

Polarization of light on reflection by some natural surfaces

HSI-SHU CHEN† and C. R. NAGARAJA RAO

Department of Meteorology, University of California, Los Angeles, U.S.A.

MS. received 19th May 1967, in revised form 26th February 1968

Abstract. The polarization features of light reflected by soil, desert sand, white sand and water under different conditions of illumination with natural (unpolarized) and linearly polarized light have been investigated in three narrow spectral intervals (bandwidth ~ 150 Å) centred on wavelengths 3975, 5000 and 6050 Å. A simple 'rotating-analyser' type photoelectric reflectometer was used in the measurements. The data were acquired in computer compatible format to facilitate Fourier analysis of the photosignal. The degree of polarization and relative intensity variations have been determined from a knowledge of the Fourier coefficients. The polarization of light reflected by soil, desert sand and white sand exhibits pronounced wavelength dependence. There is over-all similarity in the behaviour of soil and desert sand. White sand shows a strong tendency to behave like an ideal diffuser (Lambert surface). The hypothesis of scattering of light by an 'optically rough, locally smooth' surface has to be invoked to explain the reflection characteristics of an apparently smooth surface of water.

1. Introduction

The reflective properties to be associated with a planetary boundary play a decisive role in defining the polarization features of radiation emerging from the top of the planetary atmosphere, especially when observations are confined to spectral intervals over which the atmosphere can be considered fairly transparent. It is reasonable to suppose that most of the substances which may perhaps constitute planetary boundaries are 'optically rough'. However, rigorous quantitative theories which could explain the observed state of polarization of light reflected or scattered by 'optically rough' surfaces have not yet been put forth even though some of the observed features can be explained on the basis of the earlier work of Stokes (1860), Kubelka and Munk (1931) and others. It is then to be hoped that analysis of extensive experimental data obtained with a number of samples under a variety of conditions of illumination may yield an empirical solution. Consequently the main purpose of the present investigation, some of the results of which are reported herein, has been to determine in as much detail as possible the state of polarization of light reflected by typical natural formations such as desert sand, white sand, soil and water under different conditions of illumination. Such information can in turn be used in further studies of radiative transfer problems in planetary atmospheres and, in the more immediate context of the earth's atmosphere, in the determination of the effect of surface reflection in reconnaissance studies and in the interpretation of radiation measurements from meteorological satellites. The investigations of Bartman (1967), Coulson (1966), Coulson *et al.* (1966), Dollfus (1966, pp. 155–72) and Fraser (1965) must be mentioned in this context.

The first step in incorporating the reflection characteristics of a planetary boundary in radiative transfer problems was taken by Chandrasekhar (1950, p. 147) when he solved the problem of radiant energy transfer in a purely scattering molecular atmosphere with the ground reflecting light according to Lambert's law. The reflected radiation would be isotropic and unpolarized independent of the state of polarization of the incident radiation and the angle of illumination. The other extreme case of a planetary boundary governed by the Fresnel laws of reflection has been investigated by Sekera and Fraser (1955) and more recently by Fraser (1965). However, it is very seldom that a natural formation can be characterized either as a perfect Lambert surface or as a perfect specular reflector. As a first approximation reflection characteristics which are intermediate between these

† Present address: Electro-Optical Laboratory, Doall Science Center, Inc., Escondido, California, U.S.A.

two extremes should be associated with these natural formations and such a task would be greatly facilitated by experimental studies such as those reported here.

2. Theory of the method

The theory underlying the determination of the polarization characteristics of the beam of reflected light from the Fourier analysis of the response of a linear photoelectric device will now be briefly outlined. The Stokes vector formalism (Stokes 1852) will be adopted to describe the state of polarization of the light beam in what follows. In the most general case of a quasi-monochromatic beam of elliptically polarized light the Stokes polarization parameters are given by

$$\begin{aligned} I &= \langle a_l^2 \rangle + \langle a_r^2 \rangle \\ Q &= \langle a_l^2 \rangle - \langle a_r^2 \rangle \\ U &= 2 \langle a_l a_r \cos \delta \rangle \\ V &= 2 \langle a_l a_r \sin \delta \rangle \end{aligned} \quad (1)$$

where a_l and a_r denote the amplitude components along two mutually orthogonal directions in the transverse plane containing the electric and magnetic vectors and δ is the phase difference between these two components. The l and r directions, together with the direction of propagation, form a right-handed triad and the angular brackets denote time averages. The polarization features of the light beam characterized by the above set of parameters can be determined with the use of the formulae given below:

$$\text{degree of polarization } P \leq (Q^2 + U^2 + V^2)^{1/2} / I \quad (2)$$

where the equality sign denotes complete polarization,

$$\tan 2\chi = U / Q \quad (3)$$

where χ gives the orientation of the plane of polarization, i.e. the plane containing the major axis of the ellipse with respect to the l direction, and

