GEOPHYSICAL RESEARCH LETTERS, VOL. 9, NO. 6, PAGES 719-722, JUNE 1982

SEA FOAM REFLECTANCE AND INFLUENCE ON OPTIMUM WAVELENGTH FOR REMOTE SENSING OF OCEAN AEROSOLS

Charles H. Whitlock
David S. Bartlett
Ernest A. Gurganus

NASA Langley Research Center, Hampton, Virginia 23665

Abstract. According to previous investigations, sea foam is a major variable in the accurate determination of aerosol turbidity over the oceans with remote-sensing systems. As a result, tests have been conducted to measure sea foam reflectance at wavelengths from 0.55 μm to 2.8 μm. Data from the tests offer an improved knowledge of the effects of sea foam on radiation upwelled from the ocean surface at near-infrared wavelengths. Application of the new data suggests potential for a 40 percent improvement in signal to noise characteristics of aerosol measurements over the oceans if a 1.56 μm waveband is used instead of 0.75 μm.

Introduction

Several investigators have considered the potential for remote sensing of aerosol optical depth over the ocean. Most studies have focused on use of either Landsat (Griggs, 1975 and 1977) or SMS/GOES (Griggs, 1979; Koepke and Quenzel, 1979; and Norton et al., 1980) data at wavelengths below 1 μm.

Most recently, Koepke and Quenzel, 1981, have extended their studies to near-infrared wavelengths as high as the 1.6 μm atmospheric window. In a parametric study it was found that the parameter with the greatest influence on results at near-infrared wavelengths above 1.05 μm was the wind-roughened ocean surface (Koepke and Quenzel, 1981). As wind speeds were varied from 1.4 m/s to 7 m/s, sea foam coverage of the surface was assumed to range from zero to one percent. Individual foam patch reflectance of 50 percent was taken from Payne, 1972, and was assumed to be constant at all wavelengths (Quenzel, 1982). This latter assumption was made because no data have been published on the optical properties of individual white caps (Gordon and Jacobs, 1977). Koepke and Quenzel, 1981, concluded that the optimum wavelengths for monitoring aerosol turbidity over oceans were 0.75 μm and 0.87 μm.

After considering the importance of Koepke and Quenzel's results to the selection of wavebands for future remote sensing systems, it was decided that an experimental measurement of the spectral dependence of foam patch reflectance should be conducted to verify their reflectance assumption. It was known that the absorption coefficient of water increases from 1 m^{-1} to 8000 m^{-1} as wavelength ranges from 0.7 μm to 1.8 μm (Curcio and Petty, 1951). It was unknown whether such a large change in absorption of the liquid medium would have a corresponding influence on reflectance of foam generated from that medium. This article presents results of laboratory observations of foam patch reflectance at wavelengths from 0.55 μm to 2.8 μm. The data are then applied to the methodology of Koepke and Quenzel, 1981, in an effort to re-examine the potential for remote sensing of aerosol turbidity over oceans at near-infrared wavelengths.

Experimental Technique

A sketch of the laboratory setup is shown in figure 1. The solar simulator (Spectrolab Model X-25) consists of a 2.5-kW xenon short-arc lamp and optical lens-filter system which produces a near-parallel (±2.5°) beam radiation spectrum. The light beam was directed through a first-surface mirror to the water surface in a 260 liter tank. A spot of 0.3 m diameter was illuminated with an intensity of approximately 60 percent (6000 ft candles) of clear sky Earth surface conditions.

Water inside the tank was stirred vigorously to produce an intense whirlpool with a surface slope of approximately 20°. As high pressure air was added to the water, bubbles formed on the slope and slid down to the center of the whirlpool. The base water for all tests was filtered-deionized tap water to which a very small amount of clear detergent had been added to reduce surface tension. By varying the amount of air and speed of the electric motor, steady-state foam patches could be obtained which covered the total 0.3 m diameter illuminated surface. Careful adjustment allowed foam thickness to be varied from one bubble layer (with background water visible in centers of bubbles) to multiple layers 0.1 m thick. Reflection from the tank bottom was not considered a factor because the absorption coefficient of water above 0.7 μm causes remote-sensing penetration depth to be less than the 0.7 m water depth of these tests. Remote-sensing penetration depth is less than the inverse of absorption coefficient (Gordon and McCluney, 1975). Single bubble-layer measurements were made at wavelengths above 0.7 μm, and all multiple-layer measurements were made with thickness of foam such that no background water nor bottom effects were evident even at visible wavelengths.

