AFCRL-67-0089

AD 649505

INVESTIGATIONS OF THE POLARIZATION OF LIGHT REFLECTED BY NATURAL SURFACES

Hsi-shu Chen, C. R. Nagaraja Rao, and Z. Sekera

Department of Meteorology
University of California
Los Angeles, California 90024

Contract No. AF 19(628)-3850
Project No. 7621
Task No. 762103

Scientific Report No. 2

January 1967

Contract Monitor: Mr. R. B. Toolin

Distribution of this document is unlimited

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

AFCRL-67-0089

INVESTIGATIONS OF THE POLARIZATION OF LIGHT REFLECTED BY NATURAL SURFACES

Hsi-shu Chen, C. R. Nagaraja Rao, and Z. Sekera

Department of Meteorology
University of California
Los Angeles, California 90024

Contract No. AF 19(628)-3850
Project No. 7621
Task No. 762103

Scientific Report No. 2
January 1967

Contract Monitor: Mr. R. B. Toolin

Distribution of this document is unlimited

Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

TABLE OF CONTENTS

ACKNOWLEDGMENTS

The authors are thankful to Messrs. D. Dibble, G. Chesebrough and Pradip Gupta for their willing cooperation and assistance in the experimental phase of the research program. Messrs. Dennis St. John and Larry Lyons assisted in the computational work. Mrs. Sherry Lovell is responsible for the neat execution of the manuscript. Miss Carole Sadler and Mrs. Judith Phillips prepared the illustrations.

Abstract

The polarization features of light reflected by soil, desert sand, white sand and water under different conditions of illumination with natural (unpolarized) and polarized light have been investigated in three narrow spectral intervals (band width ~ 150 A) centered on λλ3975, 5000 and 6050 A. A simple 'rotating-analyzer' type photoelectric reflectometer was used in the measurements. The data was 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 overall similarity in the behavior 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.

CHAPTER I

INTRODUCTION

The investigation of the polarization and intensity of light reflected by natural surfaces is of great practical importance for the solution of many different problems in planetary physics and meteorology. The purpose of the present investigation is to determine in as much detail as possible the polarization features of light reflected by some typical surfaces composed of sand, soil and water. This information can then be used for further studies of radiative transfer problems in planetary atmospheres; for the determination of the effects of surface reflection in reconnaissance studies, and in the interpretation of radiation measurements from meteorological satellites.

Fresnel[1], in 1832, derived the laws of reflection of light which now bear his name from the elastic solid theory. He studied reflection of light at the smooth interface of two dielectric media. The reflection process is essentially specular and hence the terms 'specular reflector' and 'Fresnel reflector' are now synonymous. Later Stokes[2] put forth a statistical method to explain diffuse reflection. He assumed the diffusely reflecting medium to have a layered structure, the thickness of each layer being of the order of the mean dimensions of the particles of which the diffusing medium was composed. The formulas derived by Stokes provide a link between the observable reflection features and the fundamental optical constants which characterize the diffusing medium.

The first step in incorporating the reflection characteristics of a planetary boundary in radiative transfer problems was taken by Chandrasekhar[3] in 1950 when he solved the problem of radiative 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[4] and more recently by Fraser[5]. The theoretical conclusions have been borne out by results of measurements of skylight polarization made over calm surfaces of water to which the description of a Fresnel reflector fits best.

Both laboratory and field measurements of the reflection features of various natural surfaces have been reported by various investigators. Extensive bibliographical references would be found in the recent publications of Coulson[6]. The instruments employed are basically of two types--the 'Integrating sphere' type and the 'Reflectometer' type. The Reflectometer type is of greater use in the study of the polarization features of reflected light.

Lyot[7], Dollfus[8] and Caliens[9] have conducted extensive measurements on terrestrial materials in their efforts to reproduce the observed polarization features of light reflected by the moon and more recently by Mars. Similar work has been reported by Hapke and Van Horn[10]. Coulson[6] has made laboratory measurements of the polarization of light reflected by selected natural surfaces illuminated with unpolarized light.

An experimental program to evaluate the reflection matrices characteristic of these natural surfaces has recently been initiated at the Department of Meteorology, UCLA. The first phase of the program consisted of the design of an experimental arrangement to facilitate the measurement of the degree of polarization and relative intensity variations of light reflected by some typical natural formations under different conditions of illumination. This was originally accomplished by Professor K. L. Coulson of the Dept. of Agricultural Engineering, University of California, Davis while he was visiting the Dept. of Meteorology, UCLA in the summer of 1965. However preliminary measurements with this arrangement indicated the need for considerable improvements and modifications in the design of the source of illumination, the auxiliary electronic circuitry and the data acquisition system. These changes were effected and the measurements reported in what follows have been obtained with the modified set-up.

After a resume of the theoretical background needed for the proper interpretation of experimental results in Chapter 2, the design and operation of a simple 'Reflectometer' are described in Chapter 3. The results of measurements made with soil, desert sand, white sand and water as samples are presented and discussed in Chapter 4.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 General Considerations

All reflection processes by natural surfaces lead to changes in the state of polarization of the incident radiation. It was Malus who first observed the polarization of light by reflection when he looked at the image of the sun reflected by a window pane through a calc-spar crystal. He noticed pronounced variations in the intensities of the two images obtained by double refraction as the crystal was rotated about the line of sight.

It has been the usual practice to assume the ground to be a Lambertian surface in investigations of the radiative transfer problems in the earth's atmosphere. Light reflected by a Lambertian surface would be unpolarized and the luminance is isotropically distributed independent of the angle of illumination and the state of polarization of the illuminating radiation. It is apparent that this is an extreme description. The other extreme description of a specular reflector which reflects light according to the celebrated Fresnel laws is at best applicable to undisturbed water surfaces. It is very seldom that a natural formation can be characterized by either of these two extreme descriptions. It is the purpose of the present investigation to draw semi-qualitative conclusions in regard to the actual reflection characteristics of such natural formations in a phenomenological fashion based on experimental data.

2.2 Representation of Polarized Light

Light is said to be polarized when the associated transverse electromagnetic wave defined by the characteristic electric and magnetic vectors exhibits dissymetry about the direction of propagation. In the most general case of elliptical polarization, it is observed that the locus of the end point of the electric vector is an ellipse in the transverse plane normal to the direction of propagation. The components of the amplitude of the electric vector along any two mutually orthogonal directions ℓ and r in the transverse plane (see Fig. 1), which together with the direction of propagation k form a right handed triad will be time harmonic. The ℓ and r directions are usually chosen to be parallel and perpendicular to the plane of interest which, in the present context, will be either the plane of incidence or the plane of reflection.

The conventional description of an elliptically polarized stream of radiation would involve the determination of the instantaneous values of the intensity components along the ℓ and r directions, the ratio of the semi minor and major axes of the vibrational ellipse and the angular displacement of the major axis of the ellipse from the ℓ direction. This description of polarization presents considerable difficulties in experimental studies because of the dimensional inhomogeneity of the quantities to be determined (intensities, a ratio and an angle). Stokes[11] realized the advantages of formulating a set of parameters all of which would have the dimensions of energy and would hence be easily amenable to experimental determination. The four parameters are

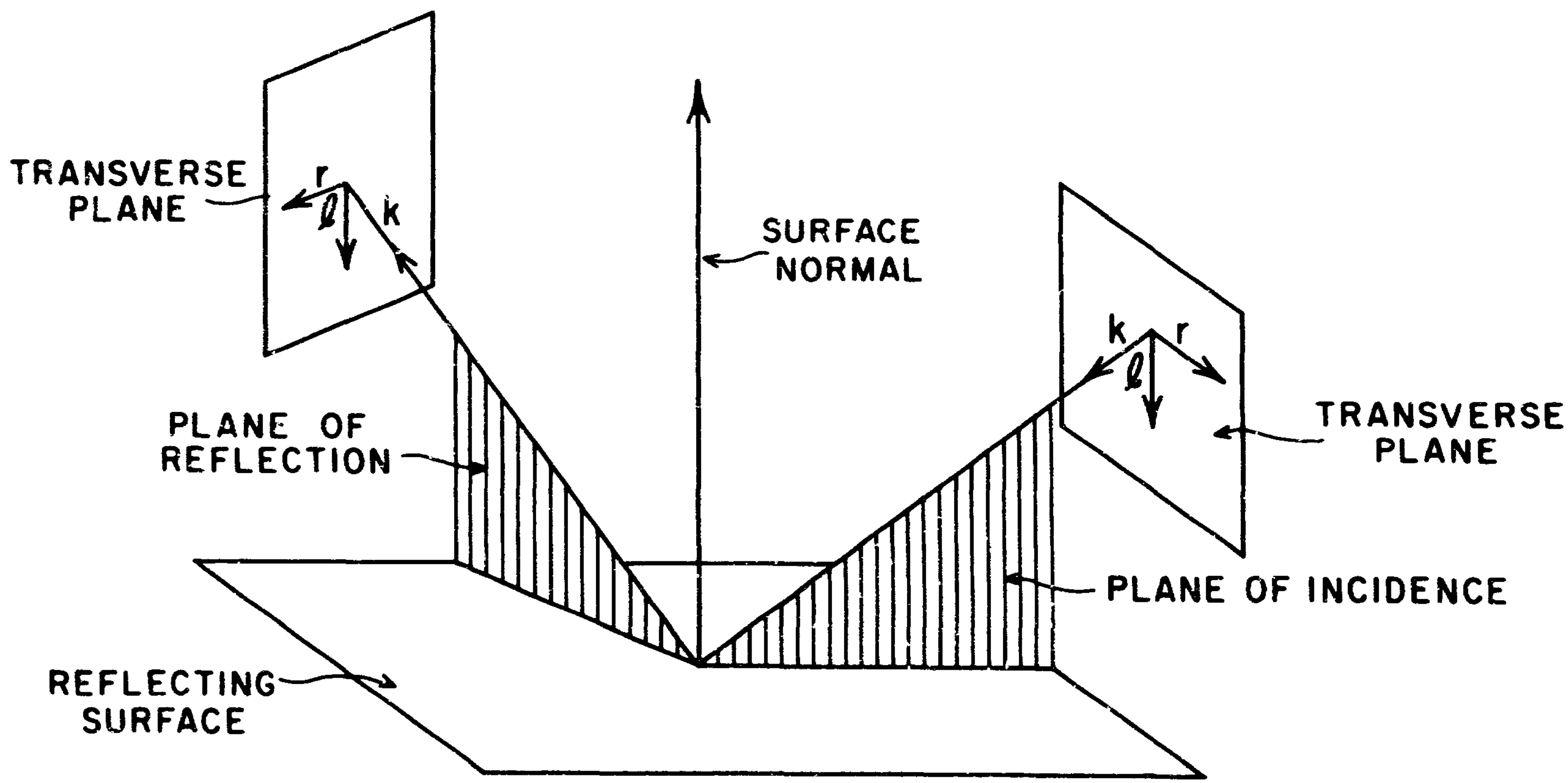


FIG. 1. DIRECTIONAL PARAMETERS TO DEFINE THE STOKES VECTOR

known as the Stokes polarization parameters. They can be thought of as the elements of a four element column vector--the Stokes vector. Of the four parameters pertinent to a quasimonochromatic beam, two are functions only of the amplitude components along the ℓ and r directions and the remaining two are, in addition, dependent on the phase difference between the amplitude components along the ℓ and r directions.

The Stokes polarization parameters of a quasi-monochromatic beam can then be represented as

$$\begin{aligned} I &= (a_\ell^2) + (a_r^2) \\ Q &= (a_\ell^2) - (a_r^2) \\ U &= 2(a_\ell a_r \cos\delta) \\ V &= 2(a_\ell a_r \sin\delta) \end{aligned} \tag{2.1}$$

where a_ℓ and a_r denote the instantaneous values of the amplitude components along the ℓ and r directions respectively, δ is the phase difference between them and the brackets denote time averages. One noticeable feature of the Stokes parameters is their additivity when a number of incoherent streams of radiation which do not interact (interfere) are considered. This results in the optical equivalence of a number of incoherent streams of radiation to a single beam characterized by a set of Stokes paramerers each one of which is the sum of the corresponding parameters characteristic of the individual streams.

The polarization features of the stream of radiation characterized by the Stokes parameters I, Q, U and V can be determined with the use of the formulas given below:

$$\text{Degree of polarization} \quad P \leq \frac{[Q^2 + U^2 + V^2]^{\frac{1}{2}}}{I} \tag{2.2}$$

where the equality sign denotes complete polarization,

$$\operatorname{Tan} 2X = \frac{U}{Q} \tag{2.3}$$

where X 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

$$\operatorname{Sin} 2\beta = \frac{V}{[Q^2 + U^2 + V^2]^{\frac{1}{2}}} \tag{2.4}$$

where β, a measure of ellipticity is given by arc tan $^b/a$, a and b being the semi major and minor axis of the ellipse respectively.

In the case of linearly polarized light $V = 0$

and
$$P \leq \frac{(Q^2 + U^2)^{\frac{1}{2}}}{I} \tag{2.5}$$

At present extensive use is made of the Mueller[12] calculus, which is a natural extension of the Stokes vector formalism, to describe the interaction of radiation with matter. In this phenomenological theory, a physical process or an optical instrument which affects radiation is characterized by a 4 x 4 matrix known as the Mueller matrix. Any phenomenon involving the interaction of a stream of radiation with matter is then defined by the result of operating with the Mueller matrix characteristic of the physical process upon the Stokes vector of the stream of radiation.

Consider now a parallel beam of quasi-monochromatic radiation incident on a reflecting surface in the direction (θ_o, φ_o) where θ_o and φ_o

define the zenith (incidence) and azimuth angles in a spherico-polar coordinate system with the reflecting surface coinciding with the equatorial plane. The reflected beam in the direction (θ, φ) is related to the incident beam through the relation

$$\mathbb{I}^R = \mathbb{R}\,\mathbb{I}^i \qquad (2.6)$$

where $\mathbb{I}^i$ and $\mathbb{I}^R$ are the four element (I, Q, U, V) column vectors representative of the incident and reflected beams respectively and $\mathbb{R}$ is the 4 x 4 Mueller matrix characterizing the process of reflection by the surface. In general the elements Rij (i,j = 1,2,3,4) of the reflection matrix are functions of θ, θ_o, φ and φ_o with the dependence on the macroscopic optical constants of the surface being rendered implicit. If the azimuth angle φ is measured with reference to the plane containing the direction of illumination (incidence) and the normal to the reflecting surface, $\varphi_o = 0$ and any one of the sixteen elements of the reflection matrix can be designed as Rij $(\theta, \theta_o, \varphi)$ (i,j = 1,2,3,4). In principle it should be possible to determine the Rij's henceforth the θ, θ_o, φ dependence will not be explicitly denoted) if the elements of column vectors $\mathbb{I}^i$ and $\mathbb{I}^R$ are known, since from Eq. (2.6) it follows that

$$\begin{aligned}
I^R &= R_{11}\, I^i + R_{12}\, Q^i + R_{13}\, U^i + R_{14}\, V^i \\
Q^R &= R_{21}\, I^i + R_{22}\, Q^i + R_{23}\, U^i + R_{24}\, V^i \\
U^R &= R_{31}\, I^i + R_{32}\, Q^i + R_{33}\, U^i + R_{34}\, V^i \\
V^R &= R_{41}\, I^i + R_{42}\, Q^i + R_{43}\, U^i + R_{44}\, V^i
\end{aligned} \qquad (2.7)$$

The form of the family of equations (2.7) suggests that the individual elements of the reflection matrix can be determined if the elements of the column vectors II^i and II^R are known. The elements of II^i can be prespecified, except for a constant multiplication factor which involves the rather tedious absolute energy measurements, by controlling the conditions of illumination. The elements of II^R can be determined by the harmonic analysis of the photosignal issuing from a suitably designed optical detector assembly with which the reflected light is examined in the manner described below.

2.3 Harmonic Analysis of the Photosignal

Let the beam of quasi-monochromatic radiation reflected in the direction (θ,φ) pass through an optical train consisting of a retardation plate of retardance δ either with its slow or fast axis along the ℓ direction and an analyzer with its transmission plane at an angle ψ from the ℓ direction. It can be shown, after some matrix algebra, that the intensity of the emergent beam is given by

$$I(\psi,\delta) = \tfrac{1}{2}[I^R + Q^R \cos 2\psi + (U^R \cos\delta - V^R \sin\delta)\sin 2\psi] \qquad (2.8)$$

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

$$I(\psi,0) = \tfrac{1}{2}[I^R + Q^R \cos 2\psi + U^R \sin 2\psi] \qquad (2.9)$$

On the other hand, when $\delta = \pi/2$, i.e. when a quarter wave plate is introduced in the optical train

$$I(\psi,\pi/2) = \tfrac{1}{2}[I^R + Q^R \cos 2\psi - V^R \sin 2\psi] \qquad (2.10)$$

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 $I(\psi_i, \delta)$. Because of the inherent periodicity exhibited by $I(\psi, \delta)$ in view of the fact that the Glan-Thompson prism transmits the same amount of light when its transmission plane in either at an angle ψ or $\psi+\pi$ from the ℓ direction, it should be possible to resolve $I(\psi, \delta)$ into the elementary components given by the Fourier series[13]

$$I(\psi, \delta) = p_o + p_1 \cos\psi + p_2 \cos 2\psi + \ldots\ldots + q_1 \sin\psi + q_2 \sin 2\psi \ldots\ldots \quad (2.11)$$

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

On comparing coefficients of similar terms in Equations (2.9), (2.10) and (2.11) it is found that

$$\begin{aligned} I^R &= 2p_o \\ Q^R &= 2p_2 \\ U^R &= 2q_2 \text{ when } \delta = 0 \\ V^R &= -2q_2 \text{ when } \delta = \pi/2 \end{aligned} \quad (2.12)$$

The method of determination of the p's and q's is briefly outlined below.

Let the n equidistant values of Si be denoted by $S_o, S_1, S_2 \ldots S_{n-1}$ (with $S_n = S_o$) corresponding to values of i equal to 0,1,2,3 ..., n-1 respectively. For the case $k < n/2$, it can be shown that

$$p_o = \frac{1}{n} \sum_{i=0}^{n-1} S_i$$

$$p_k = \frac{2}{n} \sum_{i=0}^{n-1} S_i \cos(ik\theta)$$

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

with $\theta = {}^{360^\circ}/n$. The amplitude of the kth harmonic is then given by $a_k = (p_k^2 + q_k^2)^{\frac{1}{2}}$. In the present investigation, n has been chosen to be 12, thereby rendering $\theta = 30^\circ$ and the Fourier coefficients up to and including the fourth harmonic have been determined. Because of the symmetry introduced by the use of the Glan-Thompson prism, only the even harmonics will be dominant. 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 Eq. (2.12) in Eq. (2.2).

CHAPTER 3

EXPERIMENTAL STUDIES

3.1 General

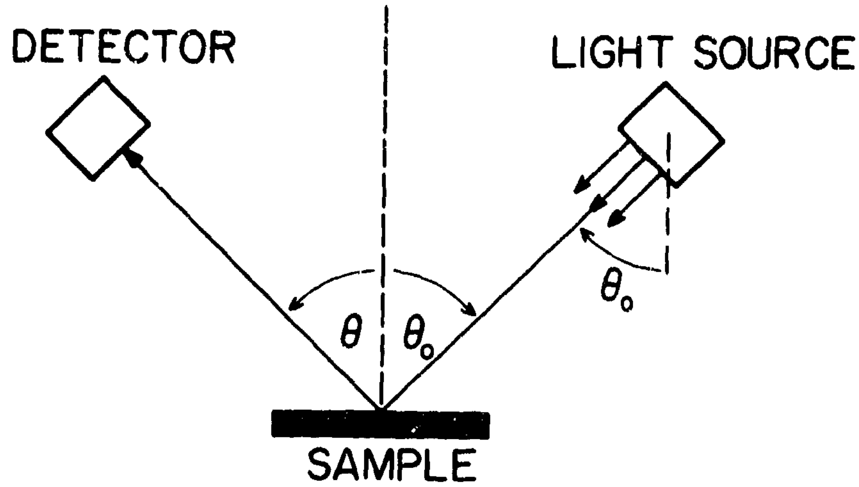
The majority of instruments that have been employed in reflectance studies so far belong to either of the two basic types illustrated in Fig. 2. In the 'Integrating Sphere' type a sphere or hemisphere coated on the inside with a highly reflecting substance is used to integrate the radiation reflected by the sample. However, for the primary purpose of the investigation which is the study of the polarization features of the reflected light, an instrument of the 'Reflection' type is better suited. Accordingly a simple photoelectric polarimeter of the 'rotating analyzer' type was designed and used in the experimental studies described in what follows.

3.2 Experimental Arrangement

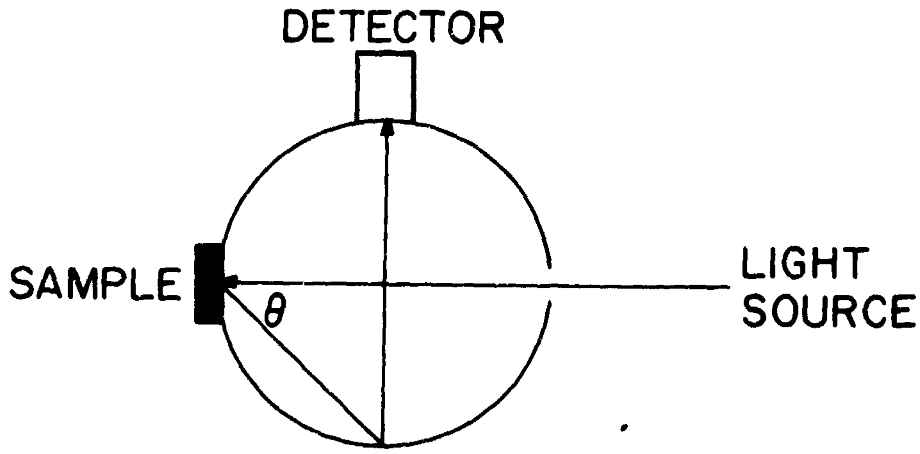
3.2.1 The Experimental Geometry

The experimental geometry is shown in Fig. 3. The reflecting surface of the sample defines the equatorial plane. θ_o 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 $\pi/2$ it is adequate to confine the measurements to planes of observation projections



(a) REFLECTION TYPE



(b) INTEGRATING SPHERE TYPE

FIG. 2. BASIC REFLECTANCE INSTRUMENTS

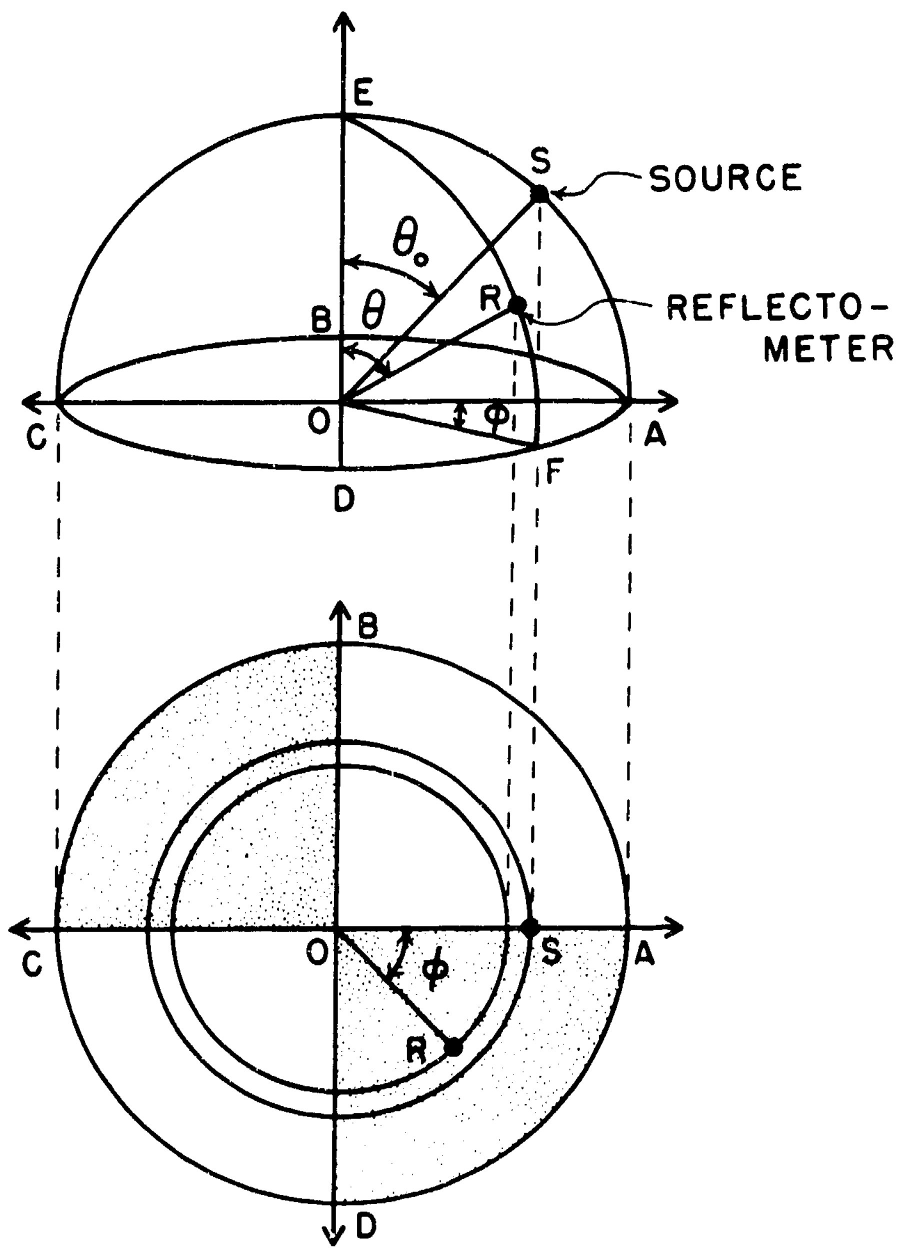


FIG. 3. EXPERIMENTAL GEOMETRY

of which onto the equatorial plane are contained within the pair of opposite quadrants AODA and COBC in Fig. 3. The nadir angle θ assumes values between 0 and $\pi/2$ on either side of the normal to the equatorial plane. When $\Phi = \pi/2$, θ need vary between 0 and $\pi/2$ on only one side of the normal. Further when $\theta_o = 0$, i.e. for normal illumination, measurements need be made only in the principal plane of the source.

3.2.2 Source of Illumination

A G.E. Mazda airway beacon lamp, operating on 30 V d.c. and rated at 1000 watts 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 uniformally 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_o, can be varied by moving the lamp-housing over a length of rigid tubing bent into the shape of an arc of circle of radius 7 1/2 feet. The sample is located at the center 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 is slightly dispersive. On examination with a simple photoelectric detector, it was found that the degree of linear polarization of the emergent beam had values of 95.8%, 99.83% and 99.86% at wavelengths of 3975, 5000 and 6050 A respectively.

3.2.3 The Reflectometer

The reflectometer is schematically shown in Fig. 4. It is of the conventional rotating analyzer type with a photomultiplier tube as the detector. Measurements of the degree of polarization can be made in three narrow spectral intervals (bandwidth ~ 150 Å) centered on λλ 3975, 5000 and 6050 Å.

The field of view of the instrument is limited to 3°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 rpm also actuates a programmed cam which operates a micro-switch in such a fashion that the output of the photomultiplier tube is sampled at 30°00' intervals over one complete revolution of the analyzer. Initial conditions are so arranged thot 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 endwindow is used as the detector. The antimony-cesium photocathode exhibits S-11 response. The spectral intervals of interest are isolated with multilayer, dielectric interference filters characterized by fairly steep pass bands. The transmission curves of the filters are seen in Fig. 5. The dynamic range of the detector is confined to two orders of magnitude with the use of neutral density filters that are introduced in

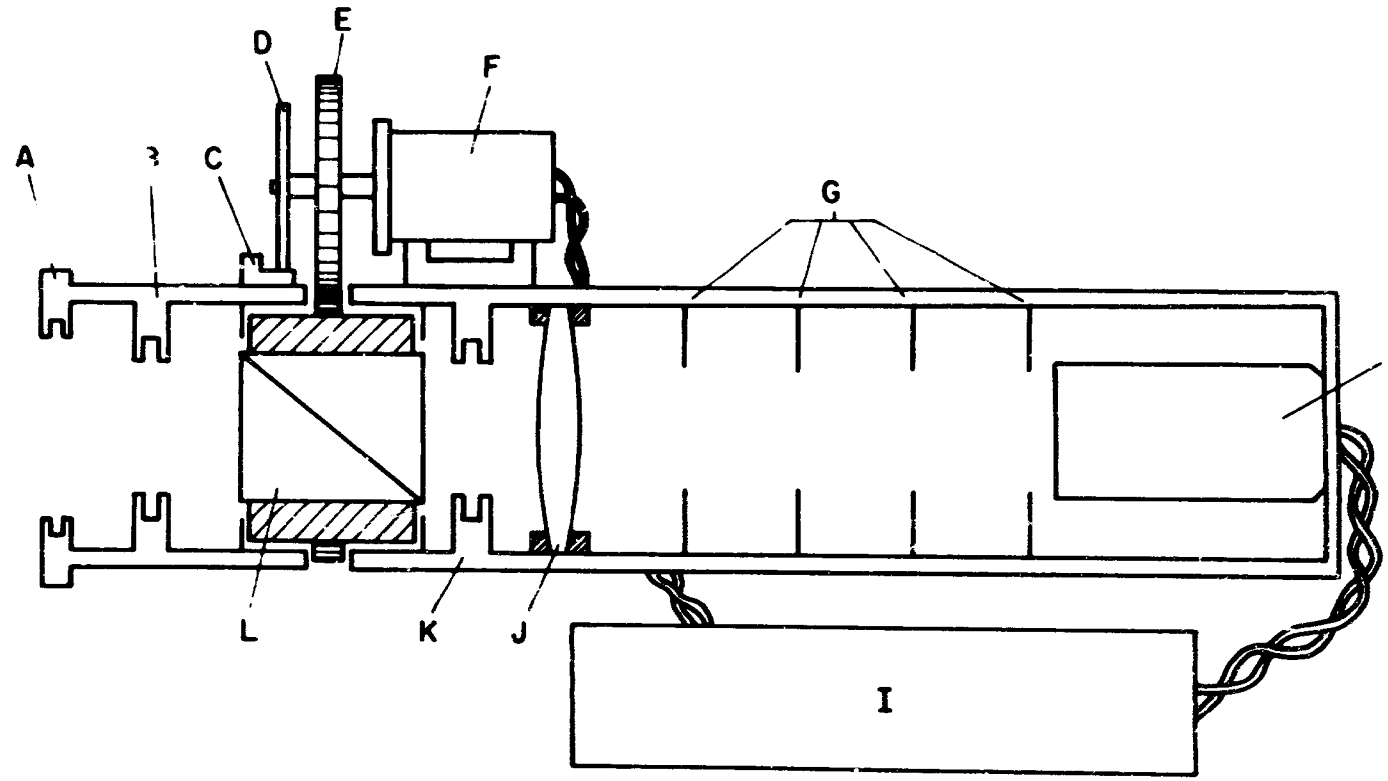


FIG. 4. THE REFLECTOMETER

A: HOLDER FOR NEUTRAL DENSITY WEDGE B: HOLDER FOR QUARTER WAVE PLATE C: MICROSWITCH D: PROGRAMMED CAM E: ANALYZER 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

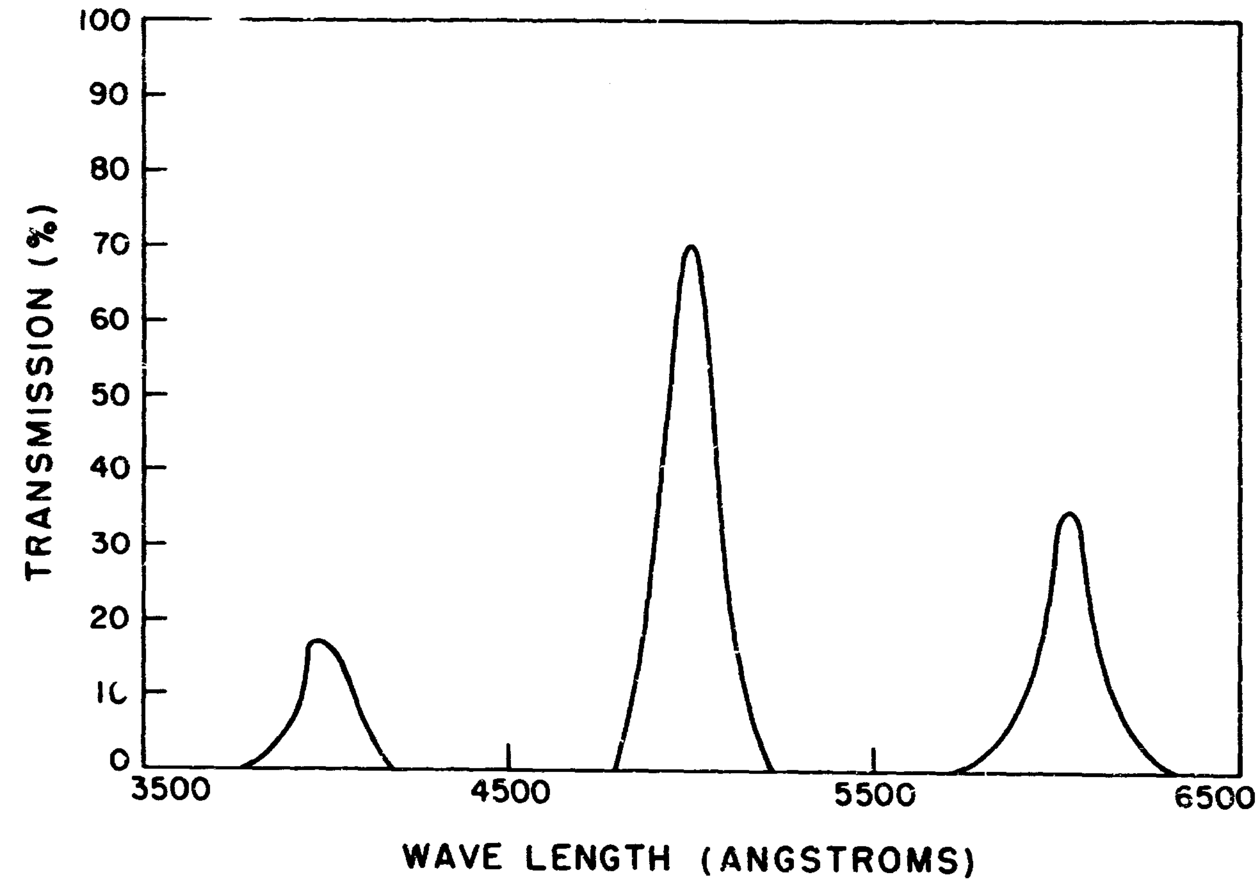


Fig. 5. TRANSMISSION CURVES OF THE FILTERS

the light path 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 continuously monitored or discretely sampled 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". The entire assembly measures about 20" in length and weighs about 5 lbs. 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" with the sample at the center. 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" x 12" x 3". 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 center. Figure 6 is a photograph showing details of the source, sample and the reflectometer.