$$\sin 2\beta = V / (Q^2 + U^2 + V^2)^{1/2} \quad (4)$$

where β , a measure of ellipticity, is given by $\arctan b/a$, a and b being the semi-major and minor axes of the ellipse respectively. In the case of linearly polarized light $V \equiv 0$ and equation (2) reduces to

$$P \leq (Q^2 + U^2)^{1/2} / I. \quad (5)$$

Let the light beam pass through an optical train consisting of a retardation plate of retardance ϵ with the fast axis along the l direction and an analyser with its transmission plane at an angle ψ from the l direction. It can be shown after some matrix algebra (Chandrasekhar 1950, p. 29) that the intensity of the emergent beam is given by

$$I(\psi, \epsilon) = \frac{1}{2} \{ I + Q \cos 2\psi + (U \cos \epsilon - V \sin \epsilon) \sin 2\psi \}. \quad (6)$$

When $\epsilon = 0$, i.e. in the absence of a retardation plate in the optical train,

$$I(\psi, 0) = \frac{1}{2} (I + Q \cos 2\psi + U \sin 2\psi). \quad (6a)$$

On the other hand when $\epsilon = \frac{1}{2}\pi$, i.e. when a quarter wave plate is present in the optical train,

$$I(\psi, \frac{1}{2}\pi) = \frac{1}{2} (I + Q \cos 2\psi - V \sin 2\psi). \quad (6b)$$

Let us consider the emergent beam to be examined with a linear optical detector. Let the response of the detector be S_i corresponding to impressed signal $I(\psi_i, \epsilon)$. Because of the inherent periodicity exhibited by $I(\psi, \epsilon)$, in view of the fact that an analyser, such as a Glan-Thompson prism, transmits the same amount of light when its transmission plane is either at an angle ψ or $\psi + \pi$ from the l direction, it should be possible to resolve $I(\psi, \epsilon)$ into elementary components given by the Fourier series

$$I(\psi, \epsilon) = p_0 + p_1 \cos \psi + p_2 \cos 2\psi + \dots + q_1 \sin \psi + q_2 \sin 2\psi + \dots \quad (7)$$

provided n equidistant values of S_i over the interval $0 \leq \psi \leq 2\pi$ are known.

On comparing coefficients of similar terms in equations (6a), (6b) and (7) it is found that

$$\begin{aligned} I &= 2p_0, & Q &= 2p_2 \\ U &= 2q_2 \text{ when } \epsilon = 0, & V &= -2q_2 \text{ when } \epsilon = \frac{1}{2}\pi. \end{aligned} \quad (8)$$

The method of determination of the p 's and q 's is as follows. Let the n equidistant values of S_i be denoted by $S_0, S_1, S_2 \dots S_{n-1}$ (with $S_n = S_0$) corresponding to values of i equal to 0, 1, 2, 3, ... $n-1$ respectively. For the case $k < \frac{1}{2}n$, it can be shown that (Pollak 1949)

$$p_0 = \frac{1}{n} \sum_{i=0}^{n-1} S_i, \quad p_k = \frac{2}{n} \sum_{i=0}^{n-1} S_i \cos(ik\alpha) \quad (9)$$

and

$$q_k = \frac{2}{n} \sum_{i=0}^{n-1} S_i \sin(ik\alpha)$$

with $\alpha = 360^\circ/n$. The amplitude of the k th harmonic is then given by $a_k = (p_k^2 + q_k^2)^{1/2}$. It is a matter of simple algebra to derive expressions for the degree of polarization and other relevant polarization parameters in terms of the Fourier coefficients from substitution of equation (8) into equations (2), (3) and (4). In the present investigations n has been set at 12, thereby rendering $\alpha = 30^\circ$.

It should be mentioned at this juncture that the Stokes parameters could have been determined in a relatively simpler fashion by making four interdependent measurements according to the scheme to be found in any well-known textbook on optics (Born and Wolf 1959, p. 551, Stone 1963, pp. 315-6). However, it has been pointed out by Budde (1962) that, under the assumption that the standard deviations σ_i of S_i are independent of i and are the same for all i , the standard deviations of all polarization parameters are functions of σ_i and S_i and are directly proportional to $(1/n)^{1/2}$ where n is the number of equidistant points at which values of S_i are measured. Thus an increase in the value of n results in a corresponding increase in the precision with which the polarization parameters could be determined.

