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SECTION 9

RADIOMETRIC OCEAN COLOR SURVEYS THROUGH A SCATTERING ATMOSPHERE

by

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INTRODUCTION

The color of the ocean surface is strongly dependent upon the amount and type of material suspended in its top layers. Low altitude aircraft spectral reflectance measurements have shown that the color signature of water can be related to the concentration of chlorophyll in the top few meters of water. White in 1969 and Clarke, Ewing and Lorenzen in 1970 presented measurements of the spectral reflectance of the ocean surface for several different chlorophyll concentrations. Some of these spectral reflectance measurements together with a determination due to Ramsey (1968) for water with extremely low chlorophyll concentrations are presented in Figure 1. The measured data plotted here is surface level reflectance versus wavelength in nanometers. For each curve the chlorophyll concentration, in units of milligrams per cubic meter of water, is noted on the left hand portion of the diagram. It may be noted in this figure that as the chlorophyll concentrations increase the reflectance in the blue decreases and the reflectance in the green stays roughly constant. As a result of this change in reflectance with change in chlorophyll concentration, Clarke, Ewing and Lorenzen have suggested that two wavelengths will be an efficient measure of the chlorophyll concentration. The wavelengths suggested by these authors are 460 nanometers and 540 nanometers.

Dr. Hovis of our Laboratory has initiated a series of aircraft flights to measure the spectral reflectance of ocean waters containing various concentrations of chlorophyll. The first of these flights occurred during August 1971 and was made off Santa Catalina Island near southern California. During this set of measurements two distinct values of chlorophyll concentration were encountered. The color ratios and chlorophyll concentrations measured are shown in Figure 2. This figure shows the relationship between the color ratio and the chlorophyll concentration in millgrams per cubic meter. The low level aircraft measurements made off southern California are indicated by the circled-crosses. Previously existing data values are indicated by symbols corresponding to the previously mentioned reference. The general relationship between the two variables is indicated by the diagonal line. For low values of the chlorophyll concentration the correlation between color ratio and chlorophyll concentration is not satisfactory. However, it should be noted that some of this problem is related to the difficulty of measuring the low chlorophyll concentrations and also some of the difficulty can be attributed to the presence of other particulates suspended in the water. The increased turbidity of the water obscures the lower values of color ratio more easily. More measured data is required to define the relationship satisfactorily.

The data shown in this slide pertain to low altitude aircraft measurements and presumably should be free of the effects of atmospheric transmission losses. Because of the interest in observing the global distribution of the chlorophyll containing phytoplankton it is anticipated that scanning satellite borne radiometers will be used to collect data. To simulate the problems one may encounter in measuring ocean color from satellite altitudes further aircraft measurements have been made at higher altitudes.

Figure 3 gives a comparison between the nadir spectral radiance measured at very low and high altitudes. These measurements were made for a solar zenith angle of approximately 60 degrees. The high altitude measurement made at 14.9 kilometers has more than two thirds of the atmosphere below it. In general the radiance is much larger at the high altitude because very little of the incident solar irradiance has been attenuated before reaching this level. In comparing the measurements made at two different altitudes, the enhanced atmospheric reflectance at the shorter wavelengths is very much in evidence. This wavelength dependent distortion of the surface level reflectance poses the problem of "how to correct for the light scattered in the atmosphere when observing the surface from satellite altitude?"

METHOD OF ANALYSIS

We have approached this problem by modelling the radiative transfer properties of the atmosphere. Figure 4 gives a schematic representation of the various transfer processes which occur. The incident solar irradiance may either be scattered in the atmosphere and returned to space or be transmitted to the air-water interface and then be reflected, or finally be transmitted through the interface and then be scattered back by the phytoplankton and particulates which are suspended in the water. It is the radiation which suffers this latter process which contains the spectral information as to the presence of chlorophyll. Because of the high probability of light being scattered or reflected before reaching the turbid water, and also because of the probability of being reflected or scattered before the satellite radiometer; a very small fraction of the incident solar radiation accomplishes this latter process.

