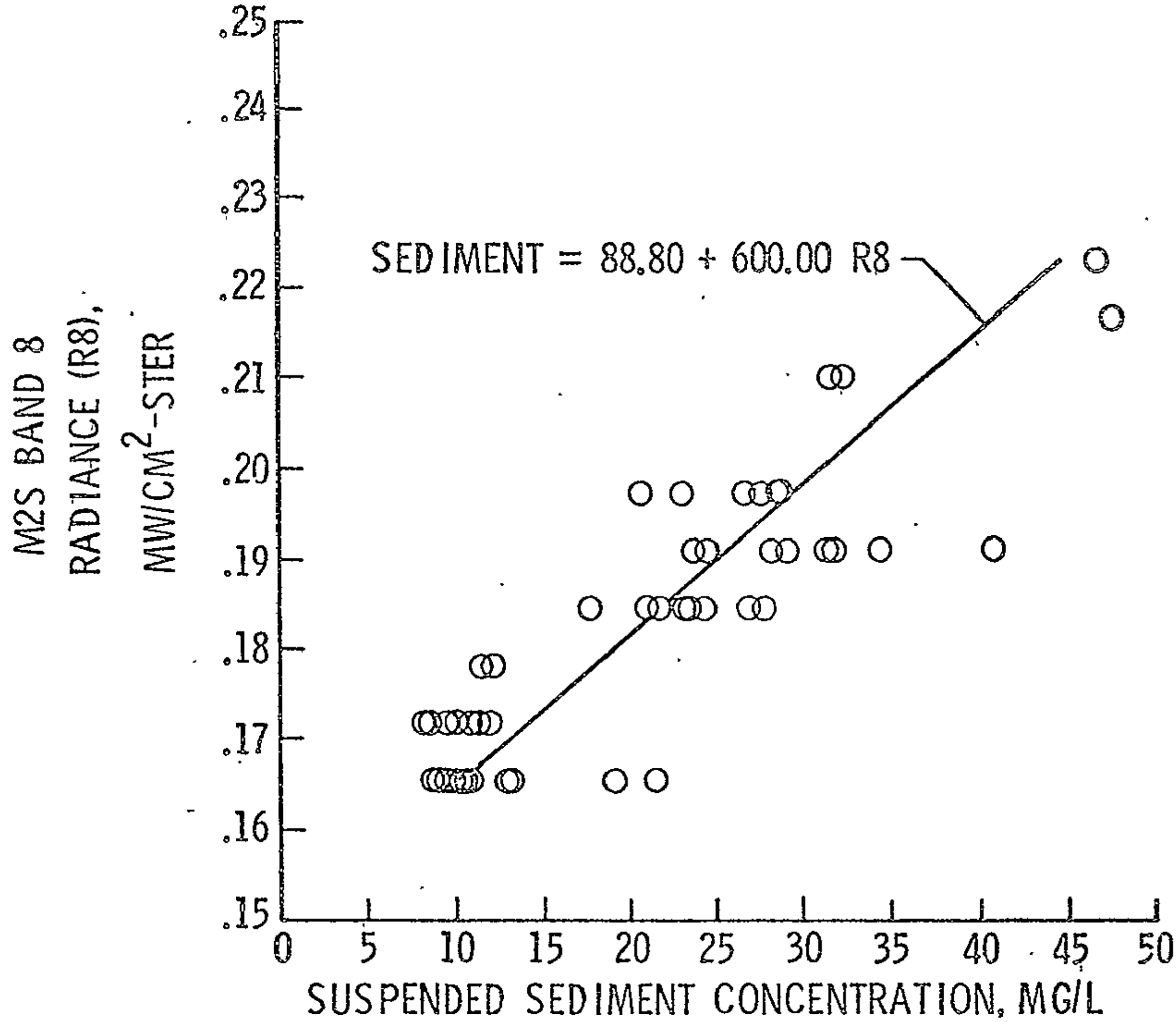
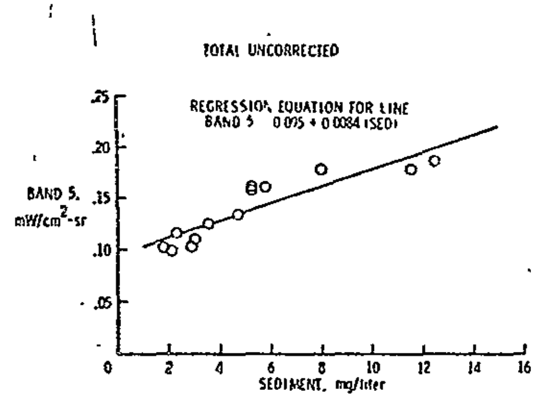
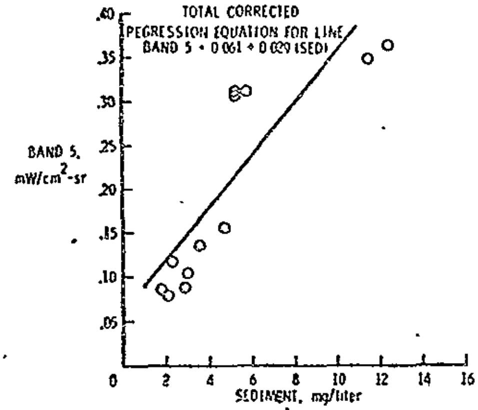