3. Experimental studies

The experimental geometry is shown in figure 1. The reflecting surface of the sample defines the equatorial plane. θ_0 is the angle of illumination, θ is the angle of observation. θ is generally referred to as the nadir angle of observation. The principal plane of the source S is defined by the direction of illumination and the normal to the equatorial plane. It is the reference plane for the determination of the azimuth Φ of the plane of observation defined by the direction of observation and the normal to the equatorial plane.

Because of prevalent symmetry, when Φ assumes values from 0 to $\frac{1}{2}\pi$ it is adequate to confine the measurements to planes of observation having projections on to the equatorial plane which are contained within the pair of opposite quadrants AODA and COBC in figure 1. The nadir angle θ assumes values between 0 and $\frac{1}{2}\pi$ on either side of the normal to the equatorial plane. When $\theta_0 = 0$, i.e. for normal illumination, measurements need be made in any one plane only.

A G. E. Mazda airway beacon lamp, operating on 30 v d.c. and rated at 1000 w has been used as the primary source of illumination. It is housed in an enclosure through which a continuous stream of coolant air flows. The emergent beam is rendered *almost* parallel and uniformly bright over its cross section with the use of a suitable combination of a matt glass diffuser and short focal length condenser lens. The angle of illumination θ_0 can be varied by moving the lamp housing over a length of rigid tubing bent into the shape of an arc of a circle of radius $7\frac{1}{2}$ feet. The sample is located at the centre of this circle.

The illumination can be rendered plane-polarized by introducing a sheet of type HN38 polaroid in front of the condenser lens. The circular polaroid sheet can be rotated inside a graduated circle and thus the orientation of the plane of polarization with respect to the principal plane of the source can be varied. The degree of linear polarization of the emergent beam varies slightly with wavelength. On examination with a simple photo-electric detector it was found to have values of 95.8%, 99.83% and 99.86% at wavelengths 3975, 5000 and 6050 Å respectively.

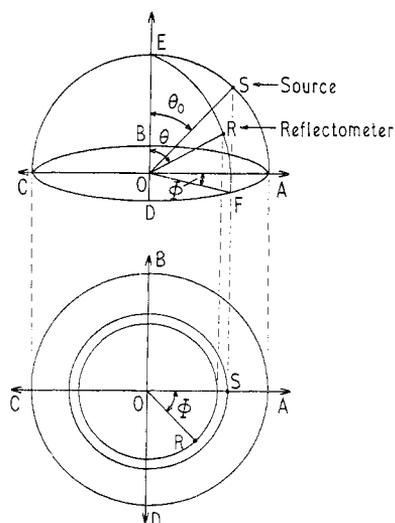


Figure 1. Experimental geometry.

The reflectometer is shown schematically in figure 2. It is of the conventional rotating-analyser type with a photomultiplier tube as the detector. Measurements of the degree of polarization can be made in three narrow spectral intervals (bandwidth $\sim 150 \text{ \AA}$) centred on wavelengths 3975, 5000 and 6050 \AA .

The field of view of the instrument is limited to $3^\circ 00'$ with the use of the quartz achromat and the light-limiting baffles. The d.c. motor which rotates the Glan-Thompson prism at 4 rev min^{-1} also actuates a programmed cam which operates a microswitch in such a fashion that the output of the photomultiplier tube is sampled at $30^\circ 00'$ intervals over one complete revolution of the analyser. Initial conditions are so arranged that the transmission plane of the Glan-Thompson prism is normal to the plane of observation at the beginning and end of a complete revolution. It is also possible to monitor continuously the output of the photomultiplier tube.

A 14 stage Ascop model 541 A photomultiplier with an end window is used as the detector. The antimony-caesium photocathode exhibits S-11 response. The spectral intervals of interest are isolated with multilayer dielectric interference filters characterized by fairly steep pass bands. The dynamic range of the detector is confined to two orders of magnitude with the use of neutral density filters that are introduced in the light path

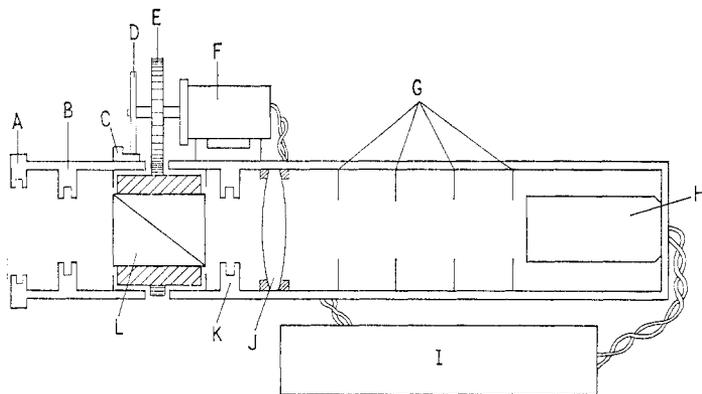


Figure 2. The photopolarimeter (not to scale). A, holder for neutral density wedge; B, holder for quarter wave plate; C, microswitch; D, programmed cam; E, analyser driving mechanism; F, d.c. motor; G, light-limiting baffles; H, Ascop 541-A photomultiplier tube; I, auxiliary electronics; J, fused quartz achromat; K, filter holder; L, Glan-Thompson prism.

to attenuate the intensity of the beam entering the instrument. Interference filters and companion quarter wave plates can be easily introduced into the light path.