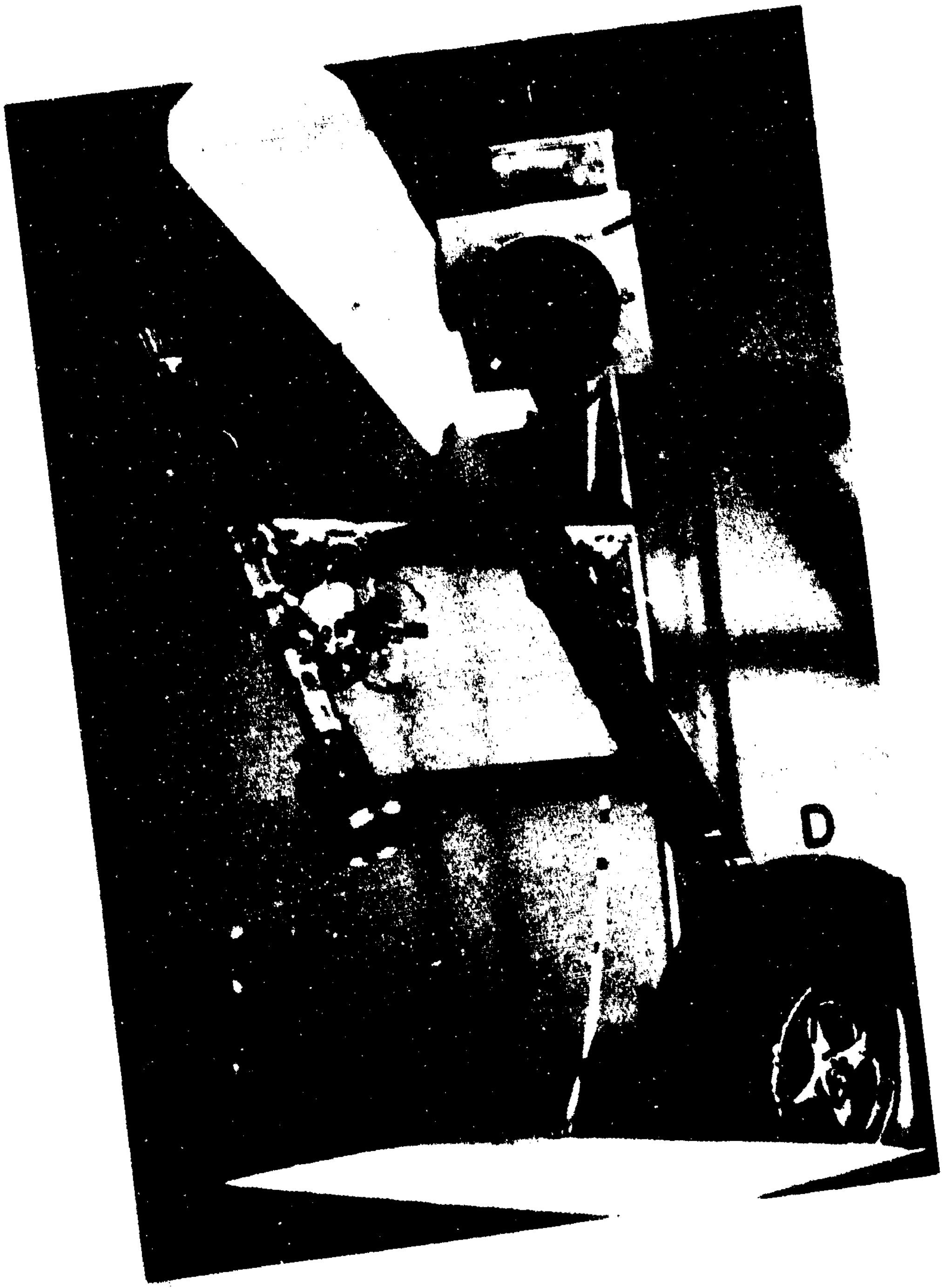


FIG. 6. EXPERIMENTAL ARRANGEMENT
A: Source B: Reflectometer C: Sample
D: Altazimuth Drive

3.2.4 Data Acquisition System

The photosignal developed across a precision signal resistor of 1.0 megohm passes through an inverting, variable gain operational amplifer. The output of the amplifier is fed into a Varian Model G-10 strip chart recorder and a Wyle Model 1504 A/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.

The linearity of response of the reflectometer and the detection system is shown in Fig. 7 . Figure 8 is a schematic representation of the principal stages of the data acquisition system of which Fig. 9 is a photograph.

3.3 Description of the Experiments

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°00' to the principal plane of the source have been examined. In the initial stages of the work it was deemed necessary, when the illumination

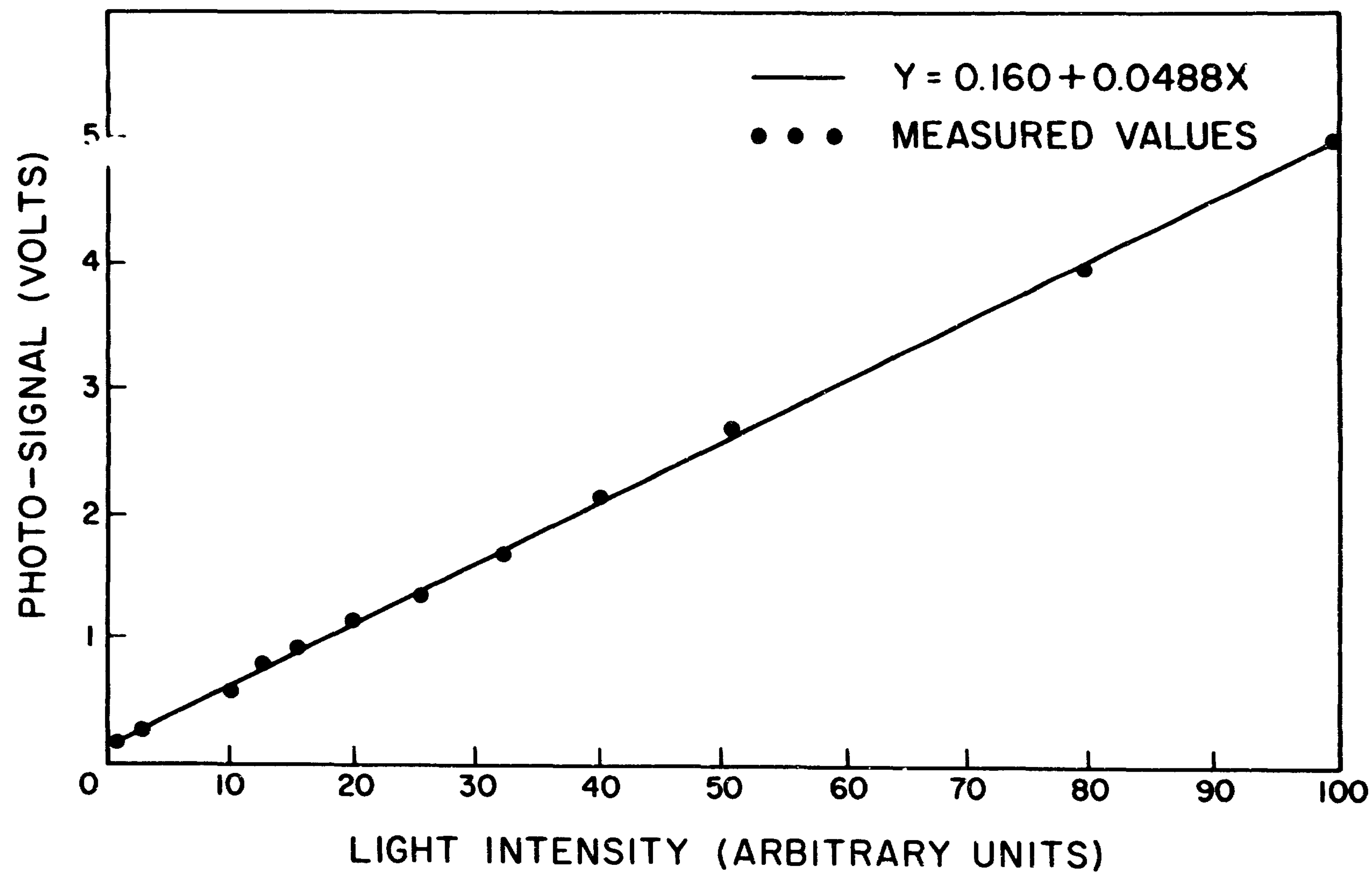


Fig. 7. REFLECTOMETER RESPONSE

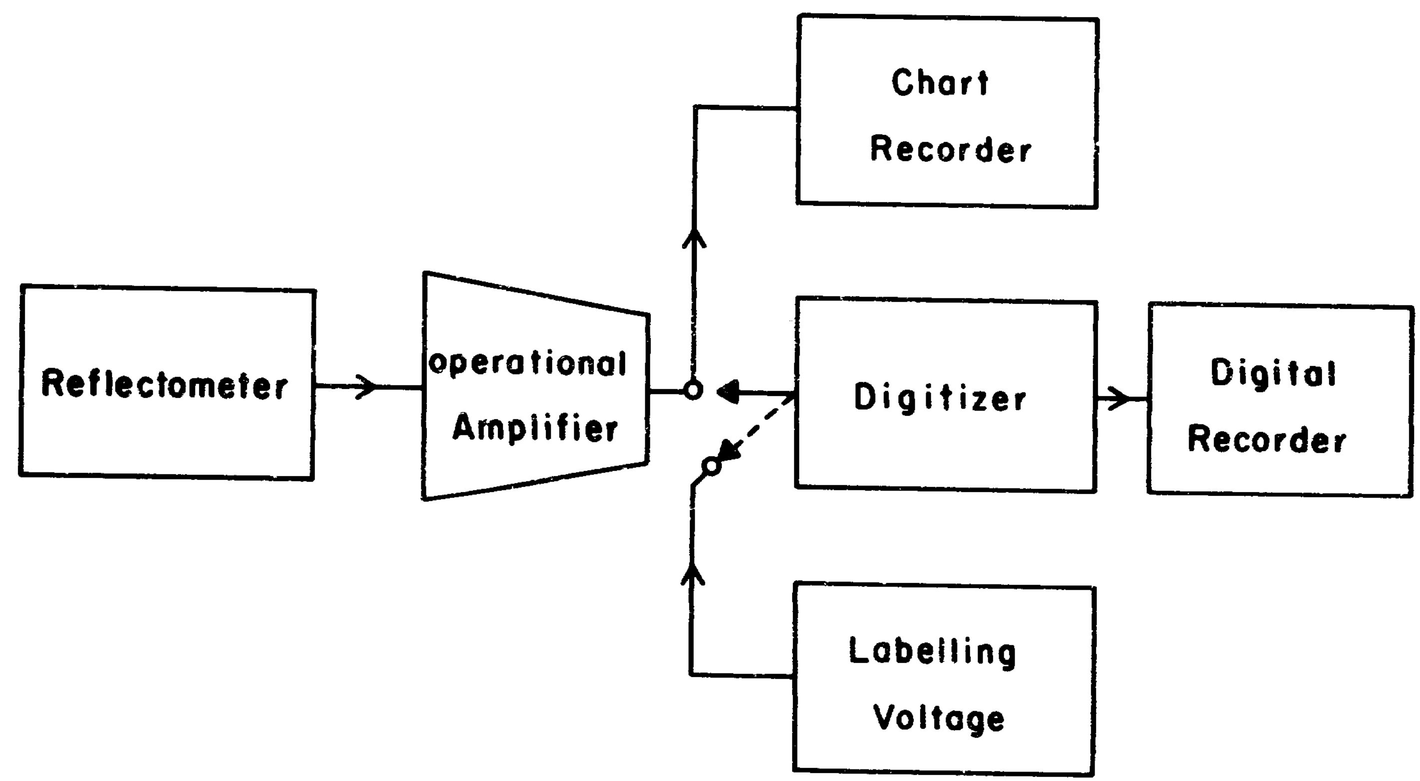


FIG. 8. SCHEMATIC DIAGRAM OF THE DETECTING SYSTEM

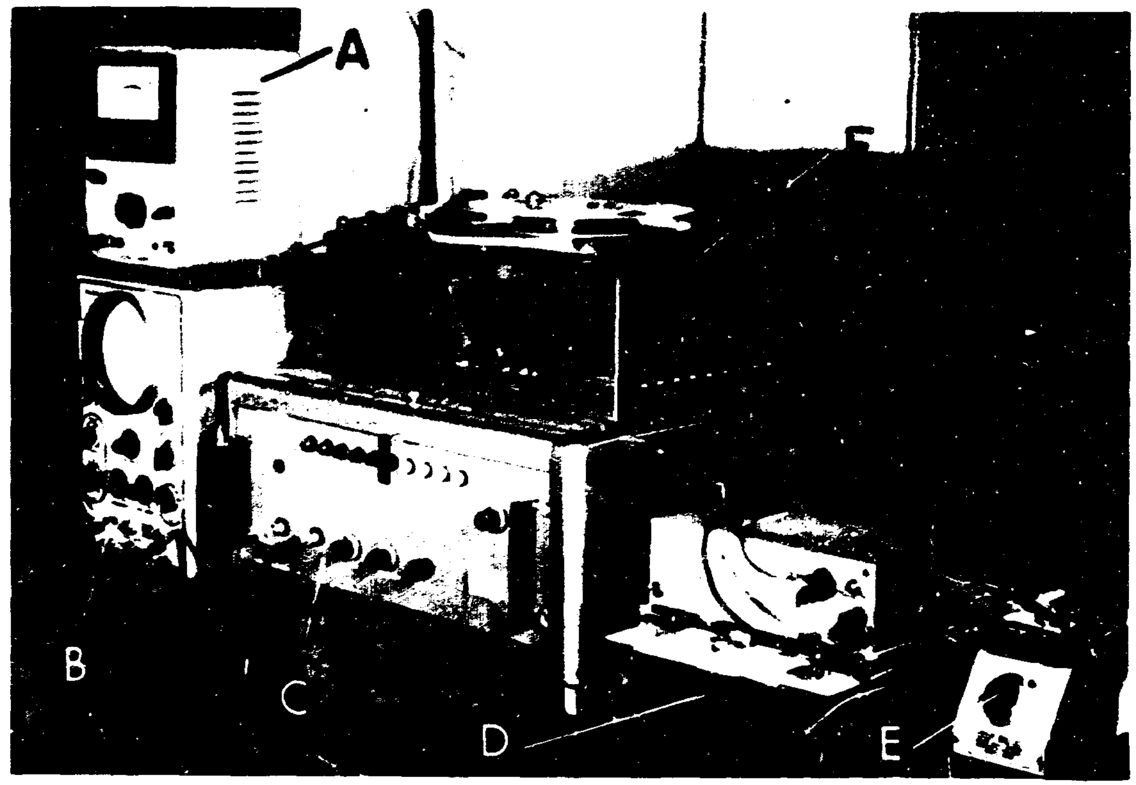


FIG. 9. DATA ACQUISITION SYSTEM
A: VTVM B: Oscilloscope C: 'Wyle' A/D Converter
D: Strip Chart Recorder E: Variable Gain Amplifier
F: 'Digidata' Digital Recorder

was polarized, to make duplicate sets of measurements with and without a quarter wave plate in the path of the reflected beam in order to detect ellipticity, if any, in the reflected beam. However this was soon discontinued because of limitations imposed by the present experimental setup.

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, a 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 $\Phi = 0^\circ (180^\circ)$, $45^\circ (225^\circ)$ and $90^\circ (270^\circ)$. Conditions of illumination have been varied by setting the angle of illumination $\theta_o = 0^\circ$, $53^\circ 00'$ and $78^\circ 30'$. This choice of angle of illumination was governed by considerations of possible comparison with computational and experimental work done elsewhere.

CHAPTER 4

RESULTS, DISCUSSION AND CONCLUSION

4.1 General

The intensity and the degree of polarization of the reflected light are directly related to the constant $a_o (= p_o)$ and the amplitude of the second harmonic, $a_2 \{ = (p_2^2 + q_2^2)^{\frac{1}{2}} \}$, occurring in Eqs. (2.11) of Chapter 2. Hence it is worthwhile to examine how reliable the scheme adopted for the harmonic analysis of the photosignal is before a discussion of the results is attempted. A typical set of computed values of the constant a_o and the amplitudes of the harmonics up to and including the fourth are shown in Table 1. These values correspond to measurements made in the principal plane with desert sand, illuminated with natural light, as the sample. This particular set was chosen since the values of the degree of polarization p computed from the formula $p = 100\, a_2/a_o$ could be compared with the results of independent measurements by Coulson who used the formula $p = 100(V_{max.} - V_{min.})/(V_{max.} + V_{min.})$ where V_{max} and V_{min} are the photosignals corresponding to the maximum and minimum values of the intensity of light transmitted by the rotating analyzer respectively. Such a comparison has been made in Fig. 10 and the close agreement between the two sets of values establishes the reliability of the particular scheme of harmonic analysis that has been adopted. Examination of Table I also reveals that a_2 is considerably greater than a_1, a_3 or a_4 over the greater part of the range of measurements; it becomes comparable to or less than any of a_1, a_3 and a_4 only

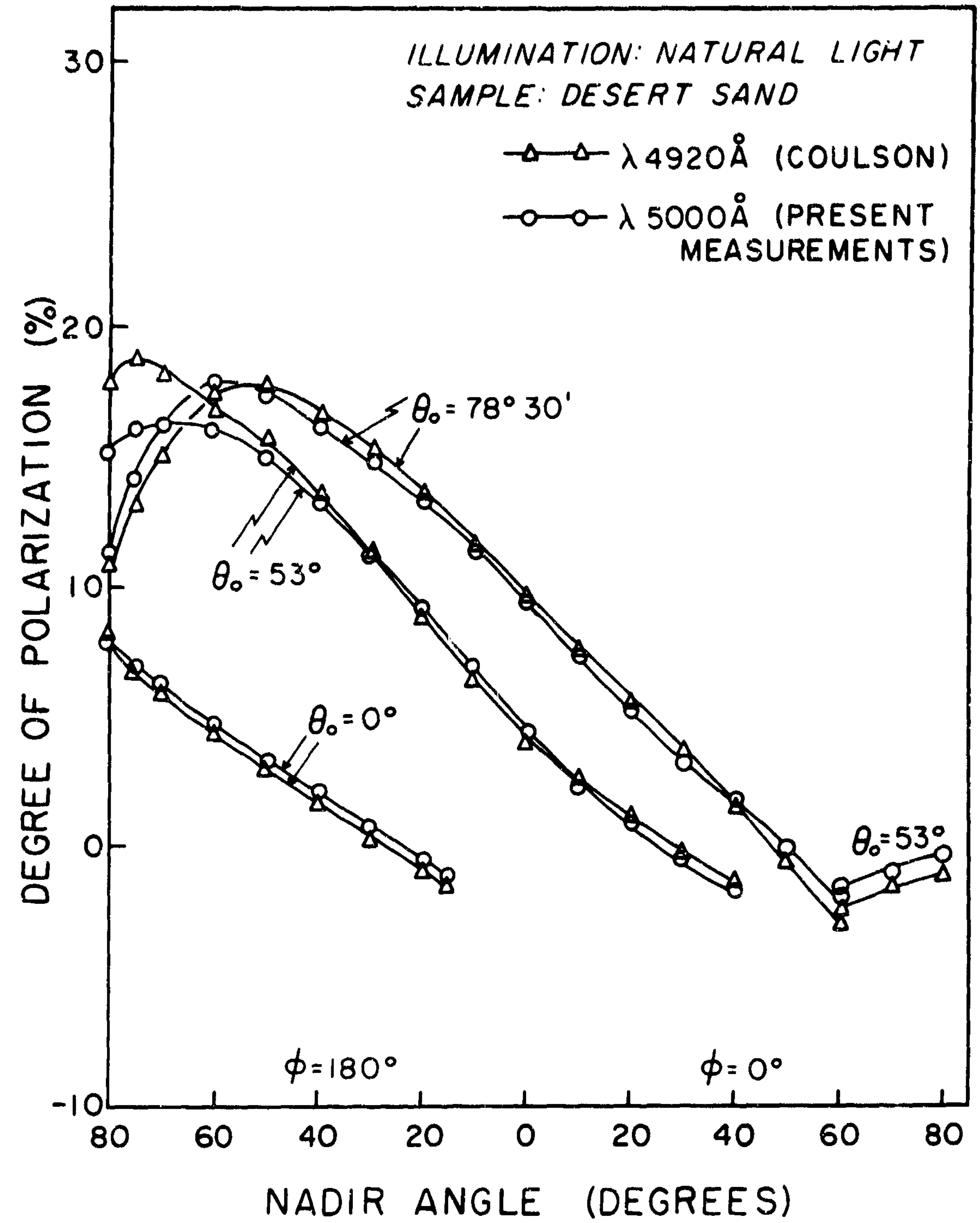


FIG. 10. COMPARISON OF THE RESULTS OF THE PRESENT MEASUREMENTS WITH COULSON'S RESULTS

in the vicinity of a neutral point where the degree of polarization is of the order of 1 or 2%. Examples of such behavior are denoted with an asterick in Table 1.

A word or two regarding the notation that has been adopted in the diagrams to follow may not be out of place. The results of measurements made under identical conditions of illumination and observation with the four samples are shown together to facilitate intercomparisons. The state of polarization of the illuminating radiation is indicated by an appropriately drawn arrow. Thus a vertical arrow indicates that the illumination was parallel to the plane of incidence; a horizontal arrow indicates that the illumination was polarized normal to the plane of incidence and an arrow drawn at 45° (approximately) to the horizontal would indicate that the illumination was polarized at an angle of 45° to the plane of incidence.

The normalized intensity shown in the diagrams is defined as the ratio of the intensity of the light reflected in the direction (θ, φ) to the intensity of the light reflected along the vertical $(\theta = 0)$ in the two cases when the angle of illumination (θ_o) is either 53° or $78^{\circ}30'$. However, when $\theta_o = 0$, i.e. for normal illumination the definition of normalized intensity has been changed to imply the ratio of the intensity of the light reflected in the direction $(\theta, \varphi = 0 \text{ or } \pi)$ to the intensity of the light reflected in the direction $(15^{\circ}, \varphi = 0 \text{ or } \pi)$.

TABLE 1. Specimen Computations of the Amplitudes of the Harmonics

Sample: Desert Sand, Illumination: Natural Light

$\vartheta_o = 78^\circ 30'$, $\lambda = 5000$ A

ϕ°	ϑ°	a_0	a_1	a_2	a_3	a_4
180	80	0.992	0.02747	0.11268	0.02319	0.02411
180	75	4.070	0.06384	0.43155	0.00636	0.00729
180	70	3.100	0.01891	0.41902	0.01147	0.02314
180	60	2.520	0.01328	0.37920	0.00711	0.02032
180	50	1.660	0.01323	0.32770	0.00573	0.01835
180	40	1.490	0.00775	0.25977	0.01006	0.01930
180	30	1.280	0.00855	0.21165	0.00159	0.01102
180	20	1.150	0.00219	0.17423	0.00656	0.01144
180	10	1.050	0.00339	0.14415	0.00356	0.01682
0	0	0.995	0.00798	0.10660	0.00356	0.01114
0	10	0.975	0.00843	0.06646	0.00318	0.00729
0	20	1.000	0.00514	0.05364	0.00318	0.00573
0	30	1.060	0.00627	0.03214	0.00159	0.00159
0	40	1.160	0.01499	0.02454	0.01309	0.00795
0	50	1.330	0.01222*	0.00694*	0.00318*	0.00477*
0	60	1.620	0.01090	0.02943	0.00599	0.00729
0	70	Shadow				
0	75	Shadow				
0	80	Shadow				

*Neutral Point

4.2 Discussion of the Results

A quick look at the results indicates the overall similarity in behavior of soil and desert sand and hence these will be discussed together. The very strong depolarization characteristics exhibited by white sand places it under a different category. However, in all the three cases , because of the finite grain size which is very large compared to the wavelength of illuminating radiation, the results are to be interpreted, at least partially, in terms of the laws of geometric optics. On the other hand, water, in this particular experimental setup, exhibits some of the properties of an 'optically rough, locally flat' surface and hence some of the results must be examined at least in a qualitative fashion in the light of laws governing scattering of radiation by rough surfaces. One of the possible reasons for such behavior on the part of water is that the sample tray containing water was subjected to high frequency, small amplitude vibrations in the building resulting in a system of ripples on the surface. This was borne out by the observation that most of the surface of the water outside of the illuminated area was shimmering. These ripples on reflection at the edges and corners of the sample tray presumably caused enough departures of the actual surface from the mean surface.

In what follows, for the sake of brevity and to minimize redundancy, the convention will be adopted that a reference to diagrams would imply most of the diagrams from Fig. 11 through Fig. 38. Specific reference to a particular diagram will be made only when it is felt that a physically important aspect may go unnoticed otherwise.

4.2.1 Soil and Desert Sand

It is obvious from the results that the polarization of the reflected light has a very strong wavelength dependence. It decreases with increasing wavelength and such behavior is uniformly noticed under all conditions of illumination and observation. For normal illumination with natural light, the degree of polarization shows a steep increase towards larger nadir angles in the principal plane. However a steep decrease towards larger nadir angles in the principal plane is observed for normal illumination with light polarized either parallel to the plane of incidence or at an angle of 45° to the same (Fig. 25 and 32). When the illumination is polarized perpendicular to the plane of incidence, minima in the polarization distribution curves are observed around intermediate values of nadir angles. When the angle of illumination assumes values of 53° or 78°30' definite maxima in the polarization curves are observed in all the three colors when observations are made in the principal plane with natural illumination. These maxima are situated in a broad region about 90-120° removed from the direction of antisource point (Figure 12 and 15). This trend is reversed and minima are observed when the incident light is polarized either parallel to the plane of incidence or at 45° to it. This behavior can be seen in Figs. 26, 29, 33 and 36. When the incident light is polarized perpendicular to the plane of incidence, only a gradual increase in polarization towards the limb on the antisource side is observed (Fig. 19 and 22).

In the plane perpendicular to the plane of incidence, i.e. when $\varphi = 90^\circ$ (270°) for $\theta_o = 53^\circ$ or $78^\circ 30'$, the degree of polarization of the reflected light shows a gradual increase towards the limbs when the incident light is either unpolarized or polarized parallel to the plane of incidence. The reverse trend of decreasing polarization towards the limbs is observed when the illumination is polarized either normal to the plane of incidence or at an angle of 45° to it. In the latter case, a slight hump is observed at intermediate values of the nadir angle (Figs. 35 and 38). The two samples continue to exhibit overall similarity when observations are made in the plane $\varphi = 45^\circ$ (225°). The polarization distribution is asymmetrical.

Neutral points, (i.e. points at which unpolarized light is detected) are observed in the principal plane on either side of the antisource point when $\theta_o = 0^\circ$ or 53° and above the antisource point when $\theta_o = 78^\circ 30'$. No set behavior either in their dispersion or in their angular distances from the antisource point is observed. An interesting feature is the occurrence of very pronounced minima ($\sim 1\%$)--especially at longer wavelengths-in the polarization of the reflected light in the plane $\Phi = 225^\circ$ when the samples are illuminated at an angle of $53^\circ 00'$ with light polarized parallel to the plane of incidence (Fig. 27).

For normal illumination, both samples exhibit darkening towards the limbs the reasons for which are obvious. When $\theta_o = 53$ or $\theta_o = 78^\circ 30'$, in the principal plane, the samples appear brighter at larger nadir angles in the plane $\varphi = 180^\circ$. This brightening becomes very pronounced when $\theta_o = 78^\circ 30'$.

Brightening towards the limbs is also observed in planes of observation other than the principal plane. Very often a slight decrease in brightness towards the very edges of the samples is observed.

4.2.2 White sand

It has been deemed proper to consider this sample as different from either desert sand or soil because of low values of the polarization of the reflected light and because of the not so pronounced variation in the normalized intensity values over the greater part of values assumed by the nadir angle on either side of the local vertical. The wavelength dependence of the polarization of the reflected light is also not so pronounced as in the case of desert sand or soil. So far as the occurrence of the neutral points is concerned, this sample behaves like the other two.

When $\theta_o = 53^\circ$ or $78^\circ 30'$ the polarization of the reflected light assumes large values (40%) in the specular region, i.e. around $\theta = \theta_o$ in the plane $\varphi = 0^\circ$ (180°). The normalized intensity also increases rapidly in this region especially when $\theta_o = 78^\circ 30'$. This leads one to suspect that this granular sample, which is a gypsum derivative, may exhibit specular characteristics when viewed under grazing illumination like the majority of real materials.

The overall description of a strong depolarizer of the Lambert type fits best this sample because of the low values of polarization of the reflected light in the majority of the cases studied, the small dispersion that is associated with the same and because of the fact that the normalized intensi', is around

0.95 up to values of $\theta \sim 70^{\circ}$ in the principal plane under conditions of normal illumination (Fig. 11b, 18b, 25b and 32b).

4.2.3 Water

The choice of water as one of the samples for study was governed by considerations of comparison between the behavior of samples which are composed of opague or translucent particles and of one to which the description of a specular reflector would fit best. However it was realized, after the work was completed, that because of the particular experimental setup, not all of the results could be explained in terms of specular (Fresnel) reflectivity. The concept of scattering of light by an 'optically rough, locally flat' surface had to be invoked as one of the possible reasons for observed discrepancies. No attempt is made, however, to give any theoretical explanations for the same.

Observations had to be confined to the principal plane as it was realized that outside of the principal plane the signal to noise ratio of the system approached unity. This established the relatively feeble nature of lateral scattering, if any, by the eater sample of depth about 2.5" contained in a black bottomed tray. This in turn led to the association of a "mean level" with the sample. The 'mean level' would be governed by the Fresnel laws and departures from the characteristic behavior of a Fresnel reflector may be due to the presence of the system of ripples on the water surface.

Examination of the normalized intensity under non-normal illumination, i.e. when $\theta_o \neq 0$ reveals that the normalized intensity in the specular direction is a few orders of magnitude larger than the normalized intensity in any other direction. This gives credence to the hypothesis of a mean level which acts as a Fresnel reflector. However, the detection of appreciable amounts of light in non-specular directions indicates 'longitudinal scattering' (Beckman[14]) i.e. scattering in the plane of incidence, by the water surface. This could be possible only if the existence of elemental areas whose surface normals may or may not lie in the plane of incidence and which may be so randomly oriented that for any angle of illumination at least some of them would be such that with respect to these and not with respect to the mean level, the direction of observation would be the specular direction is postulated.

The dispersion of polarization is not very pronounced in the majority of observations since the governing factor is the refractive index in both the 'mean level' and 'elemental mirror' pictures and it does not vary appreciably over the wavelength region of interest. When the incident light is natural and when $\theta_o = 53^\circ$ which is very near the Brewster angle for all the three wavelengths, the polarization of light reflected in the specular direction attains very high values (> 80%) (Fig. 12). However the departure from complete polarization in the specular direction and the presence of polarized reflected light in other directions does indicate the inadequacy of the concept of a 'mean level'. Similarly the 'mean level' concept can explain the presence of the sudden discontinuity in the polarization distribution curve in the specular direction when $\theta_o = 53^\circ$ and the incident light is polarized parallel to the plane of incidence (Fig. 26a). But the presence of considerable residual polarization points to the inadequacy of the same.

The reflected light shows a very high degree of polarization (~ 80% or higher) when the incident light is completely plane polarized. (The departure from complete polarization of the incident light assumes a small but finite value of 3% for blue light because of the blue leak exhibited by the HN 38 polarized sheet). The high degree of polarization of the reflected light may be explained then in terms of the elemental surfaces whose dimensions are large compared to the wavelength of light and whose normals are properly oriented to render the direction of observation the specular direction. Under these circumstances the state of polarization of the reflected light will be similar to the state of polarization of the incident light. However the departure from complete polarization of the reflected light may be due to the depolarizing effects of some of the elemental surfaces whose normals may lie outside the plane of incidence defined by the direction of illumination and the normal to the mean level.

It should be pointed out these arguments are purely speculative, drawn in analogy with scattering of microwaves by rough surfaces. Perhaps better theoretical explanations will be forthcoming.

4.3 Conclusion

The polarization of the reflected light shows definite wavelength dependence in the case of all the samples that have been studied under different conditions of illumination. The extent of dispersion, however, varies samples to sample. It is very pronounced for desert sand and soil and not so pronounced for white sand and water. The three samples composed of opaque and translucent particulate matter, namely desert sand, white sand and soil, exhibit depolarizing characteristics when the illumination is completely linearly polarized. This may be attributed to the multiple reflections that occur in the interstices in the particulate matter. White sand depolarizes to a greater extent than either desert sand or soil. This may be because in addition to multiple reflections in the interstitial spaces, part of the illumination penetrates the individual particles which are translucent and suffers multiple reflections inside the particles before emerging in the direction of observation. Examination of the relative intensity variations indicates that white sand is nearer to an ideal diffuser of the Lambert type than either of the remaining two. The asymmetry of the distribution of the intensity of light reflected in the principal plane by soil and white sand may be attributed to the screening or shading effects of individual grains, the dimensions of which are large compared to the wavelength of the illuminating radiation.

The hypothesis of scattering of light by an 'optically rough, locally smooth' surface has to be invoked to explain the existence of certain anomalies in the polarization features of light reflected by the water surface. The concept of a 'mean level' governed by the Fresnel laws explains the very highly intense reflected beam in the specular direction and also partly the sudden discontinuity in the polarization of the reflected light in the specular direction when the angle of incidence is very near the Brewster angle and the illumination is polarized parallel to the plane of incidence. However the residual polarization under these circumstances and the fact that over the entire plane of observation the reflected light exhibits very high polarization (~80%) when the illumination is completely linearly polarized cannot be explained by the 'mean level' theory. The existence of innumerable elemental surfaces with their surface normals so oriented that at least for some of them the direction of observation is the specular direction may explain this behavior. However conclusions cannot be drawn until results of definitive, quantitative theoretical investigations are available.