We have used a numerical model for the transfer of radiation through a mixed molecular-aerosol atmosphere. The molecular and particulate scatterers in this model are distributed with altitude according to a climatological mean model. The scattering properties of these particulates are further made to correspond to nature. The results of a large number of calculations were parameterized in order to be easily usable for predicting the effects of viewing ocean color through the earth's atmosphere. It was found that the most useful parameter to use in defining the optical state of the atmosphere for a given wavelength and given solar zenith angle, was the aerosol optical depth of the atmosphere. This quantity is directly related to the total number of aerosol particles in a verticle column of atmosphere.

Figure 5 demonstrates the dependence of the reflectance of the atmosphere only on the aerosol optical depth. The two wavelengths chosen further demonstrate the contribution due to the molecular constituents. For aerosol optical depth equal to zero the reflectance is due only to the molecular atmosphere and since the molecular optical depth of the atmosphere is greater for shorter wavelengths shown. As the aerosol optical depth increases in both cases the reflectance is seen to increase.

RESULTS AND CONCLUSIONS

Naturally occurring aerosol optical depths most frequently equal 0.1 or 0.2. For the reflectances given in this graph it is seen that the color ratio for the atmosphere only, is in the interval 0.4 to 0.6 for naturally occurring aerosol optical depths. The radiation returning from the ocean surface level is attenuated before reaching a satellite borne detector. As a result of this attenuation and further because the reflectance of the ocean surface level is a fraction of the atmospheric reflection, the color ratio calculated for the ocean-atmosphere system are only slightly modified by the surface reflectance. Putting this simply the surface level color ratio is obscured by the atmosphere and forced to be closer to the value of the atmosphere alone when observed at satellite altitudes.

This effect is graphically displayed in Figure 6 where the color ratio at the top of the atmosphere is related to the color ratio at the surface by a family of intersecting lines. Each line corresponds to a different aerosol optical depth extending from a pure molecular atmosphere to an optically dense atmosphere as noted by the values for the aerosol optical depth written along the left-hand margin of the graph. If one knows the optical depth of the atmosphere at the time of a satellite measurement then using a family of curves such as these, one could relate the color ratio at the top of the atmosphere to that at the surface level. Thus, a measurement of the color ratio at the top of the atmosphere can be related to the chlorophyll concentration of the ocean water.

A comparison of the theoretical calculations and the measured data from Santa Catalina Island is given in the table of Figure 7. After correcting for ozone absorption it is seen that the measured and predicted intensities are in close agreement. To improve the quality of the models and to gather more data to support the correlation between surface level color ratio and chlorophyll concentration, several further flights are anticipated for measuring ocean color.

The results of both the experimental and theoretical investigations made to date indicate that satellite borne radiometers can sense ocean color. However, the accuracy to which the chlorophyll concentration can be measured appears to be 0.1 to 0.4 mg/m^3 depending upon solar zenith angles. These accuracies are less than desired by many of the oceanographers and presently an effort is being made to improve the quality of the chlorophyll concentration determination.

To alleviate the lack of data further ocean color measurements are planned in June 1972. These measurements will include locations with higher chlorophyll concentration in order to better understand the relationship between chlorophyll concentration and ocean color. Also the effects of high water turbidity will be investigated.

REFERENCES

Clarke, G. L., Ewing, G. C., Lorenzen, C. J., 1970: Spectra of Backscattered Light From the Sea Obtained From Aircraft as a Measure of Chlorophyll Concentration. Science, 167, 1119 - 1121.

Ramsey, R. C., 1968: Study of the Remote Measurement of Ocean Color. Final Report. TRW, NASW-1658, 89 pp.

White, P. G., 1969: Experimental Results of the Remote Measurement of Ocean Color. Second Annual Earth Resources Aircraft Program Status Review, Sept. 16-18, 1969. NASA Manned Spacecraft Center, 3, Sec. 50, 1 - 9.