Radiance from the center of the foam patch was measured using two instruments. An Exotech model 100-AX radiometer was used to collect data in the following four bands:

Channel	Bandpass - μm
1	0.498 - 0.596
2	0.580 - 0.706
3	0.687 - 0.819
4	0.767 - 0.974

Paper number 2L0694.

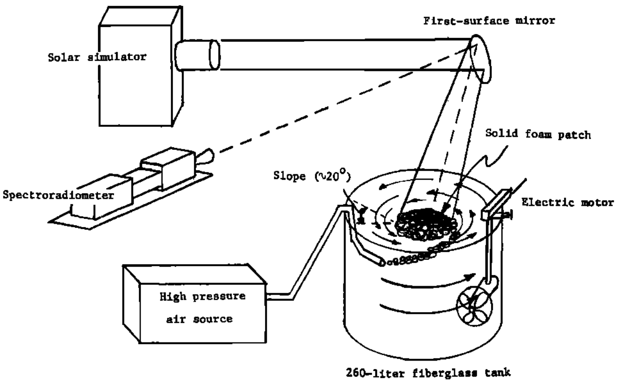


Fig. 1. Sketch of laboratory set-up.

An EG&G model 585 spectroradiometer system was used for measurements from 0.7 μm to 2.8 μm. Data were obtained at intervals of 0.1 μm over the range, and each reading had a spectral bandpass of 0.2 μm. Wide spectral resolutions were used because most satellite systems have bandwidths around 0.2 μm in the near-infrared. Following measurements of the foam, a near-Lambertian barium sulfate (EASTMAN 6080 paint) reference surface was held horizontal just above the water surface and radiance values were recorded. This standard reference surface is considered to have 94 to 99 percent reflectance at wavelengths from 0.35 μm to 2.0 μm (Frei and MacNeil, 1973). All foam patch reflectance values in this report are given as a percentage of the barium sulfate surface radiance.

Measurements were made over foam patches generated from a variety of water mixtures. Turbidity was increased from that of the baseline water by adding various amounts of inorganic sediments and dissolved humic material. Calvert soil which is composed of 50 percent clays (kaolinite and illite) and 50 percent quartz (Brice and Clement, 1981) was used as the inorganic sediment. Commercially available humic acid (Aldrich HI, 675-2) was used to produce high levels of Dissolved Organic Carbon (DOC). Table 1 gives Total Suspended Solids (TSS), Particulate Organic Carbon (POC) and DOC values for the eight mixtures which were tested. Sample 12143 is the baseline mixture which was the clearest water (and brightest foam) tested. Sample 12141 had low sediment concentration and high humic DOC giving a color similar to Baltic (Jerlov, 1968) and swamp runoff waters. Other mixtures were various combinations which might be typical of heavy spring runoff in various parts of the world.

TABLE 1. Chemical Analysis of Water Samples

Sample	TSS mg/l	DOC mg/l	POC mg/l	Appearance
12110	1	3	<1	Clear
12111	5	3	<1	Low sediment
12112	47	3	<1	High sediment
12113	445	4	1	Very high sediment
12114	2008	5	5	Very high sediment
12141	2	8	<1	Dark Humic solution
12142	1156	8	6	Dark, very high sediment
12143	1	6	<1	Very clear

Results and Discussion

Foam Reflectance

Reflectance values obtained for the various foam mixtures are shown in figure 2(a). Figure 2(b) gives absorption coefficient values for clear water obtained from Smith and Baker, 1981 (0.4 μm to 0.7 μm) and Curcio and Petty, 1951 (0.8 μm to 2.4 μm). Absorption data from the references were averaged such that figure 2(b) values have spectral resolutions as follows:

Wavelength-μm	Spectral Resolution-μm
0.4 - 0.7	0.1
0.8 - 2.4	0.2

These resolutions are necessary if a comparison between the foam reflectance and water absorption is to be made.