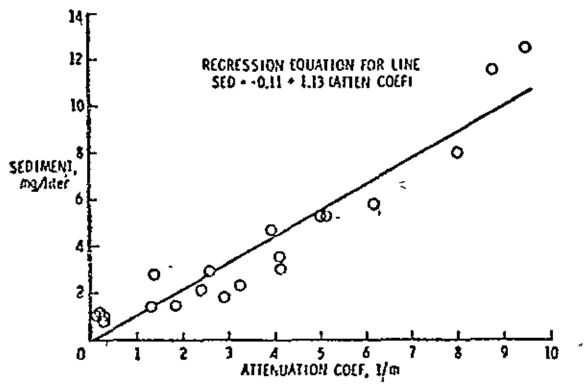
Figure 46. Suspended Sediment Concentrations, M2S Band 8 Radiances and Fitted Single Band Regression Line (ref. 29).



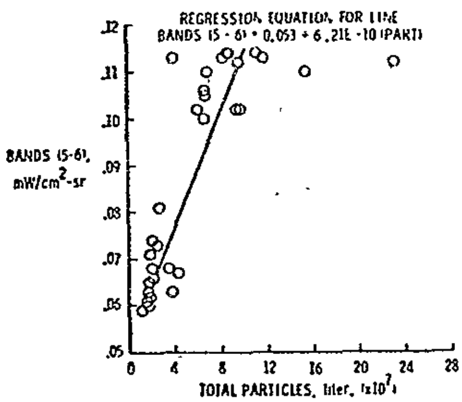
Uncorrected band 5 radiance vs. sediment for Jan. 26 and Feb. 13.



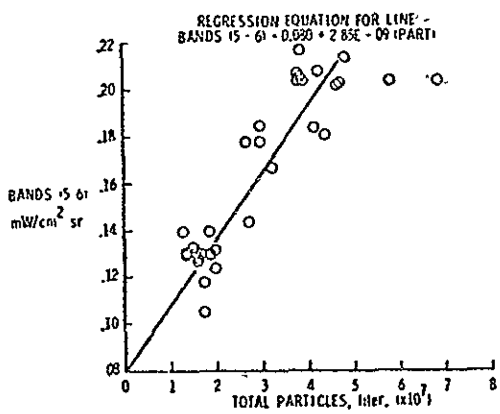
Corrected band 5 radiance vs. sediment for Jan. 26 and Feb. 13.



Attenuation coefficient vs. sediment.



Bands (5-6) radiance vs. total particles for Jan. 26.



Bands (5-6) radiance vs. total particles for Feb. 13.

Figure 47. Correlation of Bands Radiance and Sediment (Ref. 27).

