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THE USE OF SATELLITES IN ENVIRONMENTAL MONITORING OF COASTAL WATERS

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I. Introduction

Satellite remote sensing is likely to play an important and very special role in environmental monitoring in coastal waters. Satellite systems are the only tools available which are capable of truly synoptic coverage of the enormous areas requiring surveillance. Beyond the obvious role of providing a synoptic view, the role of satellite remote sensing is not easily defined. In the first place, the water parameters which can be measured remotely are often only indirectly related to measurements that would be made from ship. Shipboard measurements are the standard against which remote measurements must be compared, and which will probably never be supplanted by remote sensing, even though ships cannot be expected to provide adequate coverage of the entire coastal region. Secondly, the utility of satellite data for detection and identification of pollutants will depend on the sensor characteristics of the satellite systems (spectral bands, spectral and spatial resolution, sensitivity and dynamic range). In some cases satellite data may be adequate for positive identification of a specific pollutant, in other cases the pollutant may be only marginally detectable or entirely undetectable from the available satellite data. Thirdly, the coastal regime is a dynamic system. Characteristic features of dumps or spills will change relatively rapidly due to advection, diffusion, settling and physical or chemical changes of the material. This temporal variability will lead to stringent requirements for the temporal coverage needed for different monitoring programs. Finally, the role of satellite remote sensing in environmental monitoring will depend heavily on the specific goals of the monitoring program.

The objective of this study is to evaluate the feasibility of using satellites available during the 1978-1990 time period in an operational system for monitoring the type, concentration, location, drift and dispersion of pollutants in coastal waters.

II. General Aspects of Environmental Monitoring

"Environmental monitoring is the systematic collection and evaluation of physical, chemical, biological and related data pertaining to environmental quality, pollution sources, and other factors which influence, or are influenced by environmental quality." (EPA, 1973). We, of course, are concerned here only with the environmental monitoring of coastal and estuarine waters and the role that remote sensing will play in this task. As is suggested by the above definition, the monitoring task is broader than the detection and identification of pollutants in water; it also involves the determination of the nature of the unperturbed aquatic environment and observation of long term trends in environmental quality.

In the discussions that follow, the word "pollution" will be used frequently. We will define pollution as the presence of matter or energy whose nature, location or quantity produces undesired environmental effects (EPA, 1977). This definition includes such things as heated water discharged from a power plant and undesireable plankton blooms as well as oil spills and sewage sludge dumps. Likewise, the term "pollution event" will be used to mean the occurence of a particular incident (e.g. an oil spill) or a set of circumstances (e.g. the presence of the necessary physical, chemical and biological conditions for an undesireable plankton bloom) which results in pollution of the water.

Several very different types of monitoring programs can be developed.

The nature of the programs will depend primarily on three criteria:

1) Data requirements

Generally, the more narrow and specific the goals of the monitoring effort, the simpler the data requirements. For instance, monitoring the thermal effluent from one power plant is a relatively simple matter only requiring measurements of temperature; monitoring the effect of the thermal effluent on the area near the outfall is vastly more complex. The quality of data will also vary. For instance, for some purposes it may be necessary only to detect the presence of a pollutant while for other purposes it may be necessary to establish the concentration and/or distribution of the material.

2) Temporal constraints

Both data rate and the total period of data acquisition will vary depending on the types of measurements being made, the time scales of motion in the region being monitored and the goals of the monitoring program. Another factor which must be considered is the time frame in which the data is to be used. In cases where immediate action is necessary, the information must be available as quickly as possible. As an instance, when a large oil spill occurs, information about the location and movement of the oil is needed quickly in order to direct clean-up operations. At the other extreme are the long-term monitoring programs where no fast response is expected.

3) Geographic area

An extremely important characteristic which must be considered in designing a monitoring system is the physical size of the area which must be monitored. If the area is small it may be feasible to have permanent instrument installations, e.g. a thermistor array used to monitor the hot water wastes from a power plant. For larger areas, permanent installations are generally impractical and other means must be found. It is in the monitoring of large areas that remote sensing is most promising.

With these criteria in mind we may identify several different categories of environmental monitoring in coastal waters:

1) <u>Fast response operations</u>

In this category, the goal of monitoring is to provide early warning of a pollution event so that protective and/or corrective measures may be taken. This requires <u>early</u> detection of the pollutant and <u>fast</u> information transfer. The requirement for early detection suggests that monitoring must be either continual or very high frequency. Continual monitoring is usually accomplished with permanent systems dedicated to the monitoring of specific pollutants. This category may include both point and non-point sources.

The requirement for early detection also implies that the information about the pollution event must be made available to the responsible agency as soon as possible after the event. Thus the data must be available quickly and in a form which is readily usable.

2) <u>Long-term local monitoring</u>

This category involves the continual assessment of environmental quality in particular areas. The purpose of this type of monitoring may be 1) to evaluate long-term pollution levels, 2) to evaluate effectiveness of pollution abatement efforts or 3) to identify potential problems. Included here are such things as point sources, legal dumpsites, fishing grounds or recreational areas. This category is similar to the first category except that there is no requirement for real-time data. Data should be available in a matter of weeks or a few months. The frequency of data collection depends on the specific type of pollution and the dynamics of the system being observed but long-term changes are most important. The major defining characteristic though, is that only a limited geographic area is being monitored.

3) Long-term regional monitoring

In this case interest is in the general environmental quality of large regions over extended periods of time. The data collected in this type of program will generally be used in setting pollution guidelines (or evaluating the effect of existing programs) and in observing the long-term trends in pollution levels and their effect on the ecosystem. The geographic area covered will be large and the time scale for data availability will be on the order of months or years.

4) Enforcement monitoring

Enforcement monitoring involves documenting violations of environmental quality standards. Data in this category are generally collected through intensive, short-term monitoring efforts and are focused on detection of specific pollutants or specific effects of those pollutants.

5) Historical data acquisition

Historical data refers to data which already exists, which in some way relates to environmental monitoring problems.

The monitoring categories are intended to be quite general (except for being restricted to the aquatic environment) and to include all forms of monitoring. These are not "official" categories as outlined by any monitoring agency. Rather, these categories are delineated by characteristics which are relevant to remote sensing (nature of the data, temporal constraints, geographic area) and they are presented here in order to gain a better perspective of the role of remote sensing in monitoring programs.

III. Remote Sensing of Water

Some form of remote sensing is likely to be an important facet of the data gathering effort for many environmental monitoring efforts. Aerial photography and aircraft-mounted sensor systems have already been used for many monitoring-style applications. However, in most instances satellite remote sensing data has not figured very heavily in environmental monitoring. To some extend this is due to the limited types of data available and the fact that satellite data had not been proven to be useful for this purpose. This is changing; satellite data has been used in many studies of environmentally significant features in coastal and estuarine waters. It has been shown possible to detect oil (Deutsch, 1977) iron-acid waste (Ohlhorst and Bahn, 1978; Klemas *et al.*, 1978) and suspended solids whether occurring naturally as sediments (Maul and Gordon, 1975; Johnson, 1975) or deposited in the ocean by man (Johnson *et al.*, 1977). There has even been some limited success with detection of chlorophyll from space (Strong, 1978; Hovis and Clark, 1979; Jensen *et al.*, 1979).

Besides the detection of specific materials in ocean water, satellite data can be used for observation of other water features which are important in environmental monitoring. Circulation patterns have been inferred from sediment patterns seen in Landsat data (Klemas *et al.*, 1974; Carlson, 1974) as well as from the temperature patterns apparent in thermal imagery from the NOAA satellites (Halliwell, 1978). Satellite data has even been found useful in inferring fish distribution and abundance estimates (Kemmerer, 1979) and in observing the impacts of land use on estuarine water quality (Hill, 1979).

Given this broad range of success it is reasonable to expect that satellite data will become a standard part of many monitoring programs. Certainly there are many advantages to satellite data: (1) The most obvious of the advantages is the large area coverage - the synoptic view. This is extremely important for monitoring in coastal waters since the areas to be covered are enormous. While satellite data do not replace direct measurements they remove the restriction to the very limited point-by-point gathering of water quality information. The conventional data base can be greatly expanded and extrapolated spatially. (2) In those cases for which satellite data proves to be useful, the data volume-to-cost ratio should be significantly higher than for surface-based techniques (Alföldi and Munday, 1977). The actual cost of using satellite data in an operational system depends both on the data requirements and the type of analysis. As yet no thorough cost-benefit analysis has been done evaluating an operational use of satellite data. In fact, there are actually very few estimates of the costs involved in either research or operational uses. Such evaluations are needed and should be undertaken in the near future. (3) Another advantage to satellite data is that it can be used to provide an historical perspective on the environment. Data is available from the Landsat and NOAA satellites dating from 1972 and 1970 respectively. This data may be used as baseline information for observations of long-term environmental changes.

Satellite remote sensing is likely to play a very important role in environmental monitoring. The possible applications will depend heavily on the satellite and sensor characteristics. In this section we will consider the general characteristics of satellite remote sensing systems, the types of measurements each can make and the constraints inherent in each system. There are three regions of the electromagnetic spectrum which are useful for the remote sensing of water: the visible and near infrared (.4 μm to 3 μm, the thermal infrared (3 μm to 5 μm; 8 μm to 14 μm) and the microwave (0.1 cm to 100 cm). Each of these regions will be considered separately.

3.1 Visible and near infrared region (.4 μm - 3 μm)

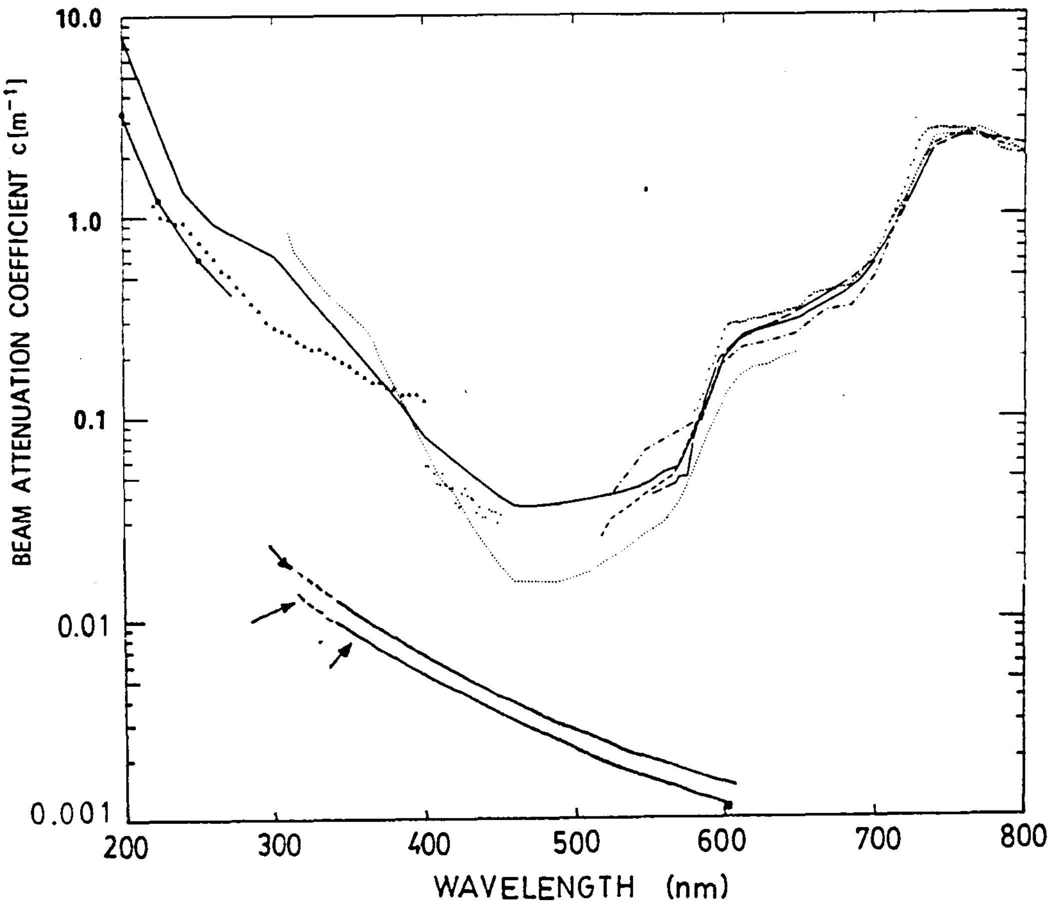
3.1.1 Physical interactions

The visible and near infrared regions are grouped together here because of the overall similarity of the physical interactions of light at these wavelengths with the water, and because the sensor characteristics are similar and sometimes identical.

Volume Interactions

The visible region of the electromagnetic spectrum is unique in that it allows information to be carried from below the ocean surface to a remote sensor. In pure water (water from which all particulate matter has been removed) the attenuation of light is dominated by the absorption of water itself (Morel, 1974). The absorption of water is quite strong below 0.3 μm and above 0.7 μm. Between these two wavelengths (0.3 - 0.7 μm) water is relatively transparent as can be seen from the experimental attenuation curves in Figure 1. Thus, remote observations of pollutants in the water column will be limited to the visible region. The scattering by the water itself is somewhat less significant than the absorption.

The presence of particulate and dissolved material in the water is



....	Sawyer (1931)	310 – 650 nm
————————————	Dawson and Hulburt (1934) and Hulburt (1945)	200 – 400 nm 400 – 700 nm
– – – – – – – – – – – – – –	James and Birge (1938)	365 – 800 nm
··—·—·—·—·—·—·—··	Clark and James (1939)	365 – 800 nm
....	Curcio and Petty (1951)	710 – 800 nm
▲ ▲ ▲ ▲ ▲	Lenoble and Saint-Guilly (1955)	220 – 400 nm
■ ■ ■ ■ ■ ■	Armstrong and Boalch (1961a,b)	200 – 400 nm
••••••••	Sullivan (1963)	400 – 450 nm 580 – 790 nm

Figure 1. Attenuation curves for water in the near ultraviolet and visible parts of the spectrum. The spectral scattering coefficient, b, is shown for distilled water and sea water. Adapted from Smith and Tyler (1976).

generally far more important to the penetration of light in water and the intensity and color of the light scattered back in the direction of the remote sensor. The strong scattering by the particulates (relatively independent of wavelength) and absorption by all types of materials (often significantly wavelength dependent) are the mechanisms which will change the spectral reflectance characteristics of the water, and it is the spectral reflectance characteristics of the water which are the most important factor in the identification of substances in the water.

