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REMOTE SOIL MOISTURE MEASUREMENTS

FINAL REPORT

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Goddard Space Flight Center
Greenbelt, Maryland 20771

GENERAL ELECTRIC
SPACE DIVISION
Valley Forge Space Center
P. O. Box 8555 • Philadelphia, Penna. 19101

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Prepared by

E. H. Stockhoff
R. T. Frost
E. J. Buerger

Space Sciences Laboratory
General Electric Company
P.O. Box 8555
Philadelphia, Pennsylvania 19101

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ABSTRACT

The degree of polarization of visible sunlight reflected from bare soils in agricultural test areas in the southwestern United States was measured by an airborne photopolarimeter. Surface soil specimens provided data concerning the surface moisture of the soil to which the polarization data were compared. The results indicate the feasibility of measuring soil surface moisture by airborne polarimeter instrumentation.

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INTRODUCTION

Work performed in our laboratory and in the field (Ref. 3) has shown that polarization of reflected visible light is one of the more sensitive techniques available for remote detection of soil surface moisture. This method has been found to be reasonably invariant to partial shadowing of rough surfaces being viewed and to their average inclination to the sun's rays. An advantage to be gained through the use of the optical polarization signature is the relatively large amount of reflected power available within narrow bandwidths which can be selected so as to minimize unwanted light, such as that from sparse foliage on a nearly bare field, and the relatively high quantum efficiency of available detectors in the visible range of wavelengths. Relatively small ground resolutions from satellite altitudes or from aircraft are thus feasible as a result of adequate signal statistics being readily attainable.

Instrumentation designed and assembled in our laboratory has been used for precision measurement of the degree of polarization of visible light (Ref. 5). A photopolarimeter similar to that described in reference 5, with a 3° field of view and a 100Å bandwidth centered at 6406Å was installed in NASA's Convair-990 aircraft for the purpose of measuring the polarization of sunlight reflected, i.e. scattered, from the ground as the aircraft was flown over several agricultural ground truth sites. Data were obtained from selected fields in the Imperial Valley, California and at Phoenix, Arizona during March, 1972. Ground truth samples of soil were obtained by Biospherics, Inc. to measure the moisture content of the soil at several depths along the flight path in these fields.

Auxiliary intensity data were taken at 5560Å and 8914Å.

INSTRUMENTATION

The GE polarimeter was installed above a window in the floor of the aft cargo compartment in such a manner that it could view from 42° ahead of, to 42° to the rear of, the nadir and could view from 40° to the left (port) of the nadir to directly downward (see Figure 1). A view to the right was not possible due to the presence of part of another experiment outside the aircraft blocking the view in that direction. Also mounted at the window was a television camera the body of which was fixed in single position while its lens, connected to the camera tube via a flexible bundle of fiber optics, was attached to the polarimeter so that the fields of view of the two instruments were virtually coincident.

The instrumentation rack for the polarimeter and television system was in the passenger compartment (see Figure 2). This rack contained the control panel for the polarimeter, the electronics required to sequence and process the data from the polarimeter, a television monitor, an oscilloscope, a strip chart recorder and a power supply for a heater in the polarimeter. A larger television monitor was mounted upon the rack as part of the aircraft instrumentation system to display certain aircraft data.

During each run over a ground truth site the polarimeter's data were recorded continuously by the strip chart recorder, along with a time pulse every 10 seconds, and also at a sampling rate of 100 sec^{-1} in the airborne data system (ADDAS). The location of the field of view of the polarimeter was monitored continuously during each data run by watching the television monitor and whenever it fell upon a road a button was pressed which caused a mark to be placed on both the strip chart and ADDAS records.

DATA REDUCTION

The pattern of markings on the strip chart indicating roads and towns produced a clearly identifiable pattern so that nearly all the fields from which the polarimeter was receiving reflected light were readily identified and, by reading the time code, the time of observation was determined within 0.1 second. Where it mattered and where it was not clear whether the field of view was to the left or to the right of the centerline of the pattern of fields, the location of the field of view at a particular time was calculated from the aircraft altitude, speed and attitude and from the location of the field of view of the downward viewing photographic camera at some proximate time.

The periods of time, during which the polarimeter viewed the fields chosen for study, were tabulated and the ADDAS records were then used to obtain 1) the attitude coordinates necessary to calculate the phase angle, i.e the angle between the viewing direction and the direction of travel of the light incident upon a field, the angle against which the degree of polarization is usually plotted to indicate polarization signatures, and 2) the polarimeter data from which the polarization is calculated. Data taken during periods of time for which the ADDAS records were not available were read from the strip chart.