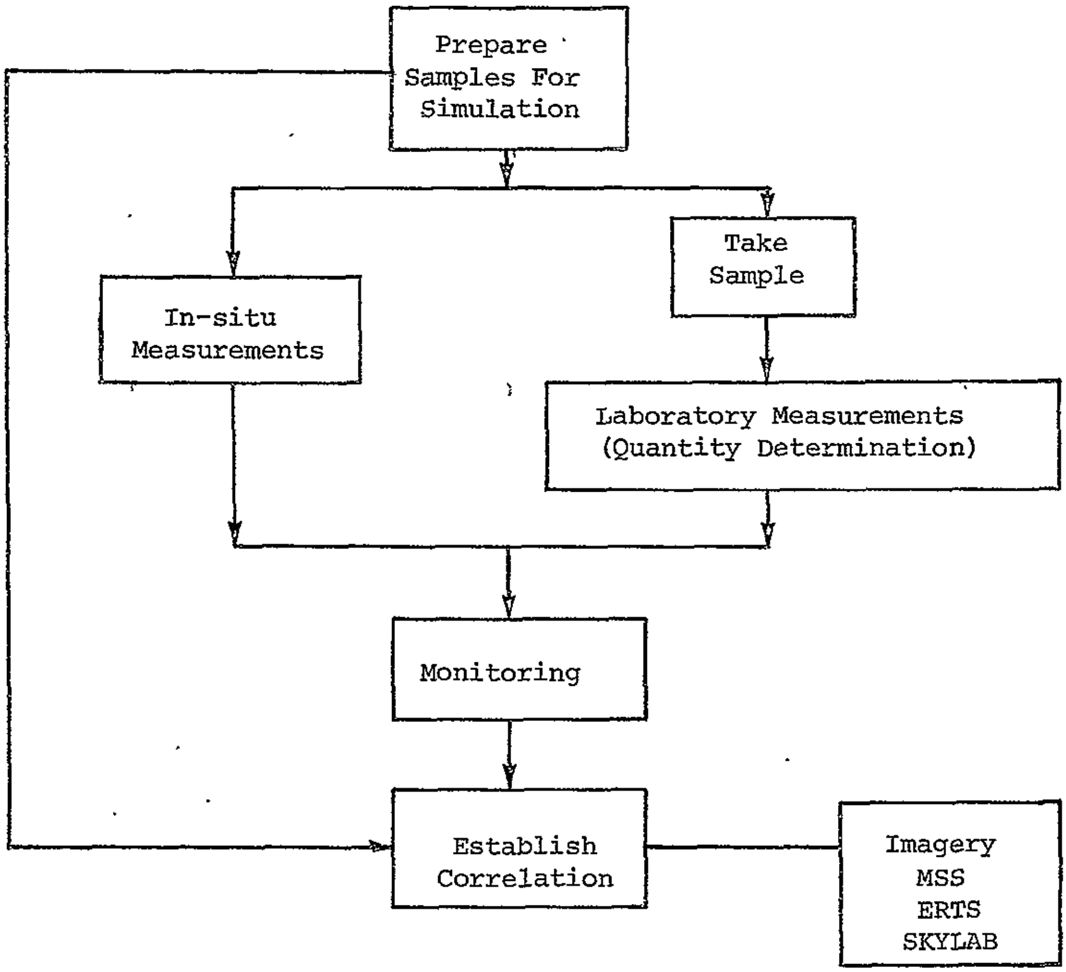


Figure 48. Flow Chart for Correlation Processes.