Typical variations in the apparent color of sea water are illustrated in Figure 2. These data representing a wide variety of water types are selected from the spectral irradiance measurements reported by Tyler and Smith (1970). The data in Figure 2 are spectra of the upwelling irradiance measured at a depth of 5 meters except for the San Vincente data which, because of the extreme turbidity of the water, was measured at a depth of 1 meter. The curves have been normalized to the maximum irradiance to facilitate comparison. The solar irradiance at the water surface at three of the stations, also normalized to the maximum irradiance, is also presented in Figure 2 in order to illustrate that the spectral variations in the upwelling radiance are primarily due to differences in the water masses and not because of spectral changes in illumination conditions. Crater Lake water is "exceptionally free of contaminants of any kind including chemical, planktonic or particulate contaminants" (Tyler and Smith, 1970) and is about as close to pure water as can be found anywhere in the world. Both the Gulf Stream and Tongue of the Ocean are clear oceanic water types. The Gulf of California represents coastal water while San Vincente, a man-made lake, represents water

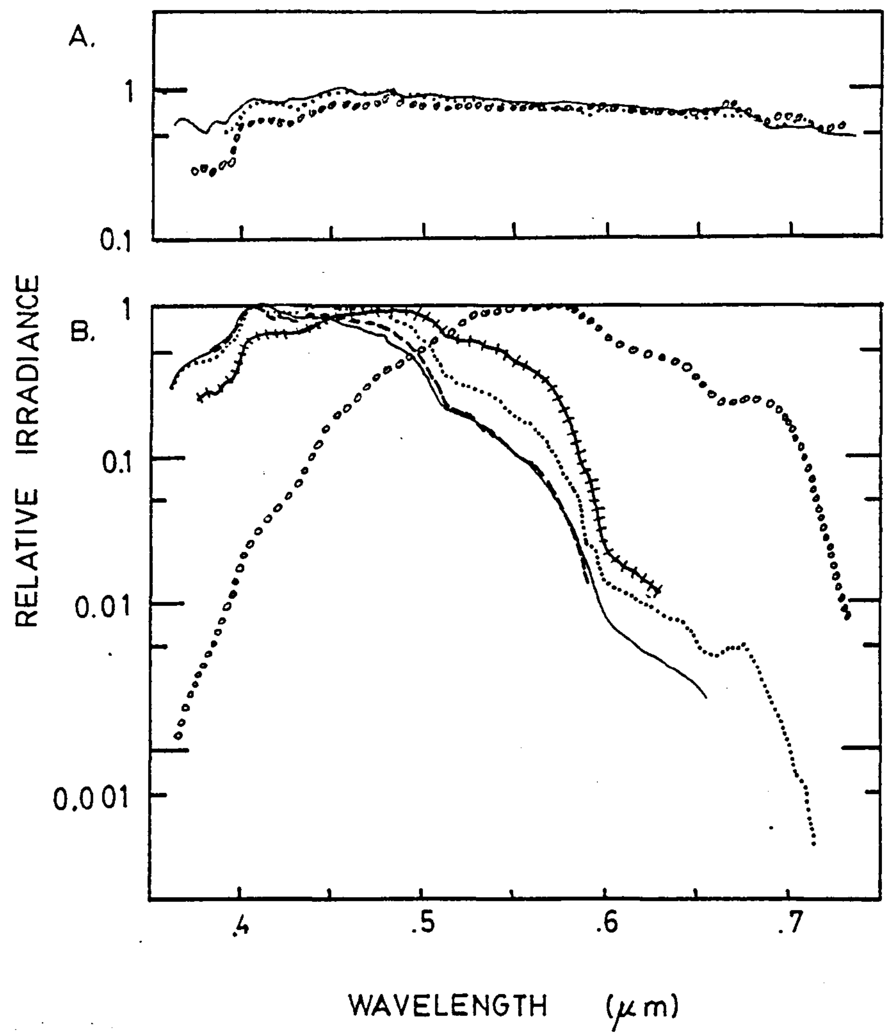


Figure 2. a) Solar irradiance on the water surface.

b) Upwelling irradiance below the water surface. Depth is 5m for all stations except San Vincente which is for a depth of 1m.

All curves have been normalized to the maximum values. The data is taken from Tyler and Smith (1970).

Crater Lake ————————
Gulf Stream ----------------
Tongue of the Ocean ••••••••••••
Gulf of California ++++++++++
San Vincente oooooo ooooo

which is "heavily contaminated with phytoplankton, zooplankton and plankton decomposition products."

There certainly appears to be a sufficient range of spectral variation in these examples for identifying water types. Unfortunately, it is not merely the type of material present in the water, but its distribution in the water column that will affect the observed radiance at the surface. The signal measured by a remote, passive, optical system represents the integrated return from the entire water column. The integration is weighted by the vertical distribution of optically important materials in the water column. It is common to assume that the water is vertically homogeneous, however this is often untrue. If a pollutant is less dense or only slightly more dense than the water it may remain near the water surface and not be distributed evenly throughout the column. When the material does sink, a pycnocline or thermocline may inhibit the sinking. This, in fact was the case for the Gulf of California during the measurements of upwelling radiance presented in Figure 2. In this case there was a strong reduction in the transmissivity of the water at a depth of 20m which was the location of the thermocline (Figure 3). Many scattering layers have been reported in the literature (Jerlov, 1976). Quite often these scattering layers are due to phytoplankton or zooplankton communities.

Duntley et al. (1974) demonstrated that the vertical inhomogeneity of material (in this case phytoplankton) in the water makes remote detection uncertain. Duntley et al. (1974) calculated the spectral diffuse reflectance just below the water surface for the two chlorophyll-a profiles shown in Figure 4. The calculated reflectance is presented in Figure 5. Unlike laboratory measurements made of homogeneous cultures,

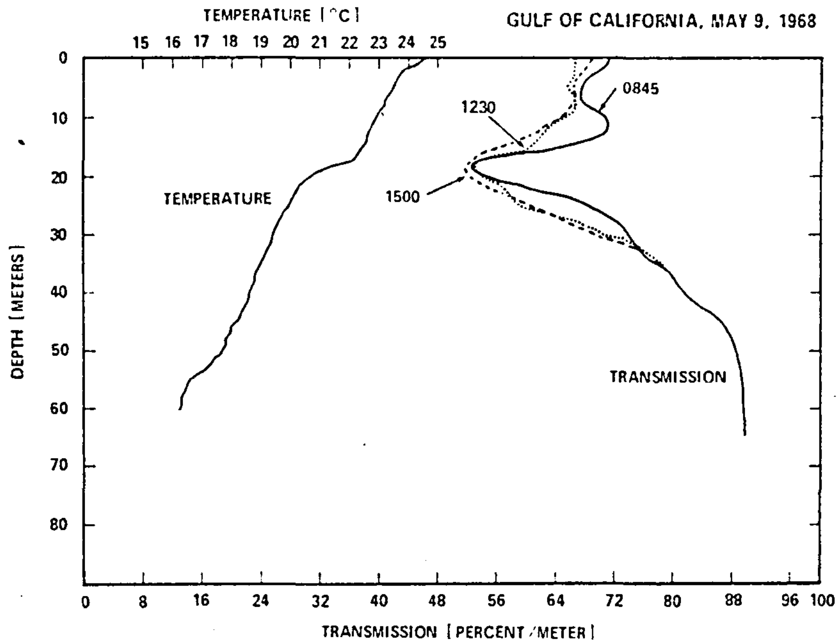


Figure 3. Transmission/meter profiles at three times and temperature profiles for the Gulf of California during the measurement of upwelling radiance shown in Figure 2 (Tyler and Smith, 1970).

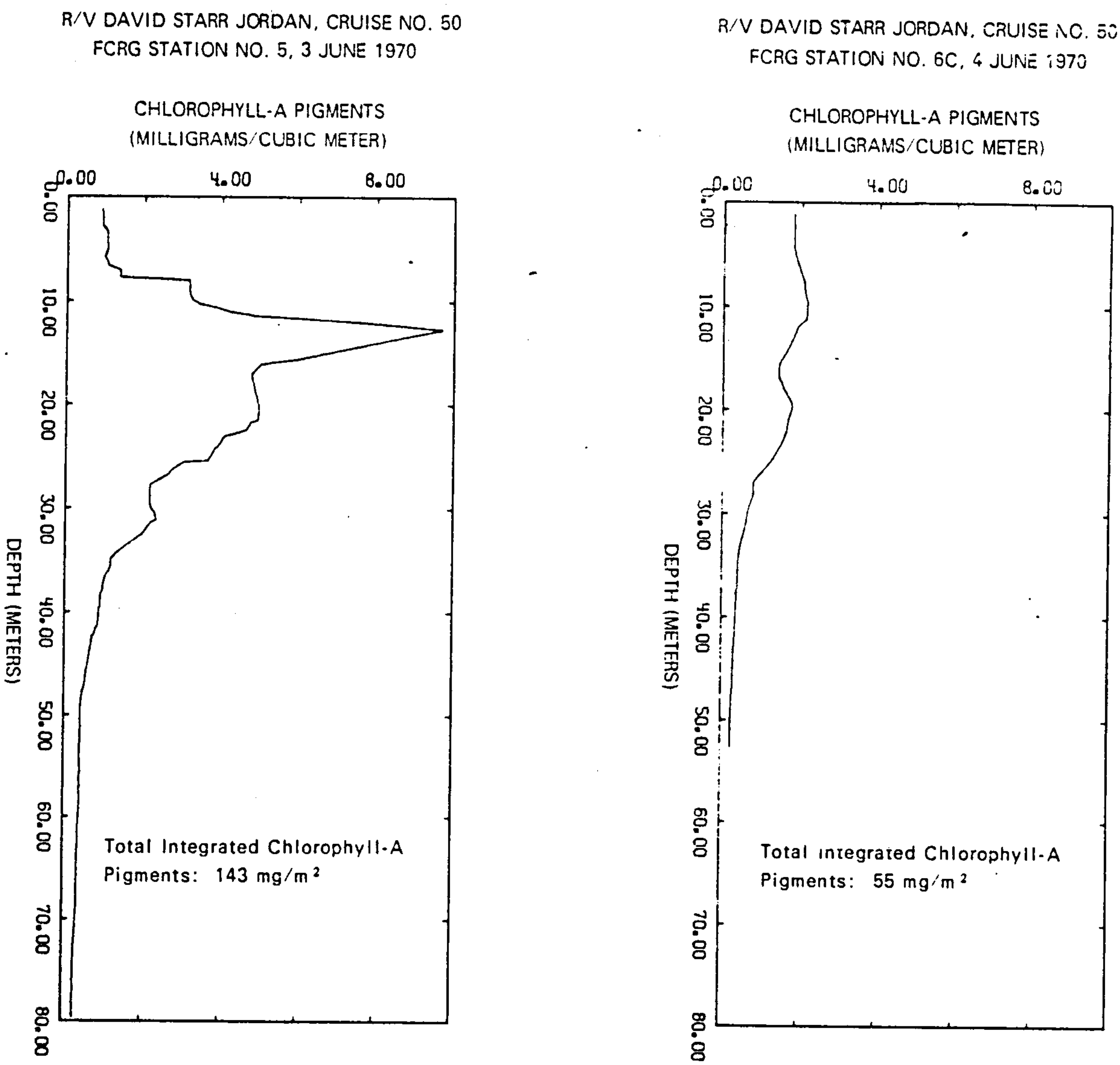


Figure 4. Chlorophyll-a pigment depth profiles measured *in situ* in waters near San Diego. (Duntley *et al*., 1974).

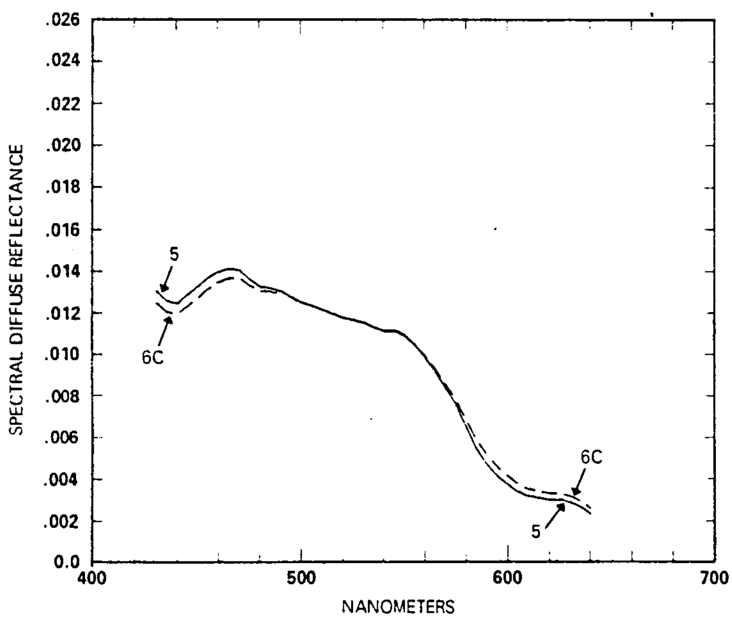


Figure 5. Subsurface spectral diffuse reflectance at station 5 (solid line) and station 6C (dashed line) calculated from the chlorophyll-a profiles in Figure 4.

for which changes in concentration of only a few tenths of a milligram per cubic meter produced significant changes in the spectral diffuse reflectance, the curves in Figure 5 are only slightly different in spite of large difference in concentration. Duntley _et al_. (1974) comment that

> "Virtually any conceivable shape of [vertical] profile can be found. . . except, perhaps, one that does not vary with depth. The two shown [Figure 4] are not extreme cases in any sense. Ocean chlorophyll occurs in stratified patterns with seemingly limitless variety . . . Thus, the subsurface spectral reflectance is wholly ambiguous as a measure of the total chlorophyll-a pigments present, even to a spectroradiometer located just below the water surface."

It seems reasonable to expect that similar problems would arise when dealing with other materials. Obviously the characteristic spectral signature of a substance in water will change both with concentration and with depth. In some cases change in color may be useful as a crude indicator of the distribution. This, in fact, has been suggested by Philpot and Klemas (1979) who found a systematic variation in the signature for an ironacid waste which appeared to be related to the sinking of the material.

While some depth information may be extracted from remotely sensed spectra, it will be difficult if not impossible to quantify the results without surface truth. The surface truth should include depth profiles over the effective depth of penetration of daylight into the water. The effective depth of penetration for a remote sensor varies with wavelength and water type. Defining the penetration depth as that depth above which 90% of the diffusely reflected irradiance (excluding specular reflection) originates, Gordon and McCluney (1975) have estimated the penetration depth for Jerlov's water types. Their results are shown in Figure 6. Jerlov's water types (Jerlov, 1976) would correspond to the base waters in which one might look for pollution. The spectral signature relative to the base water signature may be related to concentration and depth distribution of a pollutant (Philpot and Klemas, 1979), but quantitative results will at least require identification of the base water.

In general, while it may very well be possible to detect the presence of a pollutant in water by passive, optical remote sensing, quantification will usually require surface support. The situation (for satellite remote sensing) is only likely to improve if active (lidar) systems are found to be feasible for satellite. Lidar systems are presently under development for oceanographic applications (Collis and Russell, 1976; Mumola *et al.*, 1973; Leonard *et al.*, 1979). However, lidar systems are still very much in the research stage even for aircraft, and problems with power and eye-safety requirements will seriously hamper extension of this technique to satellite based observations.

Air-sea interface

The air-sea interface affects the remotely sensed radiance in two ways (1) it reduces the upwelling radiance from below the surface by internal reflection and (2) it reflects sunlight and/or skylight into the field of view of the sensor. Gordon (1969) has calculated the reflectance coefficients for different angles of view and for a variety of windspeeds. These are presented in Figure 7. According to Figure 7 the internal reflection will be less than 0.03 for most wind speeds, for observation angles of $\sim 30°$ in air. (This corresponds to an observation angle in water of $\sim 22°$.) The specular reflection is easily less than 0.03 out beyond observation angles of 30°.