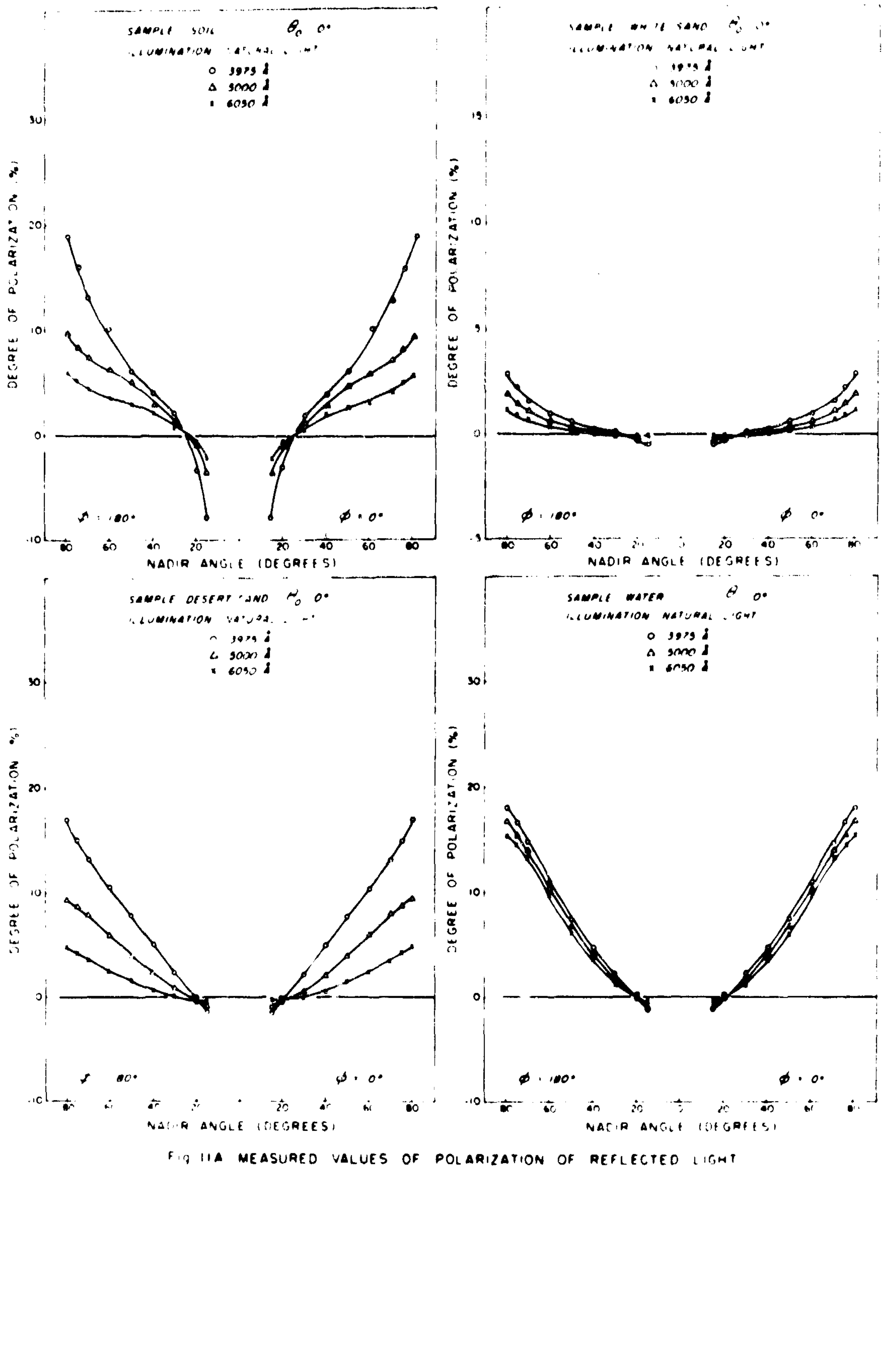


Fig 11A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

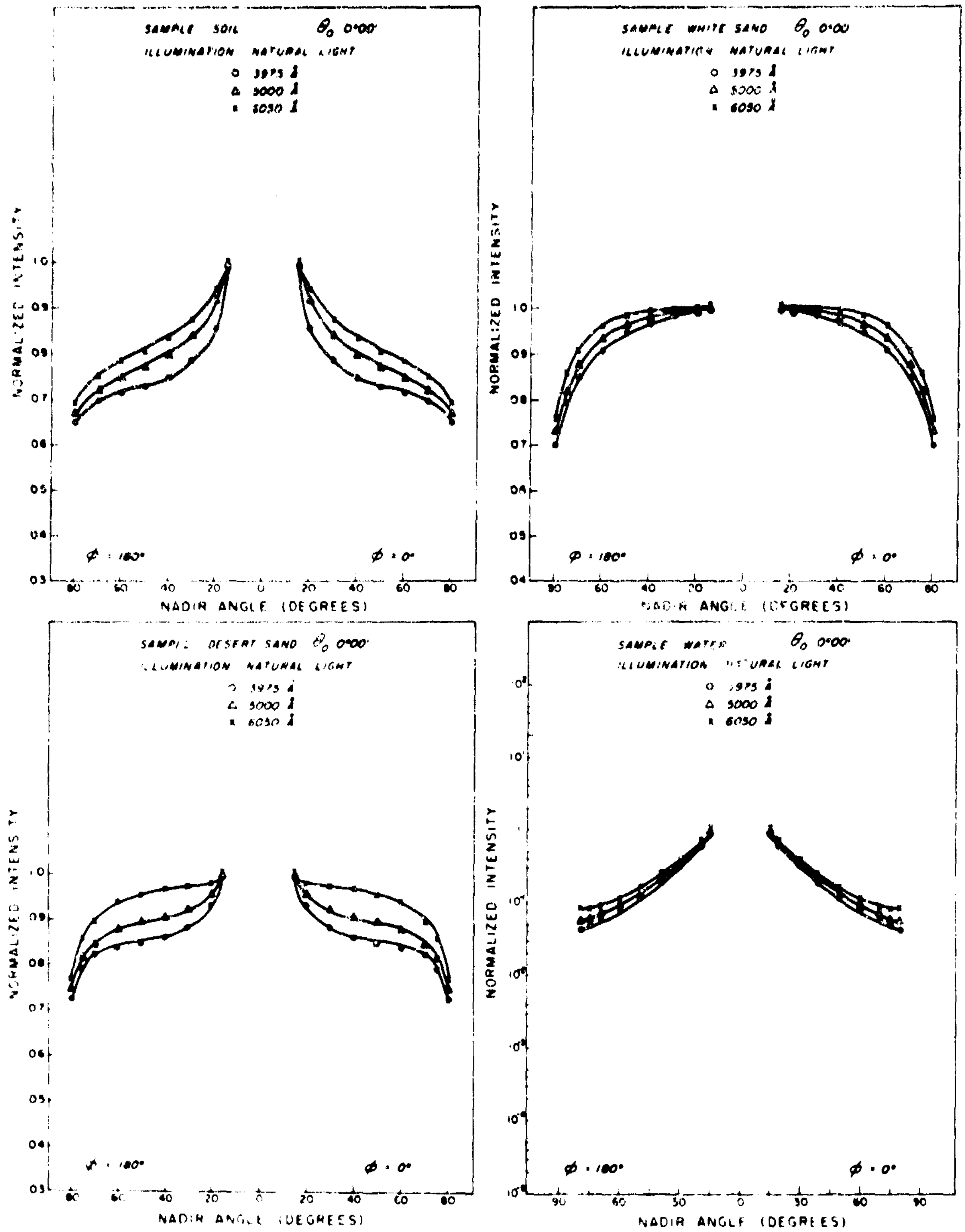


Fig 11b MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

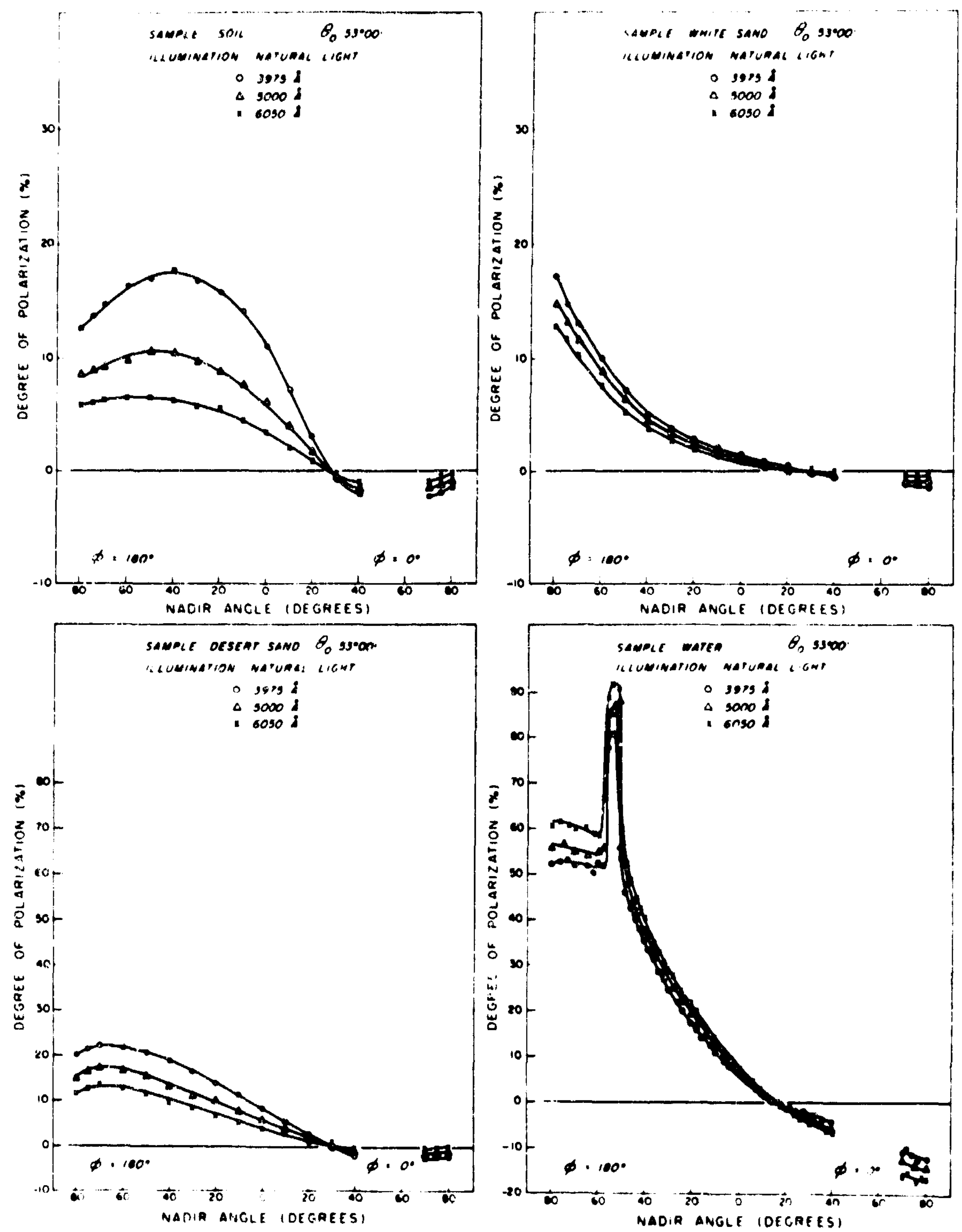


FIG 12A. MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

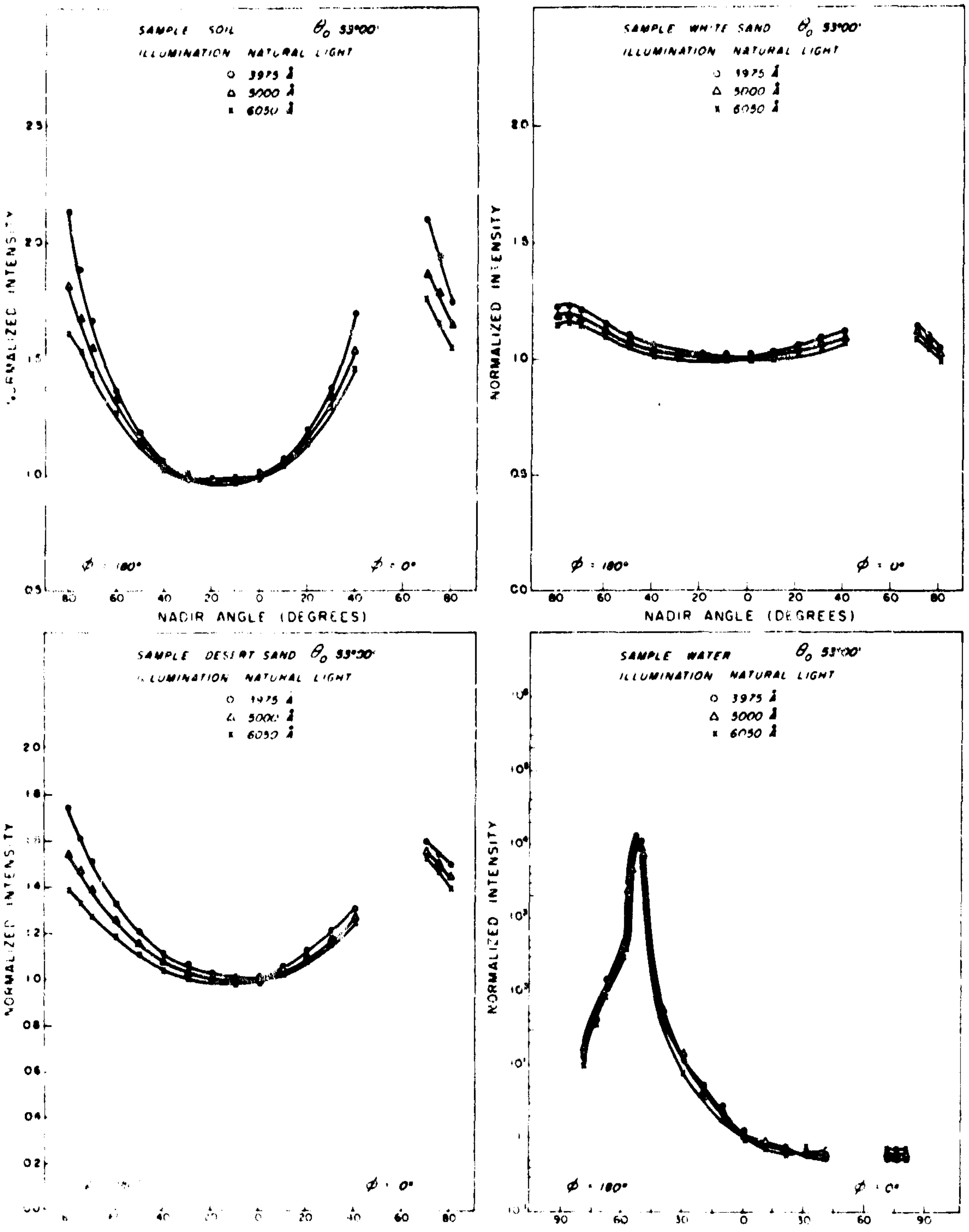


Fig 12B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

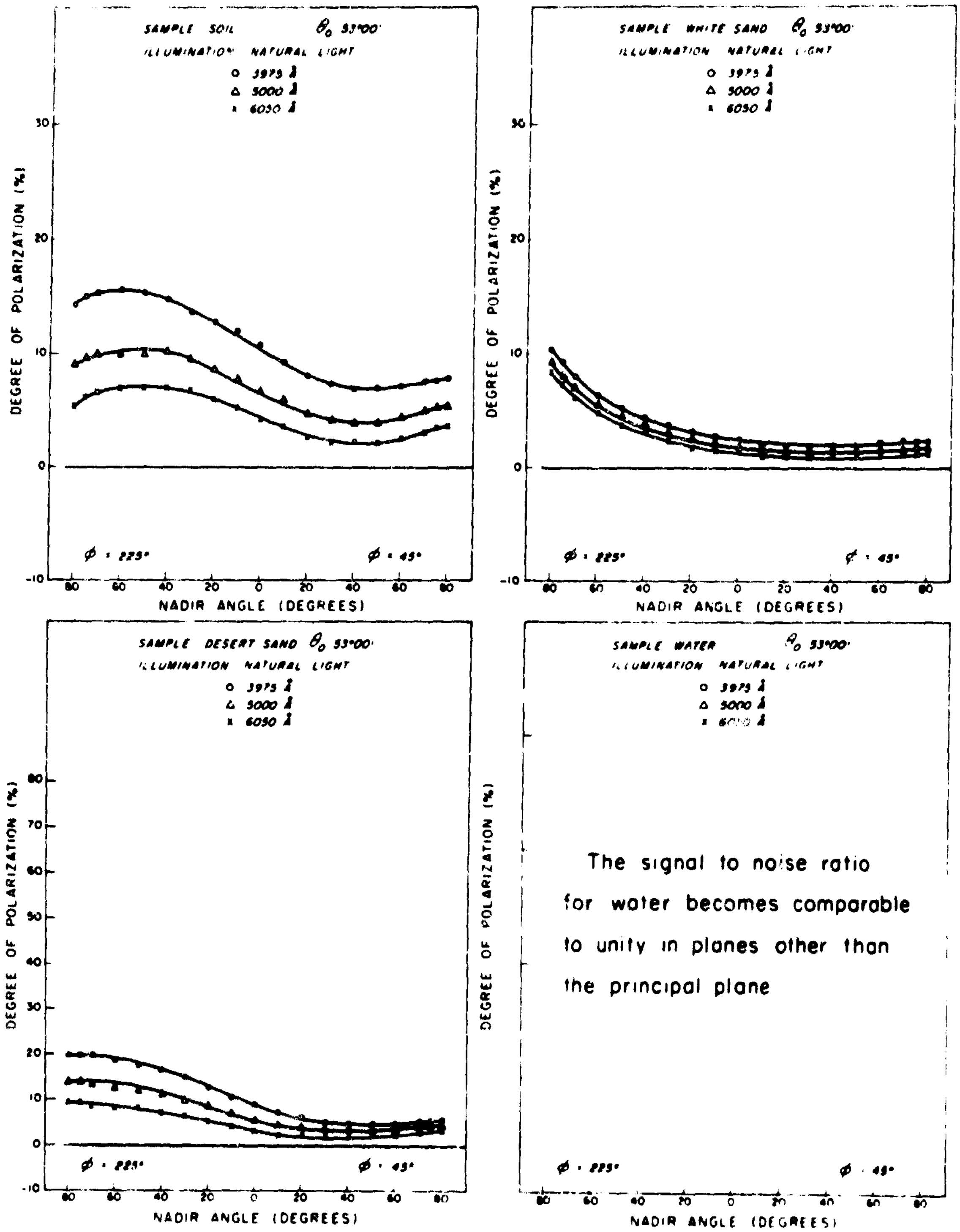


Fig 13A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

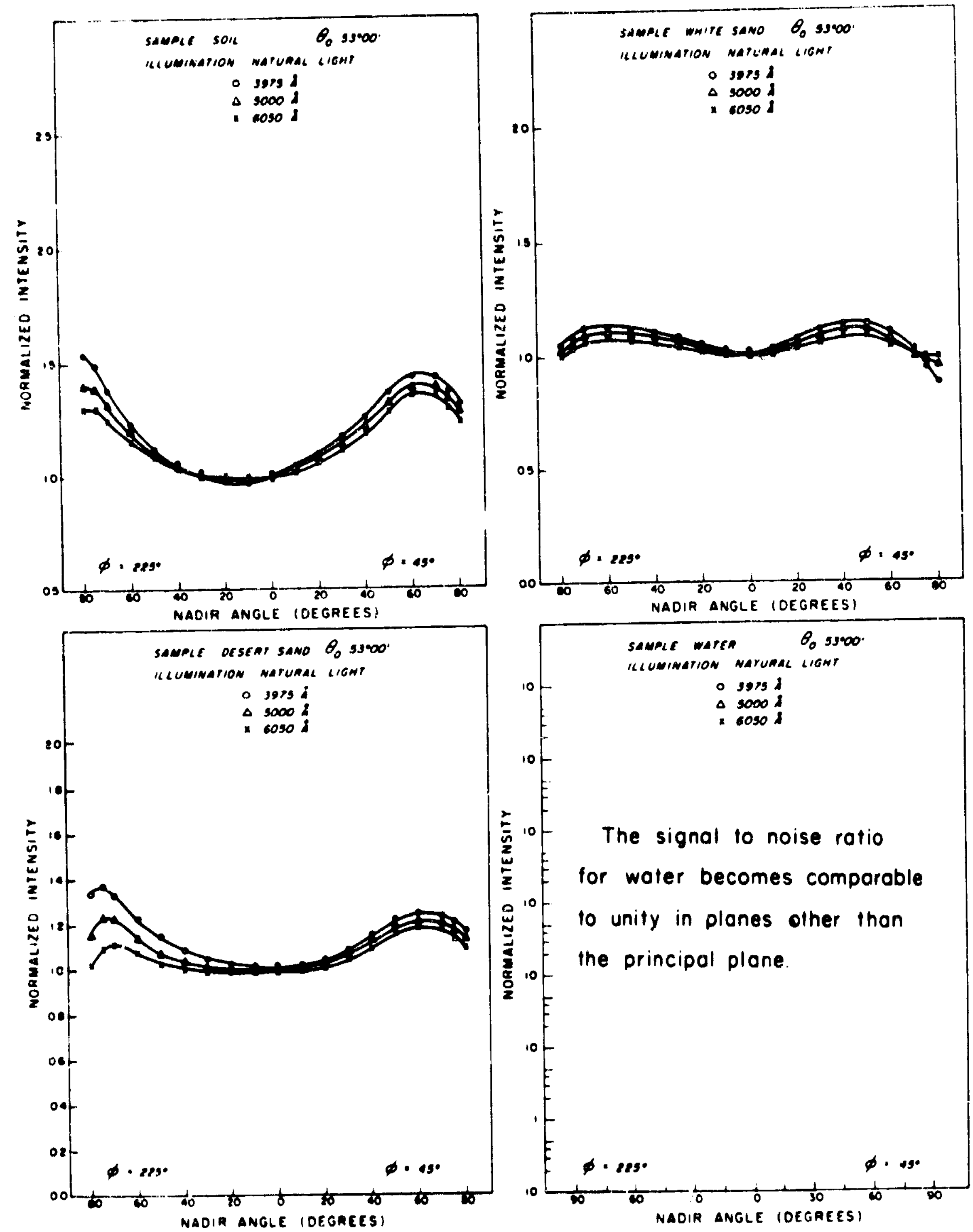


Fig 13B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

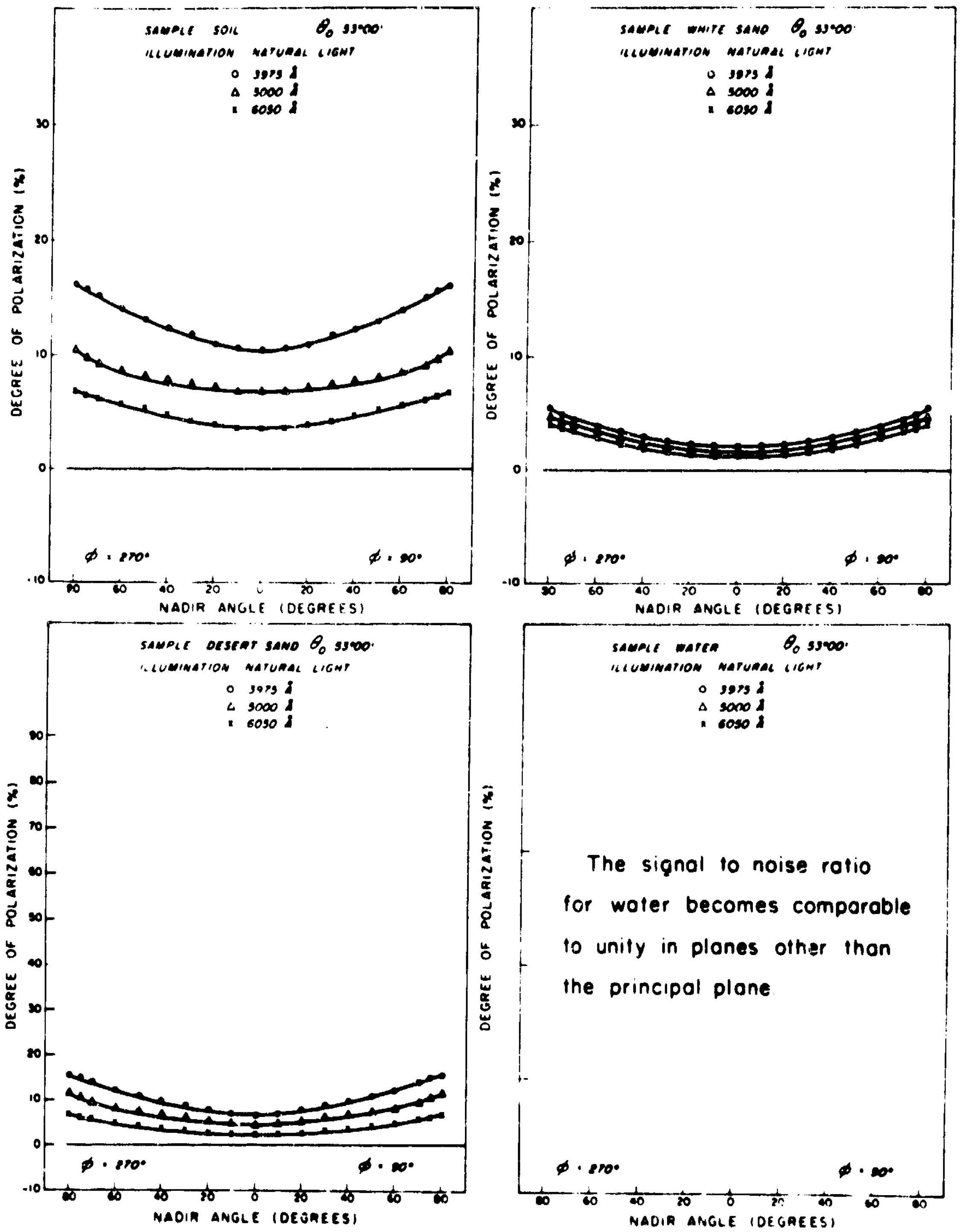


Fig. 14A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

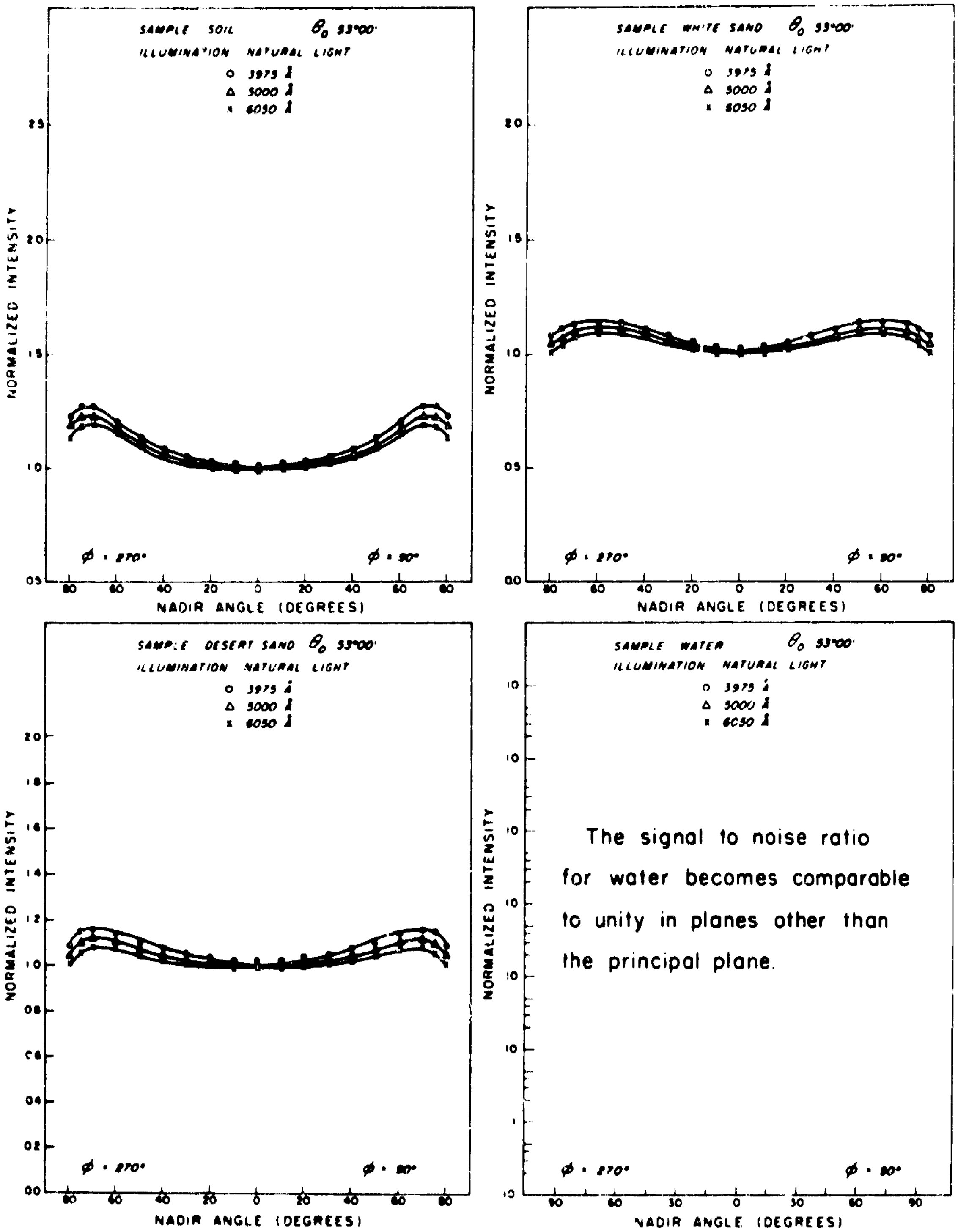


Fig 14B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

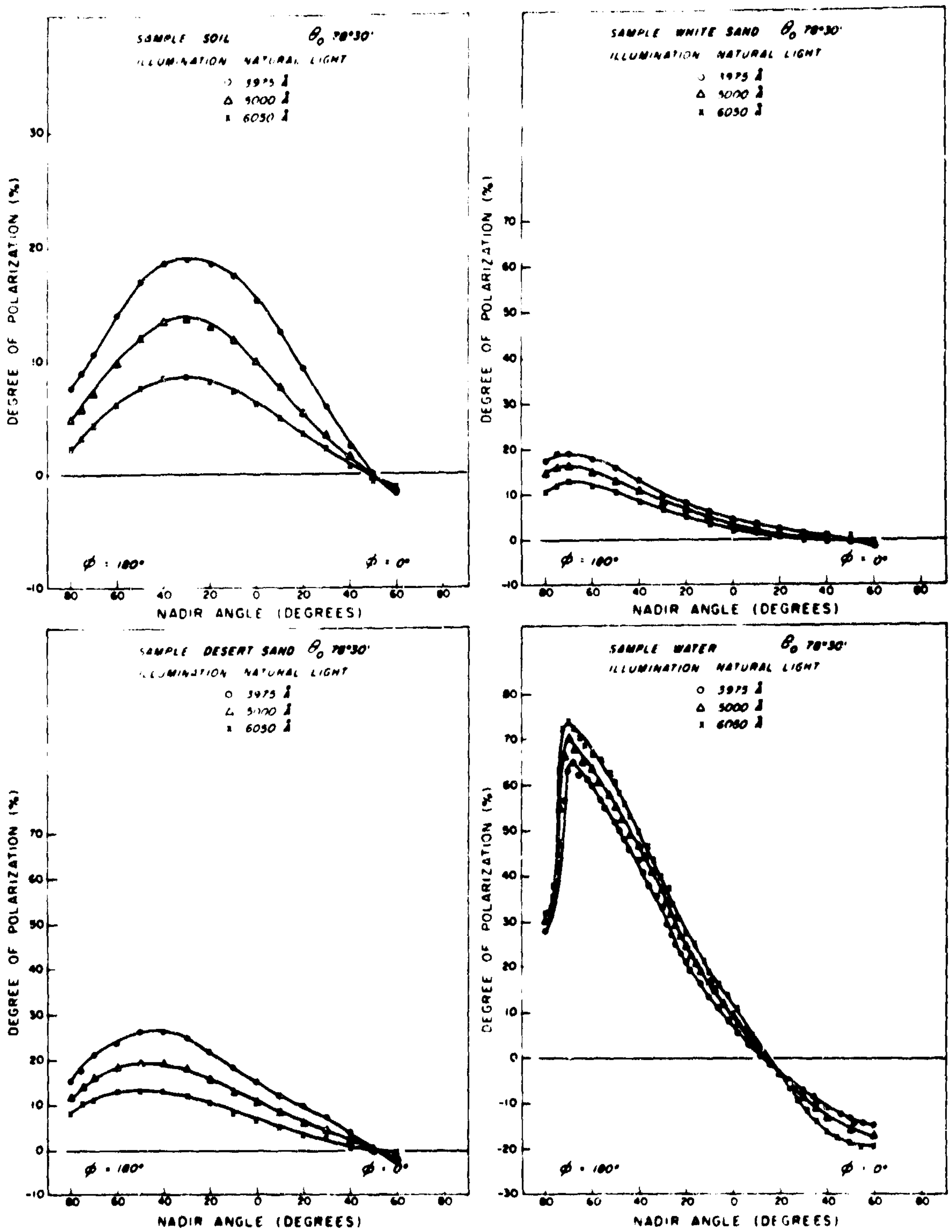


Fig. 15A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

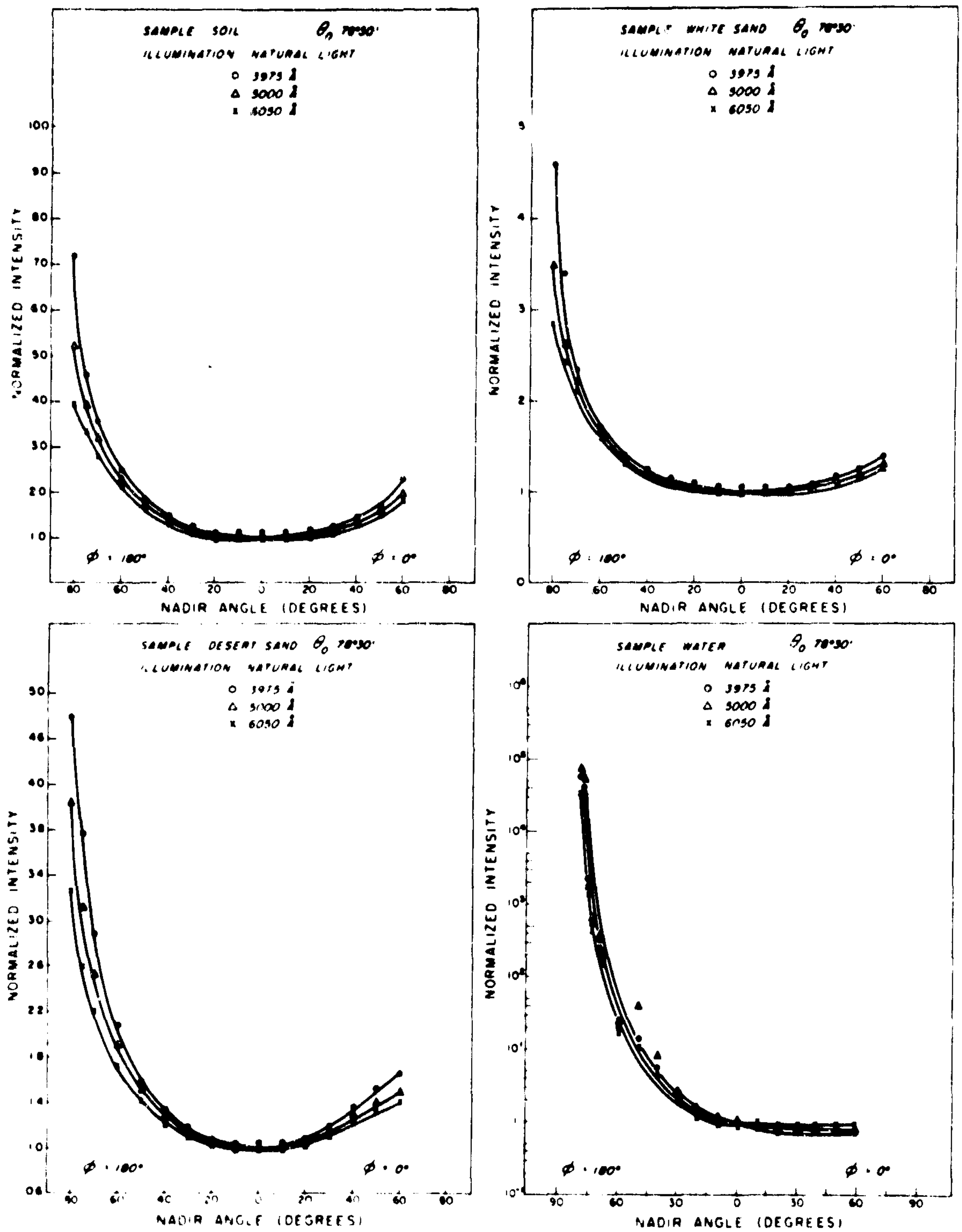


Fig 15B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

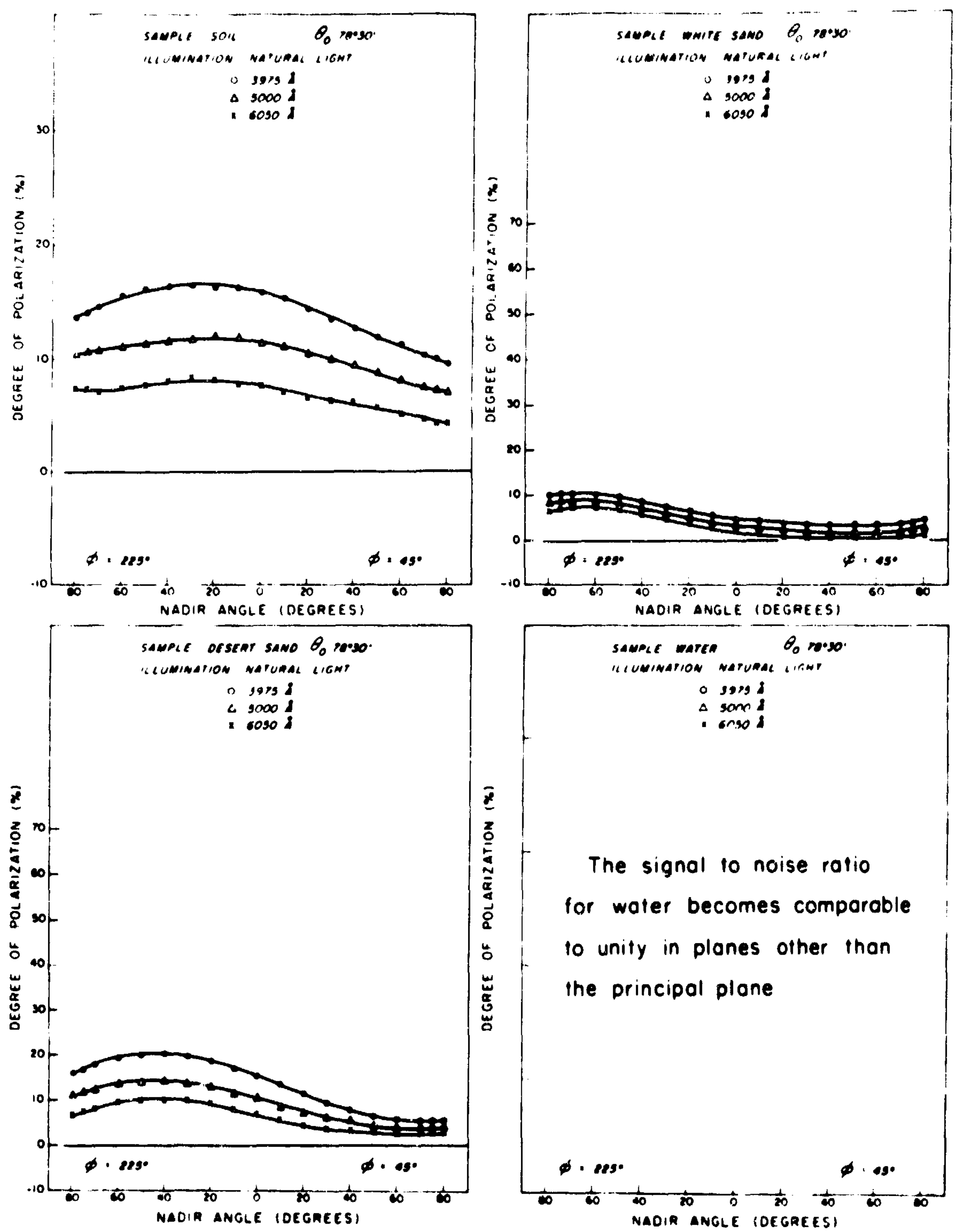


Fig. 16A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

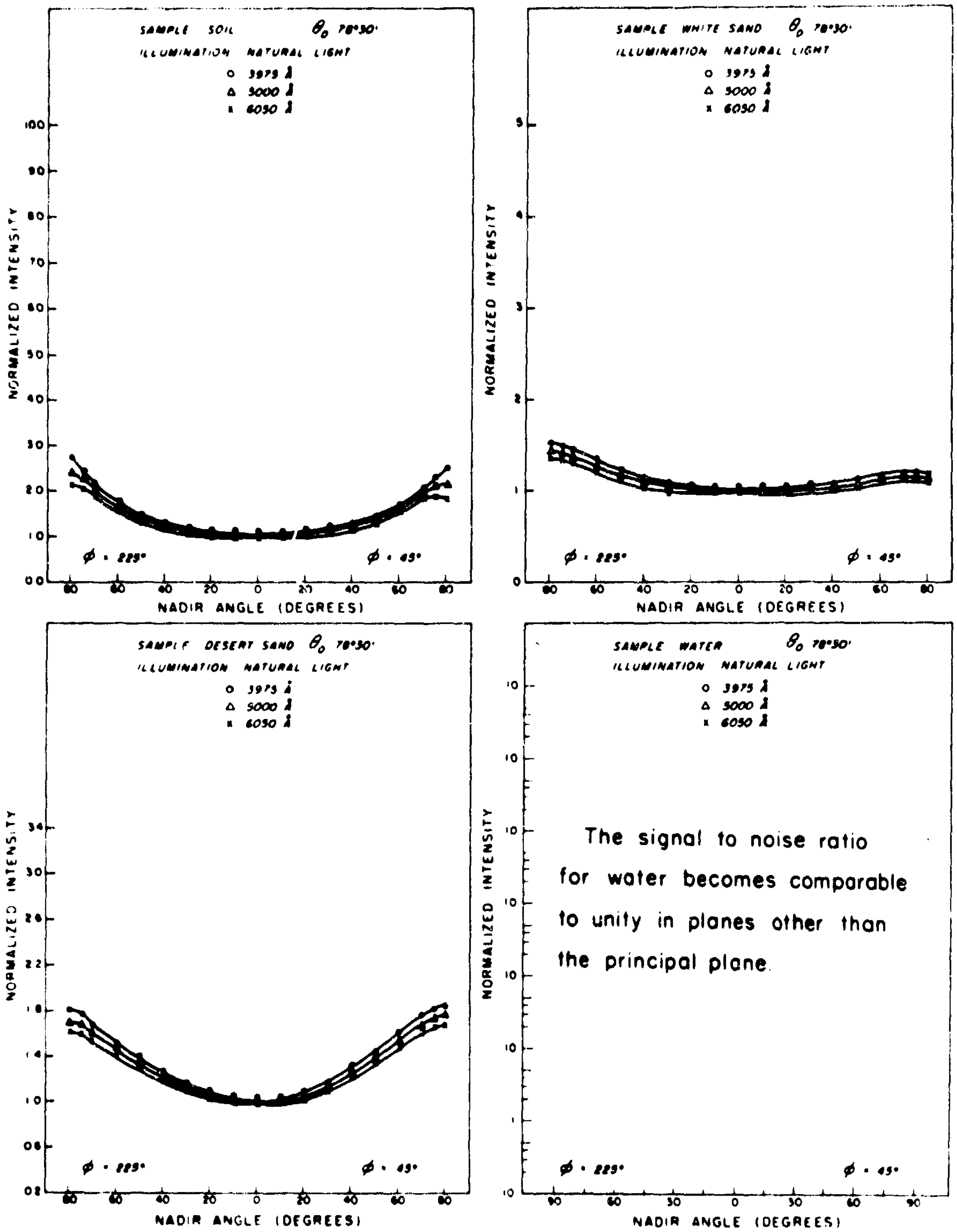


Fig 16B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

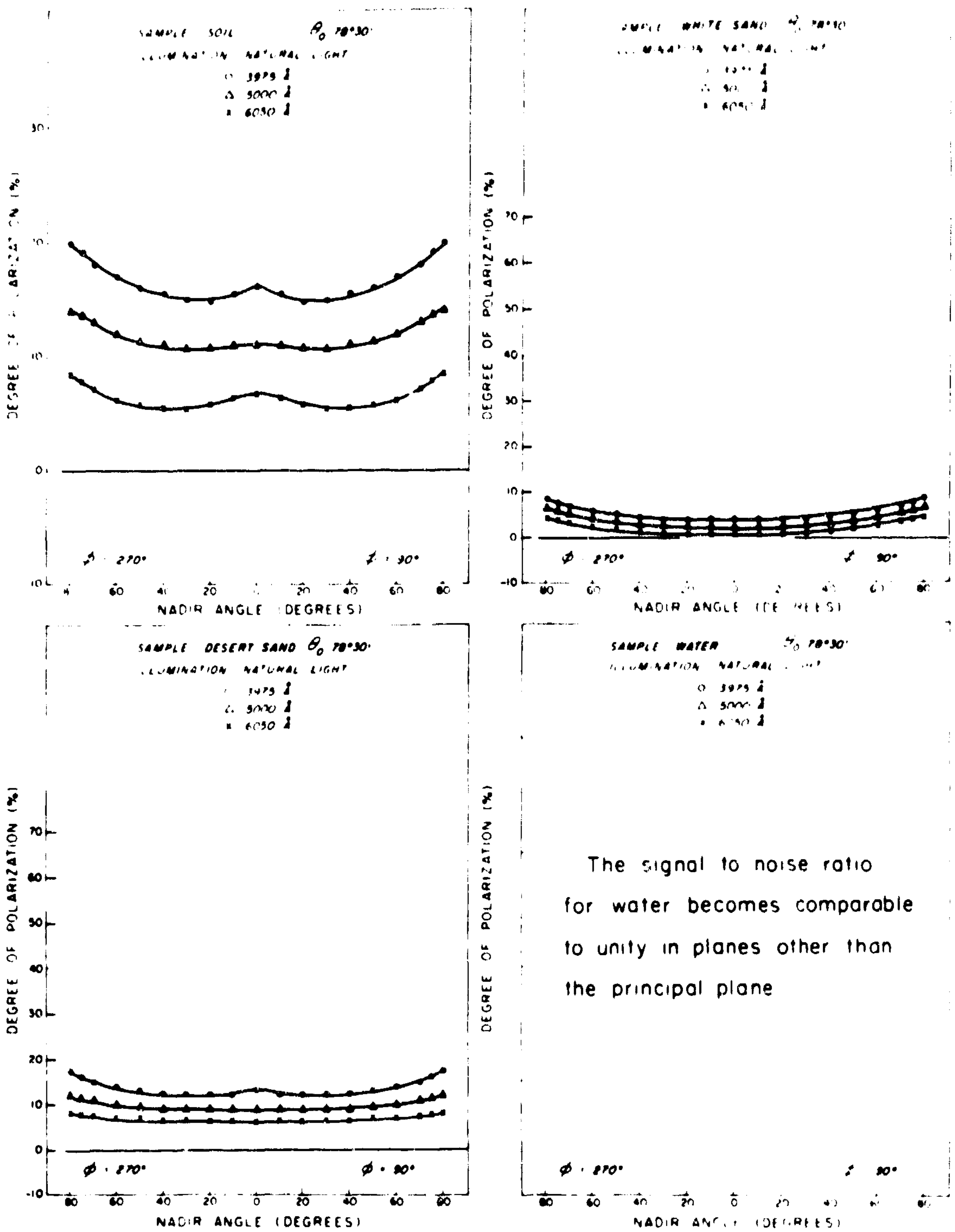


Fig 17A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

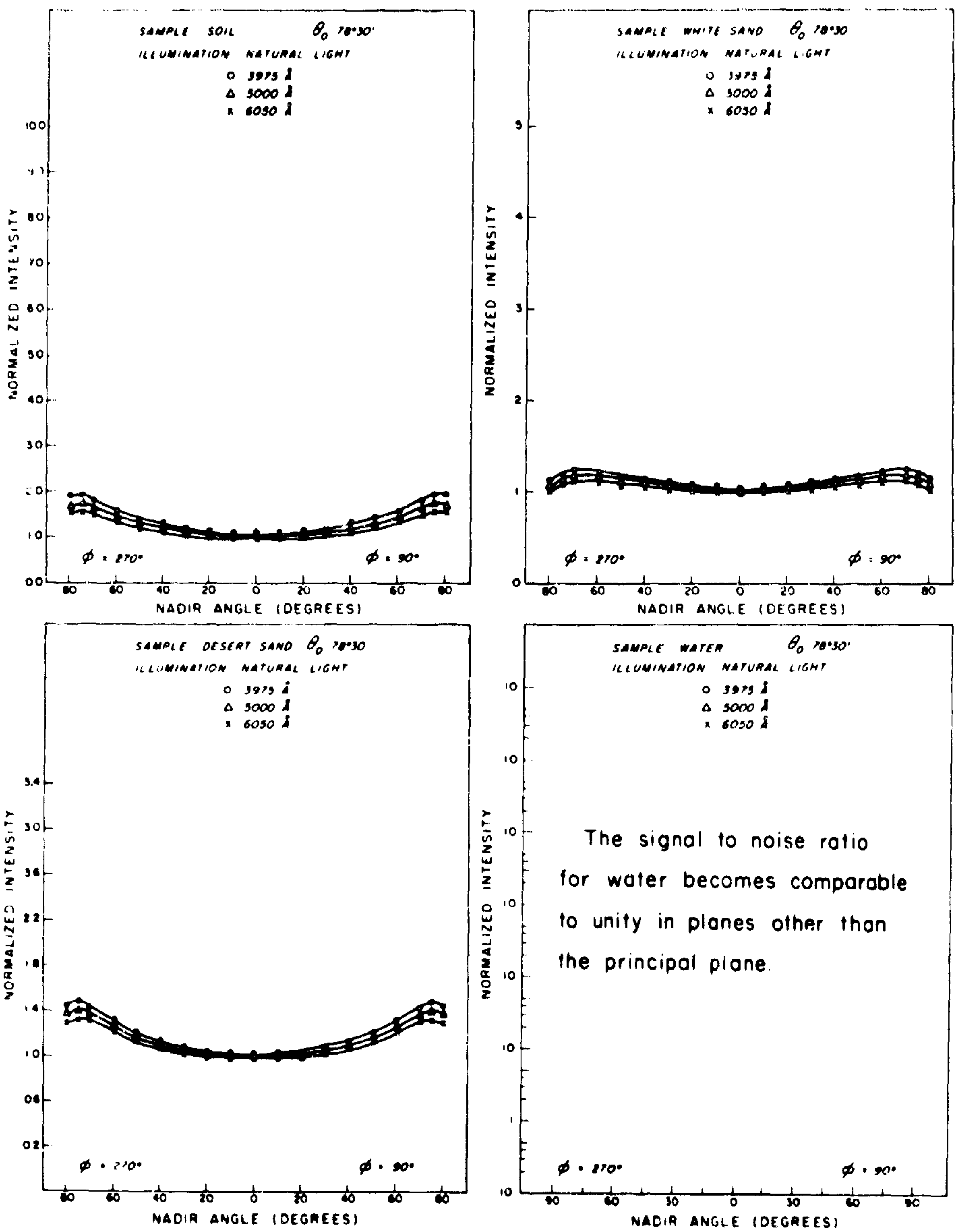


Fig 17B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