Reflectance values near 50 percent were obtained at visible wavelengths as would be expected from Payne, 1972. Foam reflectance was not independent of wavelength as has been assumed by previous investigators, however. At wavelengths above 0.9 μm, reflectance decreased rapidly. Reflectance minima at 1.5 μm and 1.9 μm correspond to peaks in the absorption coefficient for clean water. Thickness of the foam is also a factor. As described earlier, the multiple-layer data were obtained with foam thickness greater than 0.1 m such that no background water was visible. When in a single layer, background water is visible at the center of each bubble. Sample 12143 was the clearest water of these tests and produced the highest reflectance of the multilayer tests. Single-layer reflectance for that same water was approxiately 20 percent of multilayer values (fig. 2(a)).

If it is assumed that low-level contaminants have little effect on water absorption values at near-infrared wavelengths greater than 0.8 μm, then foam reflectance of sample 12143 may be correlated with the absorption of clear water. Performing least-squares correlation for exponential, geometric, linear, and polynomial types of mathematical functions, a number of relations were found in which the correlation coefficient exceeded 0.9. Maximum correlation was obtained with the following polynomial:

$$Y = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4 \qquad (1)$$

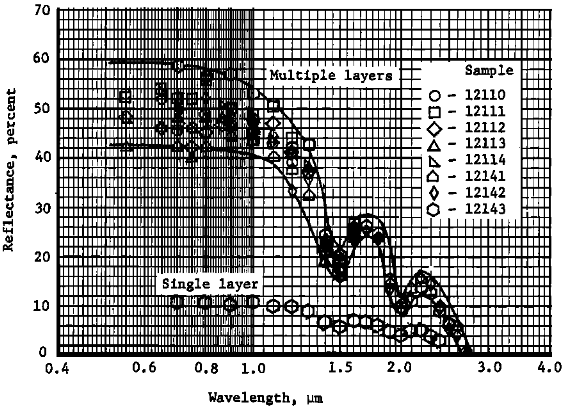
where:
Y = multilayer foam reflectance in percent.
$X = |\ell n\ (a)|$ where a = absorption coefficient in m^{-1}.
a_0 = 60.063.
a_1 = -5.127.
a_2 = 2.799.
a_3 = -0.713.
a_4 = 0.044.

Equation (1) had correlation coefficient equal to 0.979 and standard error equal to 4.36. If equation (1) is examined, it can be observed that as absorption coefficient, a, increases from 0.1 m^{-1} to 5500 m^{-1}, foam reflectance, Y, decreases from 60 percent to 10 percent in a consistent manner. Thus, equation (1) forecasts lower reflectance for turbid waters at visible wavelengths where dissolved and particulate constituents are known to increase absorption above that of pure water. In general, the more turbid mixtures (samples 12113, 12114, 12141, and 12142) had lowest foam reflectances agreeing with trends forecasted by the empirical relation.

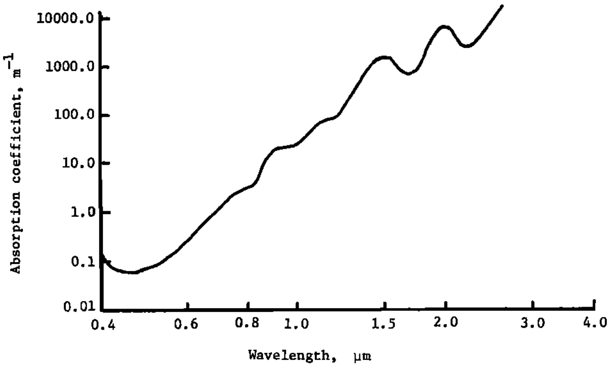
Unfortunately, polynomial-type regression equations usually give few clues to actual physical relationships of the parameters being correlated. The fact that such a strong relation can be obtained, however, certainly suggests that the wavelength dependency of absorption in pure water strongly impacts measured reflectance of foam. We conclude that the large decrease in foam patch reflectance at wavelengths above 1.0 µm is caused by the large increase in absorption of the liquid water. More complex experiments are required to determine a precise theoretical relation between foam patch reflectance and mixture absorption coefficient.