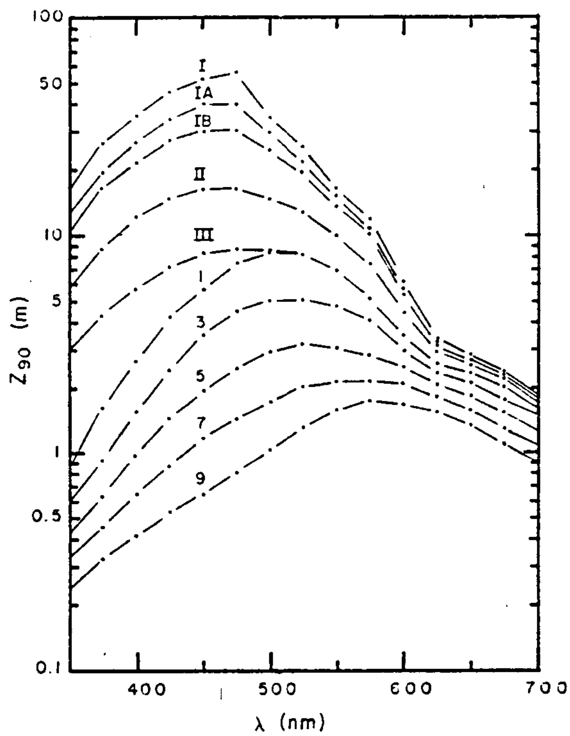


Fig. 4. Variation of z_{90} with wavelength for various water types given by Jerlov in Ref. 9.

Figure 6. Variation of the effective depth of penetration, Z_{90}, for various water types given by Jerlov (1976). Types I, II, and III are oceanic waters with I being equivalent to Sargasso Sea water. Types 1-9 are coastal waters (after Gordon and McCluney, 1975).

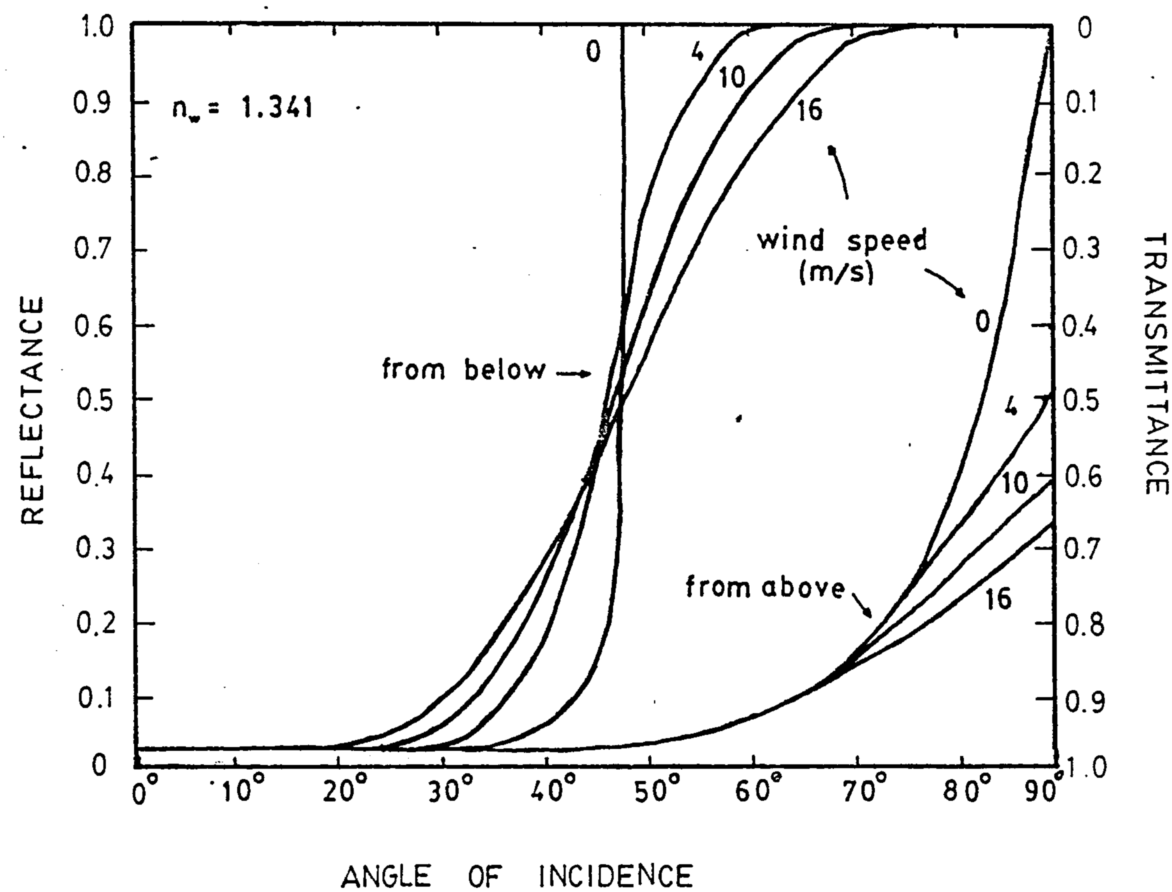


Figure 7. Reflectance and transmittance of the air-water interface as a function of the angle of observation for several windspeeds. Curves at left are for radiance incident from below the water surface; those on the right are for radiance incident from above.

For most observation angles of importance for satellite remote sensing, the loss to internal reflection will not be a significant loss due to refraction. The refraction effect is described by Austin, (1974). "The flux contained in a small solid angle, Ωw below the surface will be spread into a larger solid angle, $\Omega a = n^2 \Omega_w$, above the surface. Therefore, a radiance emerging from the water surface will be decreased further by the factor $1/n^2$ or 0.555 by virtue of refraction alone." The total reduction in radiance upon crossing the air-water interface will be $\sim$ 50%.

The above discussion refers to water surfaces which are free of contaminants. Surface contaminants can change the reflectance characteristics of the sea surface. Surface films of one sort or another are a very common feature on natural waters. These films may be naturally occurring organic slicks produced by marine phytoplankton (Wilson and Collier, 1972), by fish, or they may be the result of oil spills. Natural slicks are usually only monomolecular layers, less than a wavelength of light in thickness. Oil slicks from oil spills, on the other hand, are frequently thick enough to cause visible interference colors (Cox, 1974). These slicks may change the reflectance characteristics of the water surface either by changing the sea surface roughness due to the change in surface tension or by a direct change in the reflection coefficient. If the index of refraction of the slick is greater than water - the usual case - then the reflectance will exceed that of water alone. Cox and Munk (1956) estimated that the reflection coefficient will increase by $\sim$ 50% at normal incidence and less at other angles. Measurements by Horvath _et_ _al_. (1971) indicate that the increase in reflectance is somewhat greater. In any case, surface slicks are often detectable by passive, optical remote sensing.

Slicks are not the only surface contaminents. Detritus and living biological material will also be present on the water surface at times. In most cases, the relatively high reflectance from these surface materials relative to water makes them readily detectable. This is especially true for the near ultraviolet and infrared regions. Virtually useless for detection of volume characteristics, the ultraviolet infrared reflectance can be an invaluable aid for detecting oil (Horvath et al., 1971; White and Breslau, 1978) or phytoplankton at the water surface (Bressette and Lear, 1973).

Polarization

The use of polarization can, at least theoretically, aid in the remote sensing of water properties. At Brewster's angle, which for water is 53.3° (observation angle in air), the specular reflectance from a flat ocean is perfectly polarized. A remote sensor viewing at this angle may either reduce the subsurface radiance by half while accepting all the specularly reflected radiance - this is a useful method for observing surface features (Horvath et al., 1971) or reject the specular component entirely in order to enhance the subsurface component. Unfortunately, as Austin (1974) points out at Brewster's angle, "the air mass is increased to 1.67, which may severely increase problems associated with the atmospheric transmittance and path radiance in a significant number of instances. Additionally, the introduction of the polarizer must reduce the desired subsurface water signal by at least a factor of two and this may prove detrimental . . ."

Atmospheric effects

The radiance measured by a remote sensor is composed of several components. These components are illustrated in Figure 8. The components are as follows:

L_u = upwelling radiance immediately below the water surface.

L_w = upwelling radiance immediately above the water surface.

$= (t/n^2_w)\ L_u$

L_s = sky radiance from that part of the sky which will be the source of specular reflectance seen by the remote sensor.

L_r = specularly reflected sky radiance = $r\ L_s$.

L^* = path radiance, i.e. the radiance at the remote sensor due entirely to the atmospheric scattering of sunlight and skylight.

$L_z = (L_w + L_r)\ T_a + L^*$ = radiance at the remote sensor.

r = reflectance of the air-water interface.

t = transmittance of the air-water interface.

T_a = atmospheric transmittance.

The various relative contributions to the satellite measured radiance are illustrated in Figure 9 for two different water masses (Austin, 1974). These curves are based on in situ reflectance measurements and on atmospheric transmittance measurements. They are fairly typical for "clear" days and for clear coastal water types. The four circled points on the L^* and L_r curves for the 3 August data are values computed from shore station measurements.

The differences in color between the two water types is quite evident in the radiance immediately above the water surface, L_w. Even after the addition of the specularly reflected skylight and degradation due to atmospheric losses the major characteristics of the water color are still quite apparent (see the curves marked $T_a(L_w + L_r)$. However, the signal measured at the satellite includes the path radiance, L^*,

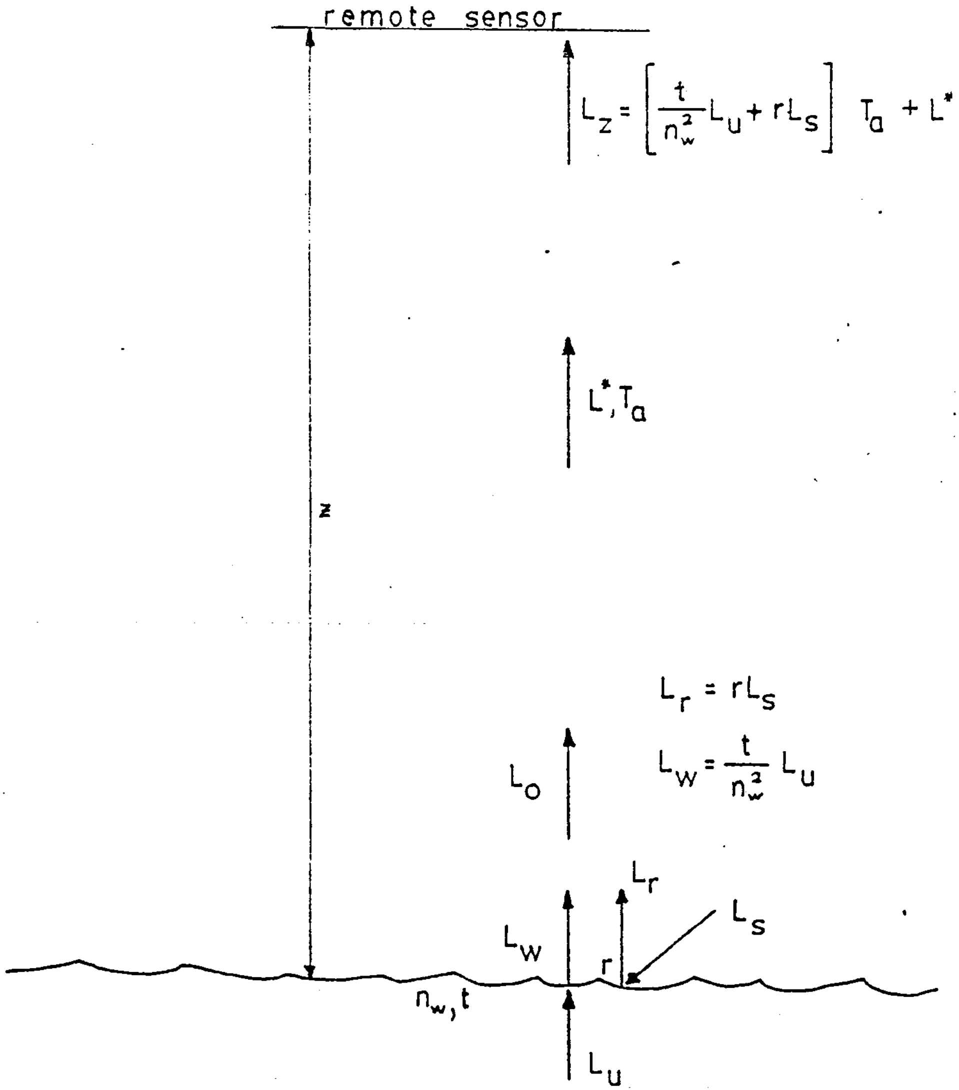


Figure 8. Components of the radiance measured by a remote sensor (Austin, 1974).

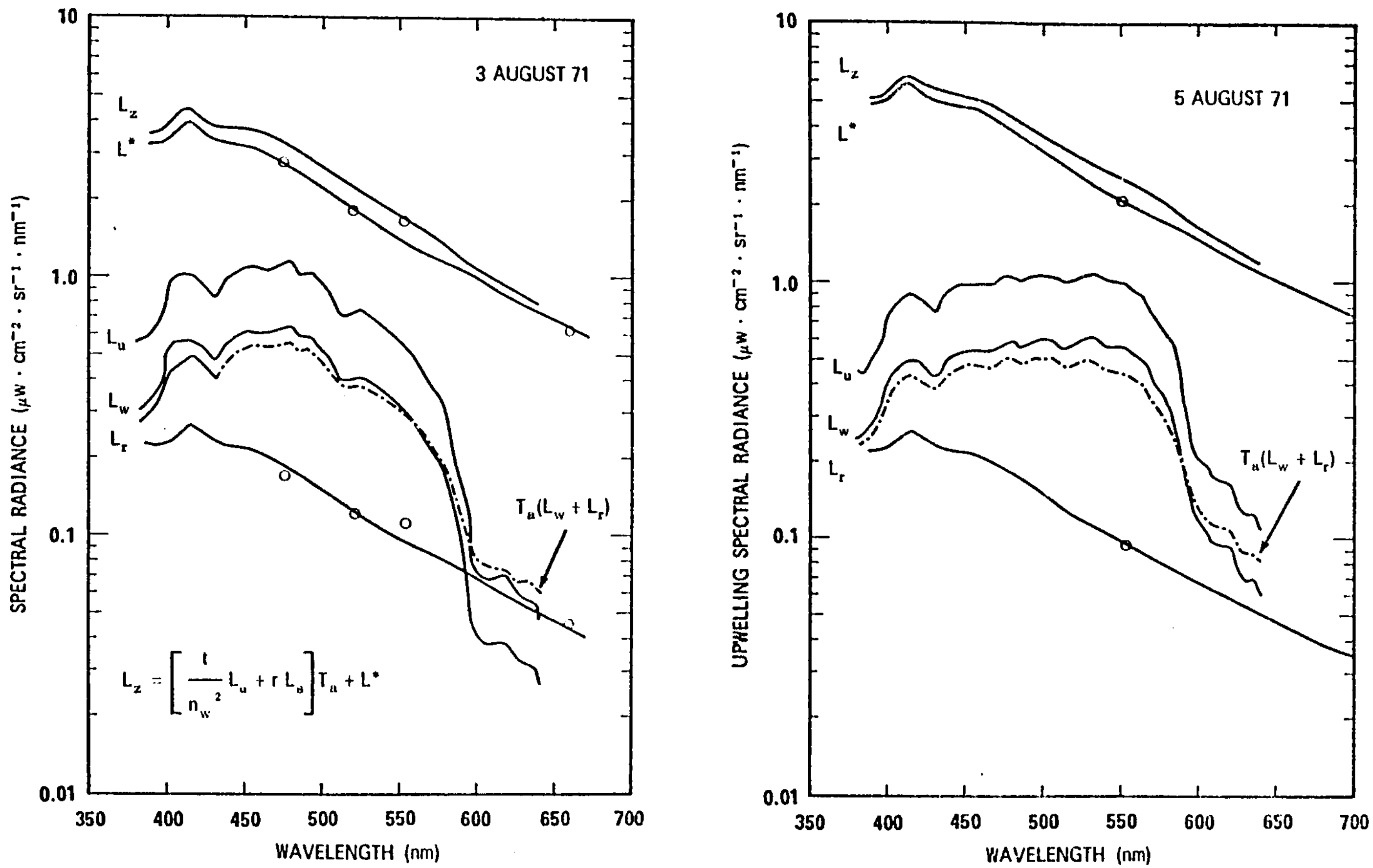


Figure 9. Computed apparent spectral radiance of the ocean, L_z, (and its components) as observed above the atmosphere. A - Blue-green water; B - Green water.

which is nearly an order of magnitude greater than the transmitted signal. In the examples shown, the transmitted signal was never more than about 20% of the path radiance and the spectral differences of the total radiances measured at the satellite, L_z, are greatly reduced.