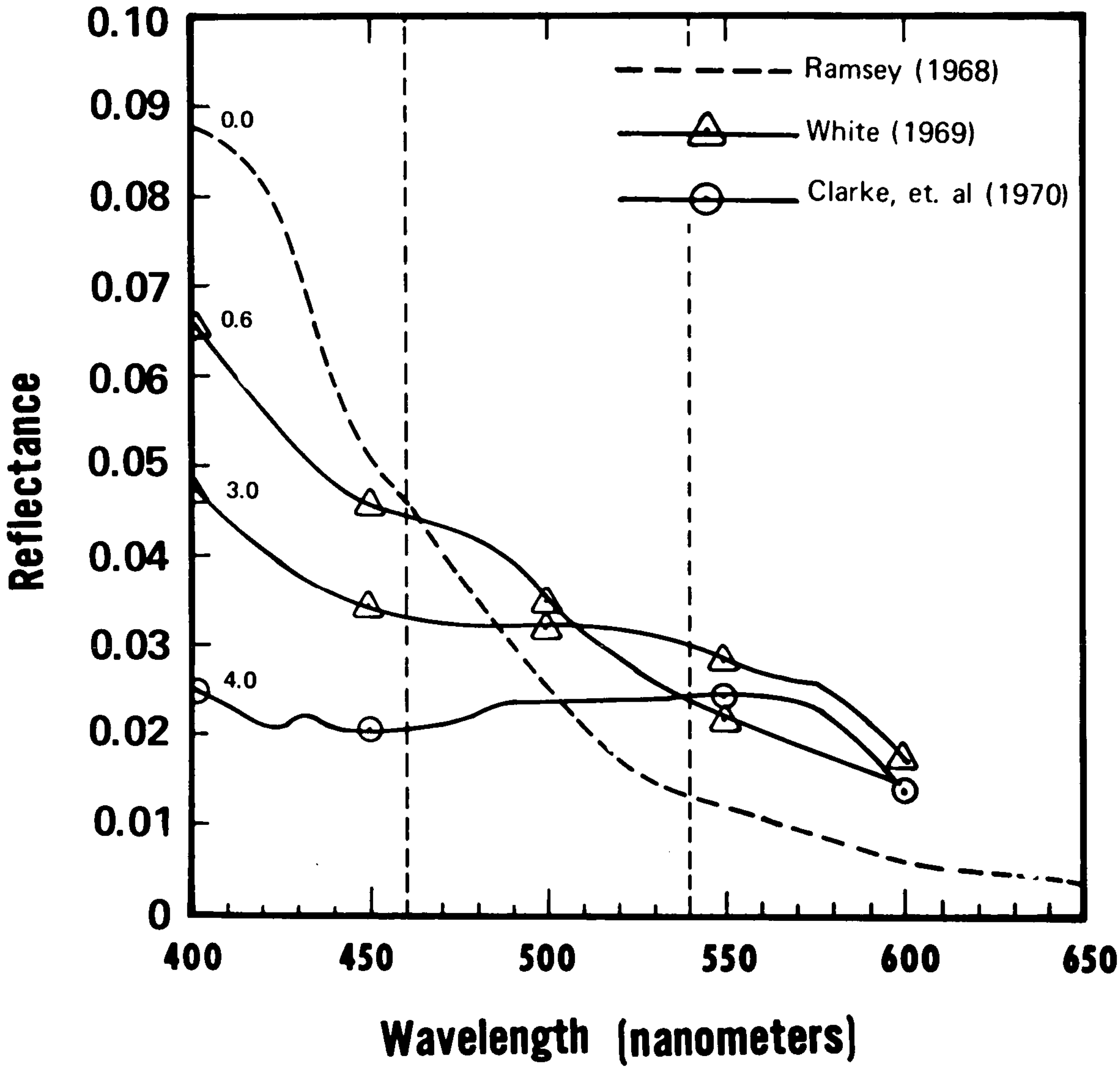


Figure 1 - Ocean reflectance as a function of wavelength. The measured chlorophyll concentrations in units of milligrams per cubic meter are noted in the left hand column of the figure.