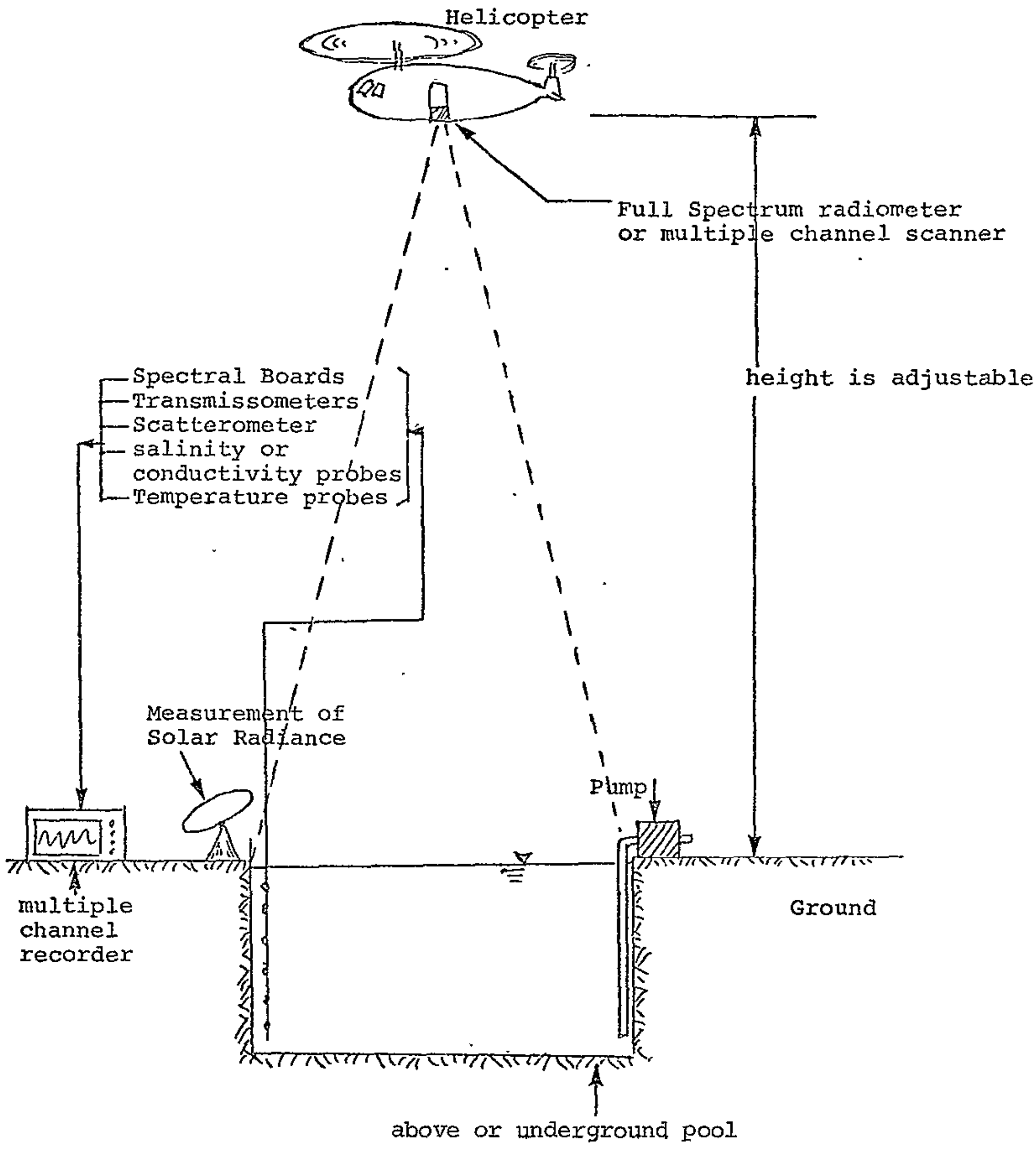
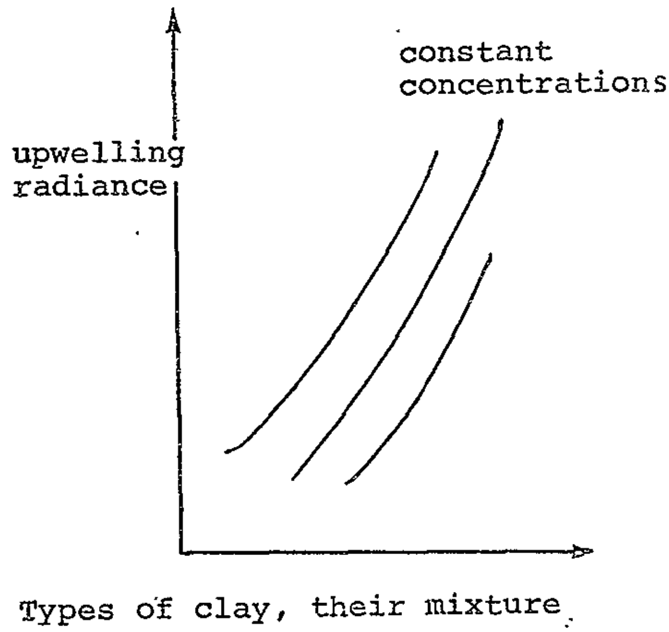


Figure 49. Proposed Test Set-Up.



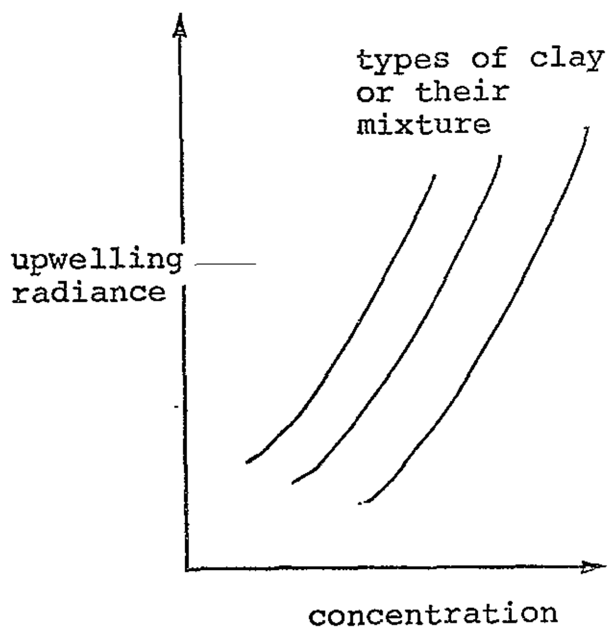
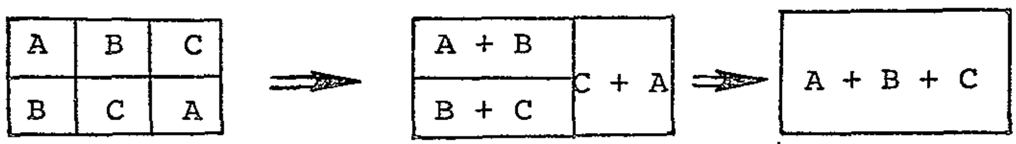


Figure 50. Variation of Type of Clay, Percent of Clay Mixture, and Concentration.