Path radiance is the single most significant problem in remote sensing in the visible region. It will vary greatly in both time and space and may, at various times, be either significantly smaller or greater than in the examples in Figure 9. There are basically two approaches to dealing with the path radiance problem. The simplest, most direct and, in many ways, most appealing approach is to emphasize the relative changes in the spectra. This can be done by using ratios of two or more bands (Arvesen et al., 1971; Curran, 1972) or by comparing the spectra obtained from immediately adjacent areas (Clarke and Ewing, 1974; Philpot and Klemas, 1979), or by using some normalizing procedure which will highlight the subtle changes in the spectra (Mueller, 1976).

The other approach is to measure or calculate the path radiance and subtract it from the measured signal. This approach is frought with difficulties. The determination of the path radiance must be quite accurate since small changes in the path radiance can, and often do, cause changes in the apparent radiance. Inaccurate determinations of the path radiance will only introduce further anomalies in the apparent radiance.

There is an awesome array of techniques proposed for determining the path radiance. We will not attempt to describe or even to list these methods here. It is an extremely important facet of optical remote sensing and is an essential prerequisite if the full potential of optical remote sensing is to be realized. It is also an extremely difficult problem and is likely to be with us for some time.

3.1.2 System characteristics

In this section we will consider some of the characteristics of remote sensing systems which will affect the utility of the system for the various monitoring tasks.

Spectral characteristics

The question of the position, bandwidth and number of spectral bands needed for the remote sensing of ocean color is not yet resolved. The preferred spectral bands will vary depending on the particular target (chlorophyll, sediment, oil, etc.) and may also vary with the base water in or on which the target substance appears. Only general spectral characteristics of ocean color will be presented here. Discussion of specific bands will be left for section IV.

The spectral characteristics of substances in the water will always be masked to some extent by the absorption and scattering characteristics of the water itself. The absorption and scattering effects of water were described earlier. A more complete and excellent discussion of this topic is provided by Morel (1974). One characteristic which has important implications for remote sensing is that the absorption and scattering effects of water are broadband phenomena; there is little fine structure. This is most explicitly demonstrated by the research of Drummeter and Knestrick (1967) who found no narrow absorption bands of any significance in water. This implies that it may not be necessary (or even advantageous) to use extremely narrow bandwidths for most observations of ocean color.

Some insight into the number of bands necessary has been provided by Mueller's (1976) study of ocean color at 31 stations off the Oregon coast. Mueller measured the complete water color spectra between 420 and 700nm at a resolution of 5nm to 7nm. Using characteristic vector analysis, Mueller found that 99% of the variance in the normalized reflectance could be accounted for by only four characteristic vectors. In principle, then, one might need only five carefully chosen wavebands to reproduce the essential variational features of the observed spectra: one for each characteristic vector and one for the mean spectrum. Of course, these spectra did not include observations of any of the more common pollutants. Thus more than five bands may be needed for pollution monitoring systems. In particular, Mueller (1979) notes that a fifth characteristic vector is required to account for the spectra of iron-acid waste.

Mueller (1979) also explored the effect of widening the bandwidth. If, as suggested above, the spectral variations are truly broadband, then 5nm bandwidth may not be necessary. Mueller found that increasing the bandwidth to more than about 20nm degrades the informational content of the spectra. This implies that 20nm may be the optimal bandwidth for remote sensing purposes; any wider and the information content will be reduced, narrower and the total power in the received signal will be reduced.

Radiometric sensitivity and dynamic range

It was stated above that one of the most important aspects of ocean color analysis is the observation of subtle variations in the spectra. This implies that the sensors must be quite sensitive. Yet the sensors must be capable of this high sensitivity over a broad enough dynamic range for the data to be usable under very hazy conditions, when path radiance is very high, as well as on clear days.

In order to estimate the needed sensitivity let us compare the spectra for blue, blue-green and green water calculated by Austin (1974). Figure 10 shows the comparison between the radiance above the atmosphere due to the transmitted upwelling radiance immediately above the water surface. $L = T_a (L_w + L_z)$. The difference in radiance is shown at 20 nm intervals from crossover points in the curves. These values are crude estimates of the minimum radiometric sensitivity needed to detect differences in the slopes of these curves. The required sensitivity is about .05 $\mu w/cm^2$-sr-nm from 400 to 600 nm but drops quickly at 600 nm to less than .01 $\mu w/cm^2$-sr-nm.

The sensitivity should, ideally, be available over a dynamic range large enough to encompass measurements of low radiance levels from very clear ocean water under clear skies as well as "bright" signals from extremely turbid water under hazy skies. We will use a combination of measured and calculated values to estimate the limits. The lower limit should be defined by the upwelling radiance above the atmosphere of a perfectly absorbing target when seen through a clear atmosphere, i.e. path radiance for a clear sky. Wilson and Austin (1978) have measured path radiance at two wavelengths for a wide variety of atmospheric conditions. These data are reproduced in Figure 11. From these plotted values it appears that, on the clearest day, the radiance at 661 nm was about 0.6 $\mu w/cm^2$-sr-nm and the path radiance at 459 nm was about 2.8 $\mu w/cm^2$-sr-nm. The solid triangles in Figure 12 represent these minimum radiances. These values represent an absolute lower limit to the upwelling radiance measured by a satellite sensor. Another estimate of this

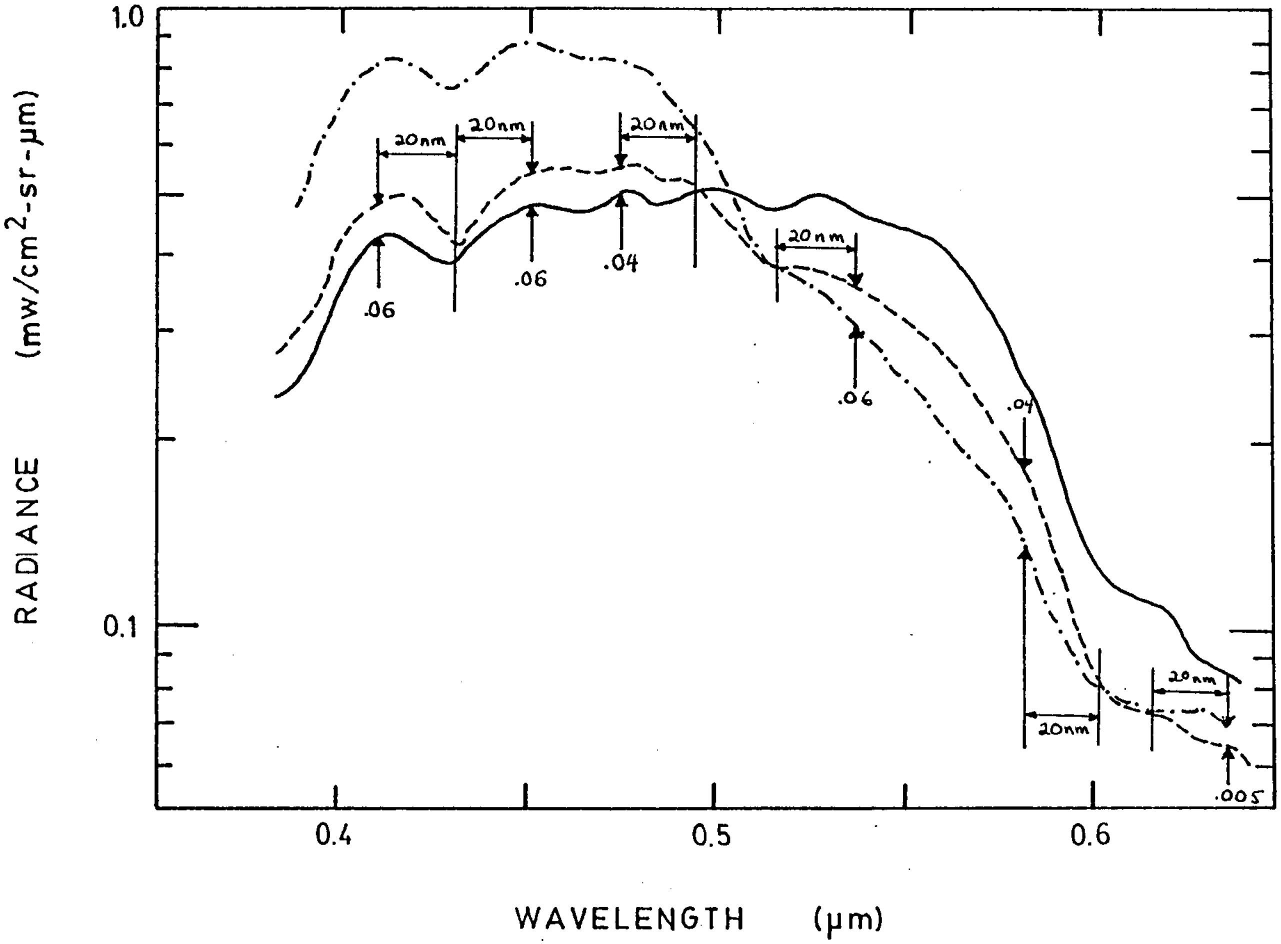


Figure 10. Upwelling radiance above the atmosphere for three different water types:

1) blue water —·—·—·—
2) blue-green water ---------
3) green water ————

Differences in radiance are in units of $\mu w/cm^2$-sr-nm.

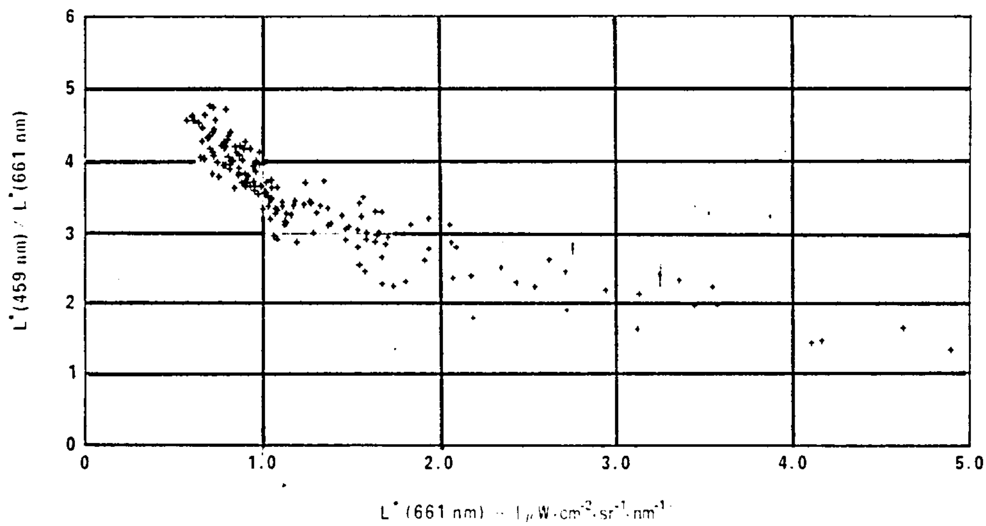


Figure 11. Relationship of the vertical path radiance at one wavelength to ratio between it and the path radiance at another wavelength. The path radiances were measured over a nine-month period at San Diego, California with sun zenith angle of 10° to 80°. Bandwidths of the measurements were about 60 nm. (Taken from Wilson and Austin, 1976).

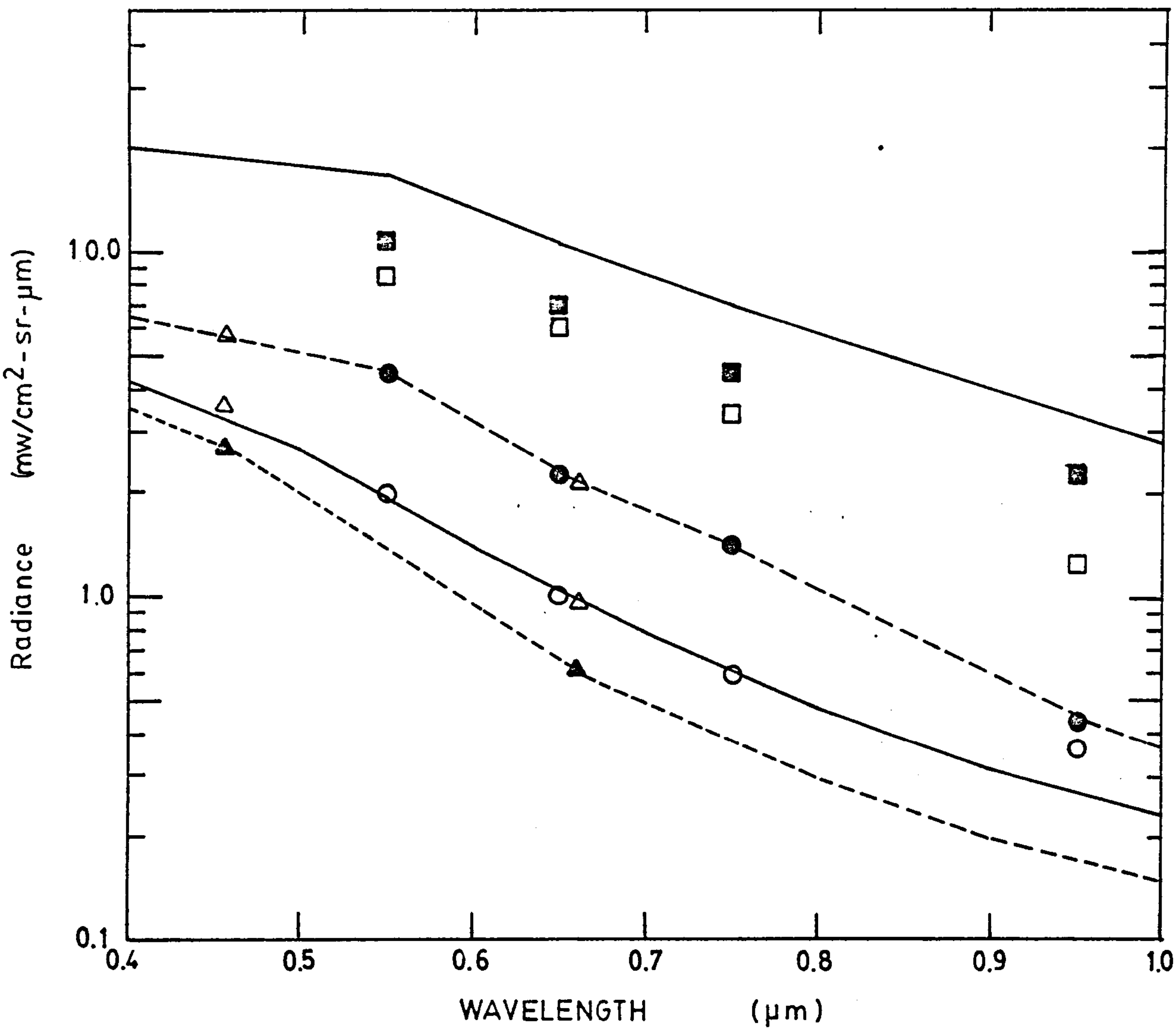


Figure 12. Estimates of the range of spectral radiances measured above the atmosphere for a variety of atmospheric conditions and water types.