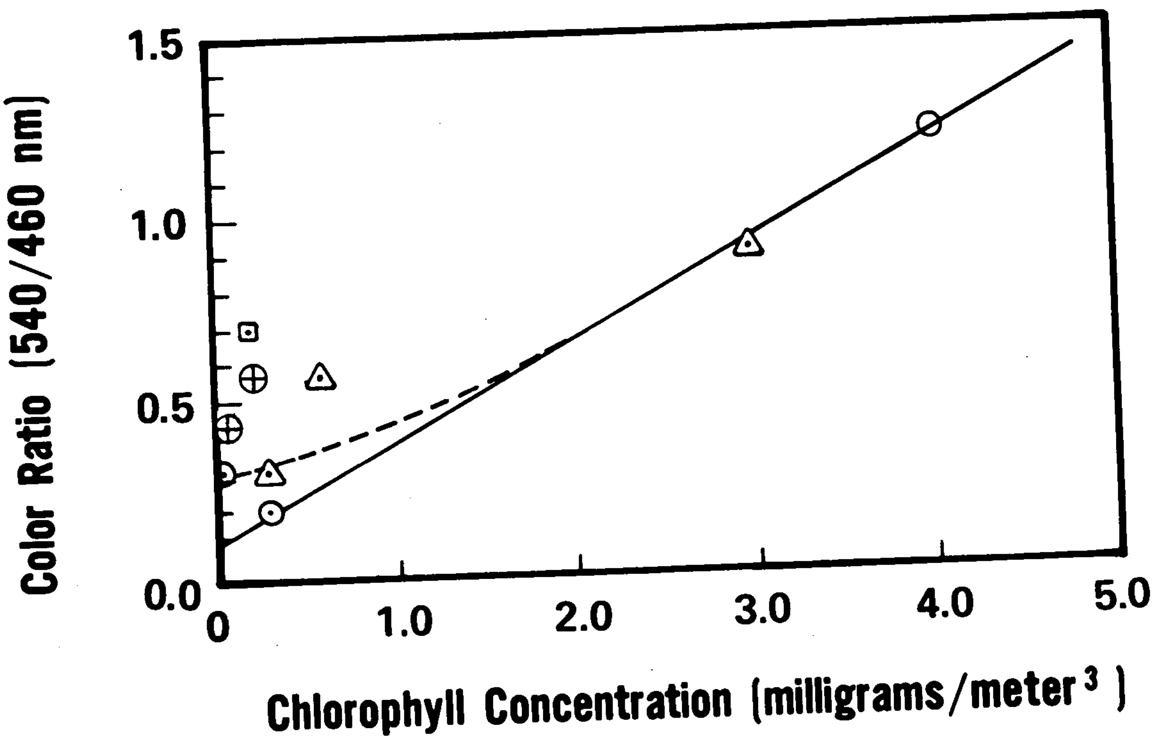


Figure 2 - Measured values of ocean color ratio for several values of chlorophyll concentration. The diagonal line represents a linear approximation to the data and the dashed line has the intercept value as given by Ramsey (1968).