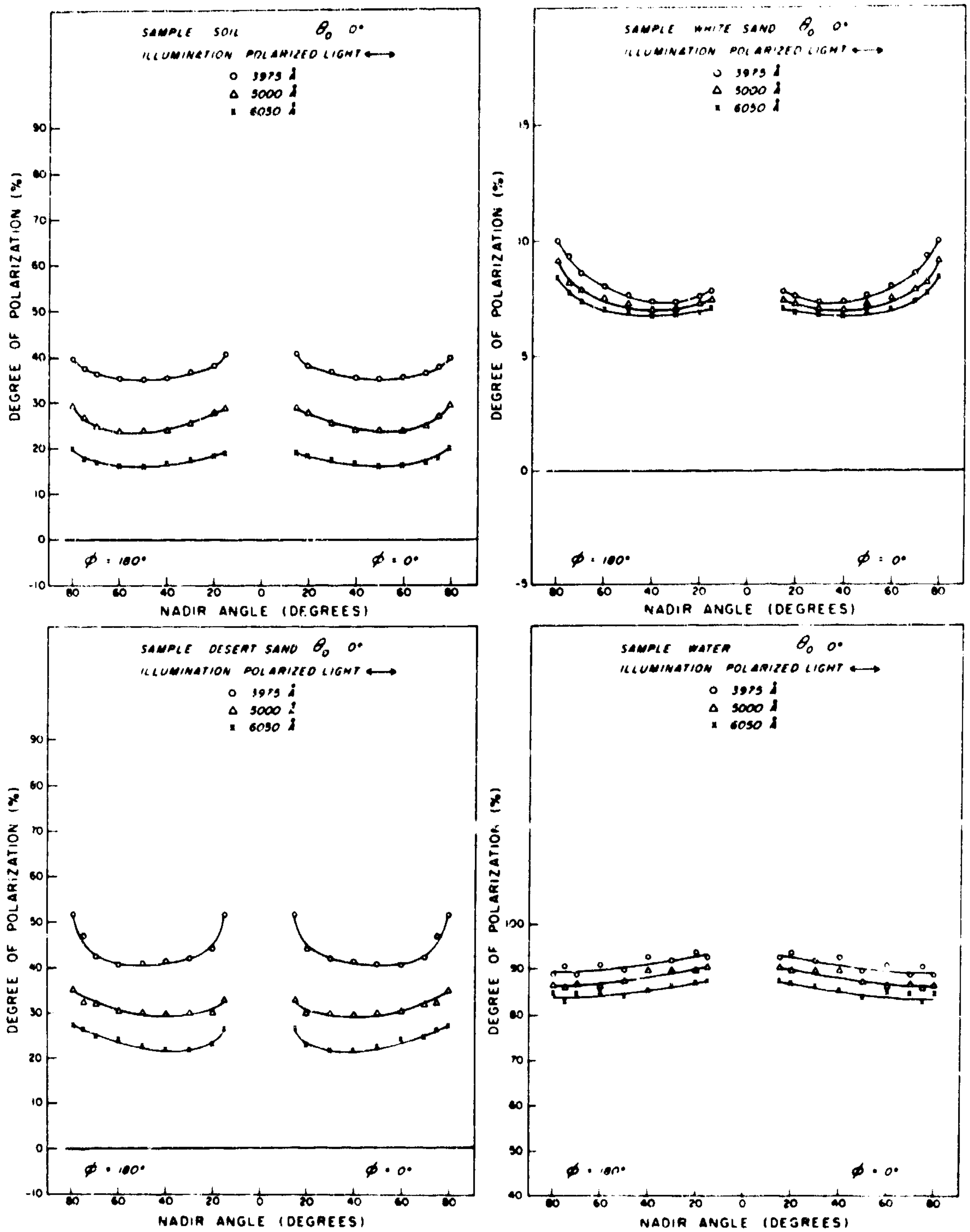


Fig. 18A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

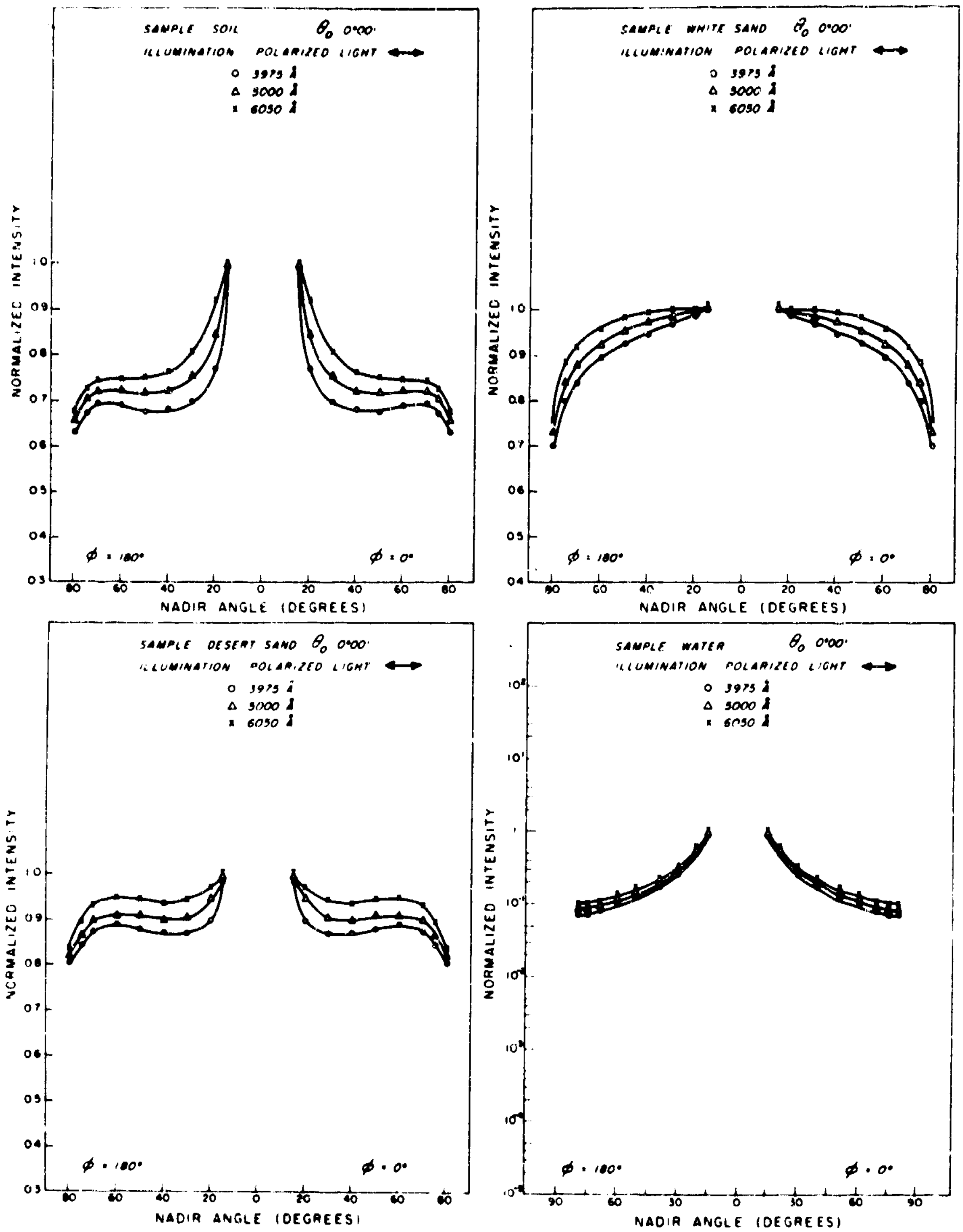


Fig 188. MEASURED VALUES OF NTENSITY OF REFLECTED LIGH

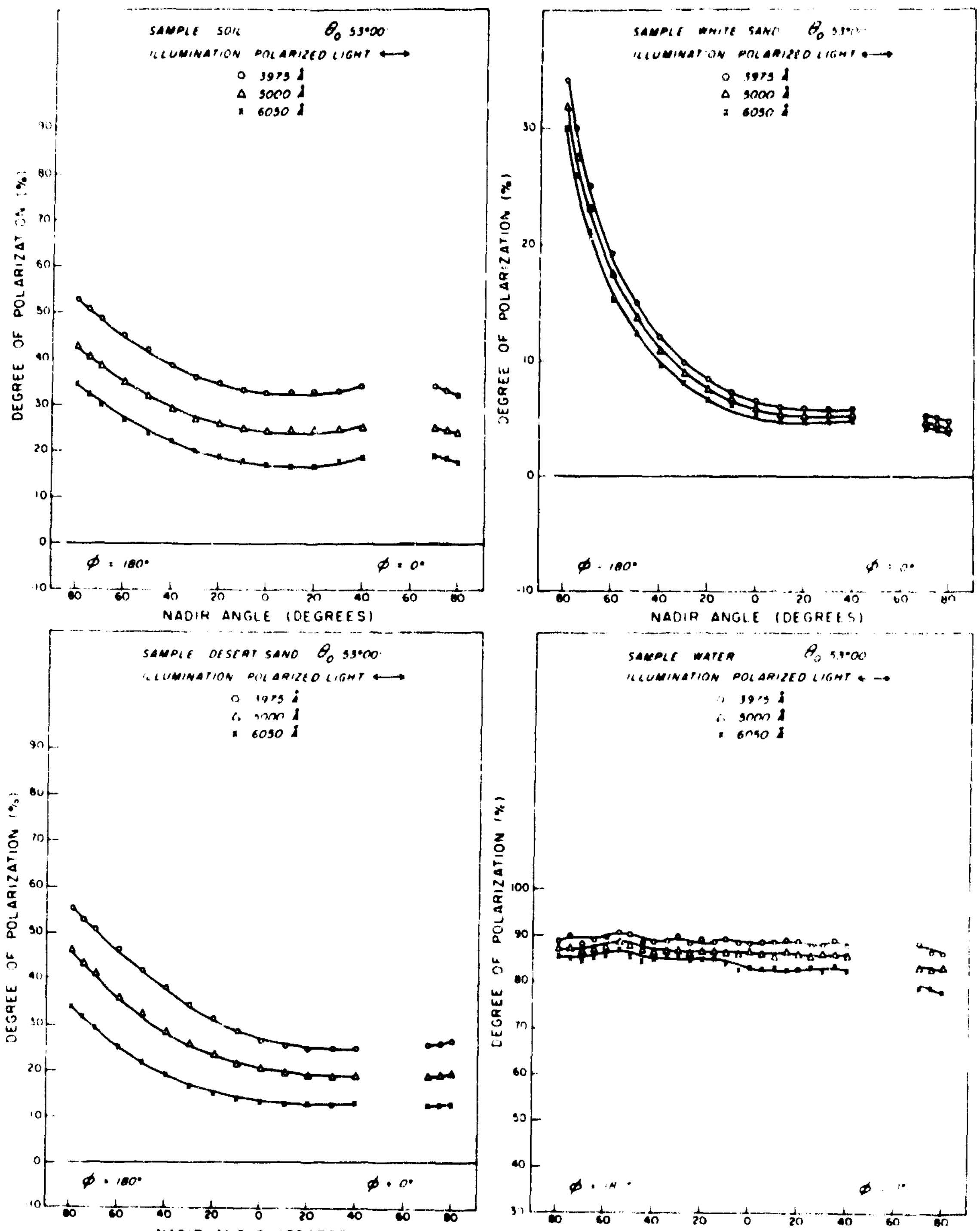


Fig 19A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

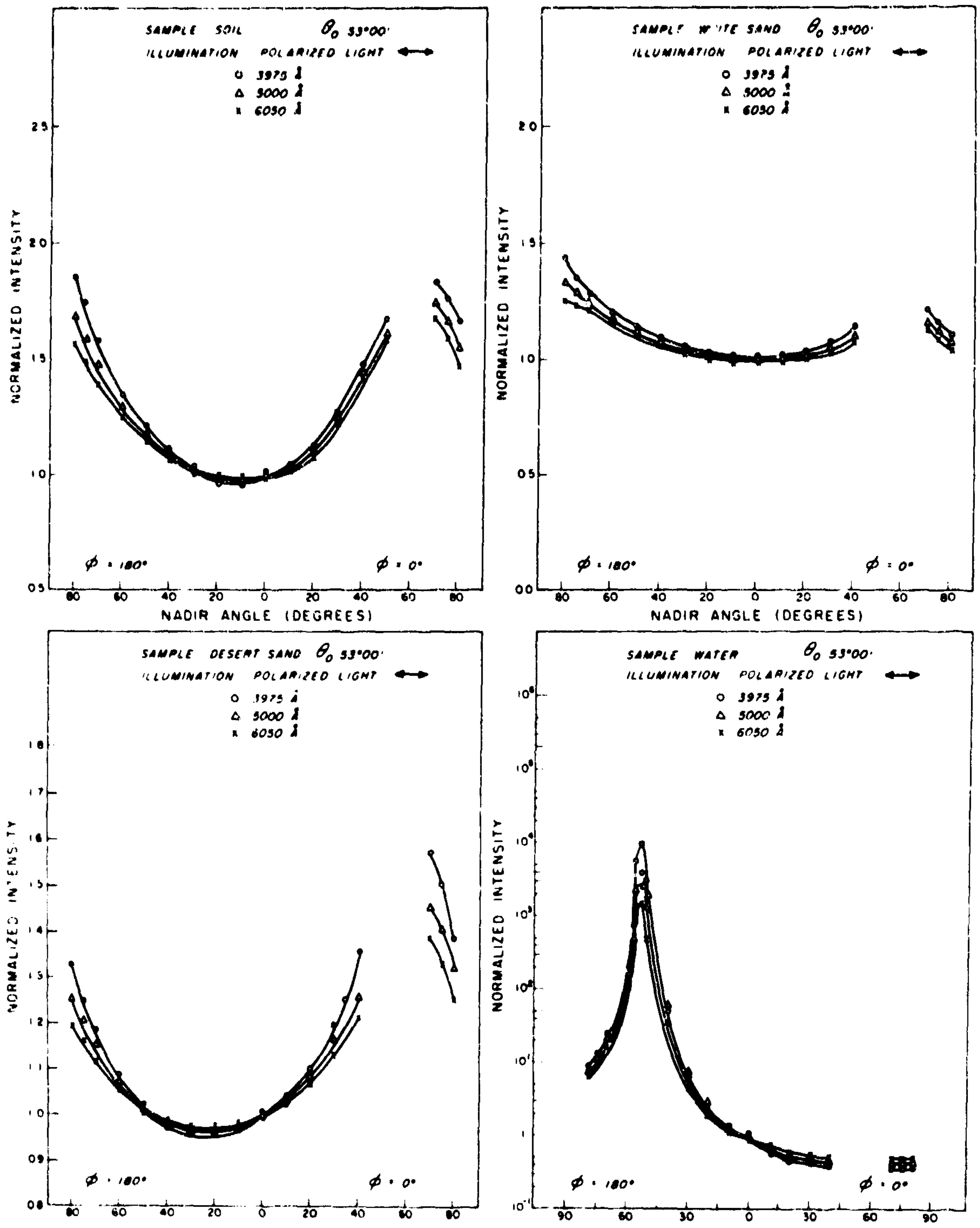


Fig 19B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

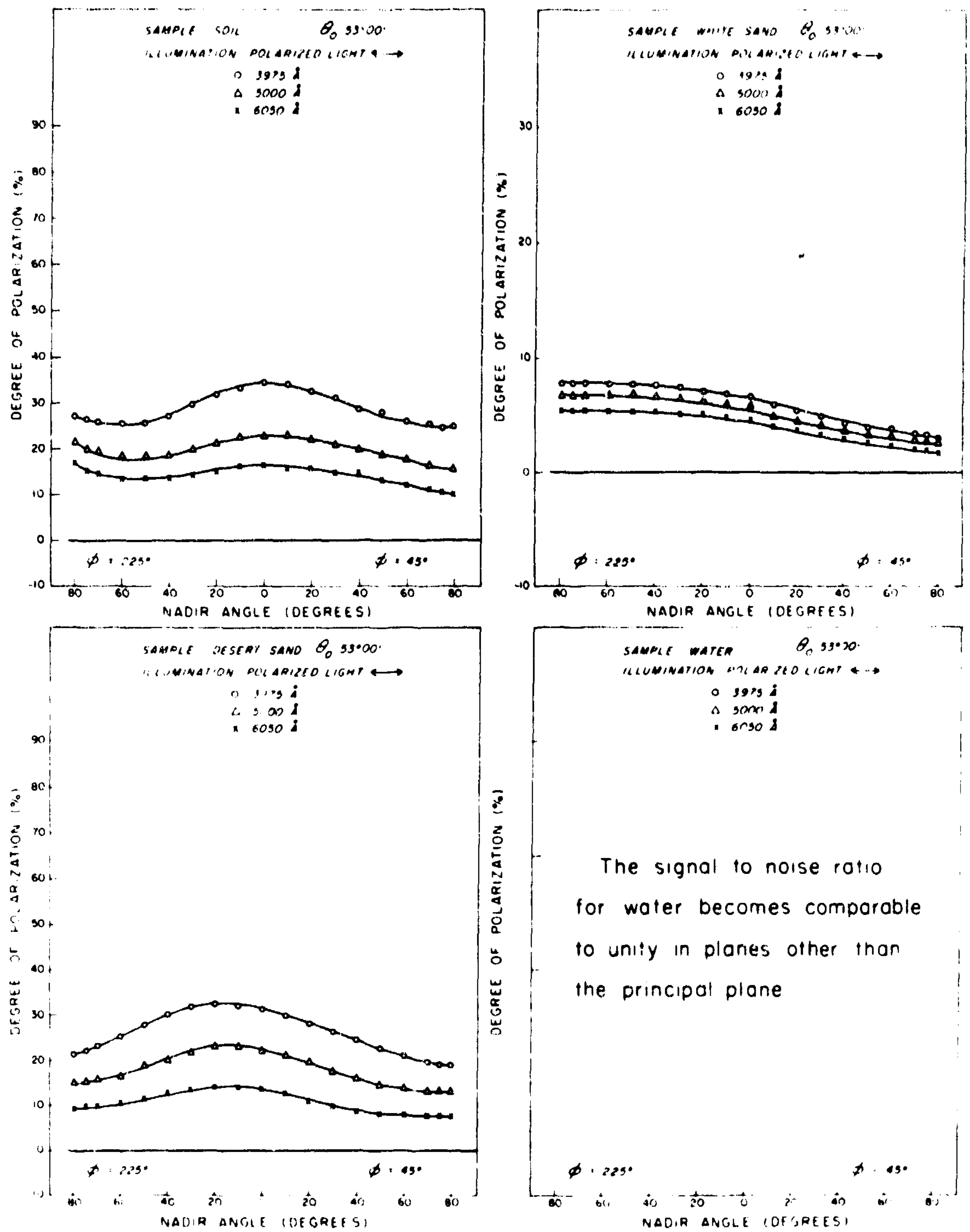


Fig 20A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

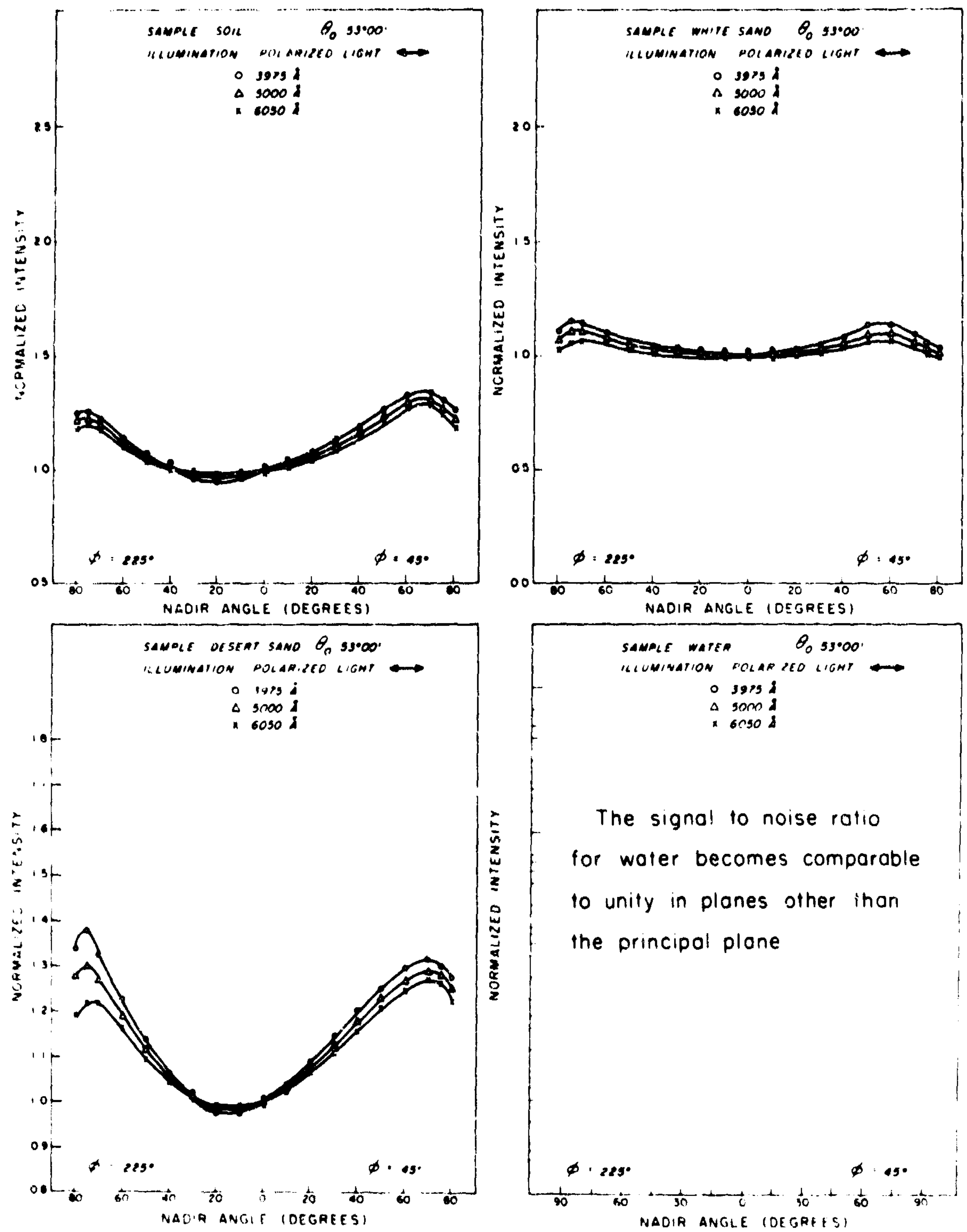


Fig 20B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

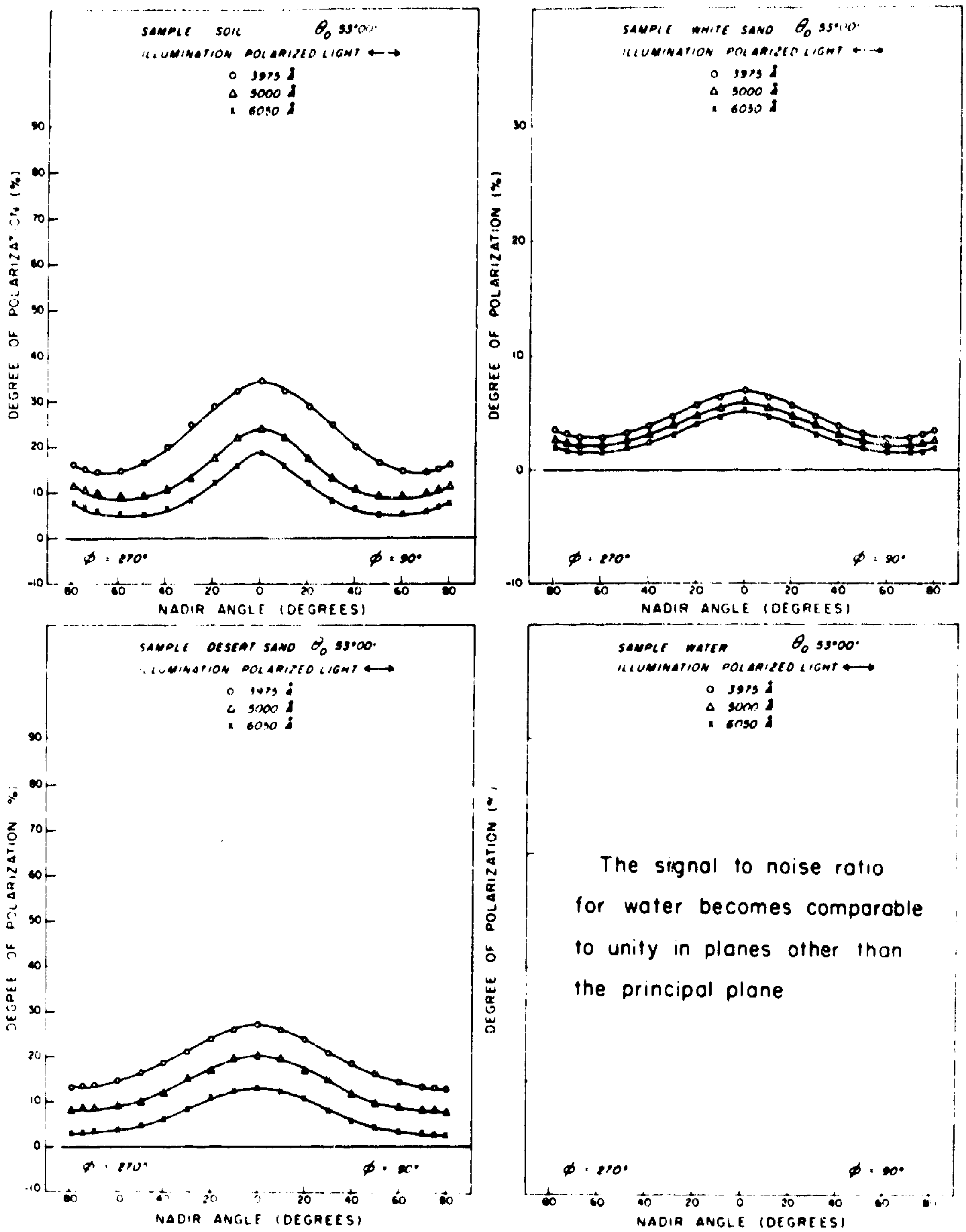


Fig 21A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

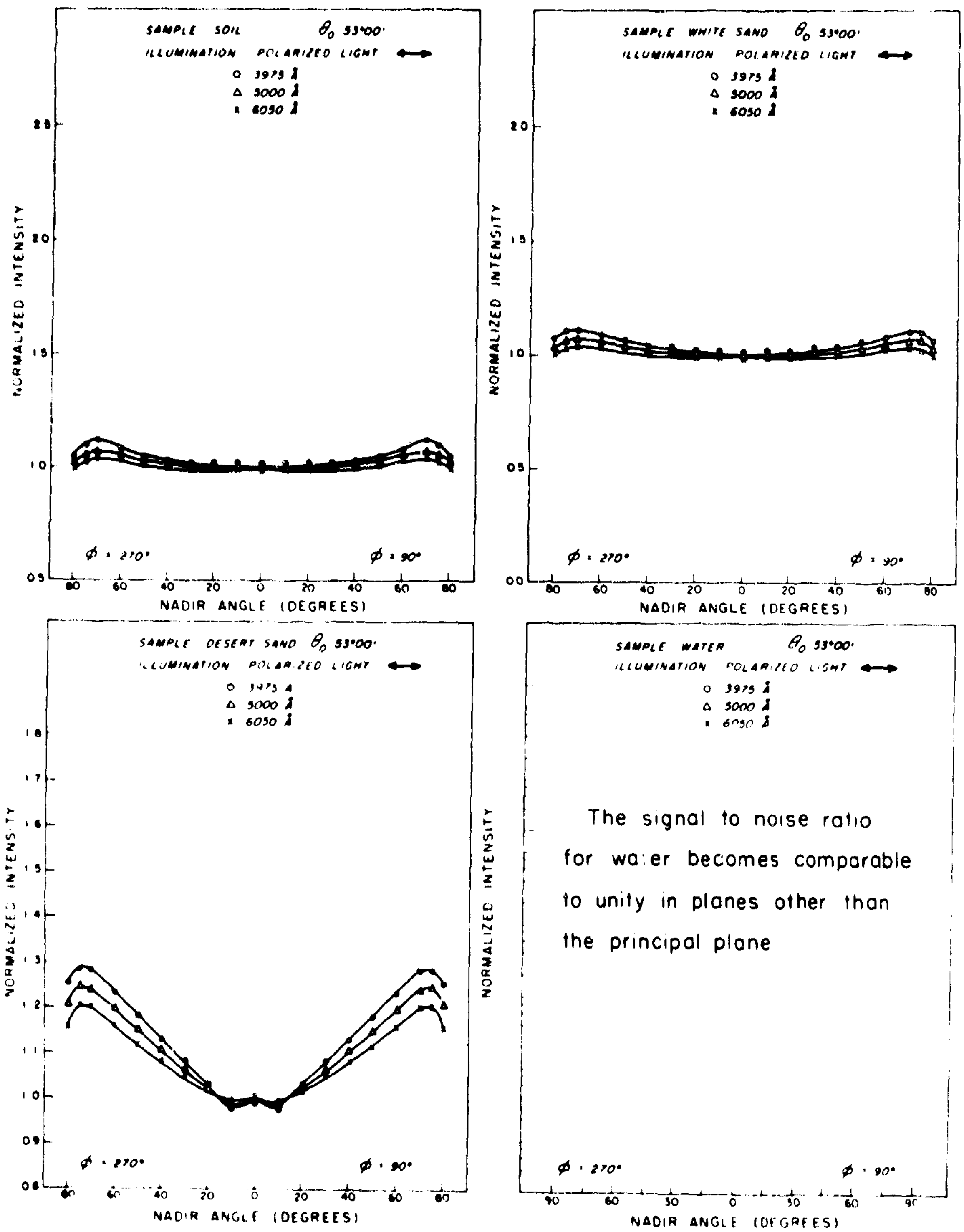


Fig 2.18. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

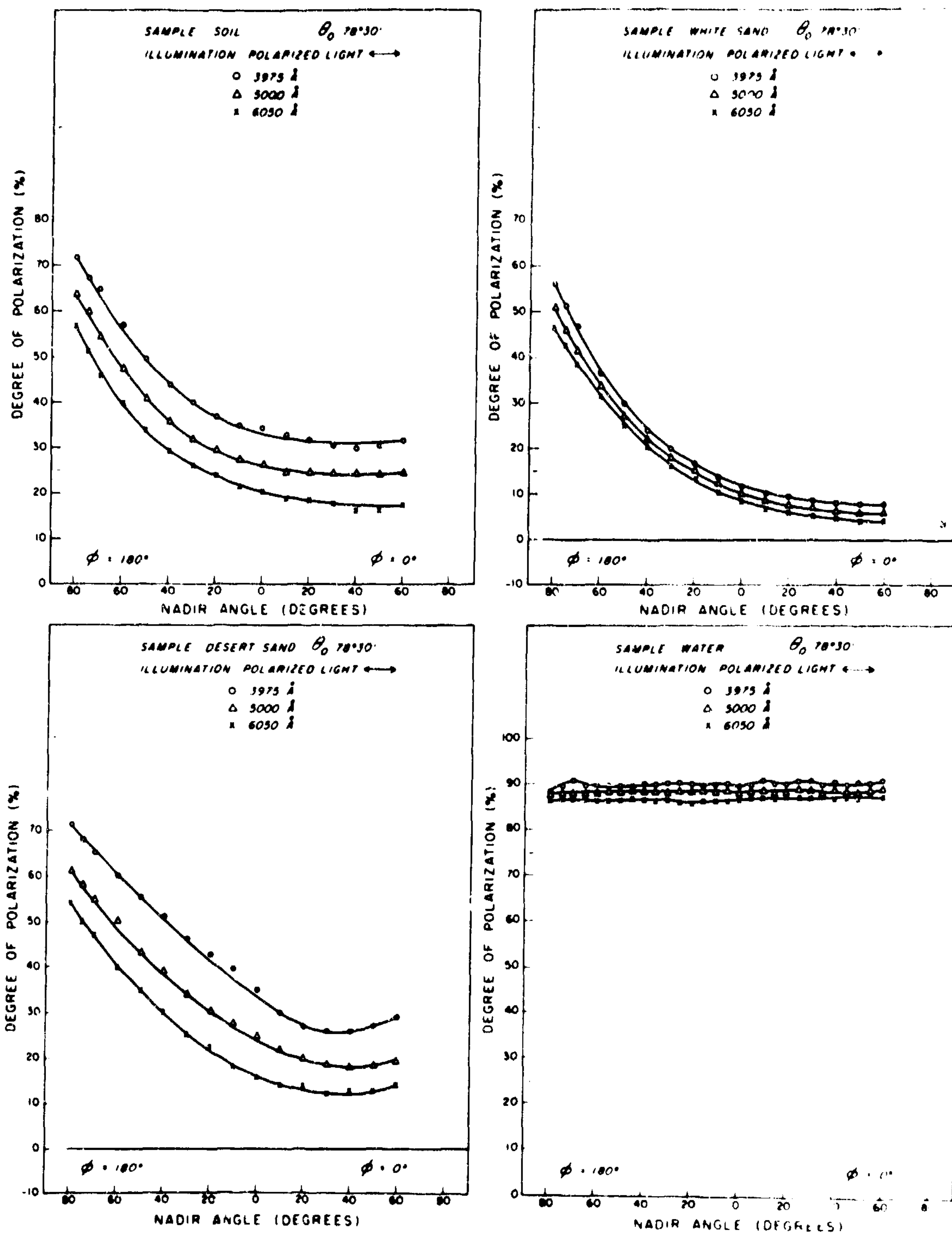


Fig 22A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

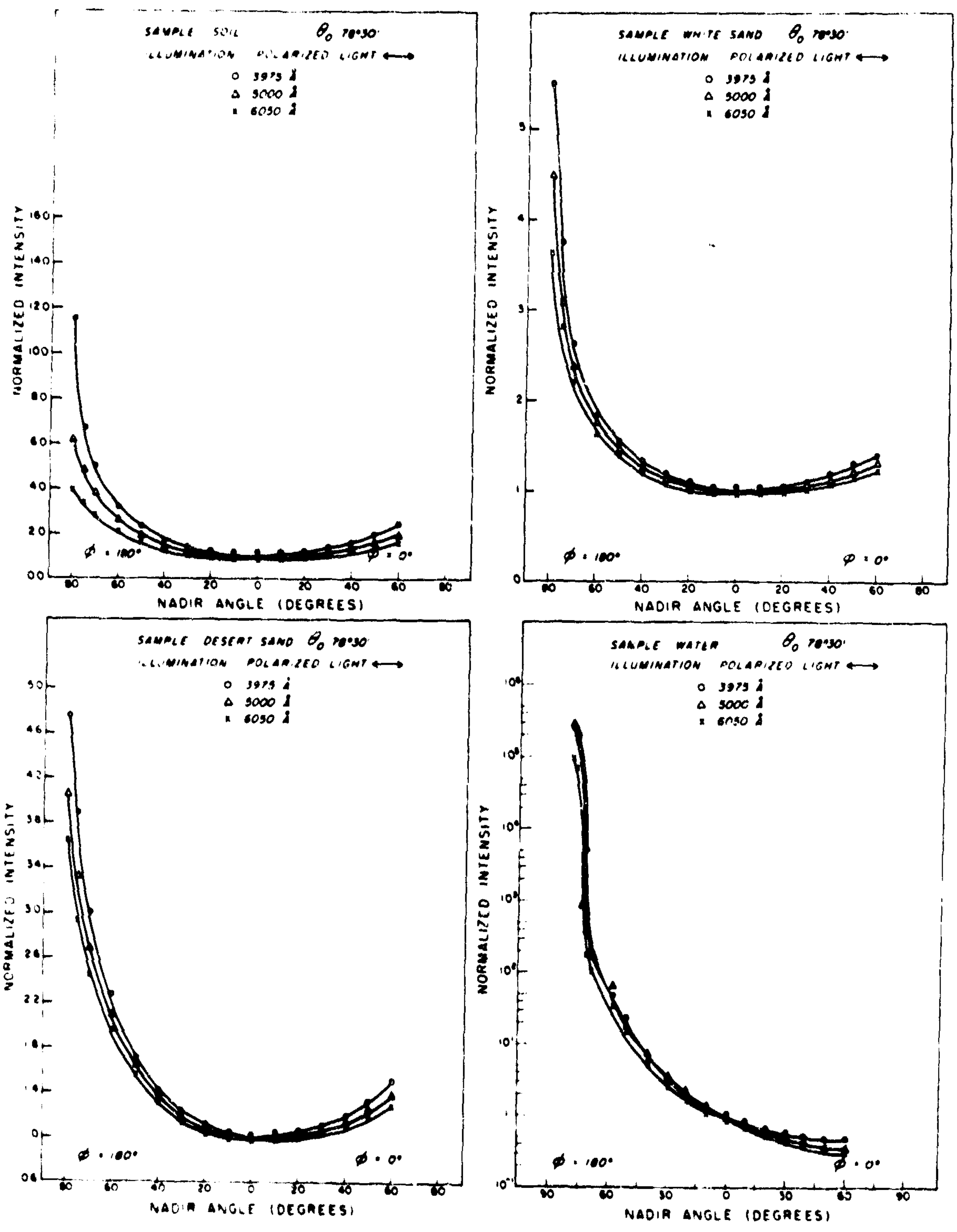


FIG 22B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

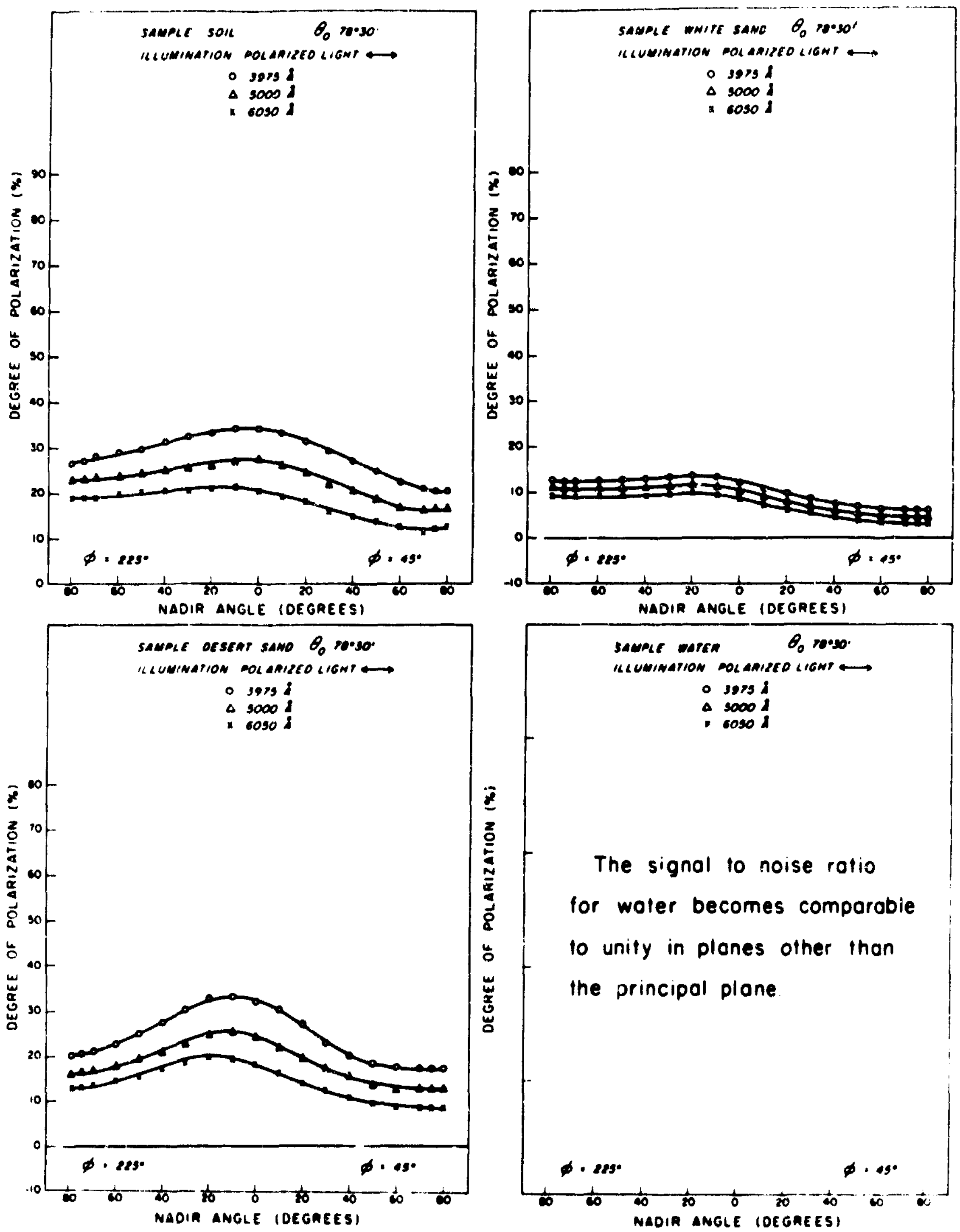


Fig. 23A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

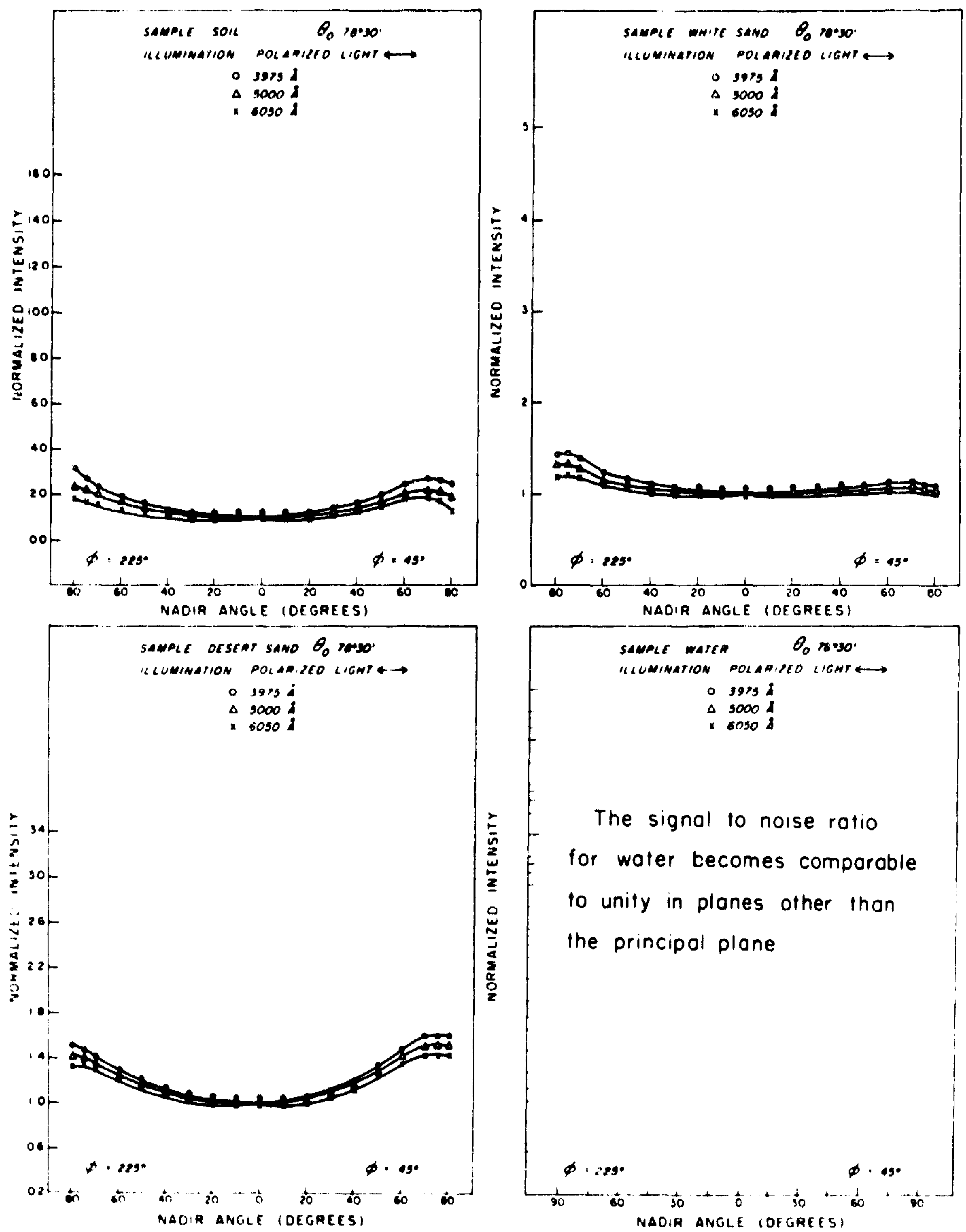


Fig 23B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

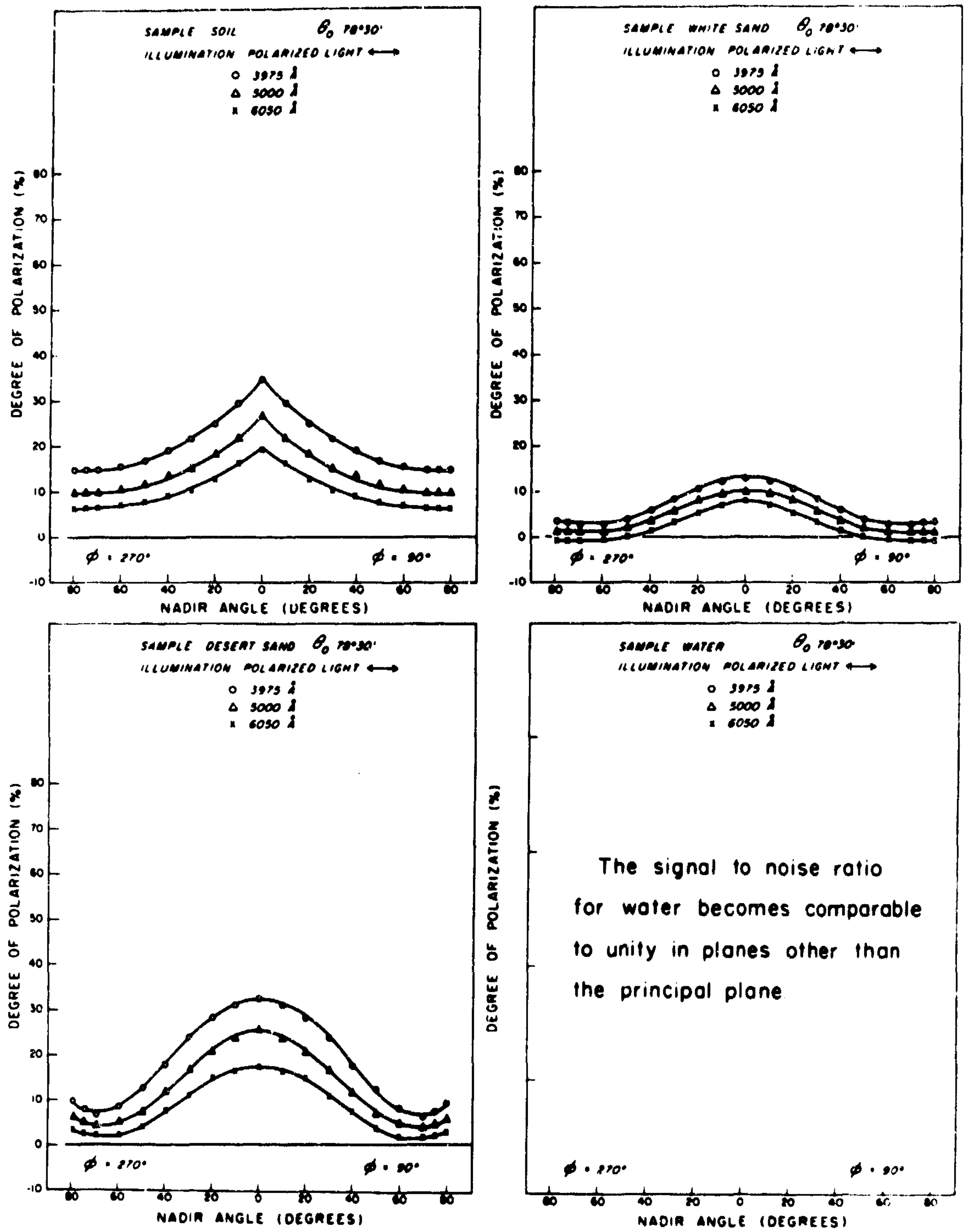


Fig 24A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

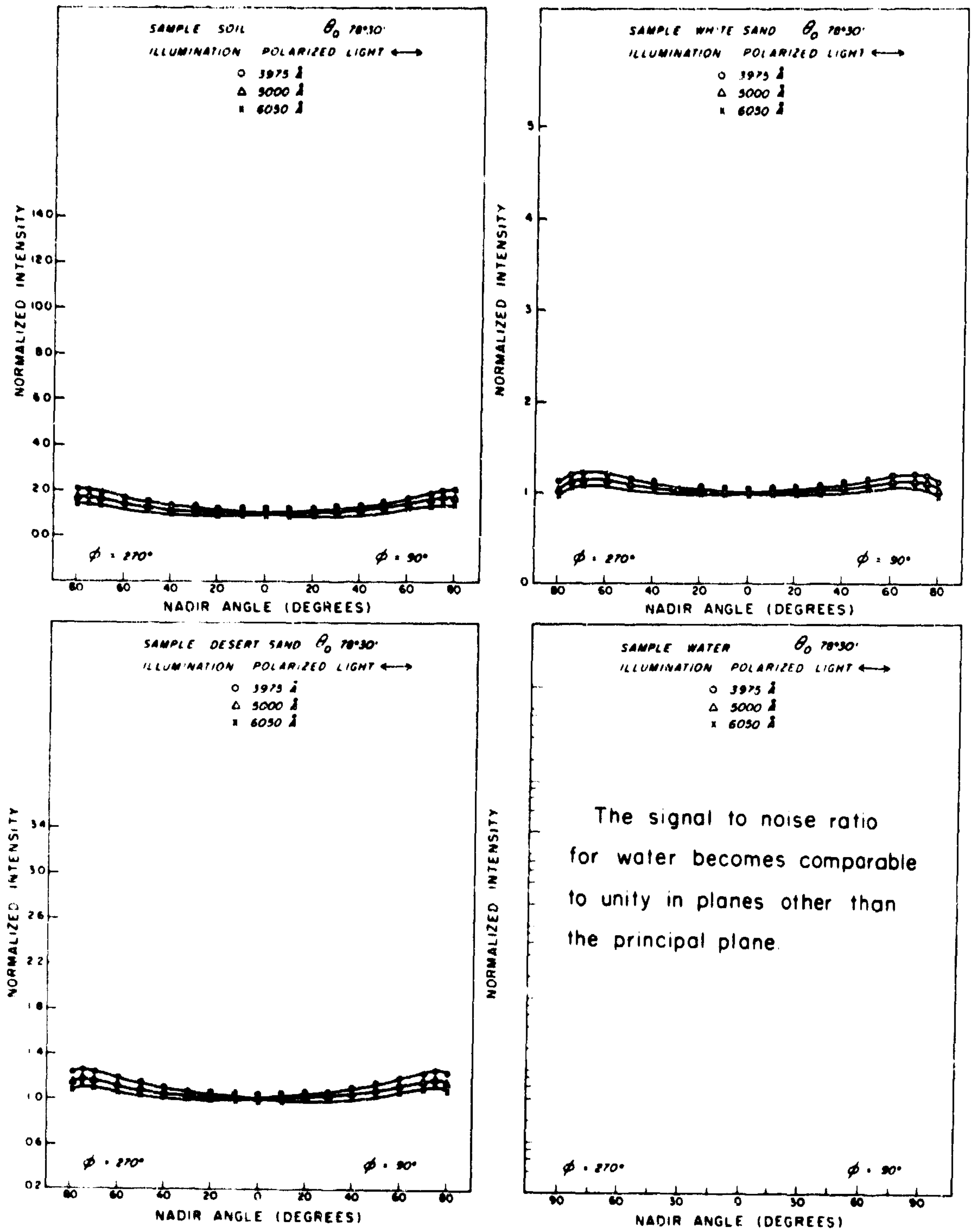


Fig. 24B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