▲ minimum path radiance (Wilson and Austin, 1978)
△ path radiance measurements (Wilson and Austin, 1978)
○ minimum radiance measurements from Landsat data over ocean waters.
● maximum clear water radiance for high haze conditions from Landsat data.
□ maximum turbid water measurements from Landsat data.
■ expected maximum radiance.

minimum radiance was provided by Wezernak et al., (1976) who calculated the upwelling radiance above the atmosphere when the solar zenith angle was 45° and the visibility was 23 km with a haze M (Diermendjian, 1969). Haze M is used to describe a marine or coastal haze. The calculated results are shown in Figure 12 as the lower solid line. This line is somewhat higher than the measured values probably because of the assumption of higher haze conditions than existed during the measurements. A pair of path radiance measurements for higher haze conditions fit the predicted curve quite well (open triangles, △ , on Figure 12).

The set of measurements in Figure 11 suggest that there is a relationship between the path radiance at one wavelength and that at another. Wilson and Austin (1978) state that this relationship has been verified. We will use this fact to draw a line through the low radiance points which is roughly parallel to the calculations by Wezernak et al., (1976). This then will be the lower end of the sensitivity range needed for water observations.

As a further check on these values, Landsat data for clear waters on the continental shelf off of Delaware was reviewed. The open circles, ○ , represent the lowest values observed in any of the available data. It is interesting to note that the circles agree well with the calculations by Wezernak et al., (1976). The value at 950 nm represents the lowest possible count value for the Landsat 2 MSS in band 7, i.e. this is the dark current. Landsat 2 is incapable of lower measurements.

In order to estimate the upper limit of radiance needed we first estimated the maximum radiance over clear water for high haze conditions. The solid circles, ●, are the radiance values from Landsat data over clear shelf water for data which was marginally useful because of haze and cloud conditions. Again, measured values for path radiance (Wilson and Austin, 1978) in this range is plotted (open circles, ○) and all the points have been connected with a line. The next step was to estimate the maximum range of radiance values which might be expected for water targets. To do this, the Landsat data was again searched, this time for the maximum radiances for water areas. The search was not limited to particular haze conditions. The open squares, □, represent the highest values found. The radiances in the visible are from extremely turbid water in the Delaware River; the IR radiances were found in shelf waters at the sight of a suspected oil slick. The high radiance values were found on different scenes than the low radiance values. Nonetheless, the difference between the high and low values were taken as the maximum range to be expected for a single scene, and this difference was used to plot the maximum radiance range expected in each band for very hazy days. These points are plotted using solid squares, ■. The upper limit for the sensitivity range was chosen to be half again higher in radiance than the maximum estimates in order to allow for the possibility of extremely bright targets that might appear. The maximum sensitivity is represented by the upper solid line. The total dynamic range needed for coastal water observations is then given by the lower dotted line and the top solid line in Figure 12.

The final question to be asked here is: "Given the dynamic range just presented, what is required in order to have the required radiometric sensitivity?" The controlling factor here is the precision of the data. Figure 13 shows the estimated radiometric sensitivity needed to detect subtle variations in ocean color spectra. Assuming the dynamic range given above and a linear gain, the precision required is 8-bit data for

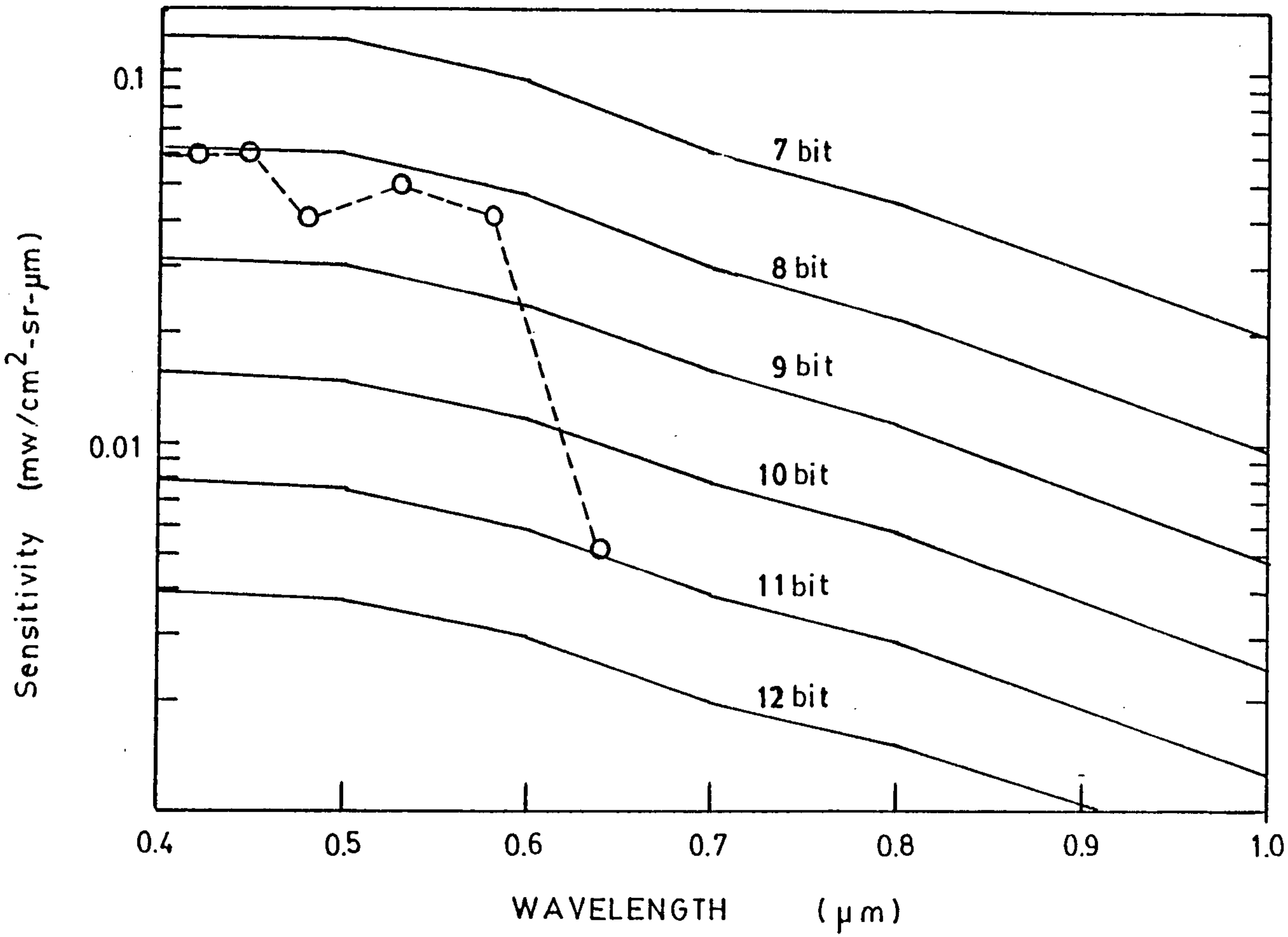


Figure 13. Precision of digital data and the effective radiometric sensitivity for the dynamic range shown in Figure 12.

the 400-600 nm region and 11- or 12-bit data for wavelengths greater than 600 nm. Certainly, 8-bit data is necessary and attainable.

Spatial resolution, swath width and coverage frequency

There is often a tendency among researchers, the present authors included, to wish for higher and higher resolution. It seems as if there is always some feature which is almost but not quite detectable and that higher resolution might bring it within the range of detection. This wish tends to wane when the researcher is faced with the very real problems usually associated with higher resolution digital data. Data processing, storage and manipulation become increasingly difficult and time consuming projects. For research purposes the increase in complexity may be acceptable for marginal improvements in results, but for operational systems higher spatial (or spectral) resolution than is necessary for the task at hand can only increase delays in processing and raise the cost of the final product. Wherever possible the resolution should be appropriate for the task.

Surprisingly little information is available on resolution requirements for any remote sensing application. Most of the stated requirements for spatial resolution seem to be estimates based more on intuition than on experimental evidence. One such set of estimates (NASA, 1973) is presented in Table 1. These values seem quite reasonable and there is little reason to alter these estimates. Some comments are in order, however. One of the principal advantages of remote sensing in general is the ability to cover relatively large areas effectively instantaneously. Monitoring projects which cover limited regions often require higher resolution and high frequency coverage than has been available from satellite systems. Such projects are often better suited to aircraft

Marine and Ocean Applications	EIFOV (Meters on Ground Unless Otherwise Specified)	Field of Coverage (km) (Minimum Swathwidth)
(1) Currents		
(a) Coastal Current Mapping	0-100	200 km
(b) Coastal Current Measurement	3-10	40 km
(c) Turbidity and Transport	50-100	200 km
(d) Global Mapping	1-10 km	400 km
(2) Sea Ice Surveillance	30-100	200 km
(3) Biological Processes		
(a) Assessment	1-2 km	400 km
(b) Coastal Pollution Detection	30-50	200 km
(c) Pollution Environmental Impact	30-300	200 km
(d) Global Ecosystem Analysis	1-10 km	400 km
(4) Coastal Geological Processes		
(a) Shoreline Mapping and Shoals	30-50	200 km
(b) Wetlands Inventory	30-50	200 km
(c) Bathymetry and Bottom Topography	50-100	200 km
(d) Mean High/Low Water	3-10	40 km

Table 1. Sensor geometrical needs for marine and ocean applications (NASA, 1973).

remote sensing. Examples might include observations of tidal marshes and creeks, surveillance of pollution along rivers, monitoring and/or mapping of thermal plumes and detailed surveillance of oil spills. For these projects a 1m to 10m resolution would be preferable.

Satellite systems are particularly well-suited to observations of large areas where extremely high resolution is not required. For most coastal water surveillance, 50-100m resolution is quite adequate. Near to shore and within bays and estuarines a 30-50m resolution may be required due to the presence of point sources of pollution and generally smaller scales of motion. Farther offshore and into the deep ocean the scales of motion become quite large and the importance of small pollution events decrease. The resolution requirements may then diminish to hundreds of meters. In such cases it is worthwhile to trade off the spatial resolution for better spectral resolution, improved radiometric sensitivity, larger field of coverage and a higher coverage frequency.

Table 2 shows our estimates of the needed spatial resolution, swath width and coverage frequency needed for adequate coverage of marine waters. There are only minor differences between the estimates in Table 1 and Table 2.

3.1.3 Visible sensors on satellites

At present there are two multispectral satellite sensor systems useful for water quality work: Landsat multispectral scanner subsystem (MSS) (Appendix A) and the Coastal Zone Color Scanner (CZCS) aboard Nimbus 7 (Appendix B). A third, the thematic mapper (TM) (Appendix A), will be on board Landsat D which is scheduled for launch in late 1981. Of these sensors, the only one strictly intended for oceanographic observations is the CZCS. None of these are really ideal for water

Regime	IFOV	Swath width	Frequency
Shelf waters			
Chlorophyll Sludge Iron-acid waste Oil Current pattern Oceanic fronts	200m	500km	daily
Internal waves	30-50m	200km	monthly
Near shore (bays & estuarines)			
Turbidity Major current pattern Wetland inventory	30-50m	200km	weekly
Pollution detection	30-50m	100km	daily
Frontal systems Shoreline mapping Shoals	10-20m	100km	bi-weekly

Table 2. Suggested spatial and temporal coverage for satellite observations of coastal waters.

quality monitoring. The Landsat MSS has adequate resolution (80m) for most monitoring tasks but the coverage frequency is too low and the radiometric sensitivity is inappropriate. The latter can be seen explicitly in Figure 14. The maximum and minimum radiance expected from a water target for extreme conditions are represented by the two solid lines which have been taken from Figure 12. The sensitivity range for the Landsat bands (vertical lines, solid arrowheads) easily exceeds the maximum expected radiance in all bands and is essentially insensitive to the lower ranges of radiance in bands 6 and 7.

The CZCS, although the bandwidths and choice of wavelengths is generally superior to that of the MSS, has poorer resolution (800m, nadir) which is adequate only for offshore work, and will often preclude identification of a pollutant by spatial features (dumping pattern). The gain settings on the CZCS are set for water observations, but this, too, may pose a problem. The maximum radiance (saturation) for the lowest gain setting of the CZCS is shown on Figure 14 with open triangles. These saturation values are well below the maximum radiances observed for turbid waters in Landsat data and, in fact, below the maximum radiance of a fresh iron-acid waste plume as observed by Landsat on a clear day (25 Aug. 75). It would appear that the CZCS is really designed for observation of relatively clear waters, and that spectral detail would be lost due to saturation when observing very turbid waters. Thus, the CZCS may be an excellent instrument for observations of the relatively clear continental shelf and shelf slope waters, but may not be very useful for nearshore observations.