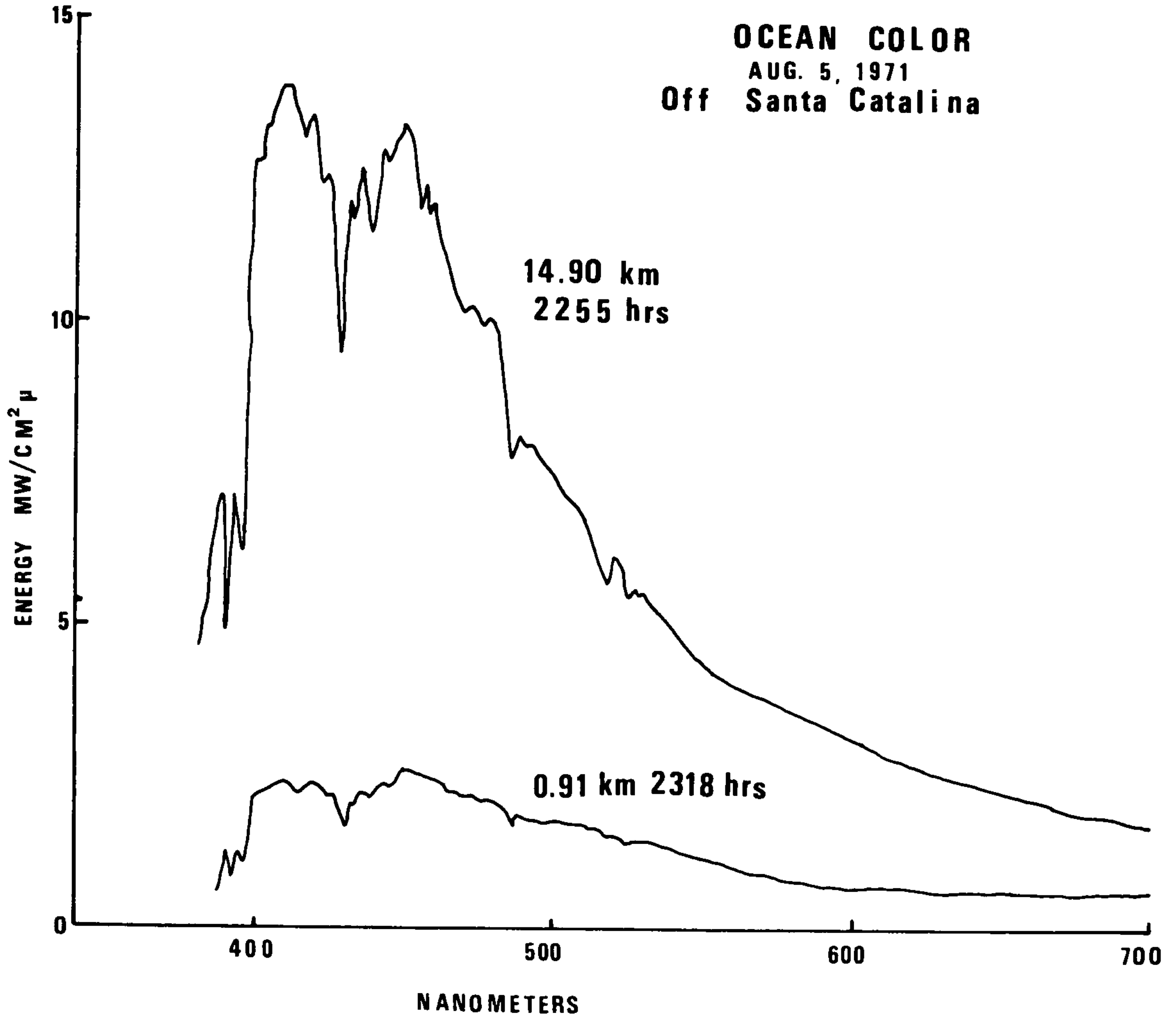