(a) Mixing method for three different types of clay, A, B, and C

A= Kaolinite B= Illite C= Montmorillonite



(b) Mixing method for one type of clay with different concentrations to get concentration of 1,1.5,2,2.5,3,3.5,4 unit

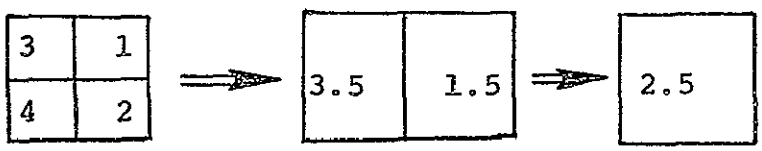


Figure 51. Mixing Methods for Clays.

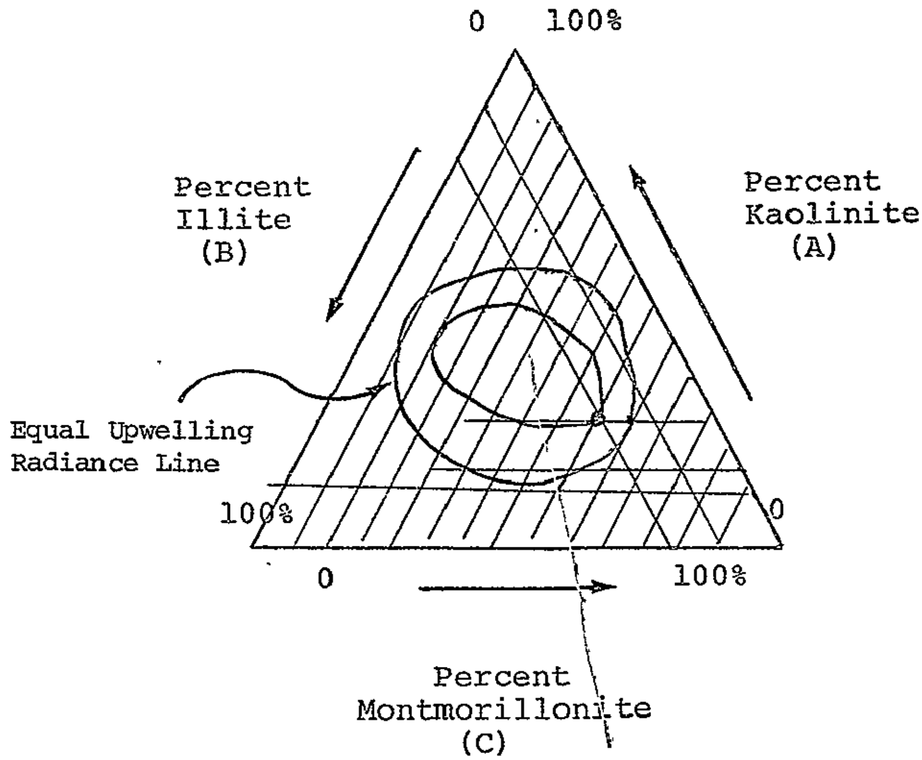


Figure 52. Equal Upwelling Radiance Lines.

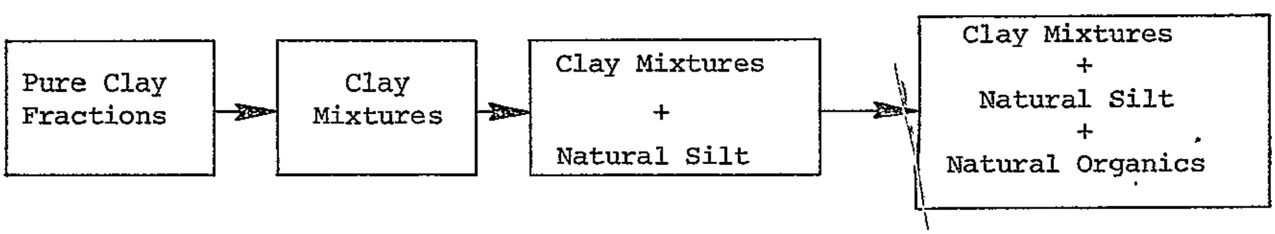


Figure 53. Mixing Method of Clay, Silt, and Organics.

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