The Thematic Mapper (TM) will provide improvements in both spatial and spectral resolution over the MSS system. The TM, however, will be

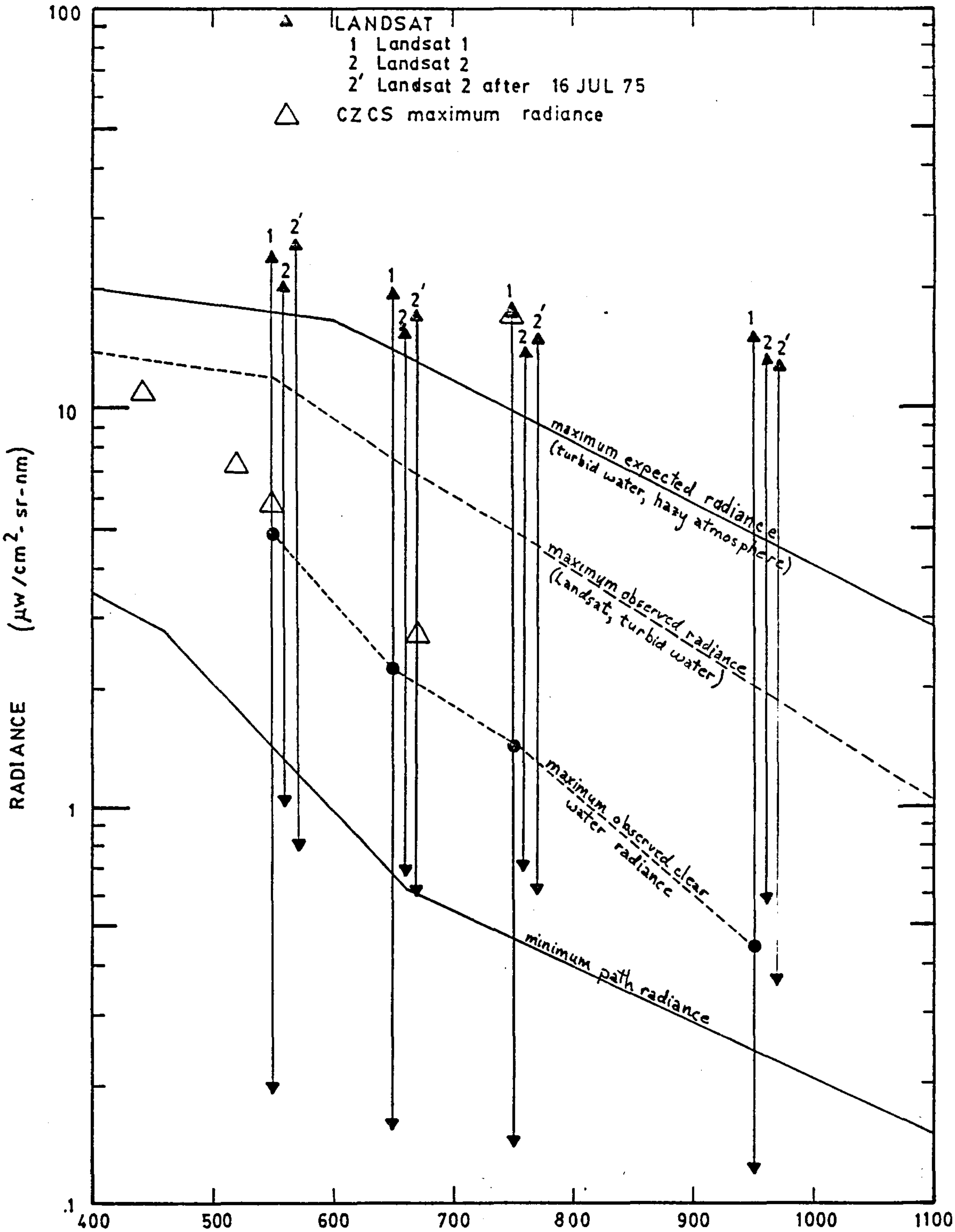


Figure 14. Radiometric sensitivity of satellite sensors.

subject to the same radiometric and temporal limitations as the MSS. Nonetheless, the TM is expected to provide a significant improvement over the MSS for nearshore and estuarine observations.

Several other sensors are either in the proposal or planning stages. Two which may be important for ocean color observations are the Multispectral Resource Sampler (MRS) (Appendix C) and the updated CZCS in the National Oceanic Satellite System (NOSS) (Appendix D) program. The MRS will mark a slight improvement in sensitivity over the MSS and TM and allow a wide variety of narrow band, filter combinations which could prove quite advantageous. Perhaps the major advantage of the MRS, though, is the pointing capability. The MRS is designed to be pointed in flight at chosen targets. Even though the MRS will be flown on a satellite which is likely to have orbital characteristics similar to Landsat, the pointing capability can increase coverage frequency to one to two days. This could be extremely useful for monitoring pollutant dispersion and transport.

The NOSS program includes an updated version of the CZCS. This CZCS will probably provide better spectral resolution by adding several bands and a slightly improved spatial resolution due to a lower orbit. However, the most important aspect of the NOSS program for water quality monitoring is that it includes plans for near real-time data products (NASA/DOC/DOD, 1979). This aspect of satellite remote sensing has not received a great deal of attention, yet the rapid availability of data is extremely important for many monitoring tasks.

3.2 Thermal infrared region

Infrared radiation at wavelengths from 3 to 14 μm is called the thermal IR region. There are two atmospheric windows within this region

(3-5 μm and 8-14 μm). For most purposes the 8 μm to 14 μm wavelength band is preferred to the other atmospheric window since 8-14 μm band includes the maximum intensity of the radiant energy flux for the earth's surface. Thermal IR radiation is absorbed by the glass lenses of conventional optical systems and cannot be detected by photographic films. Special detectors and optical-mechanical scanners are used to detect and record images in the thermal IR region.

Thermal IR images record the radiant heat of a material. The radiant heat is a measure of the ability of the material to absorb and radiate thermal energy. Thermal scanners record the radiant temperature of the water surface which, with proper calibration and surface truth, can be related to absolute temperatures in waters free of surface contamination. A major advantage of thermal imagery is that it is not dependent on daylight. It is, however, severely limited by weather and the interpretation of the data may vary depending on whether the data was collected during the day or at night. La Violette (1975) describes the difficulties:

> "When clouds are present between the sensor and the ocean, the sensor records cloud rather than ocean radiation temperatures. The surface thermal features of the ocean in these cases are effectively blocked from the satellite's view. Thin clouds and water vapor affect sensor data by making the ocean's surface appear cooler than it actually is. The amount of apparent cooling is directly proportional to the amount of water vapor in the air. . .
>
> "Another problem in the utilization of satellite infrared sensors for oceanographic purposes, is the type of energy being measured. The "sea surface temperature" collected by infrared sensors is the equivalent blackbody radiation of the first millimeter of the surface layer. . . Sufficient radiation loss occurs at night, so that the surface radiation temperature in the early morning hours can easily

> represent a dynamic mixing to a depth of several meters. Duing the daytime, however, isolation offsets the radiation loss by a variable amount. If there is no mechanical mixing, such as when wind speeds are less than 10 knots, then infrared daytime measurements may be the radiation of a surface film quite different in temperature than the water a few centimeters deeper."

Thermal IR data has been used for observations of oceanic and shelf water circulation patterns using the temporal variations of the ocean's temperature field (Halliwall, 1978; Bisagni, 1976), and for observations of coastal upwelling (Szekielda, 1973). As higher resolution systems become available, smaller details of the circulation patterns and thermal effluents will come within range of observation. Accurate absolute temperature maps are not yet possible since they require complex calibrations to account for atmospheric effects. Absolute accuracy is presently limited to about 2°C. Relative changes of about 0.5°C are detectable.

3.3 Microwave region

Microwave systems have the greatest potential for observation of ocean dynamics. A considerable amount of research has been done exploring the many applications of microwave remote sensing for oceanographic purposes. Unfortunately, very little satellite data is available at present and very little is likely to be available in the near future. Waters et al. (1975) and the CORSPERS (1977) report review the development of satellite microwave measurements. The only sensor presently available is the SMMR aboard Nimbus 7, and the only other data which will be available during the 1980-1985 time frame will be from systems flown on the space shuttle (SIR-A, SIR-B, SIMS, SMMRE). The NOSS program, should it be approved, will contain several microwave sensors and would be available 1985 or later. We will consider microwave systems, although only briefly, because of the likelihood of their eventual importance in monitoring systems.

Microwave systems are unique in that both active and passive systems are feasible for satellite applications. Active (radar) and passive (radiometer) systems have very different characteristics and applications. An excellent review of the characteristics of these systems can be found in the CORSPERS (1977) report. The description below is largely excerpted from this report.

The microwave radiometer measures the electromagnetic energy radiated towards it from some target or area. Being a passive sensor, it is related more to the classical optical and IR sensors than to radar, its companion active microwave sensor. The energy detected by a radiometer at microwave frequencies is the thermal emission from the target itself as well as thermal emission from the sky that arrives at the radiometer after reflection from the target. The thermal emission depends on the product of the target's absolute temperature and its emissivity. At microwave frequencies, it is the change in emissivity rather than the change in temperature that produces most of the significant differences between the various targets. The intervening atmosphere between the target and the radiometer can have an adverse effect on the measurement by attenuating the desired energy due to its own temperature and emissivity.

One of the major limitations of a spaceborne radiometer is its relatively crude resolution, which is a consequence of the antenna beamwidth and the long range to the target area. The thermal radiation from the body of temperature T is not as great in the microwave as in the IR region. The microwave radiometer is also less sensitive. There are, however, significant differences in the brightness temperature measurement at microwave frequencies that make the radiometer of interest as a remote sensor. Measurements at microwave frequencies, both active and passive, are less affected by haze, fog, and clouds than are those of IR and optical sensors. In fact, at lower frequencies microwave radiation is particularly insensitive to the presence of clouds, fog and haze. Since the sensitivity to water is frequency dependent, a multi-frequency system can provide measurements of atmospheric water vapor and liquid water over the oceans, thus providing sufficient information to calibrate surface temperature measurements.

Other measurements possible with the microwave radiometer are the temperature profile, sea-ice boundaries, discrimination of first-year and multi-year ice, salinity of water, oil slicks and sea state.

An active microwave sensor (radar) is responsive to the reflected energy from sharp discontinuities in the transmission medium or from those features of the target that have sizes comparable to the sensor's wavelength. Thus, the energy of a microwave radar signal interacts with those features of a target that have characteristic sizes on the order of centimeters, while optical and IR sensors are sensitive to scatterer sizes on the order of micrometers. The radar senses different characteristics of a target than an optical or an IR sensor. A radar image should therefore not be expected to look like or contain the identical information as an optical image even if the resolutions are comparable.

Large ocean waves (gravity waves) behave like an ensemble of specular reflectors so that the strength of the scattered radiation is proportional to the slope of the gravity waves. However, ocean waves comparable to the wavelengths of the microwave systems used show resonant, or Bragg, scattering effects for angles of incidence larger than 20°. This type of scattering is controlled by the capillary waves, which in turn depend on the local short-term surface wind field and the ocean water surface tension. The latter changes when an oil film covers the water surface, resulting in a modification of the character of the capillary waves. Thus, oil is detectable with active microwave systems.

There are three different instruments which will be useful for remote sensing of ocean waters: altimeters, scatterometers and imagery radars. The radar altimeter can provide information on sea-surface topographic features: sea surface height, and significant wave height. The scatterometer, viewing the oceans at 0° to 10° incidence angles, provides sea-state information through the detection of the slope statistics of the ocean waves. For higher incidence angles, local wind fields can be determined.

Perhaps the most versatile instrument is the imaging radar. This instrument can provide a variety of information on wave patterns and dynamic behavior. Imaging radar can function through clouds to provide information on wave heights, wave patterns near shore, oil spills, and current patterns.

A rather thorough discussion of the physics of radar interactions with the ocean and the uses and limitations of radar systems in remote sensing is provided in the Active Microwave Workshop Report (NASA, 1975).

The Scanning Multichannel Microwave Radiometer (SMMR), which is aboard the Nimbus 7 satellite, will provide data on sea surface temperature and near-surface winds on a nearly all-weather basis. The surface wind speed, a parameter which is not available from other remote systems will be particularly valuable for transport and dispersion predictions. The

SMMR is a five-wavelength, dual polarized scanning radiometer. The multiple wavelengths are needed to correct the observed brightness temperature for atmospheric absorption and emission.

IV. The Role of Satellite Remote Sensing in Environmental Monitoring

4.1 Specific targets

4.1.1 Photosynthetic pigments

The remote detection of chlorophyll and other photosynthetic pigments has been an important research topic for several years. The major emphasis has been on using the relationship of chlorophyll to phytoplankton to assess primary productivity of ocean waters. While primary productivity is not the goal of a pollution monitoring system, a knowledge of the productivity of the waters in the vicinity of a dump or spill can be important to the assessment of the impact of a pollution event. More directly, an unusual plankton bloom or an unusual drop in chlorophyll levels can be an indicator of a pollution event.

The uniqueness of a pigment's signature rests more in the absorptive and fluorescence characteristics of the pigment than in the scattering characteristics. Chlorophyll absorbs most strongly in the blue and has a second absorption peak around 670-680 nm with the absorption minimum occurring around 550 nm (Figure 15). Carotenoids are more effective in absorbing light in the region around 500 nm. When carotenoids are present the absorption minimum will generally shift towards the red. Several investigators have attempted to use these absorption characteristics to detect chlorophyll. Clarke *et al*. (1970) used a ratio of the upwelling radiance at 540 nm to that at 460 nm. This ratio was later also used by Curran (1972) and by Arvesen *et al*. (1971). This two band ratio has worked rather well in several instances, but has proven troublesome in applying when the chlorophyll is masked by the presence of suspended particulates, absorbing materials such as yellow substance or pigments other than chlorophyll.

Smith and Baker (1978) suggested an algorithm using measured reflectance at three wavelengths to disentangle the chlorophyll signal. Wilson et al. (1978) applied this algorithm (using the wavelengths 471 nm, 547 nm and 662 nm with a 22 nm bandwidth) to data collected in the N.Y. Bight. While the corellation with the chlorophyll measurements was quite good it was found that the algorithm had to be adjusted for the ambient water mass. Three classes were found: class 1 for near coastal waters, class 2 for offshore waters and class 3 for waters in the vicinity of an acid dump.

Duntley et al. (1972) pointed out that, for a given species of phytoplankton in an otherwise homogeneous water mass, changes in the phytoplankton concentration will not alter the reflectance of optically deep water at a particular wavelength. This "hinge point" will occur at different wavelengths for different species but appeared between 500-540 nm for the species which Duntley et al. (1972) modeled. Presumably, a band in this wavelength region would be useful for observing changes in the background water.