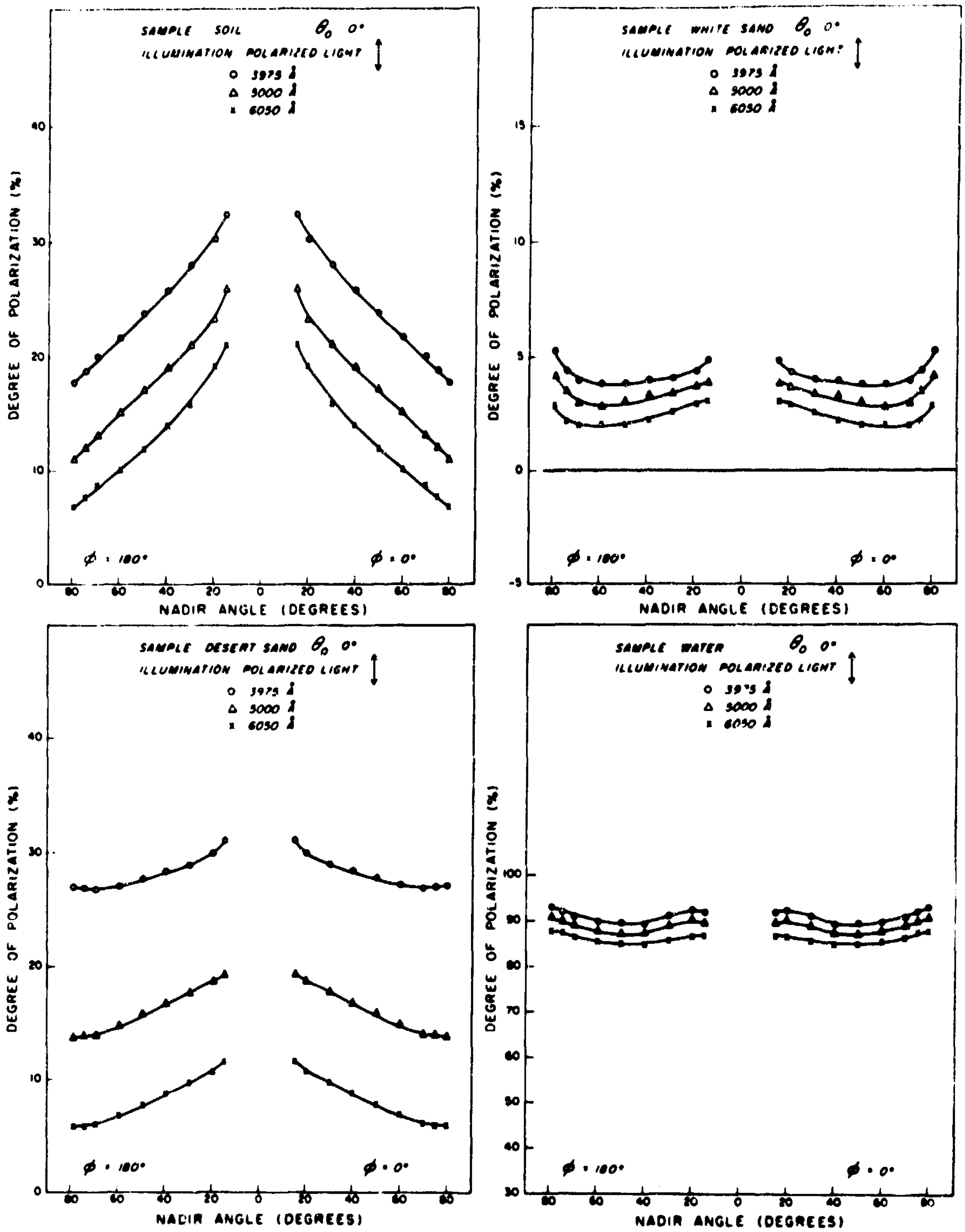


Fig. 25A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

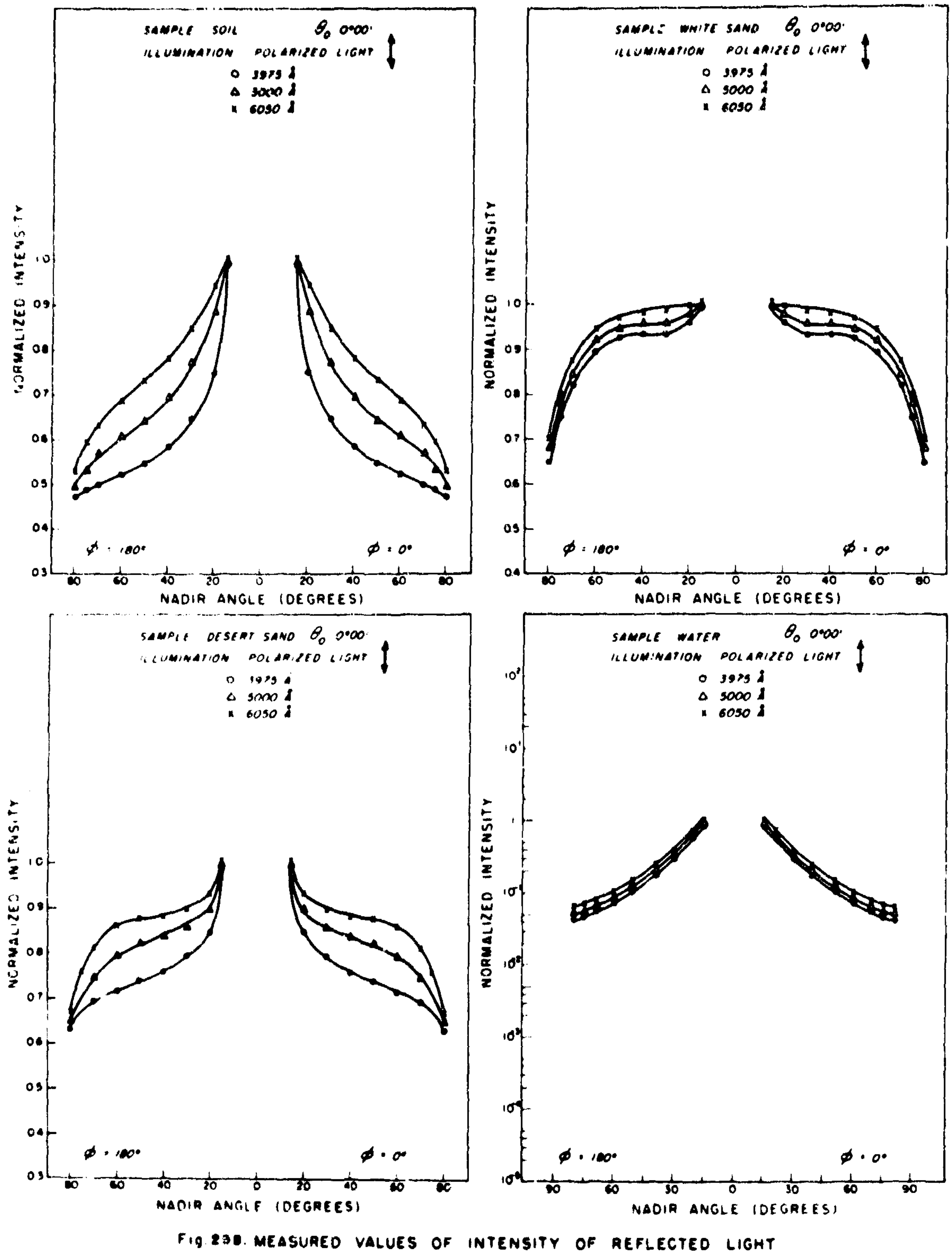


Fig. 23B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

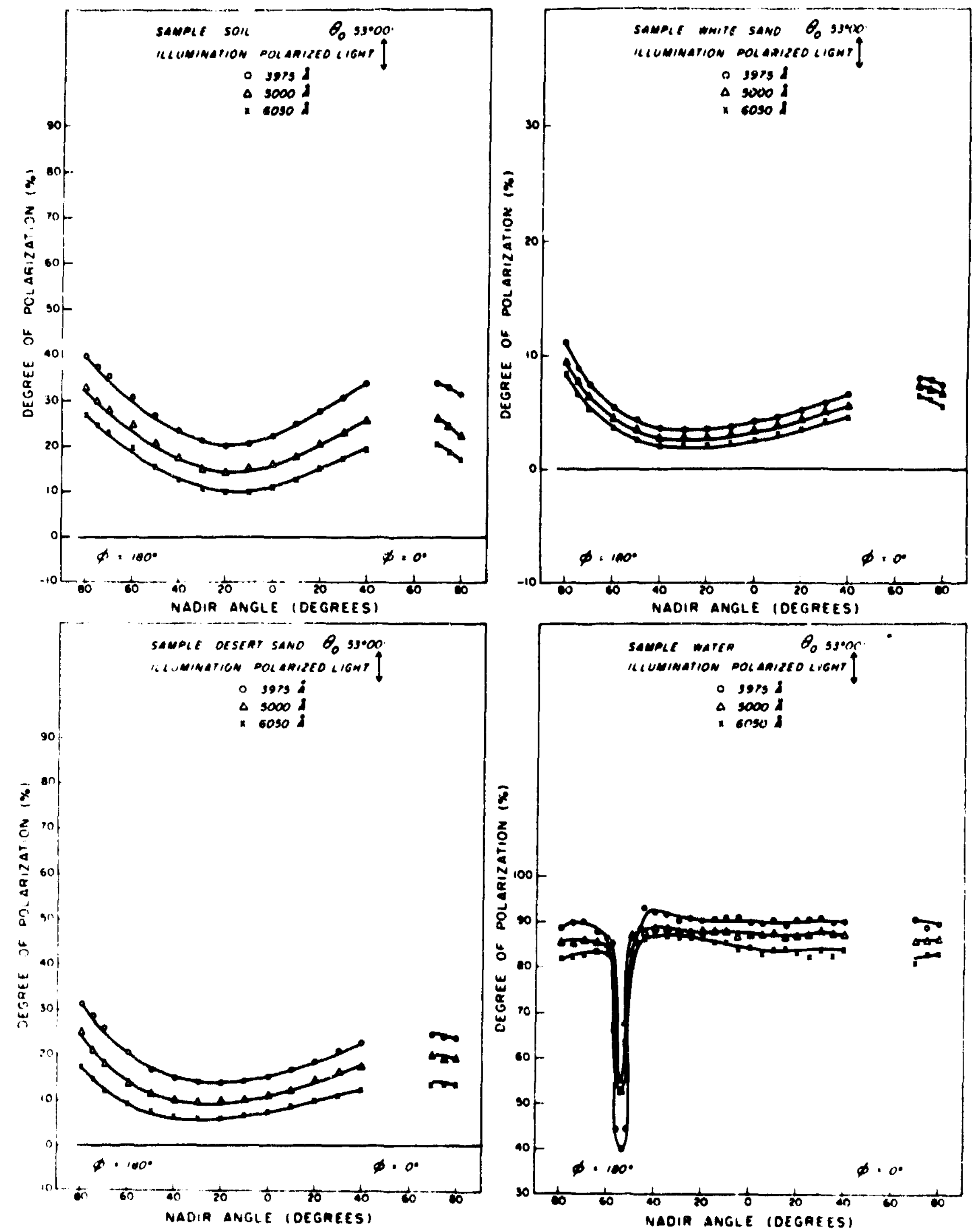


FIG 26A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

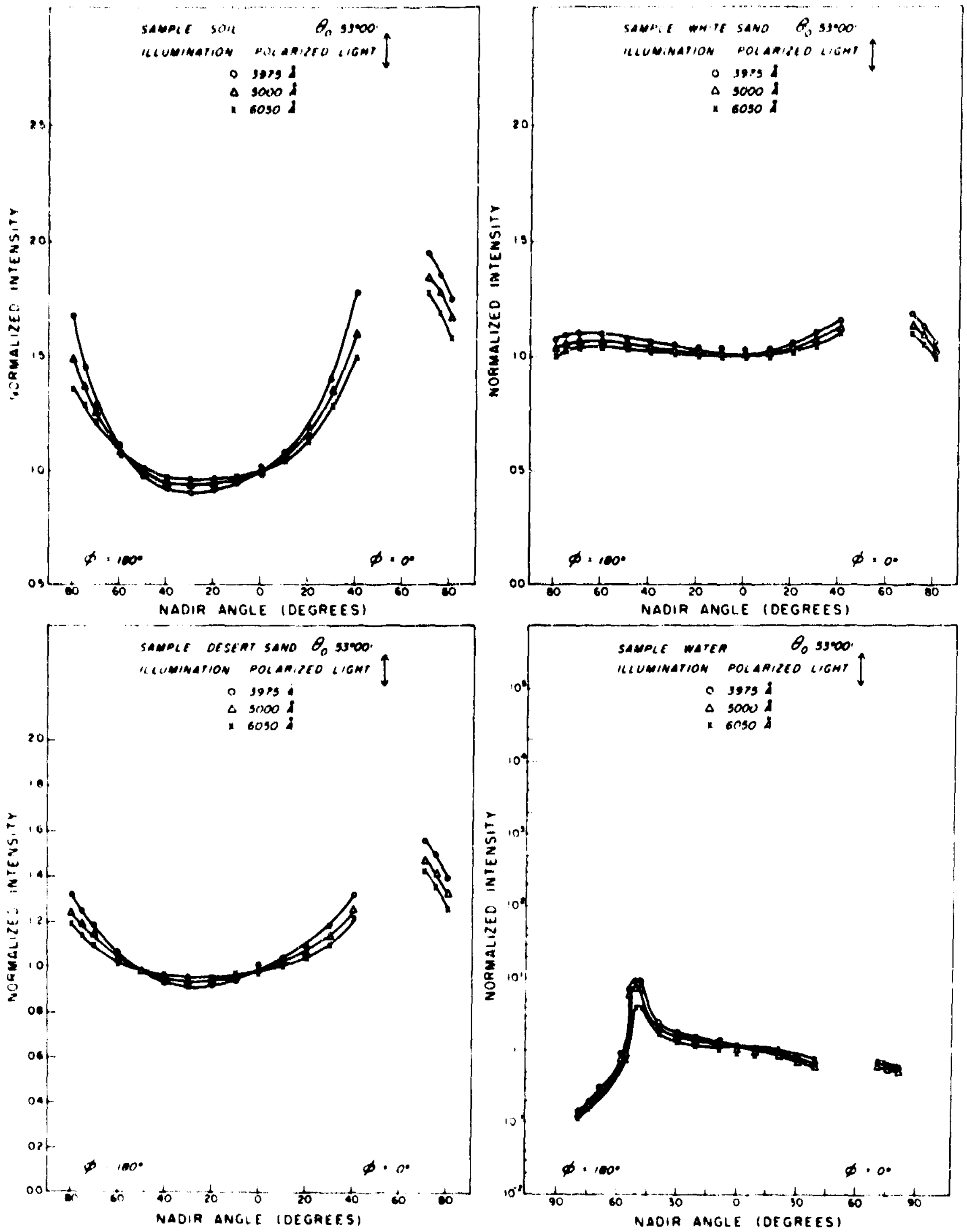


Fig 26B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

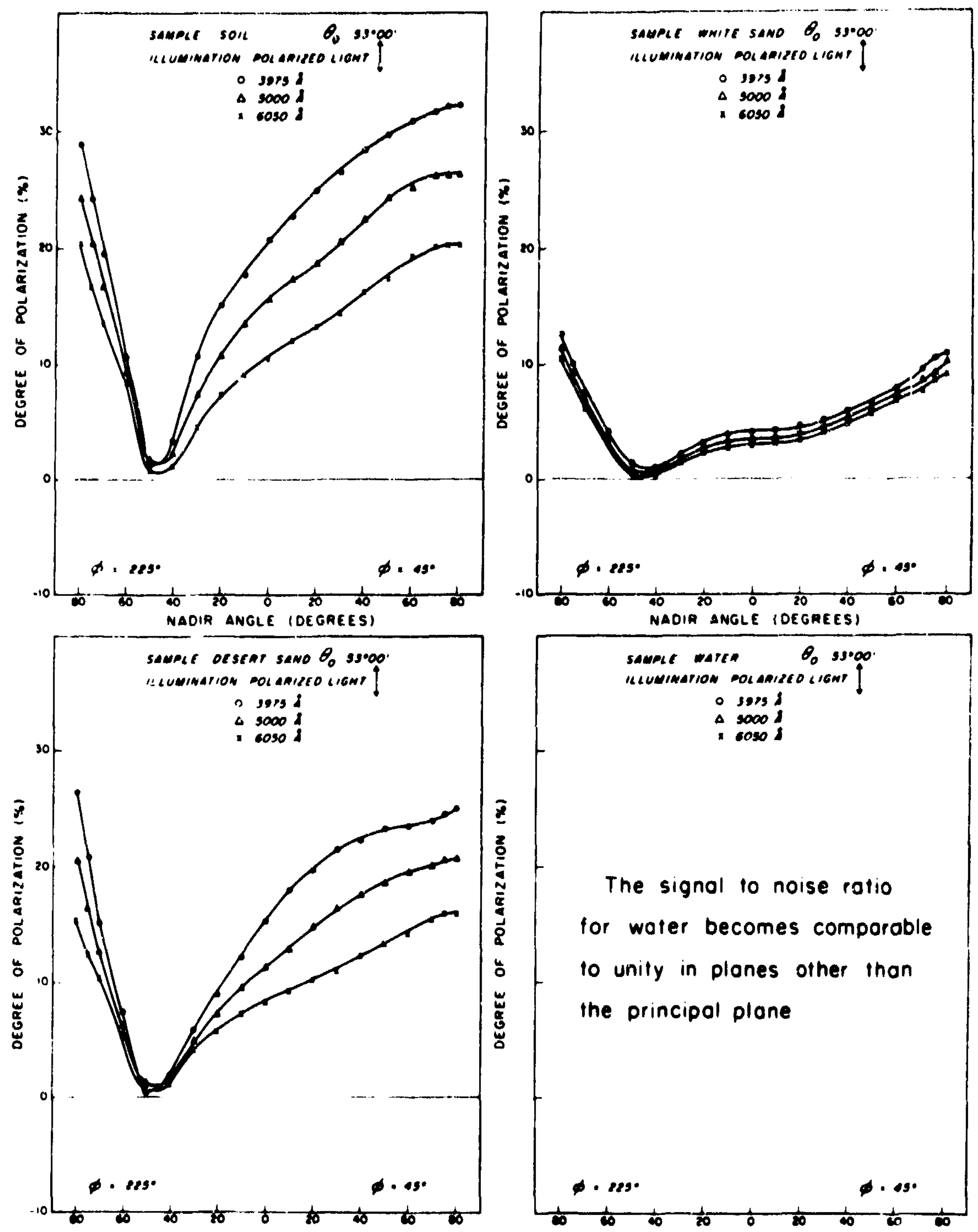


Fig. 27A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

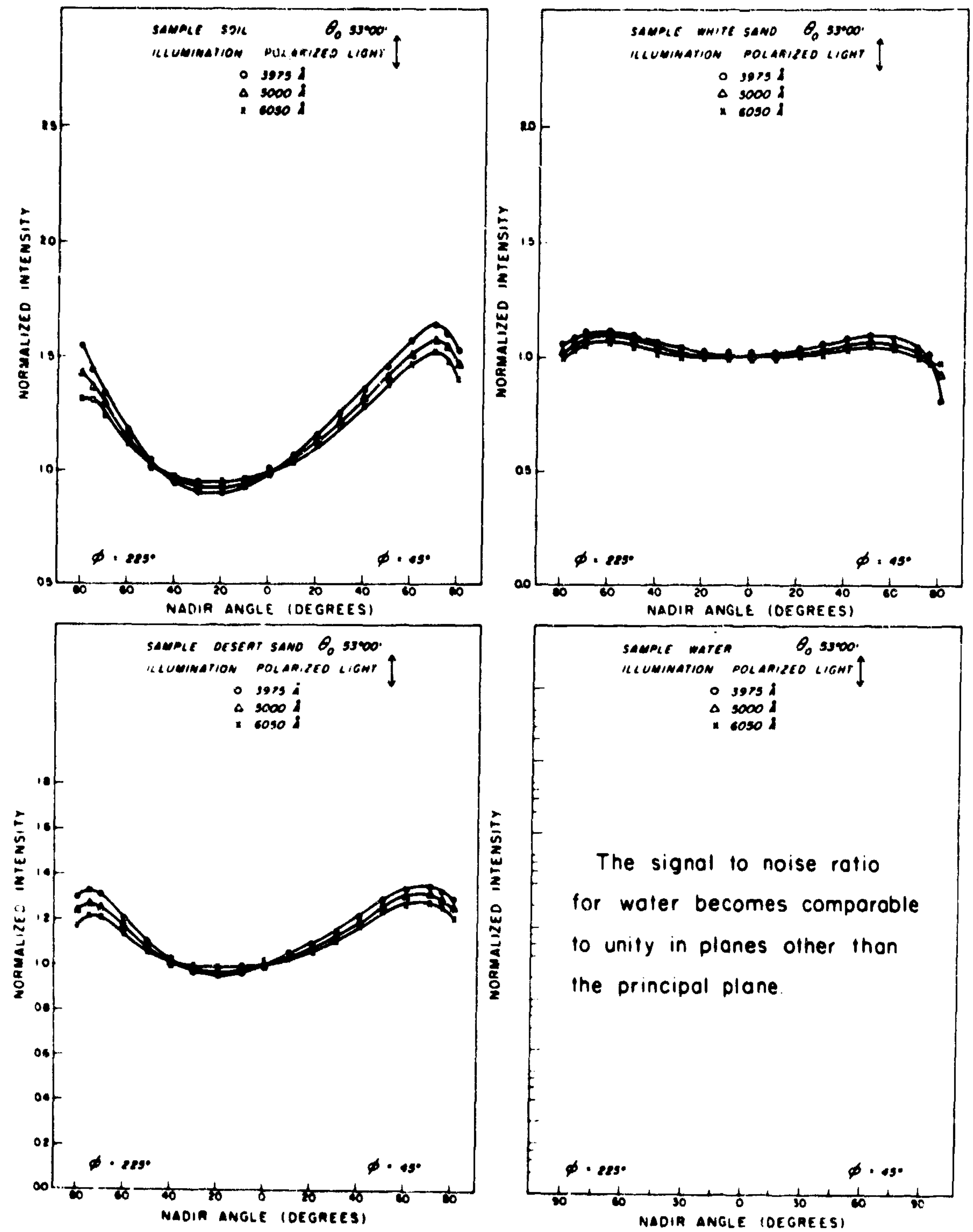


Fig 27B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

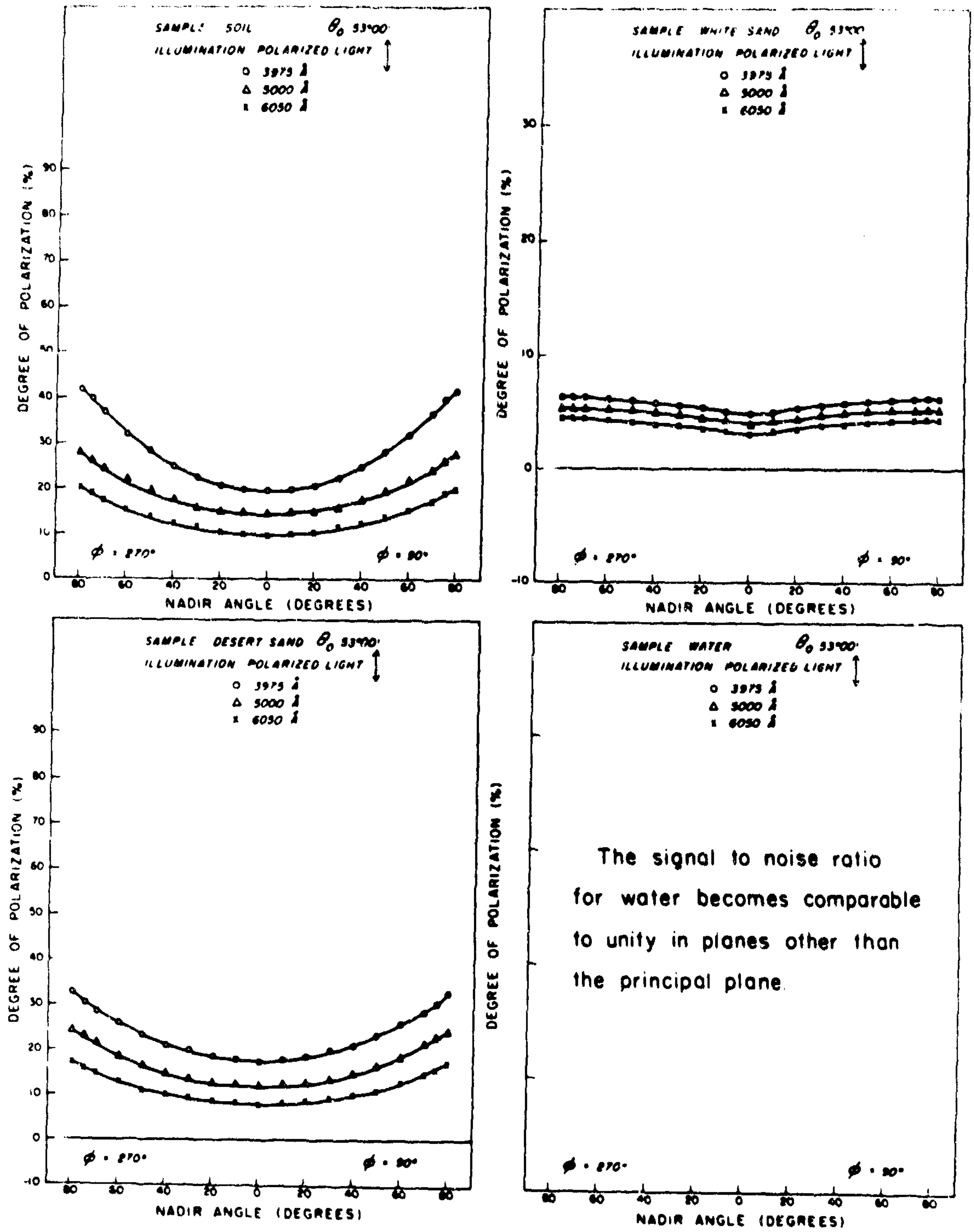


Fig 28A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

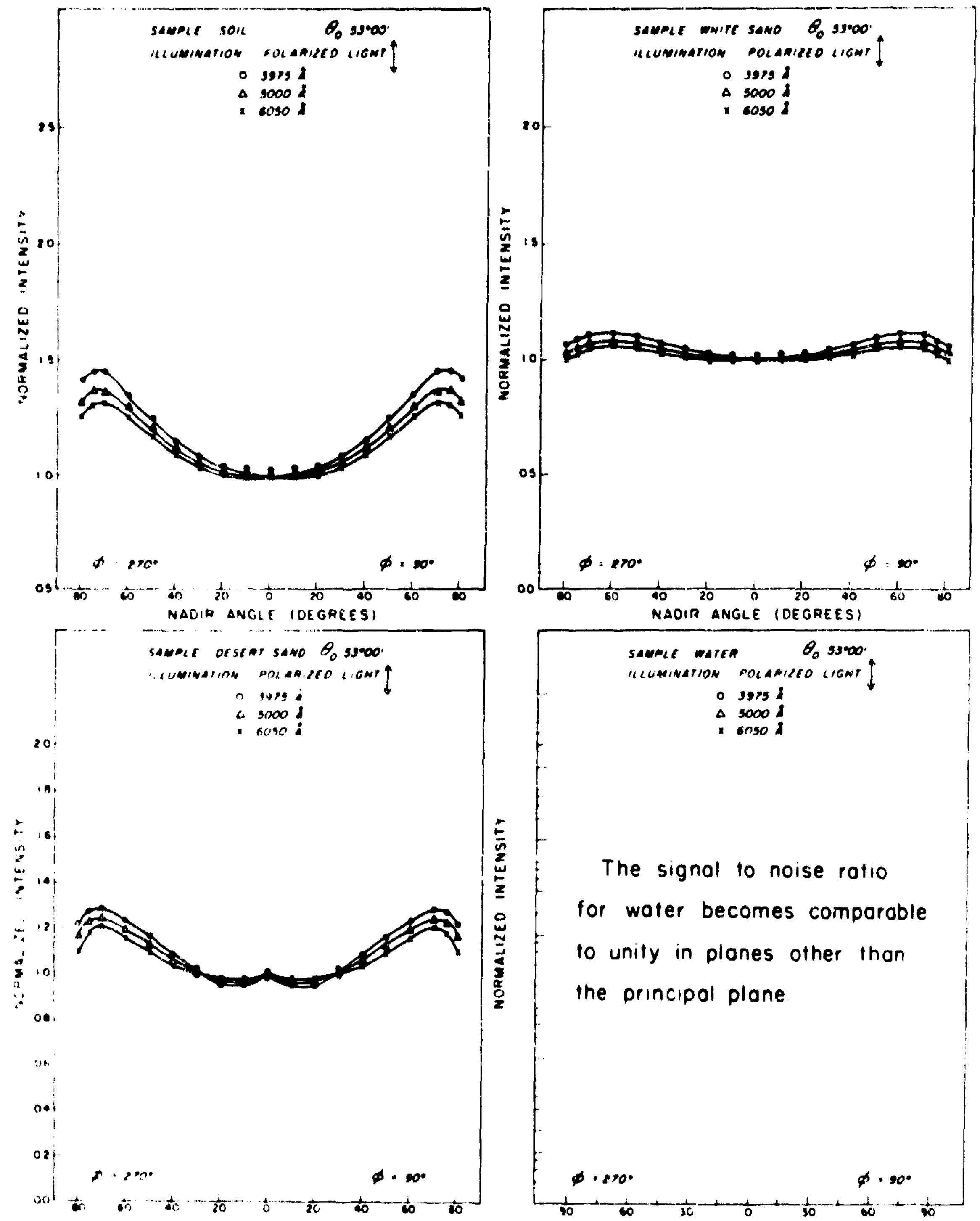


Fig 22B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

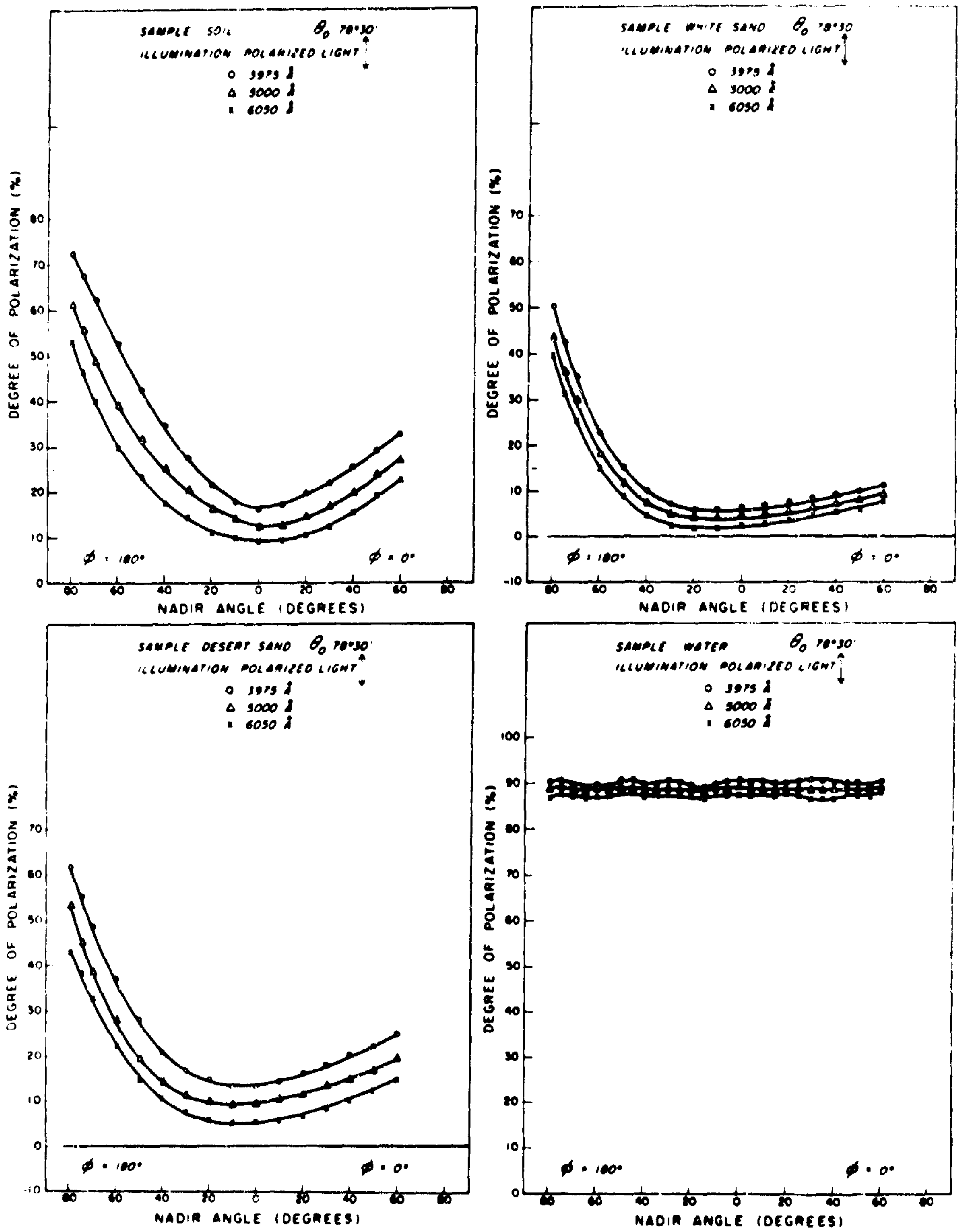


Fig 29A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

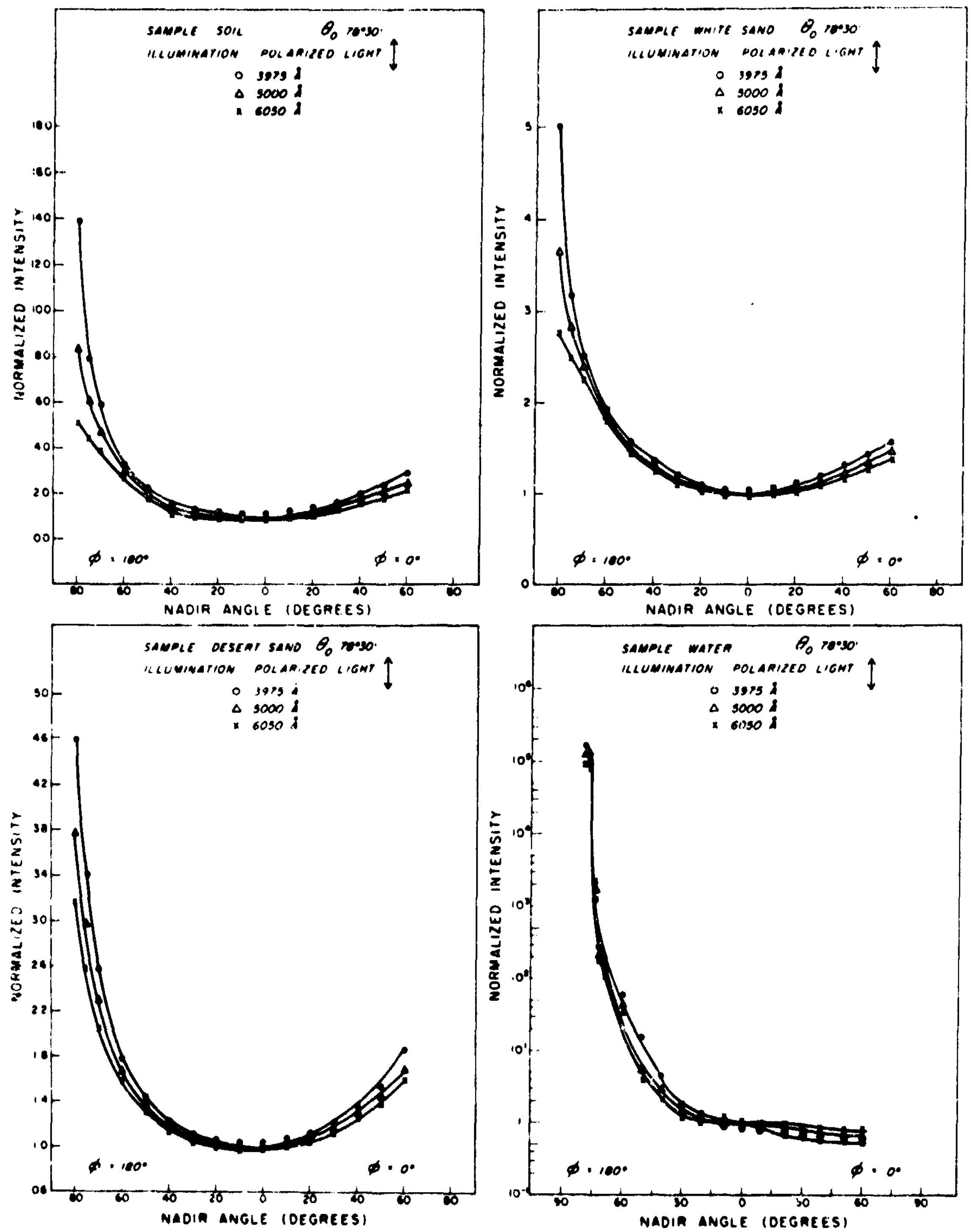


Fig 29B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

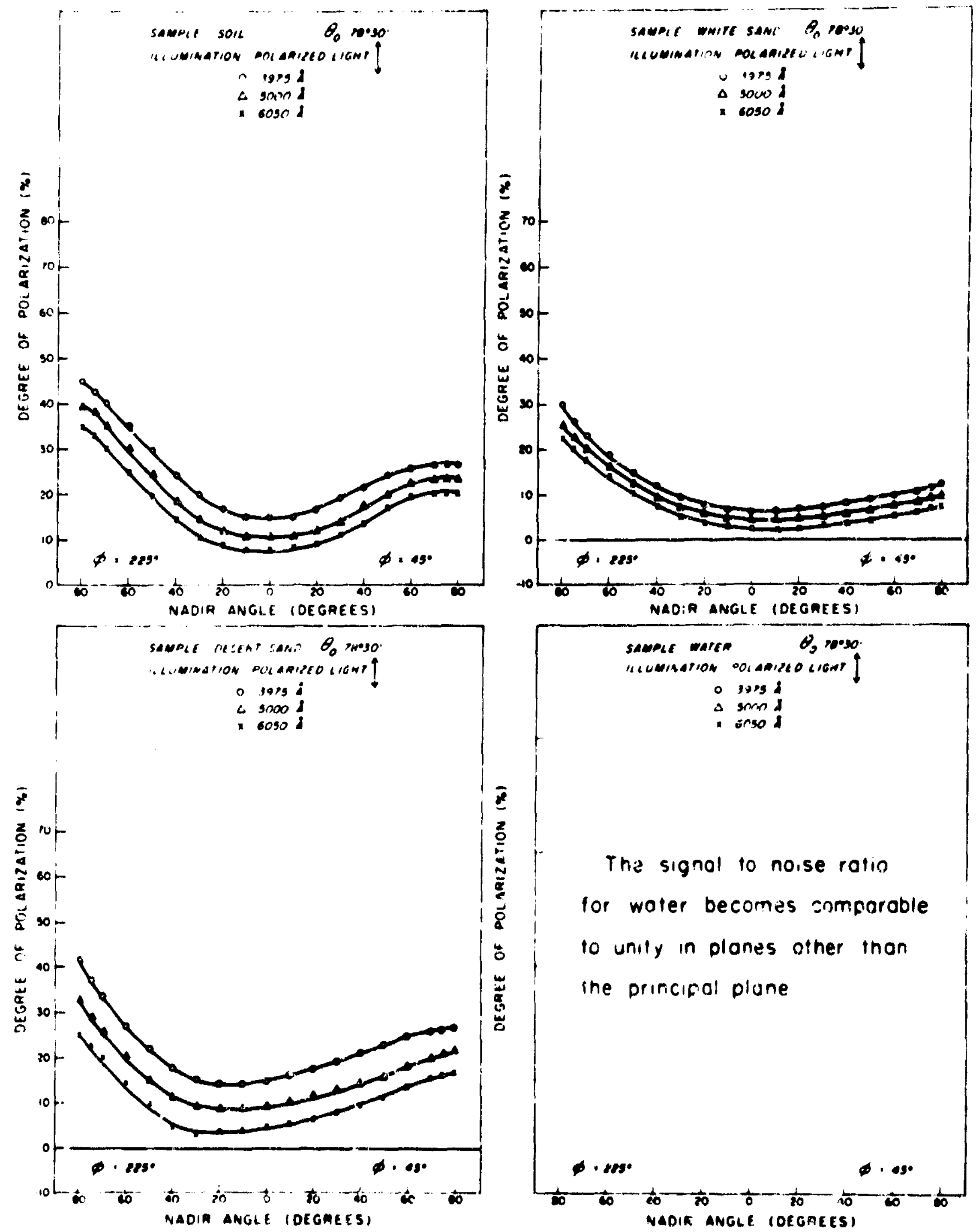


Fig 30A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

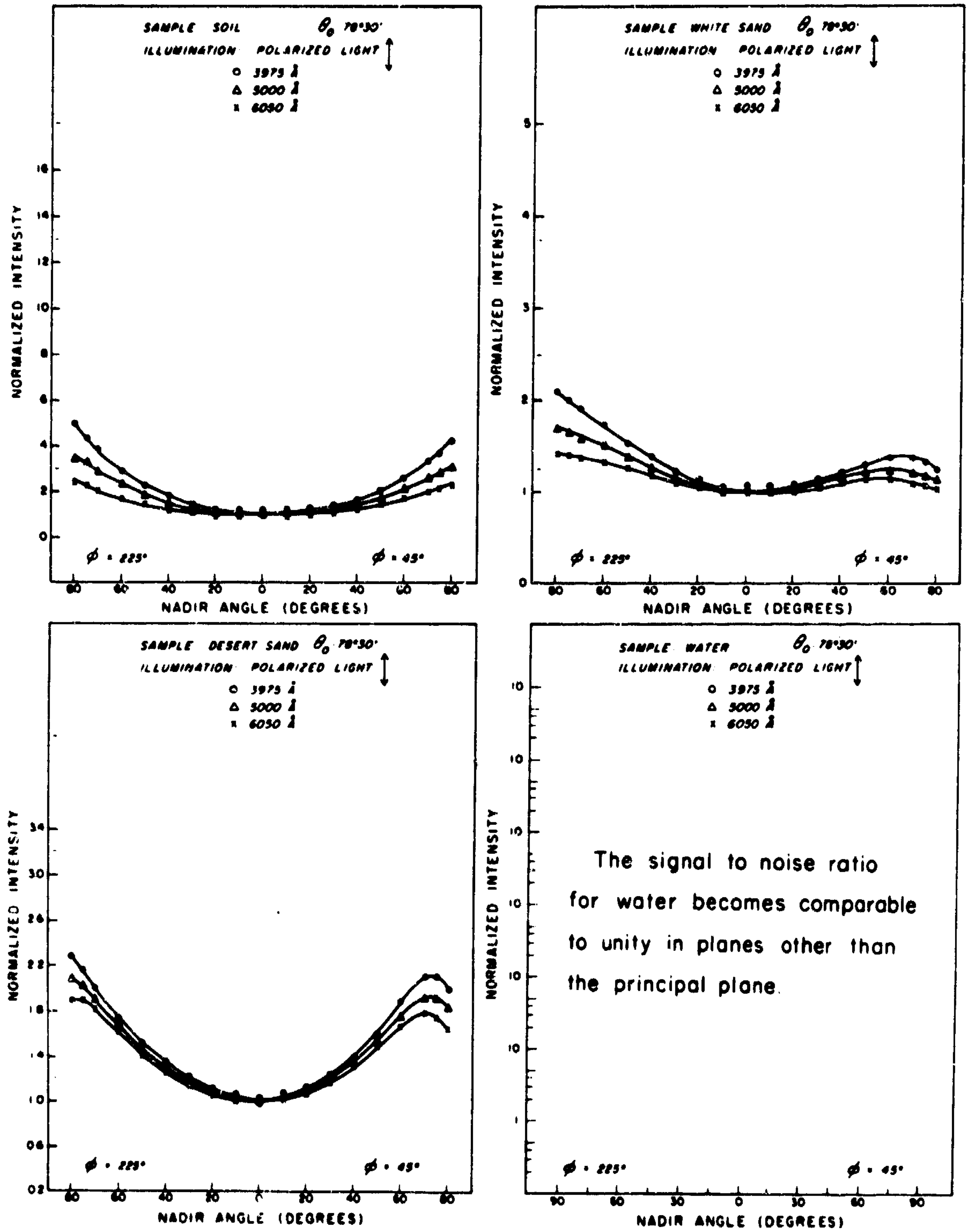


Fig. 30B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

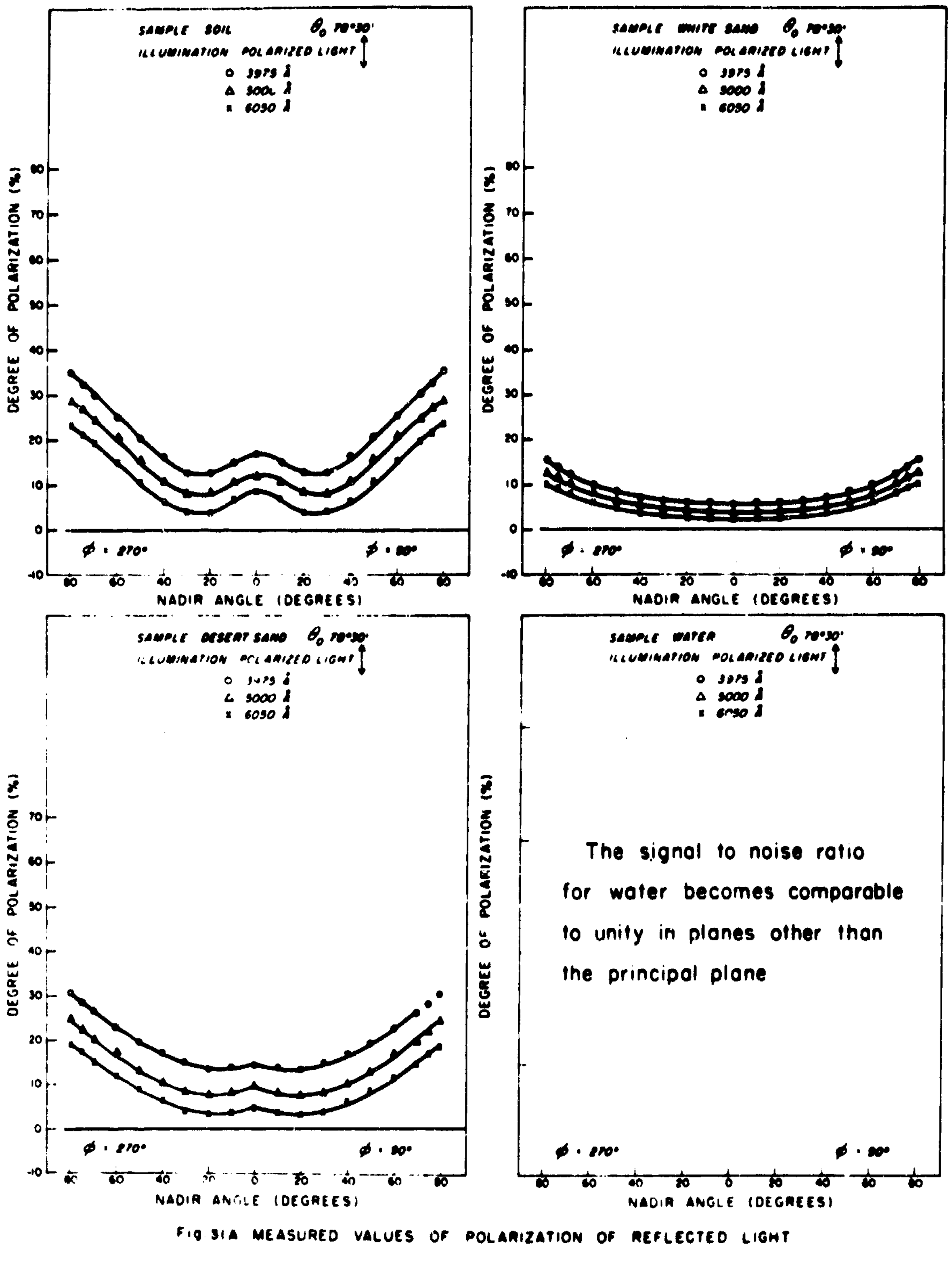


Fig 31A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

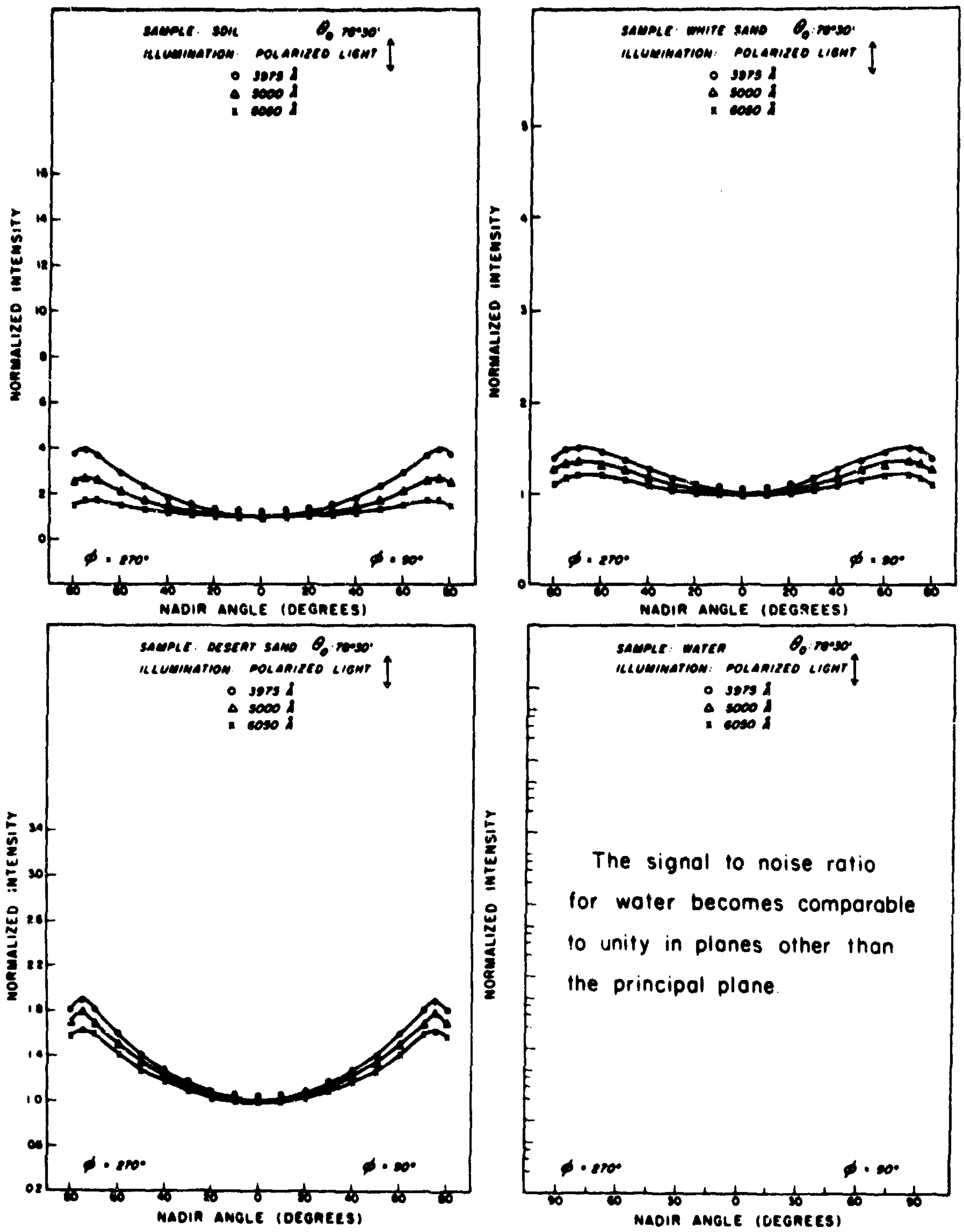


Fig. 31b. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