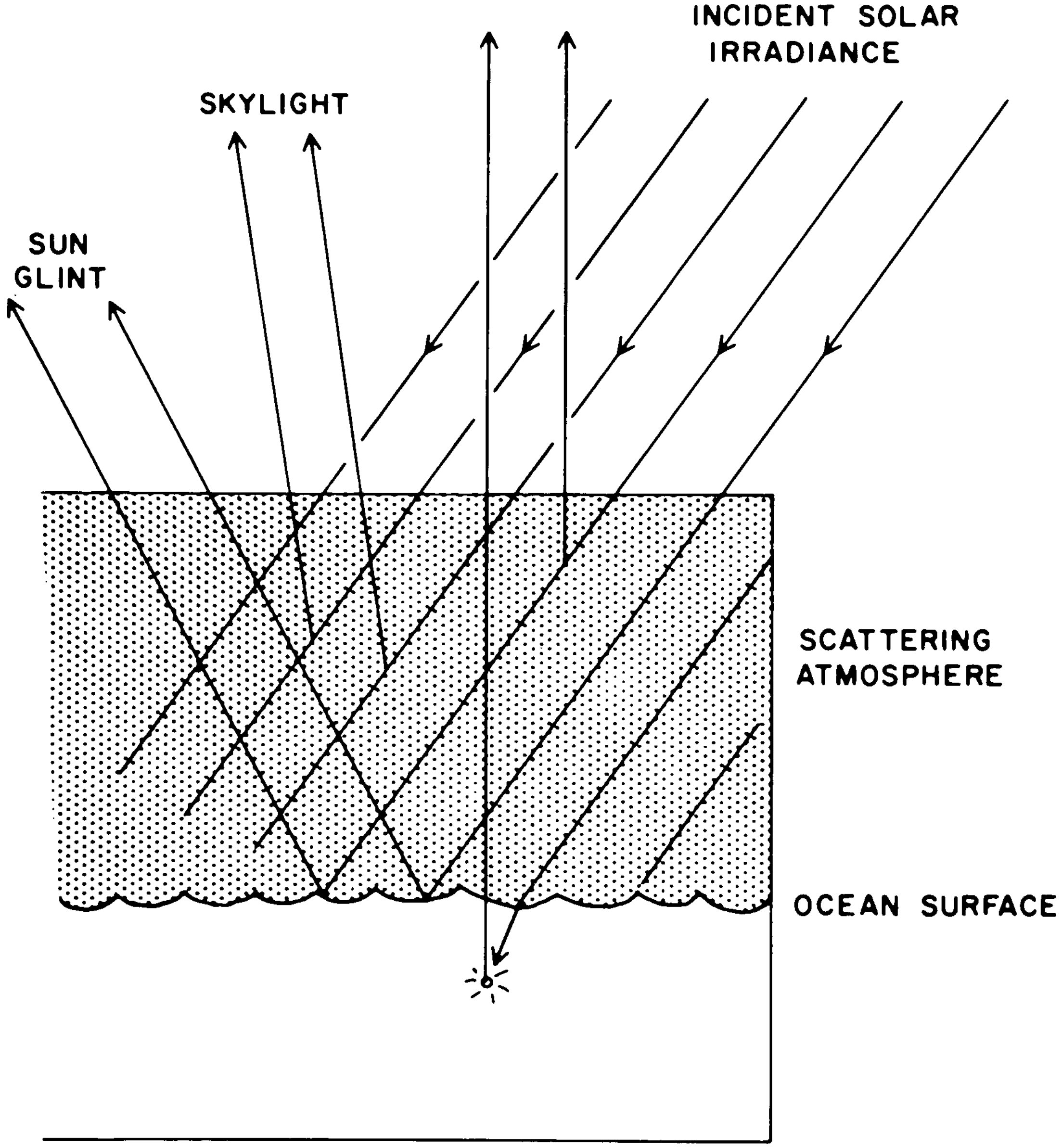