Aerosol Signal to Noise

Of primary concern is the effect of variable foam patch reflectance on the remote sensing of aerosols over the ocean. Therefore, a revision of the Koepke and Quenzel, 1981, study has been attempted using the new foam reflectance data presented here. A first-order approximation of the ratio of aerosol signal to environmental noise can be made because of the completeness and excellent nondimensional manner in which their data were presented. This calculation is described in the following paragraphs.



(a) Reflectance of foam patches.



(b) Absorption coefficient of clear water.

Fig. 2. Reflectance and absorption characteristics.

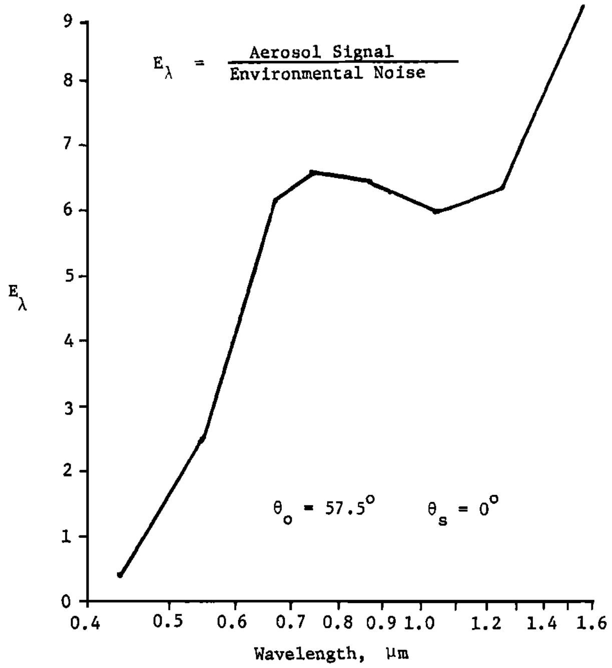


Fig. 3. Ratio of aerosol signal to environmental noise.

The aerosol signal to noise ratio (aerosol signal to perturbing parameters signal) is defined by Koepke and Quenzel, 1981, as:

$$E_\lambda = D_{\lambda turb}/(\sum_i D^2_{\lambda i})^{1/2} \qquad (2)$$

where:

$D_{\lambda turb}$ = deviation in top of atmosphere upwelled radiance about mean maritime atmosphere as a result of typical variations in aerosol optical depth.

$D_{\lambda i}$ = deviation in top of atmosphere upwelled radiance about mean maritime atmosphere as a result of ith perturbation parameter.

Parameters varied in their analysis consisted of aerosol optical depth, aerosol type, aerosol absorption, vertical aerosol distribution, particle shape, ozone concentration, sea level pressure, extraterrestrial Sun intensity, underwater reflectance, and rough ocean reflectance. As discussed previously, Koepke and Quenzel, 1981, note that the dominant factor in the deviation caused by a rough ocean ($D_{\lambda OC}$) was variation in sea foam between 0 and 1 percent surface coverage. Values for $D_{\lambda OC}$ are given at all wavelengths based on 0.5 foam patch reflectance. For this study, it was assumed that $D_{\lambda OC}$ could be revised by:

$$[D_{\lambda OC}]_{new} = [D_{\lambda OC}]_{old} \frac{[\text{foam reflectance}]_{new}}{0.50}$$