Recently it has become apparent that the presence of chlorophyll can be detected by passive remote sensing of the fluorescence maximum around 685 nm. Neville and Gower (1977) and Morel and Prieur (1977) have reported such observations and Gordon (1979) corroborated this by establishing that the quantum efficiencies of the chlorophyll fluorescence are sufficient to produce the observed effect. Thus, it would seem that a

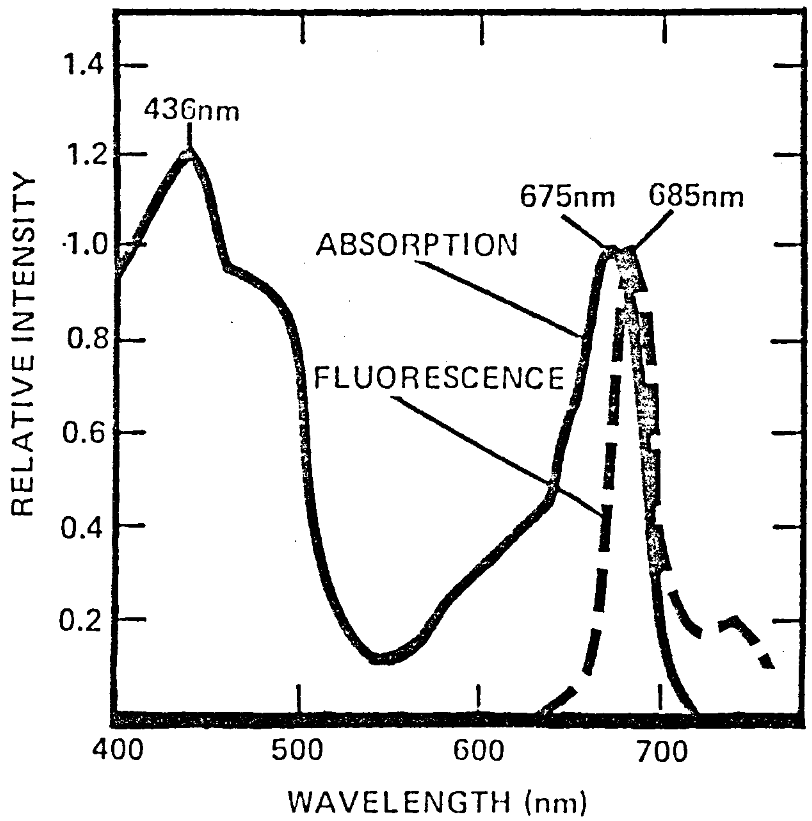


Figure 15. Absorption and Fluorescence Spectra for Chlorophyll a. (Friedman and Hickman, 1972).

band in the vicinity of 685 nm should aid in detecting chlorophyll.

Given the above considerations, we would suggest a 5-band sensor for the detection of chlorophyll. The spectral bands and their purposes are given in Table 3. The bands suggested in Table 3 are essentially the same as those of the CZCS except that the CZCS red band (660-680 nm) overlaps the two bands suggested here. If fluorescence is important, such a band would give a higher reading than might be expected. It may be somewhat premature to suggest a chlorophyll fluorescence band since passive fluorescence observations are few and none have been made from satellite altitudes. However, the observations, although few, are rather convincing and suggest that a fluorescence band would be valuable. The expanded CZCS being proposed for the NOSS program includes such a band.

As far as spectral characteristics are concerned the CZCS is far preferrable to any existing or approved satellite system for the detection of chlorophyll in oceanic waters. Yet there are limitations to the applicability of the CZCS. Because of the relatively crude spatial resolution (800 m) only large features will be seen. Features smaller than a few kilometers will not be discernable and larger areas which are dynamically complex on a small scale may appear washed out. This suggests that the CZCS would be most appropriate for continental shelf and open ocean. This predilection for offshore waters is further supported by the radiometric sensitivity of the CZCS. As can be seen in Figure 14, the CZCS channels (open triangles, $\triangle$) will probably be driven off scale when observing very turbid water or even clear waters on very hazy days even at the lowest gain settings. The CZCS should provide excellent data for the relatively clear offshore waters but will be of limited use in turbid, nearshore or estuarine waters.

Spectral Bands (Visible) (nm) Suggested	CZCS (Nimbus 7)	CZCZ (NOSS)	Observations
		390-410	
430-450 or 450-470	433-453	430-450	absorption maximum for chlorophyll a.
510-530	510-530	510-530	"hinge point" for observation of variations in background waters.
540-560	540-560	550-570	absorption minimum for chlorophyll a. Useful for observations of gelbstoff.
655-675	660-680	630-650	absorption peak for chlorophyll a.
675-695		675-695	fluorescence peak for chlorophyll a.
	740-760	740-760	

Table 3. Suggested bands for remote chlorophyll a detection and comparison with existing and proposed sensors.

Other satellite systems may be useful to some extent, especially when smaller features are of interest. The Landsat MSS spectral bands are clearly not designed for observations of marine chlorophyll. While it may be possible to use Landsat data for chlorophyll observations it will be a limited role, probably restricted to observations of offshore waters where phytoplankton can dominate as the optically important material in the water. One important use would be to use the MSS data to provide detailed spatial information in conjunction with the spectral observations of the CZCS. If the CZCS data shows an area to be high in chlorophyll, Landsat data may be able to show some of the smaller scale distribution patterns of the chlorophyll.

The TM will be an improvement over the MSS both in the spectral bands available and in the radiometric sensitivity. The spectral bands are still rather wide and do not really correspond to the ideal for chlorophyll sensing, but they are somewhat better placed than the MSS bands. Some further improvement will be possible with the MRS. Again, the bands have not been chosen with marine chlorophyll sensing in mind, but with the selectable filters it should be possible to have a reasonable set of spectral bands. Given the proposed bands the best selection for chlorophyll detection would probably be as follows:

Array 1, Filter 2 (540-560 nm): This corresponds exactly to one of recommended bands.

Array 2, Filter 2 (670-690 nm): This band should be useful for the fluorescence measurement. It is slightly shifted toward the blue into the chlorophyll absorption peak.

Array 3, Filter 3 (630-690): Subtracting the radiance measured by the red band above (670-690 nm) will give a value for the radiance in the region 630-670. This is somewhat broader than desirable but it does correspond to the chlorophyll absorption peak.

Array 4, Filter 3 (400-420) or Filter 4 (490-510): It is difficult to say which of these filters is preferable; they bracket the chlorophyll absorption maximum.

4.1.2 Iron-acid waste

Iron-acid waste, a by-product of titanium dioxide production, is one of the pollutants most visible from space. Several investigators have reported on the detection of this waste from satellite, notably Bowker and Witte (1977), Schmidt (1978) and Philpot and Klemas (1979). The optically important component of the iron-acid waste is a ferric-hydroxide precipitate which forms when the acid waste is buffered by the seawater. Lewis (1977) presents remotely measured spectra of the iron-acid waste (Figure 16). The spectra show a peak in the observed radiance at about 580 nm for high concentrations of acid. The peak shifts towards the blue for very low concentrations finally approaching the ambient water signature with a peak at about 480 nm. Little response was seen at any concentration for the spectral region from 425-470 nm and at a narrow band around 740 nm. Lewis (1977) suggested using the ratio of observed radiance at 580 nm to that at 440 nm as a measure of the acid concentration.

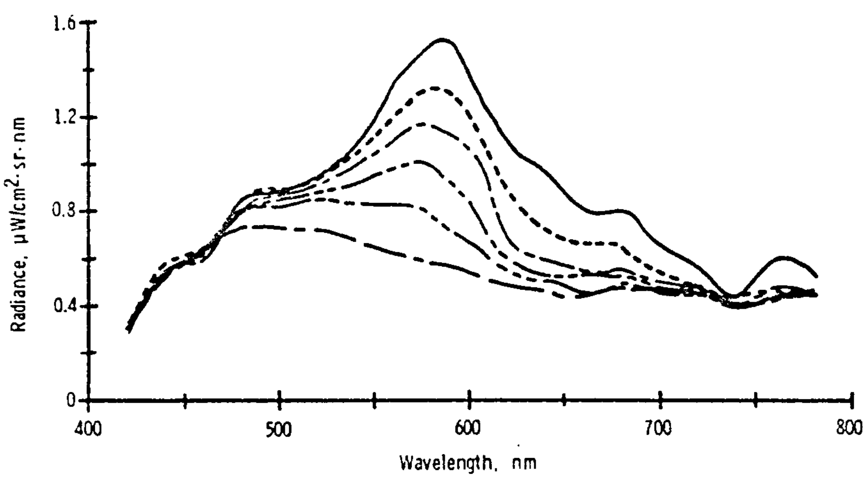


Figure 16. Remotely sensed upwelling radiance across an iron-acid waste plume (Lewis, 1977).

Further examination of the upwelling radiance curves presented by Lewis (1977) reveal that the change in radiance across an iron-acid plume does not occur at the same rate at all wavelengths. The family of curves presented in Figure 16 shows an initial rapid increase in radiance around 500 nm and then a leveling off. In contrast, at 650-700 nm the initial change is rather slow but later becomes quite rapid. It is not possible to say why these sorts of variations occur, although Philpot and Klemas (1979) have suggested that they may be due to changes in concentration with depth. Spectral bands in these regions might assist in the detection and quantification of iron-acid waste. Thus, preferred bands for observation of ironacid waste are as follows (in order of preference):

Band 1:	570-590 nm	-maximum response to the presence of the iron-acid waste.
Band 2:	450-470 nm	-minimum response to the presence of iron-acid waste.
Band 3:	500-520 nm	-indicator of the shift of the peak towards the blue, - possibly related to depth distribution.
Band 4:	650-670 nm	-radiance changes in this region are at a different rate than either Band 1 or Band 3.

The Landsat MSS bands have been used quite successfully in identifying the acid waste although some difficulty has been encountered in distinguishing between acid waste and other materials (Philpot and Klemas, 1979). The difficulty is probably due to the very broad bands of the MSS.

The TM bands are a significant improvement over the MSS bands for detection and identification of acid. Using the TM bands it should be possible to distinguish the acid from other materials. The MRS can improve on this somewhat by substituting a filter in the 490-510 nm range (Array 4, filter 4). Spectrally the CZCS bands are preferable to any of the above sensors. However, the CZCS has poor spatial resolution which will degrade the sensitivity of the sensor for iron-acid waste detection.

4.1.3 Sewage Sludge

Ocean dumping of sewage sludge has occurred for years and is likely to continue for several years to come unless acceptable alternatives are found. There have been relatively few remote observations of sludge dumps partially due to the rapid settling rate of the particulate fraction of the sludge (Kupferman and Murphy, 1973). Johnson *et al*. (1977) have reported on an experiment designed to remotely detect sewage sludge. Observations included a fresh, very highly concentrated "spot" dump as well as a fresh "line" dump. The "line" dump is the typical dumping pattern. Spectra of these dumps, normalized to ocean water spectra, are shown in Figure 17 (from Johnson *et al*., 1977). The normalized spectra of the fresh "spot" dump actually peaks in the near infrared and is quite strong in the red. The peak radiance is quite broad. The normalized spectra from the line dump also has a broad peak in the red/infrared. In both cases the spectral peaks shift toward the blue with age. These spectra suggest that it is primarily the particulate pahse which is responsible for the appearance of the sludge. The absolute change in radiance is strong in all bands (Figure 18) indicating that the upwelling spectral radiance is due to "white", or wavelength independent scattering. Since there are no apparent absorption or emission lines, a system

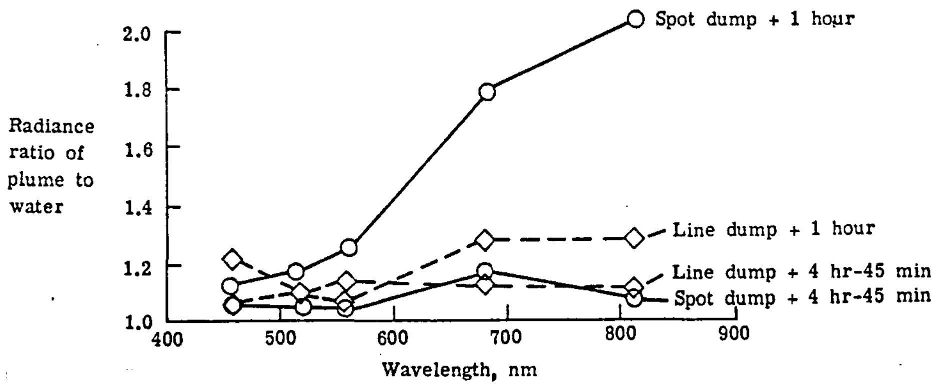


Figure 17. Upwelling radiance from sewage sludge plume relative to the adjacent water (Johnson et al., 1977).

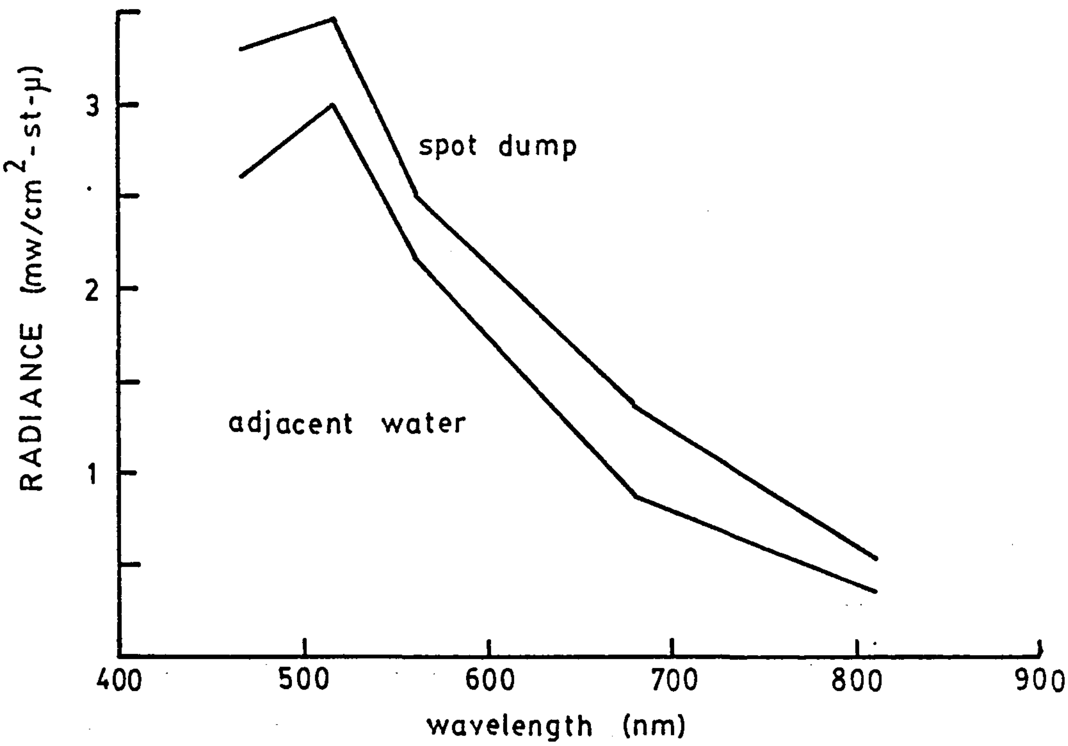


Figure 18. Upwelling radiance from a fresh "spot dump" of sewage sludge and from the adjacent water.

designed for detection of sewage sludge might best have 3 or 4 rather broad spectral bands ranging from about 450 nm to 800 or 900 nm. The first four TM bands are probably near ideal for detection of sludge. Landsat bands should be quite good. In fact the spectral bands available on any of the existing or planned multispectral systems are good for the detection of sludge. The difficulty in sludge detection will lie, not with the spectral characteristics, but with spatial resolution and radiometric sensitivity. Like the acid waste and most other regulated ocean-dumped materials, the sludge actually covers an area of less than 25 km^2 even when the dumpsites are considerably larger. The resolution of the CZCS (800m) is such that only about 50-70 pixels will cover areas with any sludge in it, and most of those pixels will view water predominantly; a line dump is often less than a kilometer wide. As can be seen from Figure 17, the spectral signature of the sludge from aircraft data in which the pixels are entirely within the boundaries of the plume, rapidly approach the background water signature. Such a low background signature would be effectively lost if averaged with the background water signature. The Landsat resolution is far better for observation of "line" dumps; unfortunately, the Landsat radiometric sensitivity is not. The TM is the best compromise available. The TM has both improved spatial resolution and radiometric sensitivity over the Landsat MSS.