The output of the photomultiplier tube passes through an inverting variable gain amplifier and is then recorded. The output of the amplifier can be either monitored continuously or sampled discretely through the microswitch operated by the programmed cam.

The optical components and the photomultiplier tube are housed inside a blackened cylindrical brass tube of diameter 1.5 in. The entire assembly measures about 20 in. in length and weighs about 5 lb. The reflectometer is mounted on a manually operated altazimuth mount in order that the nadir angle of observation θ and the azimuth Φ of the plane of observation can be varied easily. The entrance aperture of the reflectometer moves along the arc of a circle of radius 18 in. with the sample at the centre. With this arrangement the extreme apparent geometrical apertures of the system corresponding to large values of θ are contained within the illuminated portion of the sample. The samples are contained in trays measuring approximately 18 in. \times 12 in. \times 3 in. The tray is positioned on the central stationary platform in such a fashion that the axis of azimuthal rotation of the reflectometer passes through its centre. In order to minimize, if not eliminate altogether, the effects of light that would be reflected by the bottom of the tray containing the water samples, the inside of the tray was painted flat black. The depths of the samples studied ranged around $2\frac{1}{2}$ in.

The photosignal developed across a precision signal resistor of 1.0 M Ω passes through an inverting variable gain operational amplifier. The output of the amplifier is fed into a Varian model G-10 strip chart recorder and a Wyle model 1504A/D converter (binary conversion) which is connected in parallel with the strip chart recorder. The digitized information in binary form is recorded on magnetic tape with a Digidata model 1450 7 channel digital recorder with a stepping rate of 300 per second. There is provision to introduce auxiliary information such as labelling voltages to identify samples, states of polarization of illumination, scan mode, etc. on the magnetic tape through the digitizer. The record format on the tape is compatible with an IBM 7094 computer. This facilitates data reduction and analysis.

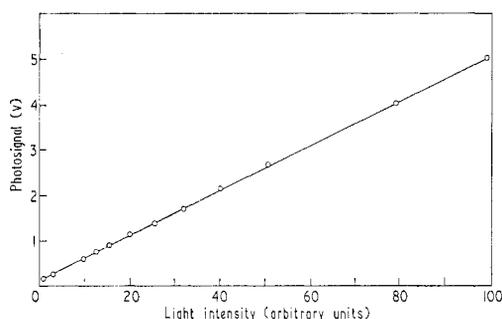


Figure 3. Response of the photopolarimeter.

The linearity of response of the reflectometer and the detection system is shown in figure 3. Simple auxiliary experiments were performed to determine the dependence, if any, of the photocathode response on the orientation of the plane of polarization of the impinging light. The results indicated that the greatest departure that such dependence could cause in the observed value of the photosignal relative to the mean value was of the order of a fraction of a per cent.

Samples of desert sand, white sand (New Mexico), soil and water have been studied in the present investigation. The samples have been illuminated both with natural (unpolarized) light and with linearly polarized light. In the latter case three situations, when the plane of polarization was parallel, normal or inclined at $45^{\circ}00'$ to the principal plane of the source, have been examined. The nadir angle of observation has been varied in steps of $10^{\circ}00'$ in the case of desert sand, white sand and soil. In the case of water, cursory examination of the reflected beam revealed the necessity to make these observations at $2^{\circ}00'$ intervals. These measurements have been made in three planes of observation

with $\Phi=0^\circ$ (180°), 45° (225°) and 90° (270°). Conditions of illumination have been varied by setting the angle of illumination $\theta_0=0^\circ$, $53^\circ 00'$ and $78^\circ 30'$.

4. Results and discussion

Attempts to detect ellipticity, if any, of the reflected light with the use of a combination of a quarter wave plate and a *relatively* broad-band interference filter did not yield meaningful results. Hence only the degree of linear polarization and relative intensity variations of the reflected light will be presented and discussed. Also it was observed in the case of water that meaningful results could not be obtained when measurements were made in planes other than the principal plane since the signal-to-noise ratio approached unity because of the absence of appreciable amounts of lateral scattering. Hence, in order to facilitate intercomparisons of all of the samples and for the sake of brevity, only the results obtained in the principal plane of the source when the samples were illuminated at an angle of $53^\circ 00'$ will be presented and discussed. However, the conclusions to be presented forthwith have been drawn on the basis of the entire set of data.