No revisions were considered necessary for values at wavelengths between 0.44 μm and 0.87 μm as the 0.5 reflectance value appears reasonable in this range. Reflectance values of 0.46, 0.37, and 0.21 were assumed (from figure 2(a)) at 1.05 μm, 1.24 μm, and 1.56 μm in wavelength, respectively. Values for all $D_{\lambda i}$ were read from figure 1 of Koepke and Quenzel, 1981, and equation (2) was used to calculate E_λ by substituting new $D_{\lambda OC}$ values in place of original quantities at 1.05 μm, and 1.24 μm, and 1.56 μm. Values from this calculation are shown in figure 3 for a satellite looking nadir ($\theta_s = 0^o$) with the solar-zenith angle (θ_0) equal 57.5°. Results are significant in that the ratio of aerosol signal to environmental noise is highest at 1.56 μm, representing a 40 percent improvement over values at 0.75 μm. While these calculations are based on a single experiment, the potential for such a large improvement should be further investigated. Radiative transfer calculations for various Sun and satellite geometries should be obtained. A more detailed investigation of near-infrared sea foam reflectance as a function of windspeed following concepts of Austin and Moran, 1974, would yield benefits to many Earth radiation studies. An indepth analysis of instrument signal and noise requirements is also a critical factor. Special designs with unusual dynamic range characteristics may be required to obtain highly accurate aerosol optical depth values over the oceans.

References

Austin, R. W. and Moran, A., Reflectance of Whitecaps, Foam, and Spray. Ocean Color Analysis, Scripps Institution of Oceanography, Ref. 74-10, (NTIS AD-783101), 1974.

Brice, K. L. and Clement, S. C., Mineralogical, Optical, Geochemical and Particle Size Properties of Four Sediment Samples for Optical Physics Research, NASA CR 165663 (NTIS N81-19650), 1981.

Curcio, J. A. and Petty, C. C., The Near Infrared Absorption Spectrum of Liquid Water. Journal of the Optical Society of America, Vol. 41, pp. 302-304, 1951.

Frei, R. W. and MacNeil, J. D., Diffuse Reflectance Spectroscopy in Environmental Problem Solving. CRC Press, pp. 28, 1973.

Gordon, H. R. and McCluney, W. R., Estimation of the Depth of Sunlight Penetration in the Sea for Remote Sensing. Applied Optics, Vol. 14, pp. 413-416, 1975.

Gordon, H. R. and Jacobs, M. M., Albedo of the Ocean-Atmosphere System: Influence of Sea Foam. Applied Optics, Vol. 16, pp. 2257-2260, 1977.

Griggs, M., Measurements of Atmospheric Aerosol Optical Thickness over Water Using ERTS-1 Data. Journal of the Air Pollution Control Association, Vol. 25, pp. 622-626, 1975.

Griggs, M., Comment on "Relative Atmospheric Aerosol Content from ERTS Observations" by Yu Meklev, H. Quenzel, G. Ohring, and I. Marcus. Journal of Geophysical Research, Vol. 82, p. 4972, 1977.

Griggs, M., Satellite Observations of Atmospheric Aerosols During the EOMET Cruise. Journal of the Atmospheric Sciences, Vol. 36, pp. 695-698, 1979.

Jerlov, N. G., Optical Oceanography, Elsevier Publishing Co., New York, pp. 164, 1968.

Koepke, P. and Quenzel, H., Turbidity of the Atmosphere Determined From Satellite: Calculation of Optimum Viewing Geometry. Journal of Geophysical Research, Vol. 84, pp. 7847-7856, 1979.

Koepke, P. and Quenzel, H., Turbidity of the Atmosphere Determined from Satellite: Calculation of Optimum Wavelength. Journal of Geophysical Research, Vol. 86, pp. 9801-9805, 1981.

Norton, C. C. et al., A Model for Calculating Desert Aerosol Turbidity over the Oceans from Geostationary Satellite Data. Journal of Applied Meteorology, Vol. 19, pp. 633-644, 1980.

Payne, R. E., Albedo of the Sea Surface. Journal of Atmospheric Physics. Vol. 29, pp. 959-970, 1972.

Quenzel, H., Personal Communication, January 5, 1982.

Smith, R. C. and Baker, K. S., Optical Properties of the Clearest Natural Waters (200-800 nm). Applied Optics, Vol. 20, pp. 177-184, 1981.

(Received February 24, 1982;
accepted April 15, 1982.)