4.2 General monitoring

In Section II of this report several broad criteria were described which will define the role of satellite systems in the monitoring of coastal water properties. Using these criteria several categories of environmental monitoring were discussed. We will now review these categories in reference to the use of satellite remote sensing in the 1980's.

1) <u>Fast response operations</u>: Satellite systems will not generally be appropriate for this type of monitoring during the 1980's. The coverage frequency of satellite systems, especially those with higher resolution is rather poor. For instance, the coverage frequency for the Landsat MSS (80 m resolution) is 18 days. As the spatial resolution is degraded the swath width of the sensor can be increased. The CZCS, with 800 m resolution, will provide once daily coverage in the visible region. One answer to the problem of coverage frequency is built into the design of the proposed Multispectral Resource Sampler (MRS). This sensor may be pointed in both the along track and cross track directions allowing frequent observations of a particular target area at high resolution (15 m).

Another factor that is crucial to fast-response operations is real-time or near real-time availability of data. With the exception of thermal imagery and the accompanying visible, single-band imagery, no satellite data is presently available in anything approaching real-time. Landsat digital data is generally available to the general user in two to three months after the overpass. The lag time for CZCS data is about to 9-10 months although this should improve as the data processing procedures are finalized. The large lag times are not so much a fault in the system designs (both Landsat and the CZCS were experimental in nature and geared toward research rather than operational uses) as they are a problem in using the system for monitoring purposes. Rapid data availability is very important for monitoring purposes and efforts should be made to reduce the time delay in receiving data. Such efforts might include cost/benefit analyses of timely satellite data for a monitoring program and perhaps a pilot program to explore the problems involved in providing usable data rapidly. A program of this type is being proposed as part of the NOSS program.

As mentioned above, the one exception to the rule is thermal imagery from the NOAA satellites. The twice-daily imagery is routinely available several days after an overpass and can be made available on the same day. However, thermal imagery is something of a special case, i.e., it is single-band data which requires minimal processing and little or no enhancement to be put into a usable form. The multispectral data which could be used for environmental monitoring may require far more processing before it is in a usable form. For instance, producing chlorophyll distribution maps from CZCS data requires that the data first be corrected to remove atmospheric effects before the chlorophyll algorithms can be applied.

2) Long-term monitoring: Satellite systems are particularly well-suited to observations of large regions and for repetitive coverage over long time periods. Thus satellite observations could be extremely valuable to monitoring programs for which the goal is observation of long term changes in environmental parameters. The utility of a particular sensor for a specific monitoring task will depend heavily on the sensor characteristics and the orbital characteristics of the parent satellite.

3) Enforcement monitoring: One of the advantages of satellite remote sensing is that data is collected routinely and periodically. For enforcement purposes this means that, if a pollution event or its effects are detectable from satellite, data will be available before, after and perhaps even during the pollution event.

4) Historical data acquisition: Again, since satellite data is collected routinely and periodically, it can provide an excellent source for observation of long-term changes.

V. Conclusions

1) The satellites which will be available during the 1980's will not be ideal for water quality assessment or pollution monitoring in the near coastal waters where pollution and environmental changes may have the most obvious impact. These are areas in which small scale changes can be quite important. Unfortunately, systems having the best spatial resolution (MSS, TM, MRS) have poor spectral characteristics and the systems with the best spectral characteristics for water color observations (CZCS) have poor spatial resolution. Nonetheless, the systems having sufficient spatial resolution will provide valuable information for environmental monitoring particularly in the role of spatial extrapolation of surface measurements.

2) The CZCS is uniquely appropriate to the observation of water color. Although the spectral response was designed specifically for chlorophyll detection, the spectral bands should be adequate for many other uses. The CZCS will be primarily useful in offshore waters both because its relatively poor resolution (800 m) will not show adequate detail of very near-shore or estuarine phenomena and because the radiometric sensitivity is carefully tuned to the low radiance of offshore waters.

3) Satellite remote sensing should be an important part of most moderate or large scale monitoring programs. In most cases, if the spatial and temporal requirements of the program are compatible with the satellite data characteristics, the satellite data will be a valuable addition to the program:

a) The satellite imagery provides a synoptic view of large areas impossible to achieve by other means. Using this data a conventional data base may be greatly expanded and extrapolated spatially.

b) Satellite data can be used to provide a historical perspective on the environment. Even without simultaneous surface truth, satellite imagery can be used to develop a qualitative assessment of circulation patterns, shoreline changes, sediment distribution and surface temperature variations.

4) Much research remains to be done before satellite remote sensing data can be used to obtain quantitative results operationally. A solid groundwork has been laid by research in the use of Landsat MSS data and aircraft systems for water observations and in theoretical studies of the radiative transfer properties of the ocean and atmosphere. Research efforts in the early 1980's to demonstrate operational use of satellite data for quantitative observations could lead to operational systems in the mid to late 1980's. This is most likely to be the case with the CZCS scanner as applied to offshore monitoring of chlorophyll, and with the continually improving thermal data which will be available during the early 1980's.

5) More attention should be given to cost/benefit analysis of using satellite data especially in long-term operational monitoring efforts. A particular test project would have to be defined such as monitoring chlorophyll distributions using the CZCS and minimal surface truth compared to purely ship-based observations. While there is every reason to expect that the

remote observations would be cost effective, this has not been demonstrated by any careful study.

6) Efforts should be made to improve the time lag between a satellite overpass and the availability of the data. The proposed NOSS project (NOSS, 1979) includes real time data processing as a major part of the project. Such efforts should be undertaken since long lag times are a major drawback to the use of satellite data for operational monitoring.

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Appendix A

Landsat (formerly ERTS)

	Launch Date	End of Operation
Landsat 1	23 July 1972	January 1978
Landsat 2	22 January 1975	operational
Landsat 3	5 March 1978	operational
Landsat D	Late 1981	

Orbital Elements

Orbit:	Circular
Altitude:	919 km (570 mi.)
Inclination:	99° (near polar)
Period:	103 minutes
Coverage:	∿ 82° N-S
Cycle:	18 days

Sensors

Landsat 1 & 2:

	Wavelength (μm)	Pixel Size	Resolution	Image Format
3 Return Beam Vidicon Cameras (used only occasionally)				185 x 185 km scenes
Band 1	0.475-0.575			10% sidelap at
Band 2	0.580-0.680	57 x 79 m	80 m	Equator
Band 3	0.690-0.830			10% forward lap
Multispectral				185 km strip image
Scanner				framed to match
Band 4	0.50-0.60			RBV scenes
Band 5	0.60-0.70	57 x 70 m	80 m	10% sidelap at
Band 6	0.70-0.80			Equator increasing
Band 7	0.80-1.1			toward poles

Appendix A (cont.)

Landsat 3:

	Wavelength (μm)	Resolution (m)	Swath Width (km)
2 Return Beam Vidicon Cameras	0.505-0.750	40	185
Multispectral Scanner System			
Band 4	0.50-0.60	80	185
Band 5	0.60-0.70	80	185
Band 6	0.70-0.80	80	185
Band 7	0.80-1.1	80	185
Band 8	10.5-12.5	240	185

Landsat D:

Orbit: Circular
Altitude: 705 km (440 mi.)
Cycle 16 days

	Wavelength (μm)	Resolution (m)	Swath Width (km)
Multispectral Scanner			
Band 4	0.50-0.60		
Band 5	0.60-0.70		
Band 6	0.70-0.80	80	185
Band 7	0.80-1.10		
Thematic Mapper			
Band 1	0.45-0.52	30	
Band 2	0.52-0.60	30	
Band 3	0.63-0.69	30	185
Band 4	0.76-0.90	30	
Band 5	1.55-1.75	30	
Band 6	10.40-12.50	120	
Band 7	2.08-2.35	120	

Appendix B

Nimbus

LAUNCH DATES: Nimbus 1-6: August 1964 to June 1975
Nimbus 1-3 no longer operating
Nimbus 4-6, one or more sensors still operating
Nimbus 7: 24 October 1978

ORBITS: Sun-synchronous, near polar
Altitude: Nimbus 1-6: 1100 km average — Period: 107 minutes
Nimbus 7: 955 km (600 mi.) — Coverage: Global, twice daily

SENSORS: Various meteorological and geophysical remote-sensing instruments and data transmission and processing techniques are tested on Nimbus

Nimbus-G

	Wavelength (μm)	Resolution (IFOV)	Swath Width	Measurement
Scanning Multifrequency Microwave Radiometer (SMMR)	System identical to Seasat SMMR will cover polar areas			
	6.6, 10.69, 18, 22.235, 37 GHz	25-125 km	650 km	high wind speeds and direction; vapor content and rain rate; sea surface temperature
Coastal Zone Color Scanner (CZCS)				
Channel 1	0.433-0.453			chlorophyll absorption
Channel 2	0.51-0.53			chlorophyll correlation
Channel 3	0.54-0.56	825 m	1800 km	gelbstoffe (yellow substance)
Channel 4	0.66-0.68			chlorophyll absorption
Channel 5	0.70-0.80			surface vegetation
Channel 6	10.5-12.5			surface temperature

Appendix C

Mulispectral Resource Sampler (MRS) [PROPOSED]

Launch Date: ∿ 1985

Orbit: ∿ sun-synchronous, polar orbit, similar to Landsat
May fly on Landsat D'

Sensors (tentative)

The MRS will use multiple linear arrays (no mechanical scanning). There will be a filter wheel for each of four sensor arrays. Each wheel will contain five filters, and each wheel can be indexed independently.

Filter Position	Array No. 1	2	3	4	Remarks
1	450-520 TM 1	520-600 TM 2	630-690 TM 3	760-900 TM 4	Thematic Mapper bands
2	540-560	670-690	710-730	780-800	Vegetation
3	840-860	880-900	730-750	400-420	Geol. Veg.
4	360-400	TM 3 Vert.	930-950	490-510	Atmos. Land Use Polar.
5	TM 4 Vert.	TM 4 Horz.	TM 2 Horz.	TM 3 Horz.	Polarize

IFOV: 15m or 30m

Swath width: 15 or 30 km

Pointing: $\pm$ 40° across track
$\pm$ 55° along track

Appendix D

National Oceanographic Satellite System (NOSS) [PROPOSED]

The characteristics of the NOSS sensors are far from being finalized. The system description presented here is meant only to illustrate the characteristics of the sensors being considered and should not be taken to be final.

Launch Date: Late 1984 or 1985 on Multimission Modular Spacecraft (MMS)

Orbit Characteristics:

Altitude:	600-900 km
Inclination:	85°-110°
Orbit:	circular, polar

Sensors

Coastal Zone Color Scanner (CZCS)

Option 1: identical to CZCS on Nimbus 7

Option 2: similar to CZCS but with three additional bands

Wavelength	IFOV (nadir)	Swath Width
.39-.41		
.43-.45		
.51-.53		
.55-.57	500-800 m	1000-1500 km
.63-.65		
.675-.695		
.740-.760		
.870-.890		

Option 3: Push broom scanner design with eight visible channels and four IR channels

IFOV ∿ 250-350 m
Swath 1000-1500 km

Scanning Multichannel Microwave Radiometer (SMMR)

Antenna Diameter:	2-4m
Frequencies (GH_z):	4.3 or 6.6
	10.65
	18.6
	21.3
	37
	91

Polarization: Dual
Resolution: 3 km to 50 km depending on antenna size and frequency.

Altimeter (ALT)

Four options have been proposed. The options range from a moderate improvement of the SEASAT instrument with greater redundancy and reliability, to multiple beam systems capable of measuring sea slopes.

Scatterometer (SCAT)

Again, various options have been suggested for the scatterometer. The NOSS requirements for wind speed and direction measurements are:

	Precision	Absolute Accuracy	Range	Frequency
Speed	0.5 m/s	2 m/s	0-50 m/s	12 hrs.
Direction	5°	10°	0°-360°	12 hrs.

Thermal Mapper

Wavelengths	Range
3.55-3.93 μm	240°-320°K
(8.0-9.0 μm) 10.3-11.3 μm 11.5-12.5 μm	175°-320°K

	High Res. Mode	Global Coverage Mode
Resolution	1 km	4 km
Swath Width	1500 km	500 km
Relative Accuracy	±0.5°C (±0.25°C)	±0.25°C
Absolute Accuracy	±2.0°C (±1.0°C)	±1.0°C

Appendix E: Thermal Sensors in Orbit

Satellite	Period of Operation	IFOV	Swathwidth
TIROS 1-10	April 1960 - June 1966	1 - 3.2km	120 - 1208km
ESSA 1,2	Feb 1966 - Oct 1970	1 - 3.2km	120 - 2108km
ESSA 3-9	Oct 1966 - Nov 1973	3.8 - 7.4km	3330km
NOAA (ITOS)	Jan 1970 - Present	1km	3400km
SMS/GOES	Oct 1975 - Present	8km	Whole earth
DMSP 50 series	Sept 1976 -	0.6 - 3.7km	2890km
LANDSAT C	March 1978 - Present	240km	185km
HCMM	April 1978 - Present	500m	700km
Seasat	July 1978 - Oct 1978	3-5km	1000km
Nimbus-7	Oct 1978 - Present	825m	1800km
TIROS N	Feb 1979 - Present	1-4km	

Appendix F: Microwave remote sensors in orbit (Cosmo and Meteor satellites were launched by U.S.S.R., all others by the U.S.) Adapted from Kritikos and Shiue (1979).

Type of Sensor	Host Satellite	Launch Year	Frequency GH_z	Goal
PASSIVE SENSORS				
Radiometer	COSMO 243	1968	3.5	Water (liquid and vapor); sea surface temperature;
Radiometer	COSMO 384	1970	8.8,33,37	sea ice
Radiometer	Nimbus 5	1971	19.35	Experimental weather satellite for rain rate and sea ice
Spectrometer	Nimbus 5	1972	50-60,22, 31	Measurement of atmospheric temperature profiles, water liquid and vapor, sea ice
Spectrometer	Nimbus 6	1975	50-60,22,31	Same as above
Radiometer	Skylab	1973	1.4	Measurement of soil moisture and seawater salinity
Radiometer	Skylab	1973	13.9	Sea surface wind speed; soil moisture
Radiometer	Meteor	1974	37	Liquid water, sea ice
Radiometer	Nimbus 6	1975	37	Same as Nimbus 5 radiometer
Spectrometer	Tiros-N	1978	50-60	Temperature Profile
Radiometer	SeaSat-A	1978	6.6,10.7 18, 21,37	Water liquid and vapor, rain rate, sea-surface temperature and wind, sea ice, snow, soil moisture
Spectrometer	Defense meteorological satellite	1979	50-60	Temperature profiles
ACTIVE SENSORS				
Scatterometer	Skylab	1973	13.9	Measurement of sea surface wind
Scatterometer	SeaSat-A	1978	14.6	Same as Skylab
Altimeter	SeaSat-A	1978	13.5	Measurement of average surface height of the ocean, sea-surface roughness
Synthetic-aperture radar	SeaSat-A	1978	1.27	Measurement of sea ice and ocean waves

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