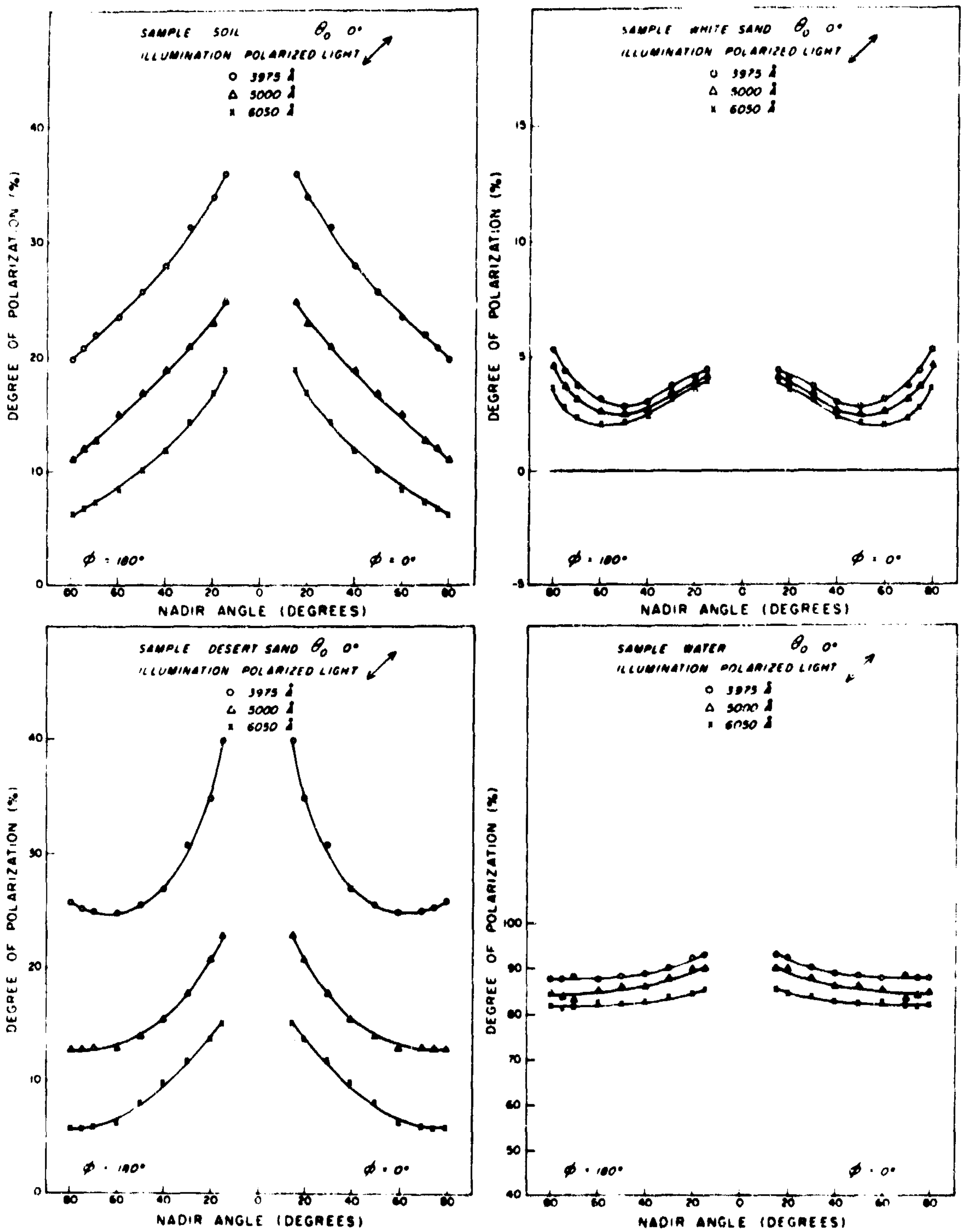


Fig. 32A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

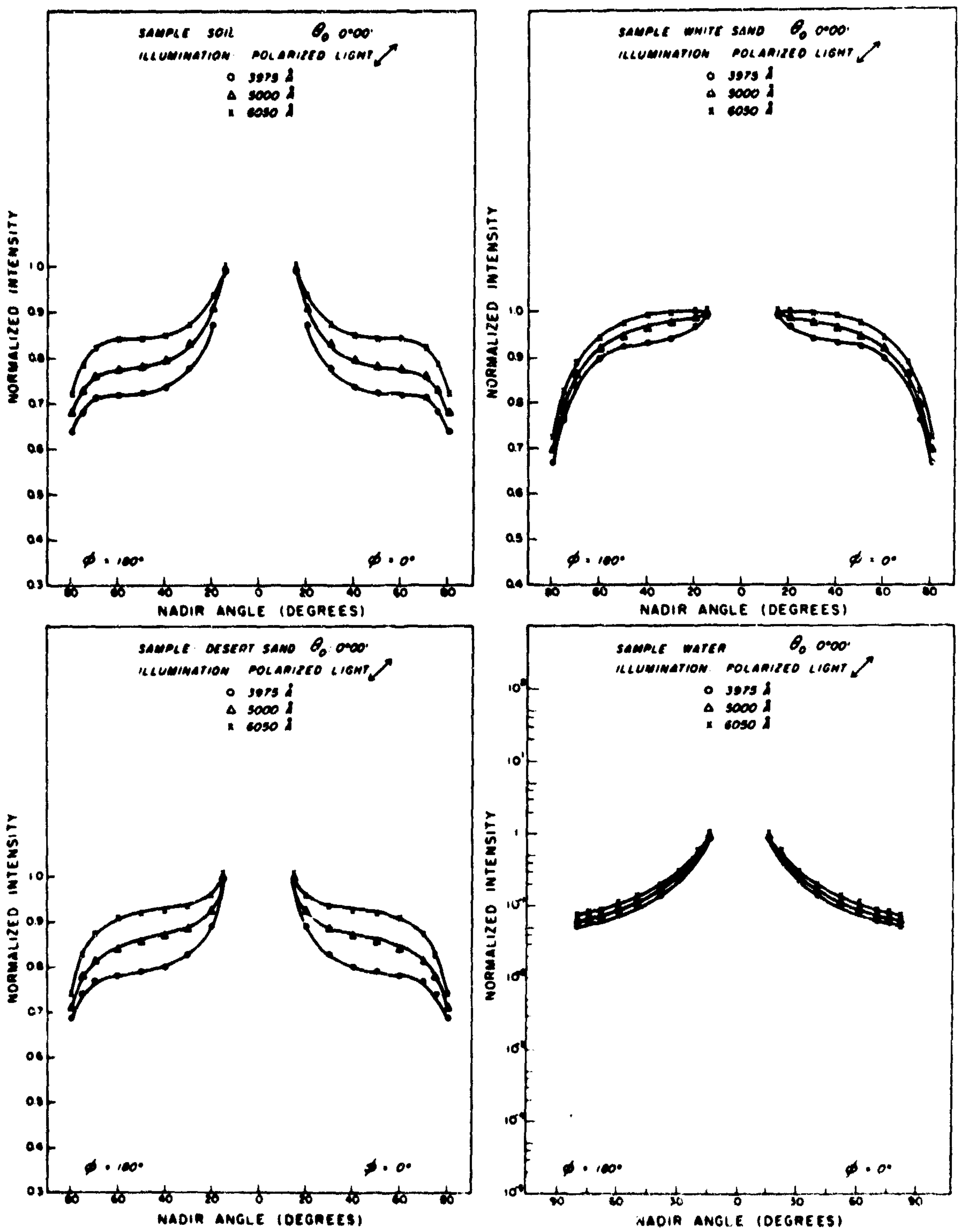


Fig. 32B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

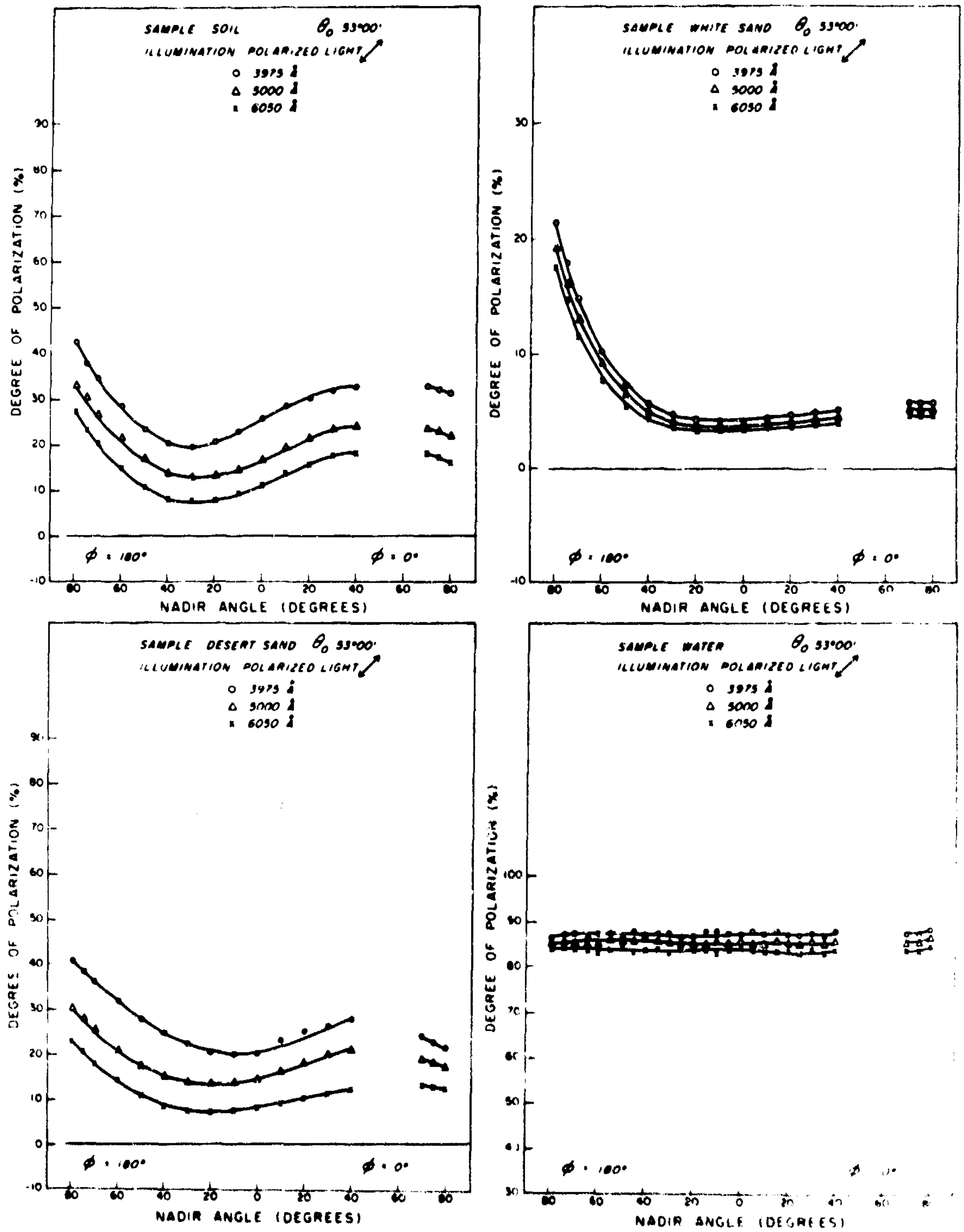


Fig 33A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

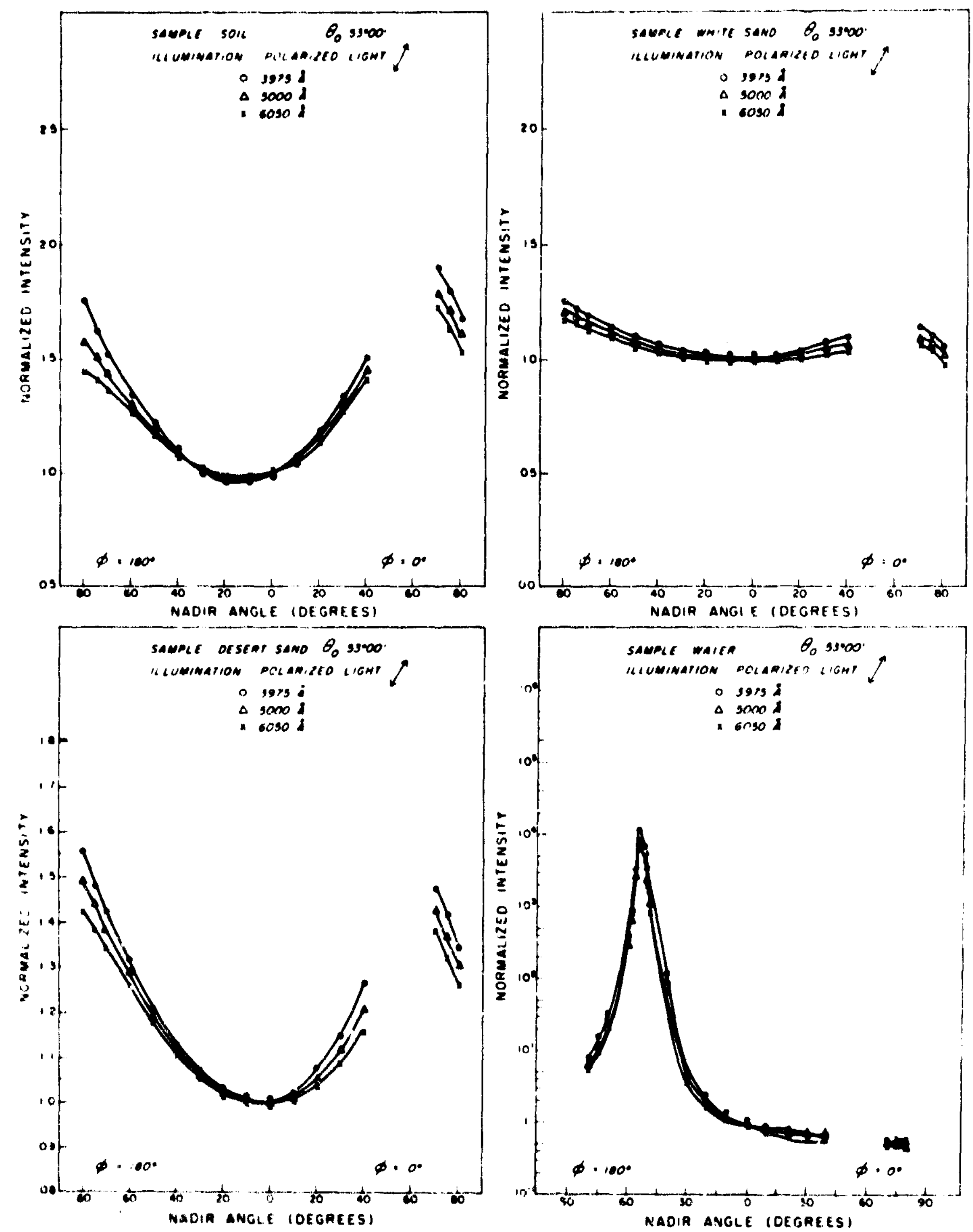


Fig 33B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

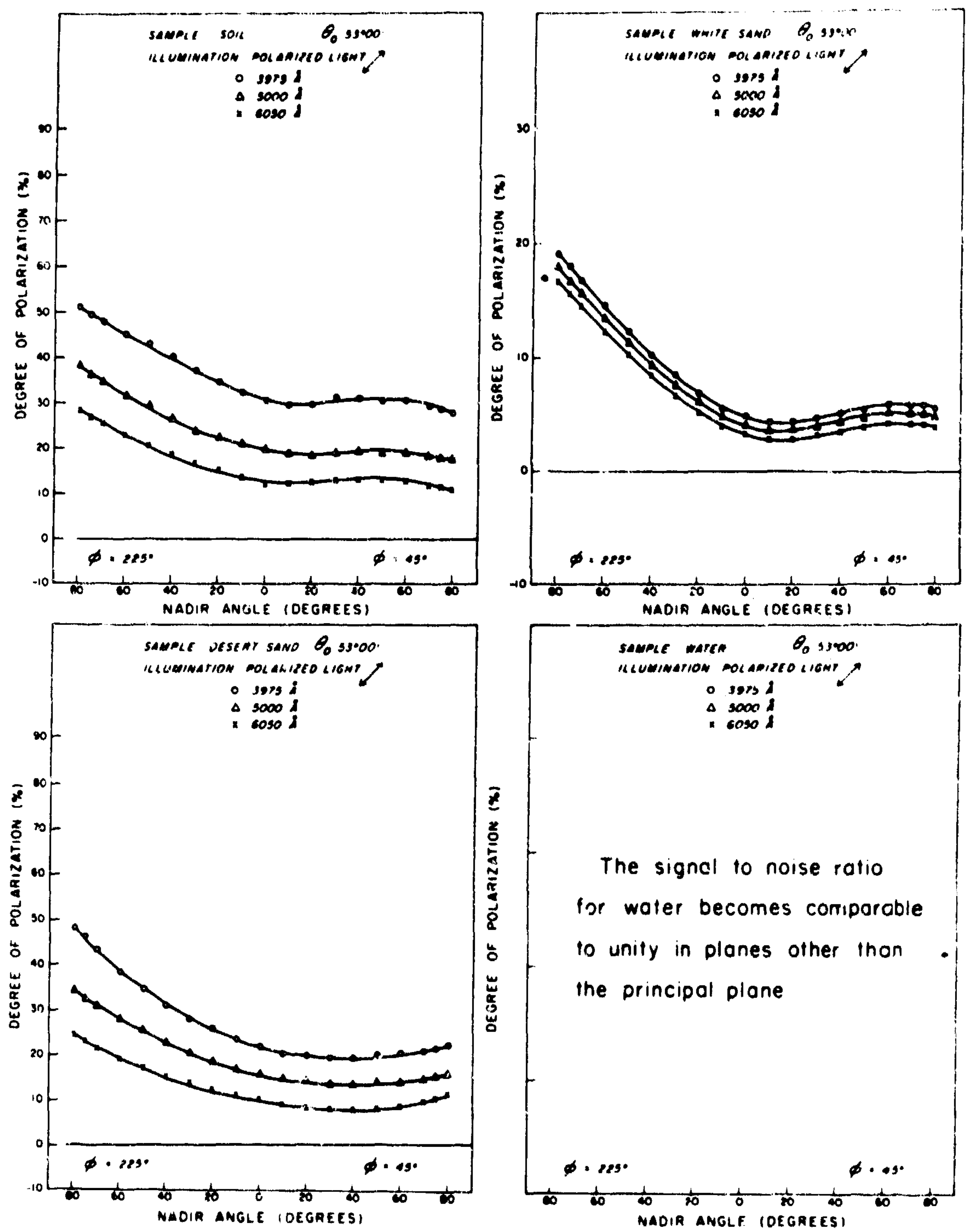


Fig 5.- MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

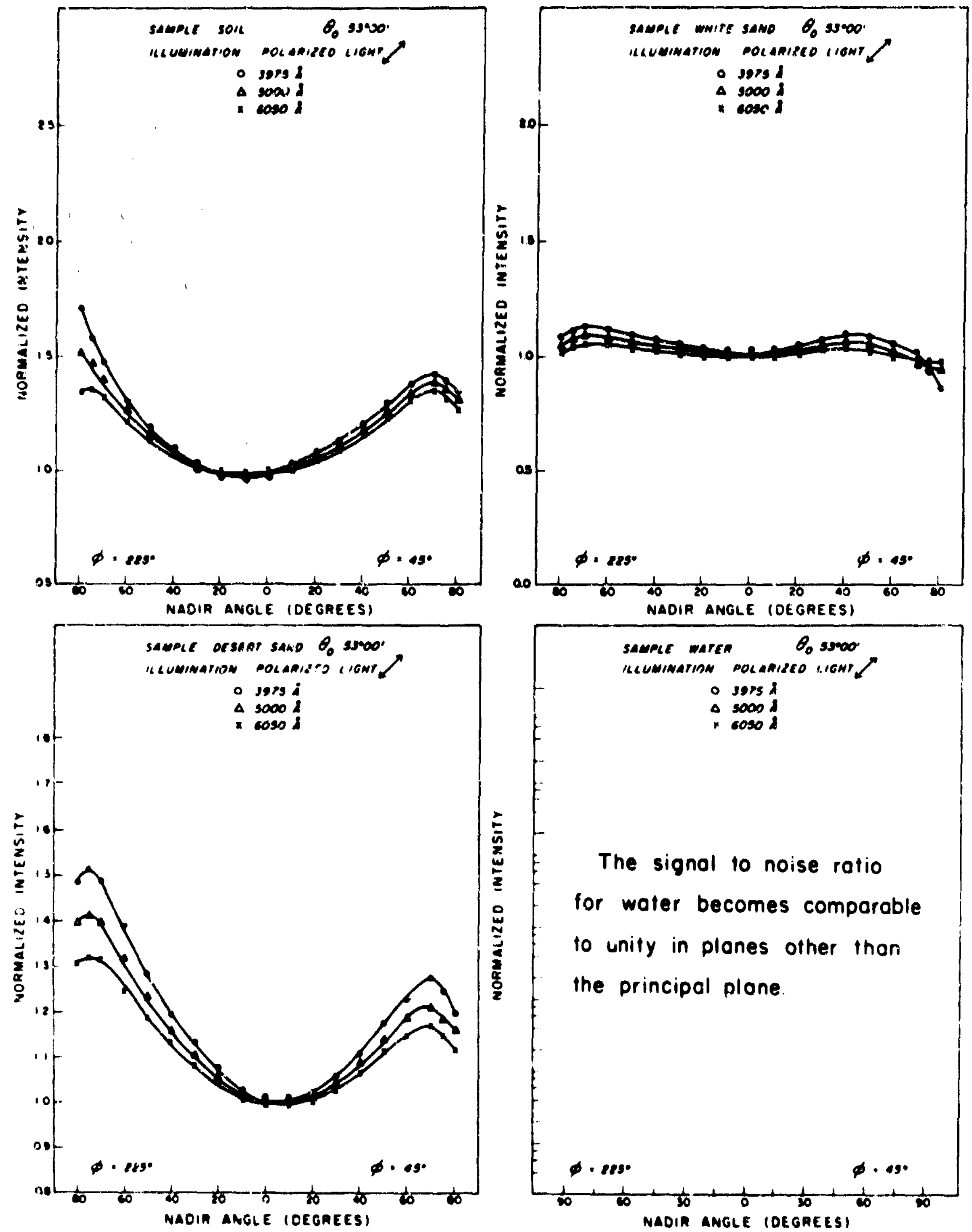


Fig. 34B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

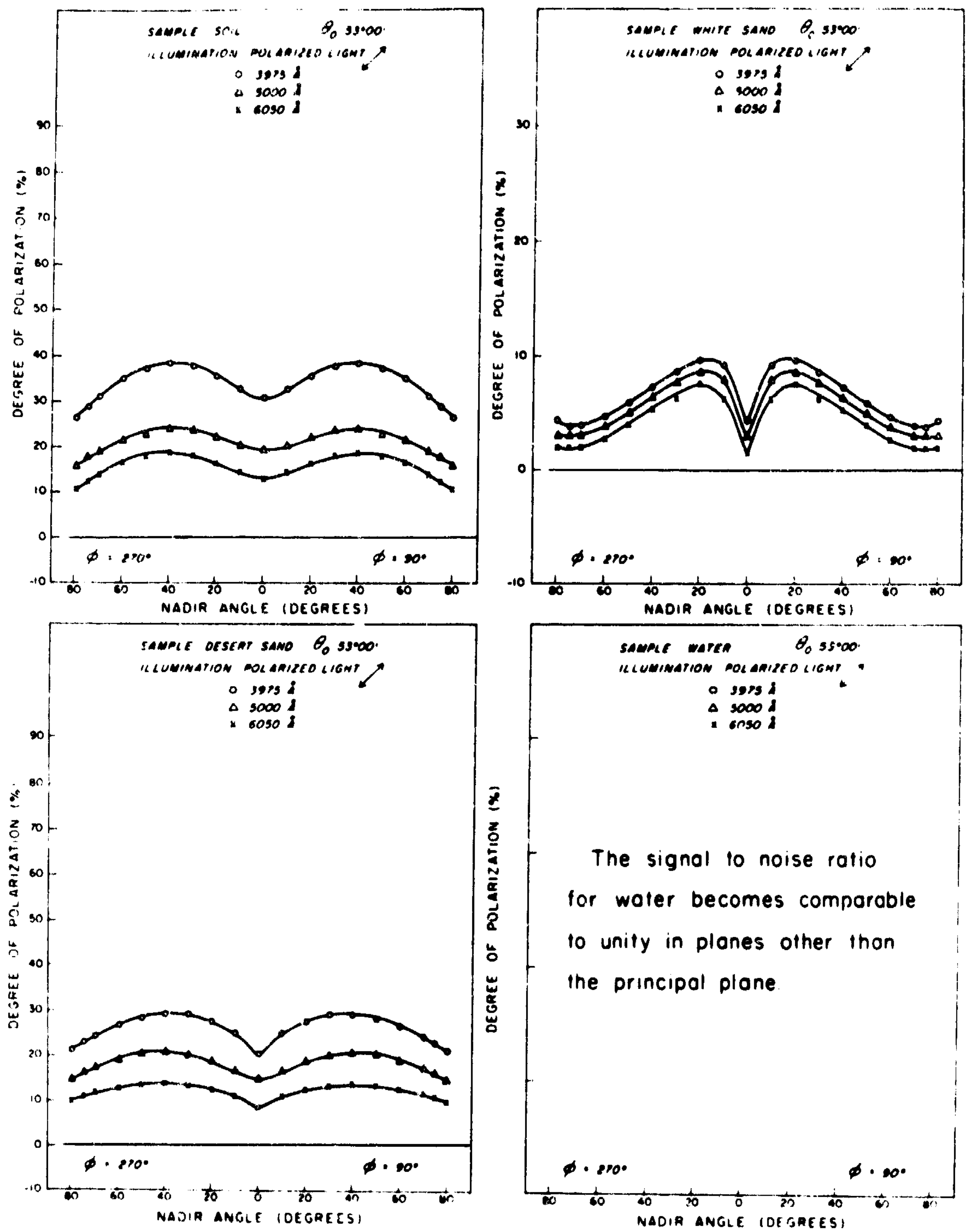


Fig 35A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

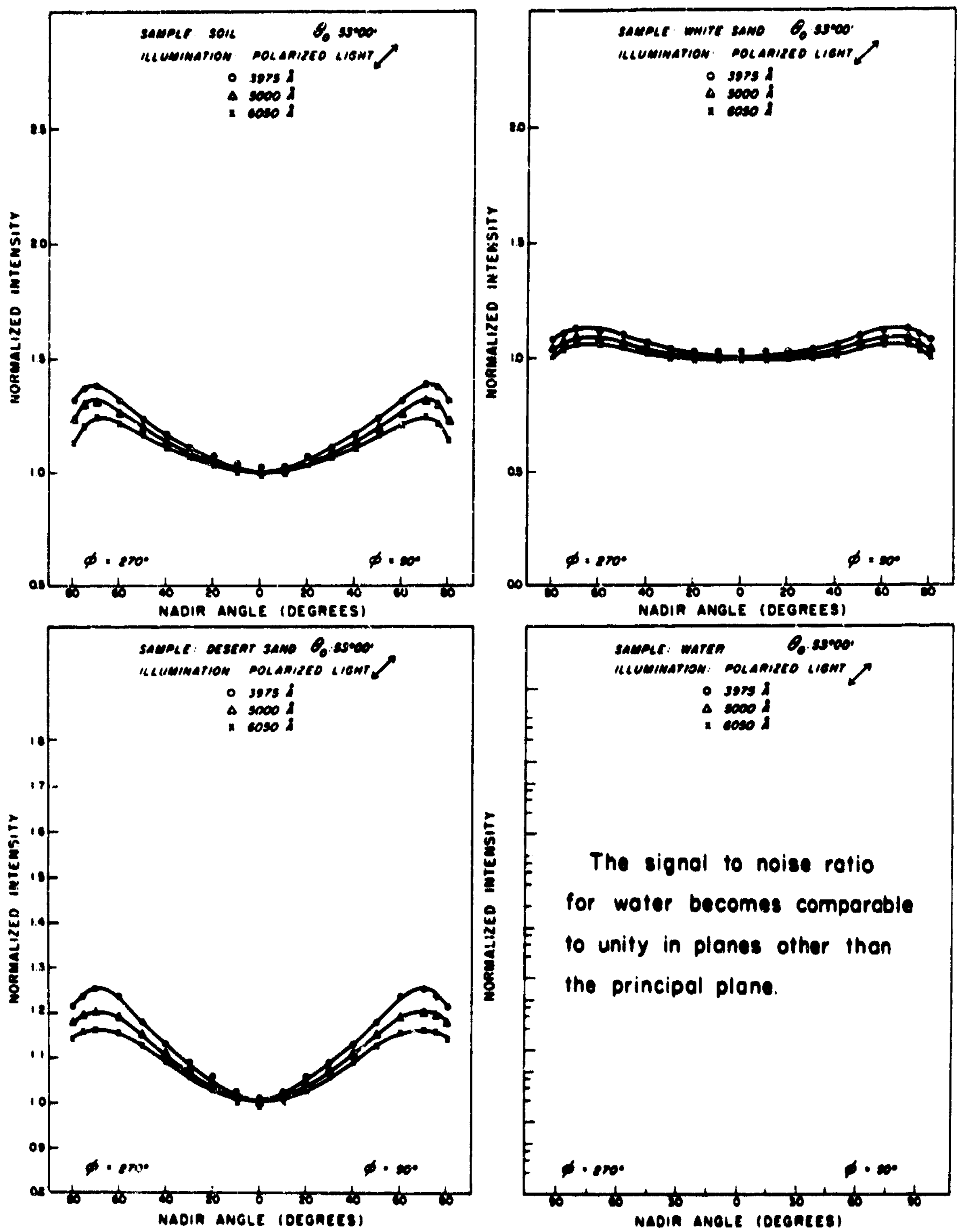


Fig.35B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

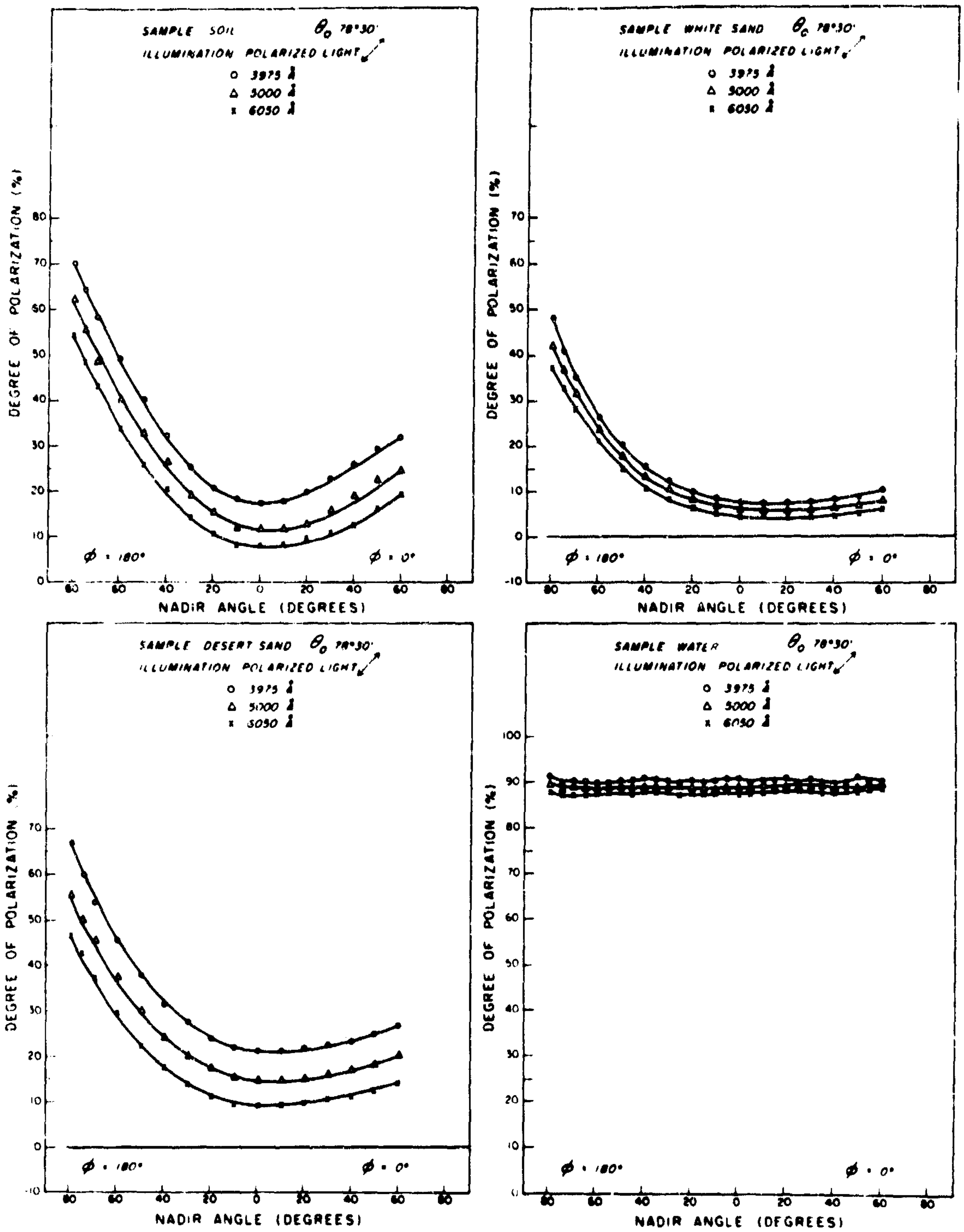


Fig. 36A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

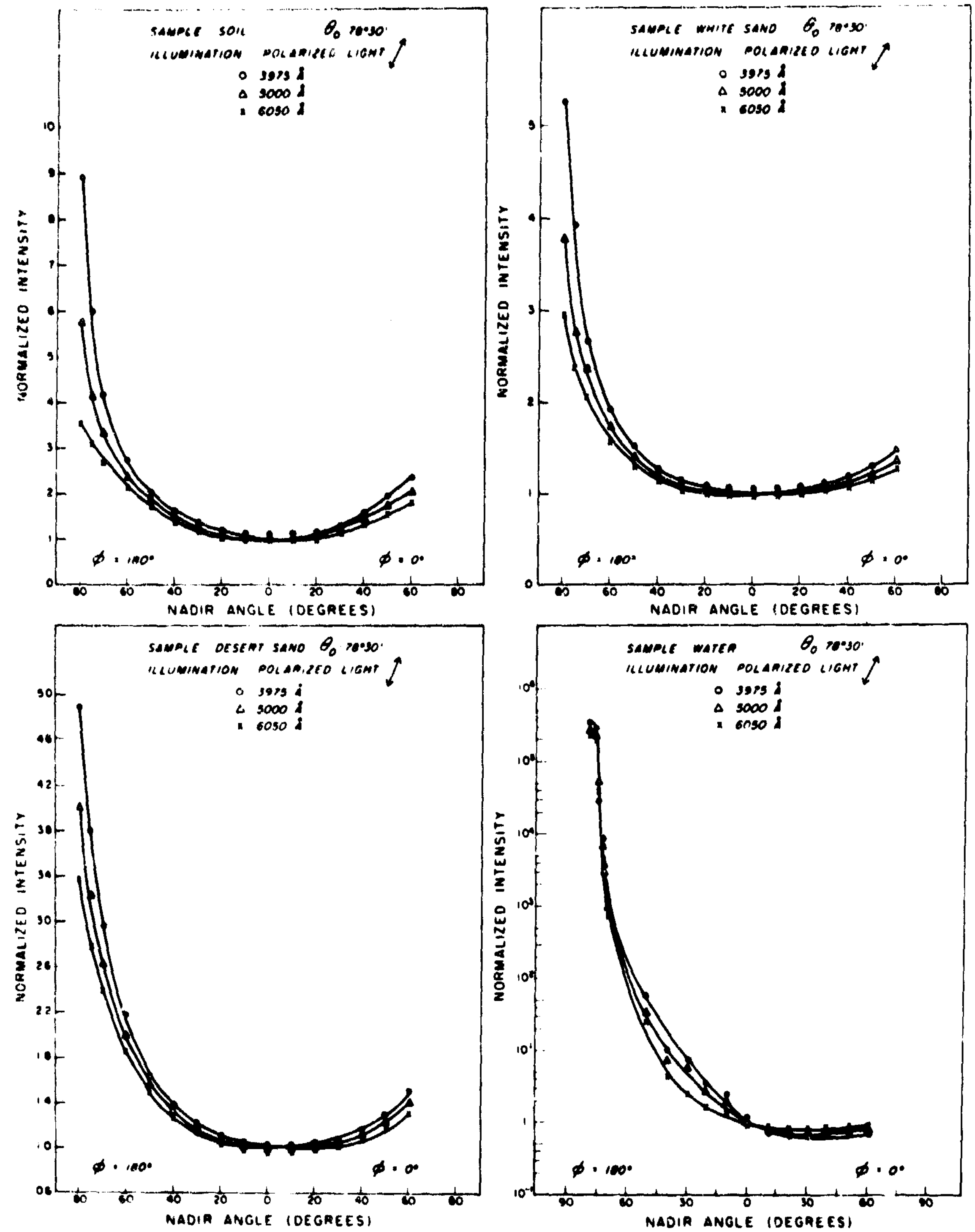


Fig.36B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

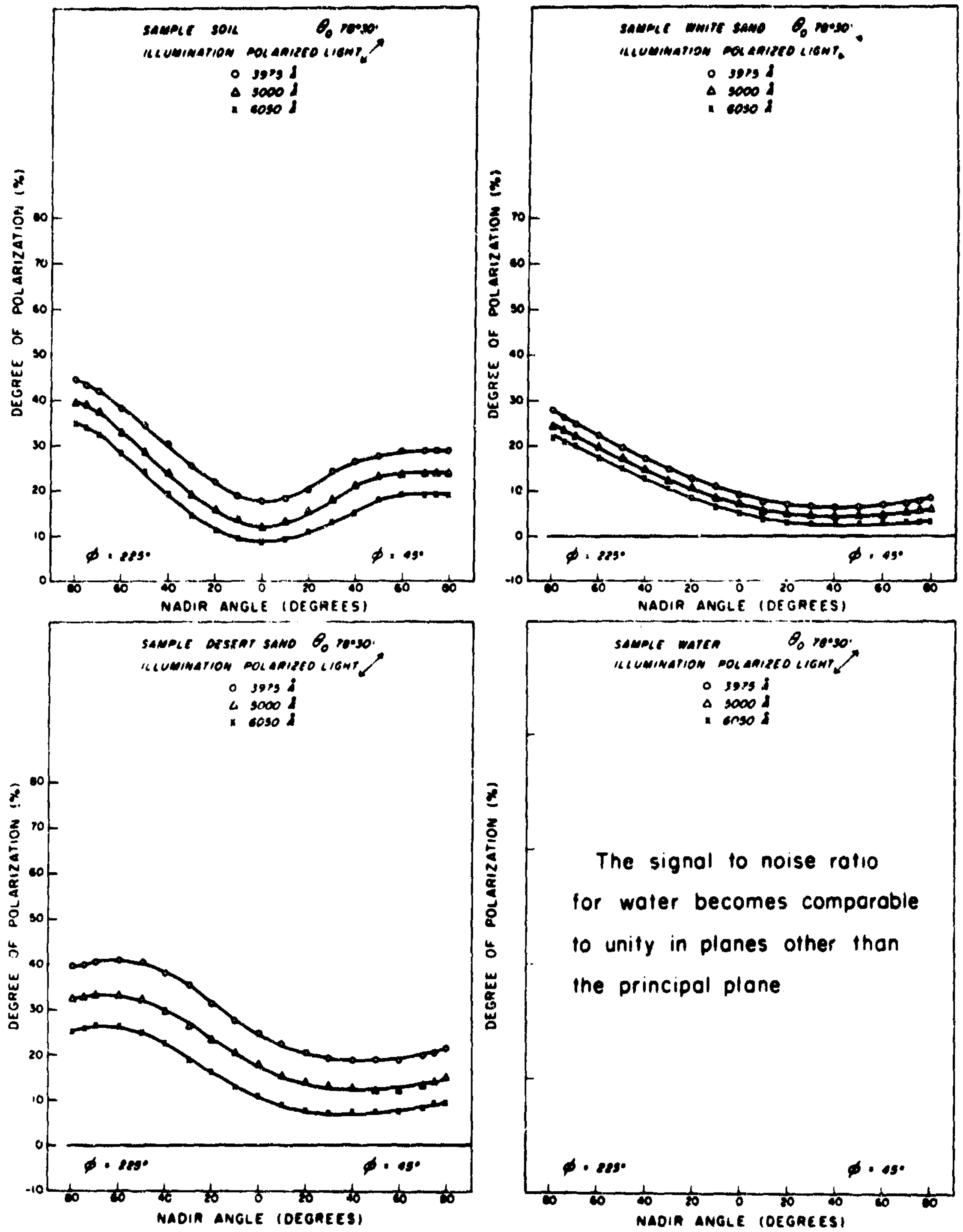


Fig. 37A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

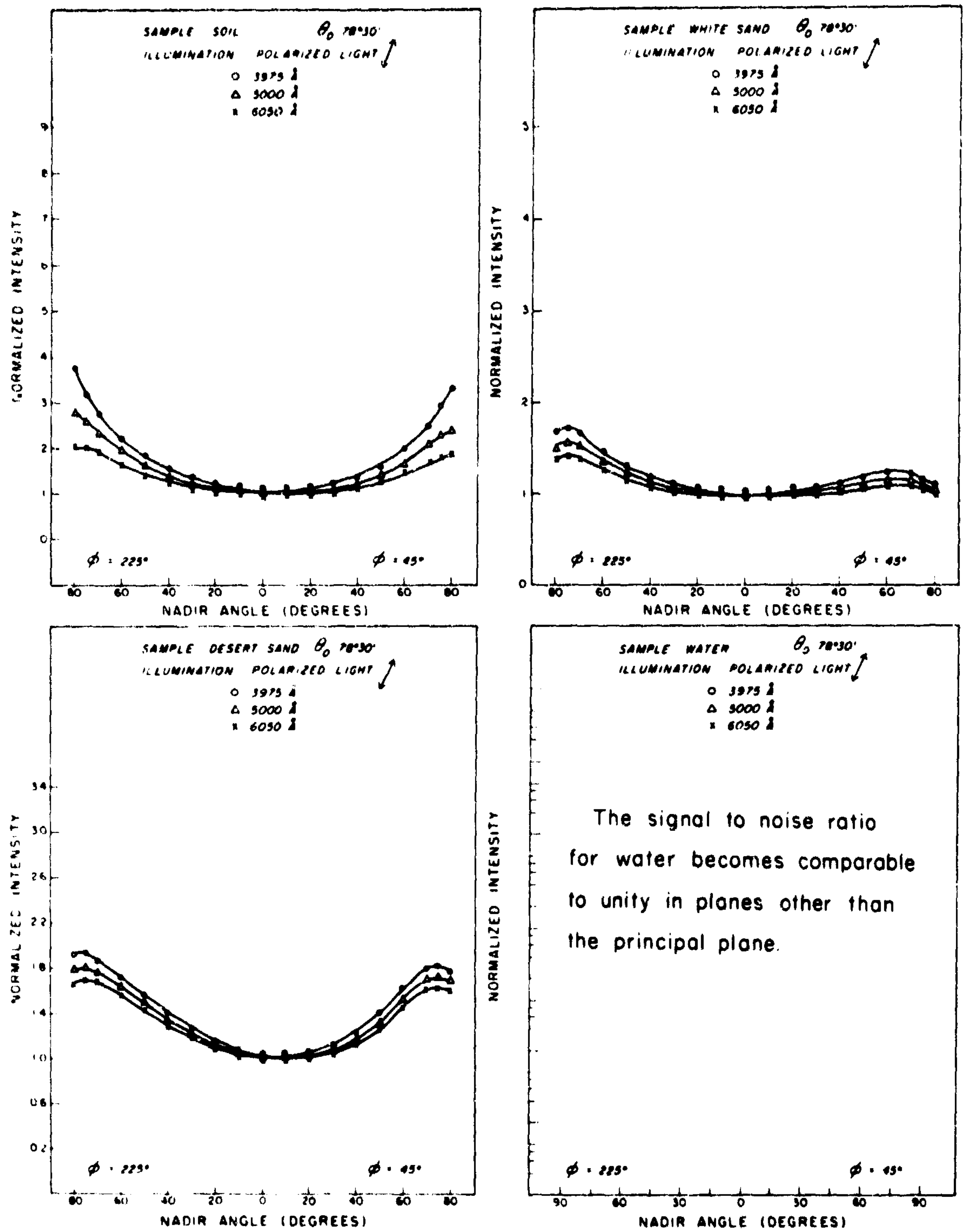


Fig 37B. MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

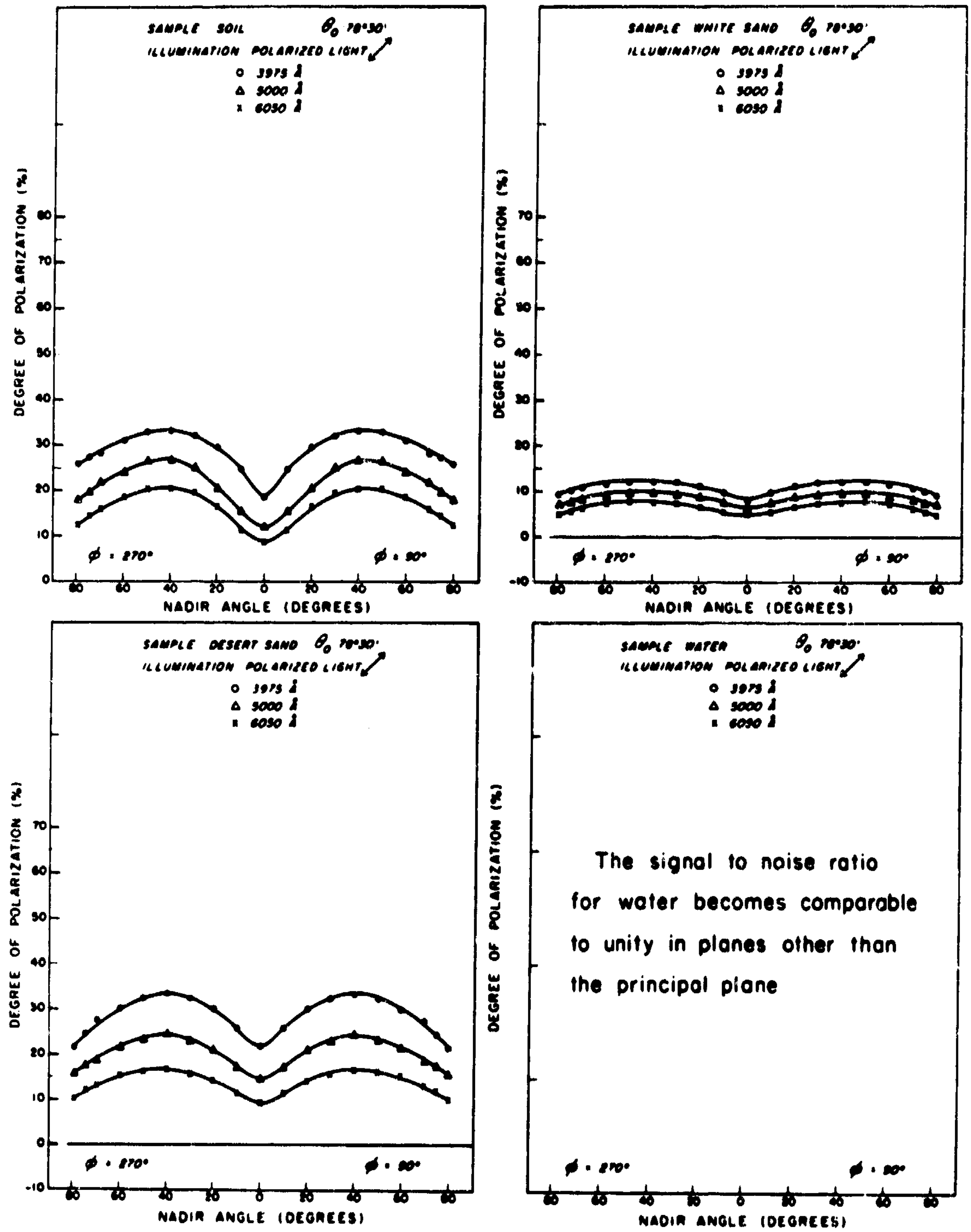


Fig. 38A MEASURED VALUES OF POLARIZATION OF REFLECTED LIGHT

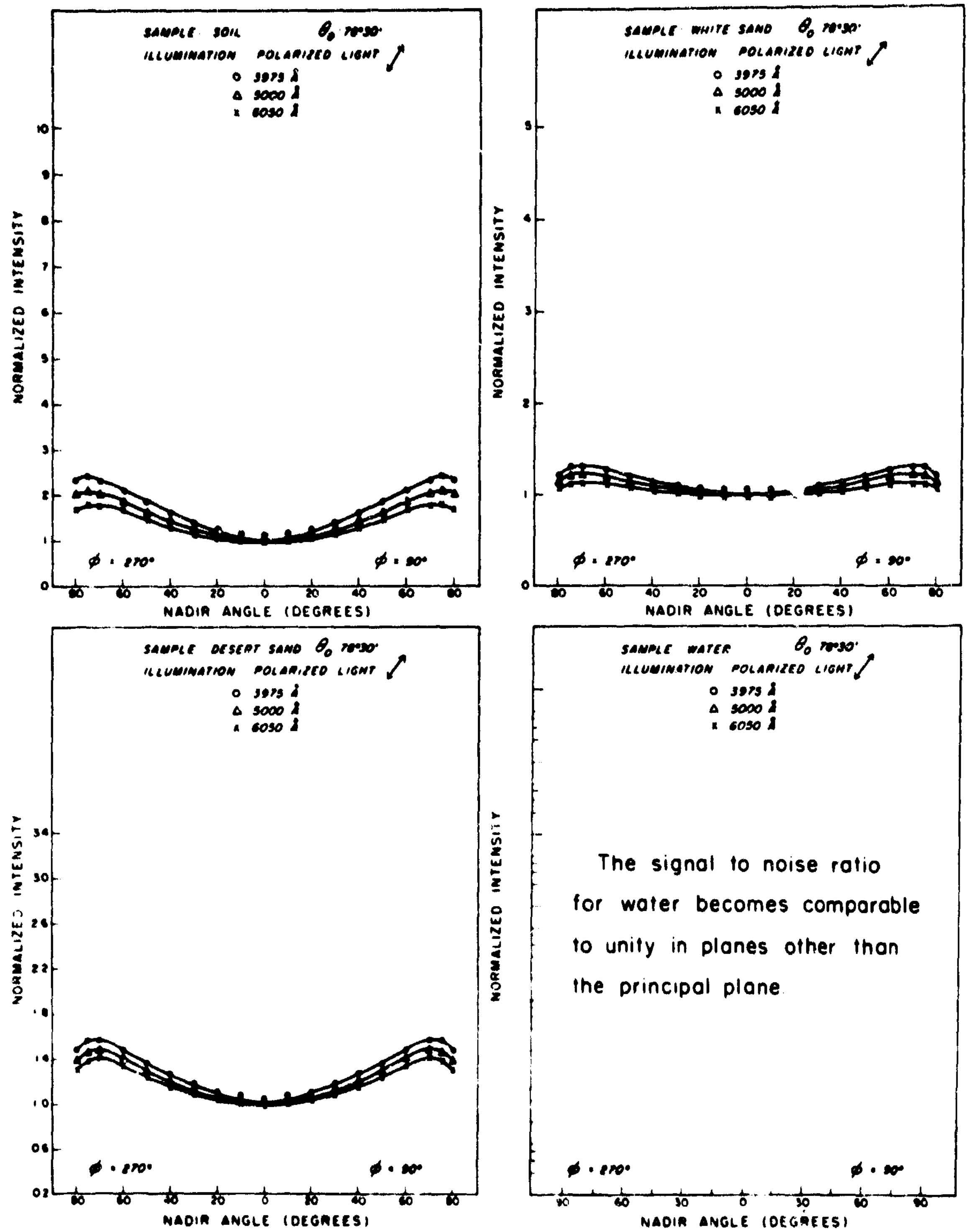


Fig 38B MEASURED VALUES OF INTENSITY OF REFLECTED LIGHT