The measured values of the polarization of reflected light corresponding to four different states of polarization of the illuminating radiation are shown in figures 4, 5, 6 and 7. Examples of the variation of the normalized intensity, defined as the ratio of the intensity of light reflected in any direction θ to the intensity of light reflected in the nadir (zenith) direction corresponding to $\theta=0$, are shown in figures 8 and 9.

The polarization of light reflected by the three particulate samples, viz. soil, desert sand and white sand, exhibits strong wavelength dependence: it decreases with increasing wavelength. Such behaviour is noticed uniformly under all conditions of illumination and observation. However, the dispersion in the case of white sand (gypsum derived translucent grains of dimensions of the order of 0.5 mm) is not so pronounced as in the case of either desert sand (silica derived translucent grains of dimensions of the order of 0.5 mm) or soil (opaque particulates of dimensions of the order of 1 mm). The dispersion is much less pronounced in the case of water.

There is over-all similarity in the behaviour of soil and desert sand. When the samples are illuminated with natural (unpolarized) light at an angle other than zero, the polarization distribution curve shows a maximum located in a region about 100° – 110° removed from the antisource point. Neutral points (i.e. points at which unpolarized light is detected) are observed on either side of the antisource point when the angle of illumination θ_0 is either 0° or $53^\circ 00'$ and above the antisource point when $\theta_0=78^\circ 30'$. The reflected light is polarized in mutually orthogonal directions on either side of the neutral points and this has been indicated in figure 4 by plotting the measured values of polarization on either side of the zero line. These neutral points have so far been observed *only* in the principal plane of the source. These results are in general agreement with the results of Coulson (1966) who has studied in detail the behaviour of these samples when illuminated with unpolarized light.

The reflected light is considerably depolarized when the samples are illuminated with completely linearly polarized light. The depolarization is much more pronounced in the case of white sand than in the case of either desert sand or soil.

An examination of the relative intensity variations (figure 8) reveals that the normalized intensity does not differ considerably from unity in the case of white sand. It is also observed that the normalized intensity retains a high value of about 0.9 up to nadir angles of 70° on either side of the source when the sample of white sand is illuminated from vertically above ($\theta_0=0^\circ$) with completely linearly polarized light. These observations, when viewed in the light of the very strong depolarizing behaviour, lead to the conclusion that white sand exhibits a strong tendency to behave like an ideal diffuser (Lambert surface).

Explanation of the behaviour of an apparently smooth surface of water presents considerable difficulties. It is observed that the normalized intensity in the specular direction is considerably larger than the normalized intensity in any other direction. The actual magnitude of the ratio of the specular reflection signal to the diffuse reflection signal varies from a low value of about 100 when the illumination is polarized parallel to the plane of

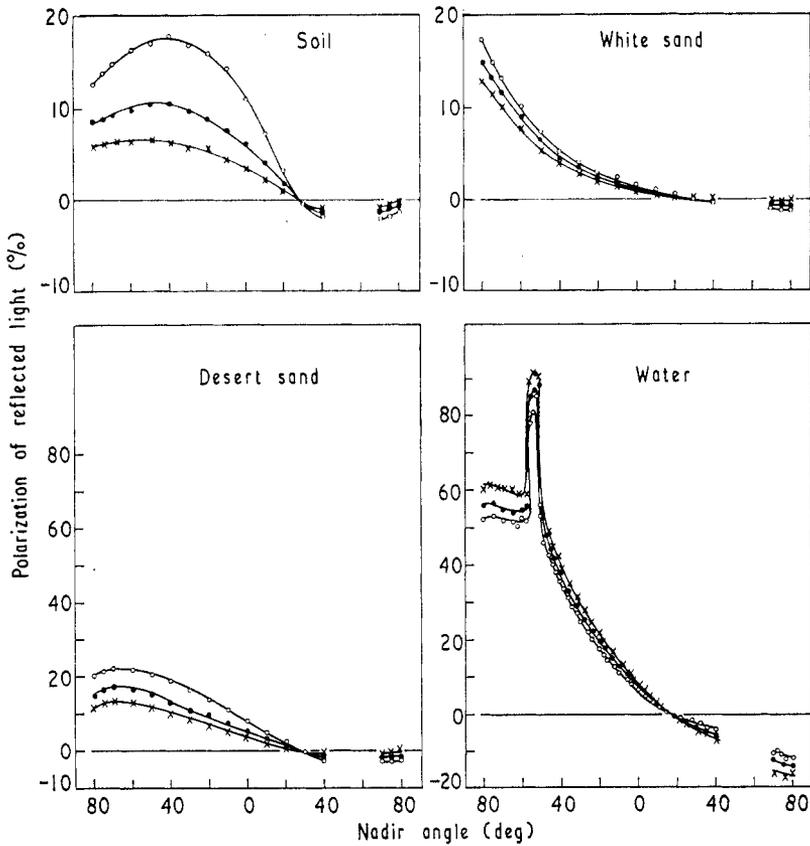


Figure 4. Measured values of polarization of reflected light in the principal plane of the source. Illumination: natural light, $\theta_0 = 53^\circ 00'$. \circ 3975 Å, \bullet 5000 Å, \times 6050 Å.