Figure 3 - Comparison between nadir spectral radiance measured at very low and high altitudes.



ATMOSPHERE - OCEAN RADIATION TRANSFER MODEL

Figure 4 - Schematic representation of the various transfer processes which occur in the atmosphere-ocean system.

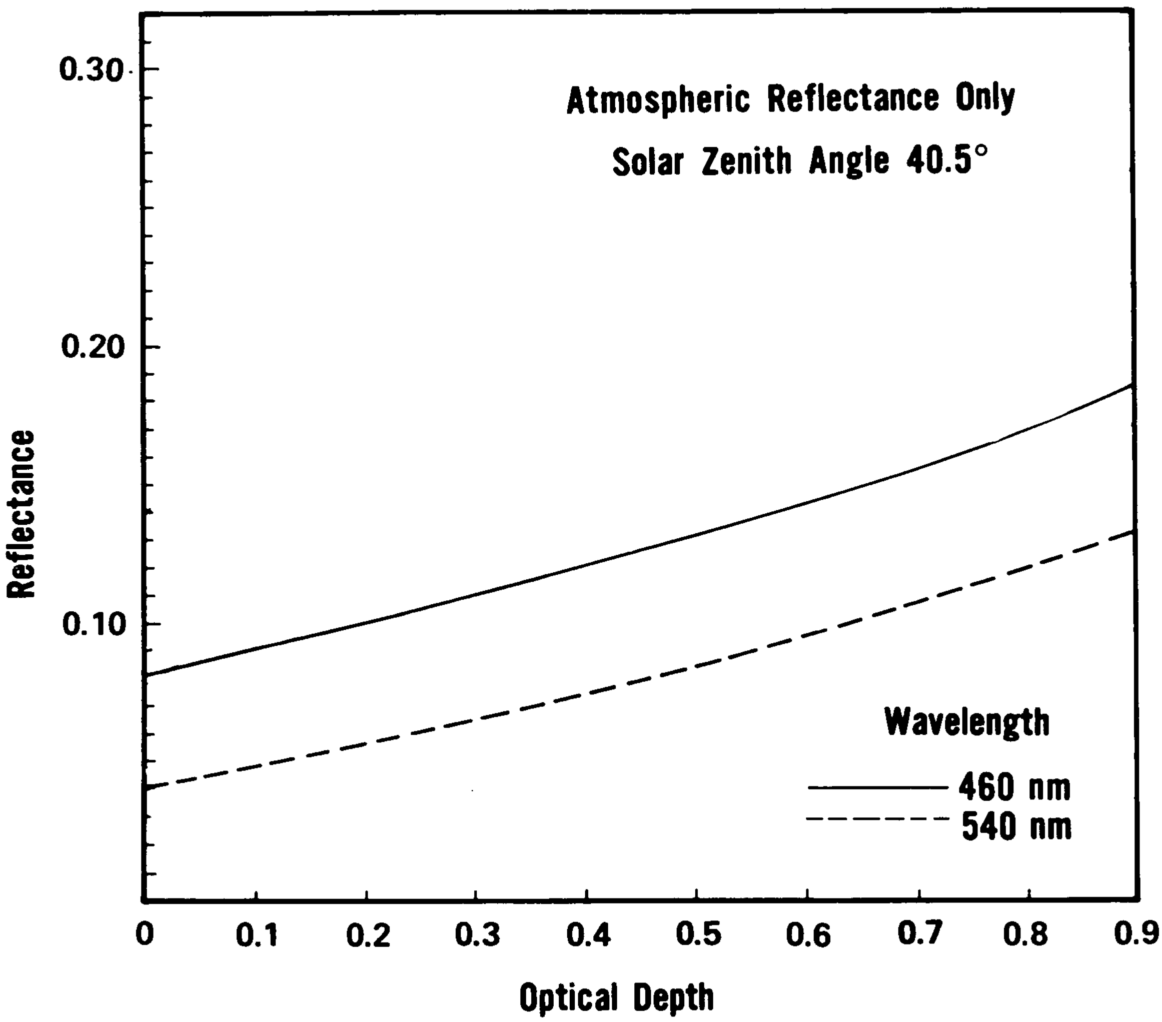


Figure 5 - Reflectance of the atmosphere as a function of optical depth.