REFERENCES

1. Fresnel, A.; Mem. de l'Acad., 11 (1832).

2. Stokes, G.; Proc. Roy. Soc., London, 11, 544 (1890).

3. Chandrasekhar, S.; Radiative Transfer, Oxford University Press, London (1950).

4. Sekera, Z. and Fraser, R.; Appendix E, Final Report, Contract No. AF 19(122)-239, Dept. of Meteorology, UCLA, (1955a)

5. Fraser, R.; Final Report, Contract No. NAS5-9678, TRW Systems, Redondo Beach, California (1966).

6. Coulson, K.; Appl. Opt. 5, 905 (1966).

7. Lyot, B.; Ann. Obs. Paris, 8 (1929).

8. Lyot, B. and Dollfus, A.; Compt. Rend. 228, 1773 (1949).

9. Caliens, A. and Dollfus, A.; Compt. Rend. 230, 1411 (1950).

10. Hapke, B. and Van Horn, H.; J. Geophys. Res. 68, 4545 (1963).

11. Stokes, G.; Trans. Camb. Philos. Soc., 9, 399 (1852).

12. Mueller, H.; J. Opt. Soc. Am. 38, 661 (1948).

13. Pollak, L.; All Term Guide for Harmonic Analysis and Synthesis, Dublin (1949).

14. Beckman, P. and Spizzichina, A.; The Scattering of Electromagnetic Waves from Rough Surfaces, The Macmillan Co. (1963).

BLANK PAGE

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* University of California Department of Meteorology Los Angeles, California 90024	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Investigations of the Polarization of Light Reflected by Natural Surfaces

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Interim Scientific Report

5. AUTHOR(S) *(Last name, first name, initial)*

Chen, Hsi-shu　　Sekera, Z.
Rao, C. R. Nagaraja

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1967	v + 96	14

8a. CONTRACT OR GRANT NO. AF 19(628)-3850 b. PROJECT AND TASK NO. 7621-03 c. DOD ELEMENT 62405394 d. DOD SUBELEMENT 681000	9a. ORIGINATOR'S REPORT NUMBER(S) Scientific Report No. 2 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AFCRL-67-0089

10. AVAILABILITY/LIMITATION NOTICES

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Hq. AFCRL, OAR (CRO) United States Air Force L.G. Hanscom Field, Bedford, Mass.

13. ABSTRACT

The polarization features of light reflected by soil, desert sand, white sand and water under different conditions of illumination with natural (unpolarized) and polarized light have been investigated in three narrow spectral intervals (band width ~ 150 A) centered on λλ 3975, 5000 and 6050 A. A simple 'rotating-analyzer' type photoelectric reflectometer was used in the measurements. The data was 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 overall similarity in the behavior 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.

DD FORM 1473 1 JAN 64

Unclassified

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
REFLECTION BY NATURAL SURFACES	8	3				
POLARIZATION ON REFLECTION	8	3				

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ____________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ____________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ____________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.