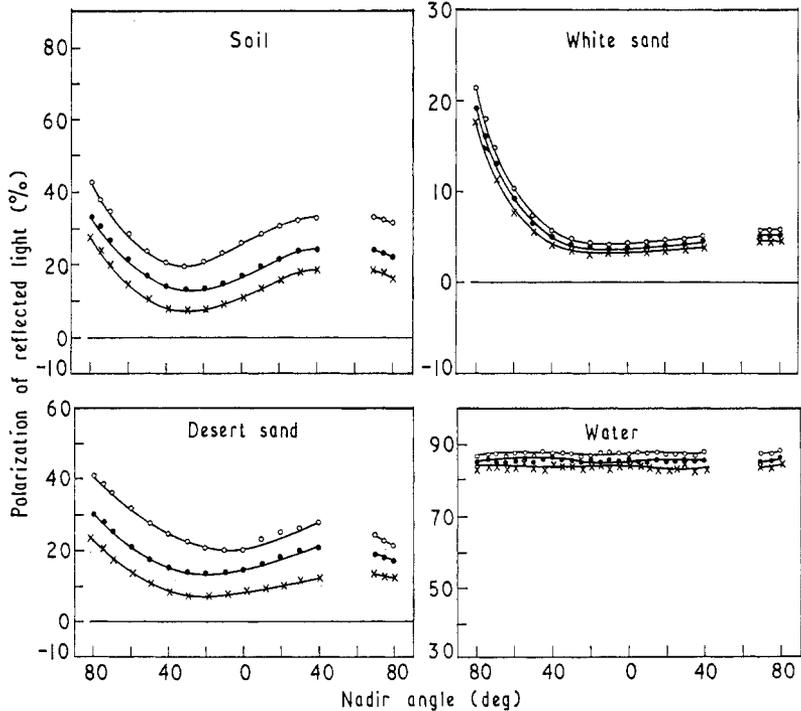


Figure 5. Measured values of polarization of reflected light in the principal plane of the source. Illumination: light polarized at $45^\circ 00'$ to the plane of incidence. \circ 3975 Å, \bullet 5000 Å, \times 6050 Å.

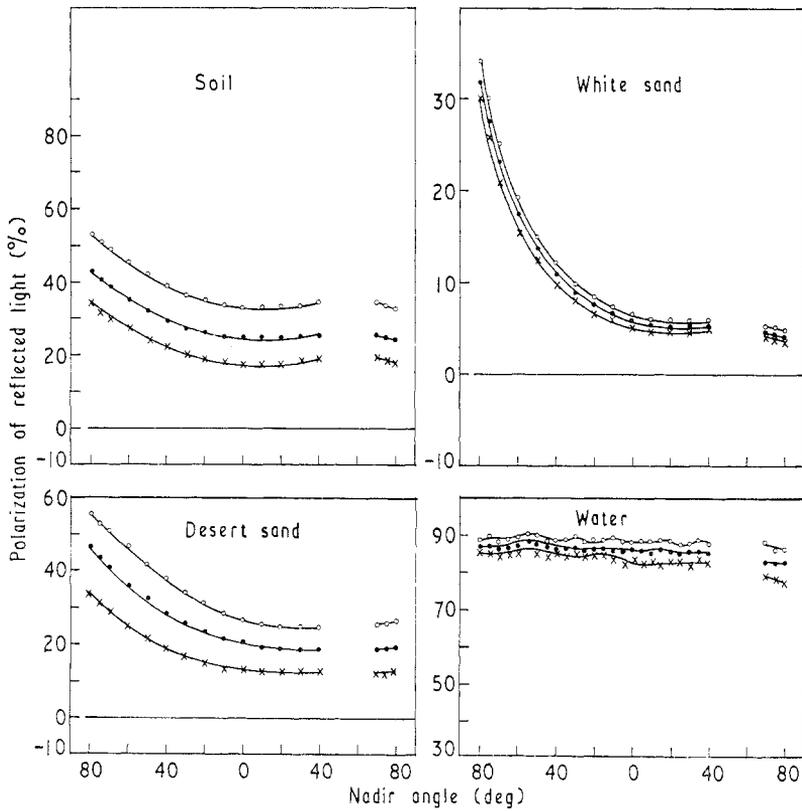


Figure 6. Measured values of polarization of reflected light in the principal plane of the source. Illumination: light polarized normal to the plane of incidence. ○ 3975 Å, ● 5000 Å, × 6050 Å.