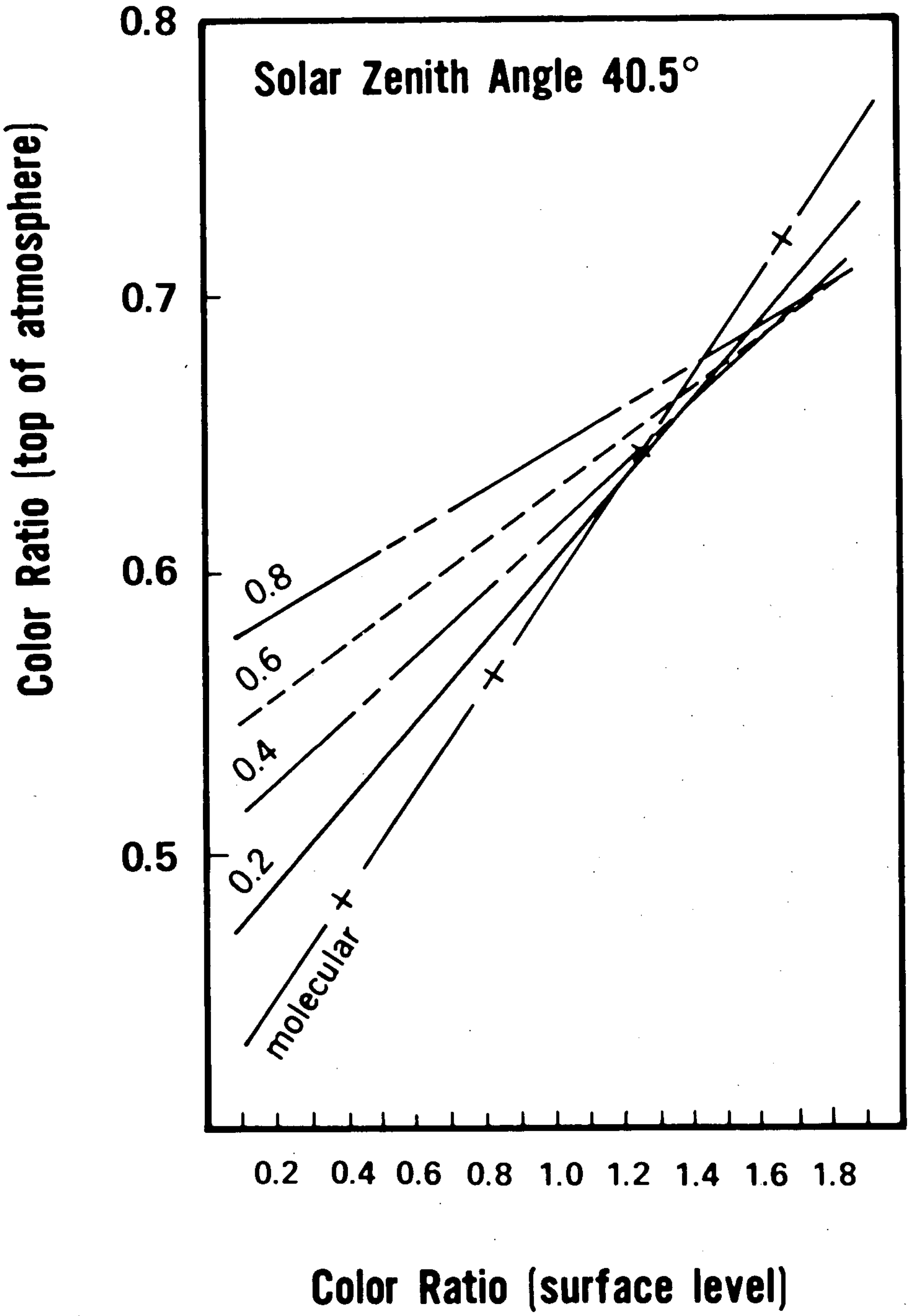


Figure 6 - Relationship between the color ratio as predicted for the top of the atmosphere and the color ratio at the surface level. The optical depth of the atmosphere is noted in the left hand column of the figure.

COMPARISON OF THEORETICAL AND EXPERIMENTAL VALUES OF OCEAN COLOR

	[CHLOROPHYLL] < 0.01mg/m^3		[CHLOROPHYLL] = 0.23 mg/m^3	
WAVELENGTH	460nm	540nm	460nm	540 nm
REFLECTANCE [SURFACE]	0.0218	0.00914	0.0180	0.0101
I [THEOR.] ★	3.90	1.68	3.83	1.69
I [MEAS.] ★	3.88	1.56	3.77	1.52
% DIFFERENCE	0.513	7.50	1.58	11.22
COLOR RATIO[SURFACE]	0.419		0.562	
COLOR RATIO TOP [MEAS.]	0.439		0.440	
COLOR RATIO TOP [THEOR.]	0.453		0.466	

★ Units of radiance are given in mw/cm2, ster., μm and are evaluated for 14.9 meters altitude.

Figure 7 - Comparison of measured and calculated values.