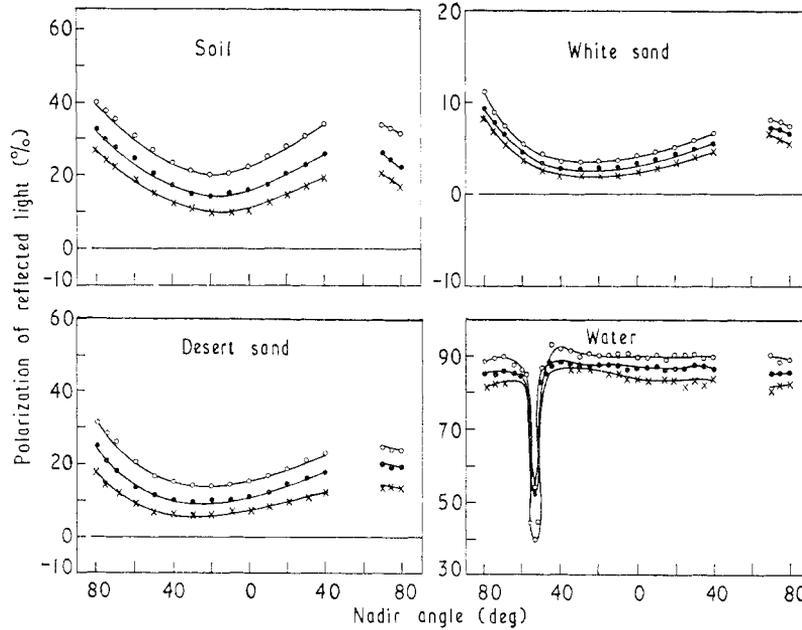


Figure 7. Measured values of polarization of reflected light in the principal plane of the source. Illumination: light polarized parallel to the plane of incidence. ○ 3975 Å, ● 5000 Å, × 6050 Å.

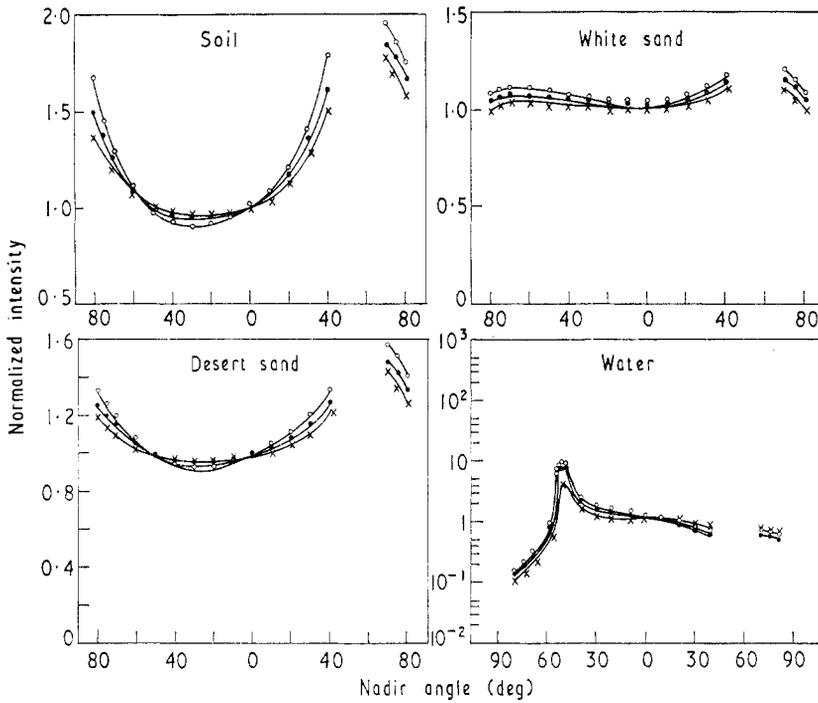


Figure 8. Variations of normalized intensity of reflected light. Illumination: light polarized parallel to the plane of incidence. ○ 3975 Å, ● 5000 Å, × 6050 Å.

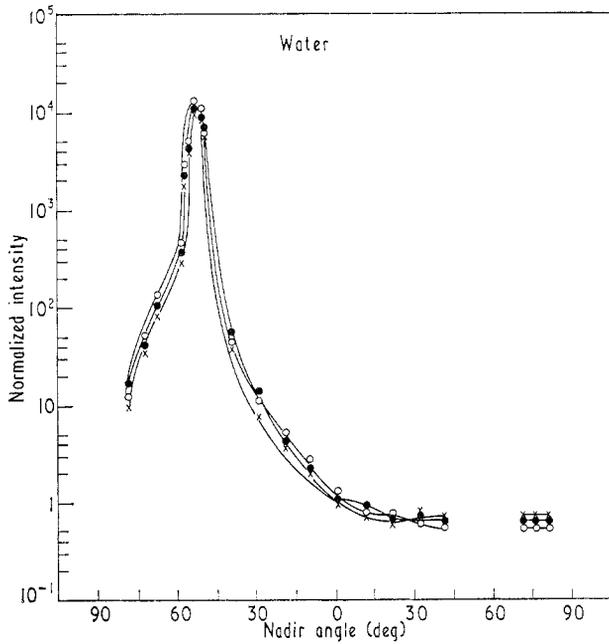


Figure 9. Variations of normalized intensity of light reflected by water sample illuminated by natural light. ○ 3975 Å, ● 5000 Å, × 6050 Å.

incidence (figure 8) to values in excess of 1000 when the illumination is either unpolarized (figure 9) or is polarized in planes other than the plane of incidence. The correspondingly high values of polarization of the reflected light in the specular direction when the sample is illuminated with natural light at an angle of $53^{\circ} 00'$ and the strong depolarization observed in the specular direction when the sample is illuminated at an angle of $53^{\circ} 00'$ with light polarized parallel to the plane of incidence lead to the hypothesis that the over-all behaviour is governed by Fresnel laws. However, the departure from complete polarization when the sample is illuminated with natural light at an angle very near the Brewster angle ($\sim 53^{\circ} 00'$) and the detection of polarized light in directions other than the specular direction indicate the presence of a considerable amount of 'longitudinal scattering', i.e. scattering in non-specular directions in the plane of incidence. These departures have been consistently noticed. It has not been possible to conceive any physical mechanism, other than that of scattering by an 'optically rough, locally smooth' surface, to account for the behaviour of the water surface, even in a qualitative fashion.

It is evident in the light of experimental evidence gathered so far that most of the naturally occurring formations which can be characterized as 'optically rough' exhibit a strong depolarizing tendency. The phenomenon of 'diffuse reflection' by these surfaces cannot be explained in terms of any simple physical process. The observed state of polarization of the reflected radiation results from diverse processes such as reflection at the boundary, refraction and absorption within the medium, penetration into the medium accompanied by multiple scattering, etc. A quantitative explanation may be forthcoming after enough experimental data have been accumulated.

Acknowledgments

The authors wish to thank Professor K. L. Coulson of the Department of Agricultural Engineering, University of California, Davis, for the loan of the samples. They are grateful to Professor Z. Sekera of the Department of Meteorology, University of California, Los Angeles, for his interest and encouragement while the work was in progress. Financial assistance from the Office of Aerospace Research, AFCRL under Contract AF-19628-67-C-0196 and the Atmospheric Sciences Program of the National Science Foundation under grant GA837 is gratefully acknowledged.

References

- BARTMAN, F. L., 1967, Ph.D. Dissertation, College of Engineering, University of Michigan.
 BORN, M., and WOLF, E., 1959, *Principles of Optics* (New York: Macmillan).
 BUDDE, W., 1962, *Appl. Optics*, **1**, 201-5.
 CHANDRASEKHAR, S., 1950, *Radiative Transfer* (London: Oxford University Press).
 COULSON, K. L., 1966, *Appl. Optics*, **5**, 905-17.
 COULSON, K. L., GRAY, E. L., and BOURICIUS, G. M. B., 1966, *Icarus*, **5**, 139-48.
 DOLLFUS, A., 1966, *The Nature of the Lunar Surface* (Baltimore: Johns Hopkins Press).
 FRASER, R. S., 1965, Final Report prepared for Goddard Space Flight Center by TRW Space Technology Laboratories, Los Angeles, California, Contract NA 55-3891.
 KUBELKA, P., and MUNK, F., 1931, *Z. Tech. Phys.*, **12**, 593.
 POLLAK, L., 1949, *All Term Guide for Harmonic Analysis and Synthesis* (Dublin: Stationery Office).
 SEKERA, Z., and FRASER, R. S., 1955, Appendix C, Final Report, Contract AF 19(122)-239, Department of Meteorology, University of California, Los Angeles.
 STOKES, G. G., 1852, *Trans. Camb. Phil. Soc.*, 399.
 ——— 1860, *Proc. Roy. Soc.*, **11**, 545.
 STONE, J. M., 1963, *Radiation and Optics* (New York: McGraw-Hill).