MEASUREMENT OF STOKES PARAMETERS

The moisture content of the soil surface viewed by the polarimeter is measured by determining the angle through which the light has been scattered by the soil and by observing the degree of polarization of this light produced during its interaction with the soil. The polarimeter then measures this degree of polarization in terms of the first three Stokes parameters, called here I, Q and U. Q and U are measured by the polarimeter as the difference between two readily measured light intensities. A development of the representation of polarized light in terms of these parameters may be found in Ref. 2 and 5 and for the purposes of this report they may be defined as follows.

$$I = \text{total intensity of light}$$

$$Q = IP\cos(2\chi) \qquad (1)$$

$$U = IP\sin(2\chi)$$

where P is the degree of polarization of the light and χ is the angle formed between a reference plane, defined by the viewing direction and, usually, the vertical, and by the plane of polarization of the light. To obtain maximum angular scanning range through the assigned window, the reference plane was oriented as shown in Figure 3 with $\beta = 22.5^{\circ}$ relative to the "plane of incidence" of the aircraft window. The plane of incidence is defined by the normal to the window and the viewing direction. One of the three optical barrels of the polarimeter measures I, in the form I/2, while each of the other two barrels measures the intensity of light as transmitted through a polarizing prism. The resulting intensity B, in one case for the prism whose transmitting axis is oriented as shown and labeled "B" in Figure 3, and intensity D, in the other case for which an axis labeled "D" is shown, were then combined electronically to produce Q and U as follows.

$$Q/2 = B - I/2$$

$$U/2 = D - I/2$$

Two of the three parameters, I, Q and U, are sufficient to calculate the degree of polarization but, to permit a choice of which combination is used, to minimize error in the calculation, all three are measured and recorded. Because it was necessary to make the measurements by oblique viewing through an already existing window in the pressure hull of the aircraft, a correction must be applied to the data to account for 1) the change in magnitude and orientation of plane of polarization of the polarized component, 2) the attenuation of the unpolarized component and 3) the generation of a polarized component from the unpolarized component, all due to the presence of the window. This correction is derived below.

CORRECTION FOR TRANSMISSION THROUGH WINDOW

The light incident upon the soil from the Sun is assumed to be unpolarized and after scattering it has independent polarized and unpolarized components having intensities of I_p^o and I_u^o respectively. Let the scattering plane, defined by the direction of observation and the direction to the Sun, make an angle ϕ with the plane of incidence at the window. This angle is measured from the plane of incidence to the scattering plane in a clockwise direction when looking toward the approaching light. Then the intensities of the altered polarized component, I_p, the remaining portion of the unpolarized component, I_u, and the new polarized component, i_p, (referred to in the preceding paragraph in 1), 2) & 3) respectively) may be written as follows.

$$I_p = b\, I_p^o$$

$$I_u = T_\perp\, I_u^o$$

$$i_p = a\, I_u^o$$

where

$$b = T_{11} \sin^2\phi + T_\perp \cos^2\phi$$

$$a = \frac{1}{2}(T_{11} - T_\perp)$$

and T_{11} and $T_\perp$ are the transmissivities of the window for components whose electric vectors are parallel to and normal to the plane of incidence, respectively. These three components are independent (Ref. 2 p. 29 (Sec. 15.2)) and the Stokes parameters of the total beam may therefore be obtained by adding the corresponding Stokes parameters of the individual components in the form of equations (1) and making use of Figure 3. The sums of the Stokes parameters as seen by the instrument behind the window are

$$I = c\, I_u^o + b\, I_p^o$$

$$Q = a\, I_u^o \cos 2\beta - b\, I_p^o \cos 2(\phi_i - \beta) \qquad (2)$$

$$U = -a\, I_u^o \sin 2\beta - b\, I_p^o \sin 2(\phi_i - \beta)$$

where

$$c = \frac{1}{2}(T_{11} + T_\perp)$$

$$\phi_i = \text{arc Tan}\left[\sqrt{\frac{T_{11}}{T_\perp}}\ \text{Tan}\ \phi\right]$$

and β is the angle measured in a clockwise direction, looking toward the approaching light, from the plane of incidence to a reference plane associated with the orientation of polarizing prisms in the polarimeter. (The angle the plane of polarization of the initially polarized component makes with the plane of incidence after it has passed through the window is $90^\circ + \phi_i$.) It has been assumed in writing the equation for ϕ_i, as has been previously assumed (Ref. 8), that the plane of polarization corresponds closely to the plane defined by the normal to the scattering plane and the viewing direction. Several checks made with the calculated values of I_p^o and I_u^o support this assumption.

CALCULATION OF POLARIZATION

By the orientation of the polarimeter with respect to the window and through measurement of the index of refraction of the window in our laboratory, values of three of the parameters in the I, Q and U equations are known to be

$$\beta = 22.5^\circ \pm 0.2^\circ$$

$$T_{11} = 0.982 \pm 0.002$$

$$T_\perp = 0.865 \pm 0.004$$

The value of ϕ is calculated from knowledge of the orientation of the polarimeter relative to the Sun at the time of each measurement. (Alternatively ϕ_i, hence ϕ, could be calculated from the equations for Q and U but this was not done.)

Thus I_p^o and I_u^o may be calculated from any two of the I, Q and U equations (Equations (2)) as follows.

a) I, Q combination

$$I_p^o = \frac{I\, a \cos 2\beta - c\, Q}{b\left[c \cos 2(\phi_i - \beta) + a \cos 2\beta\right]}$$

$$I_u^o = \frac{I \cos 2(\phi_i - \beta) + Q}{c \cos 2(\phi_i - \beta) + a \cos 2\beta}$$

b) I, U combination

$$I_p^o = -\frac{I\, a \sin 2\beta - c\, U}{b\left[c \sin 2(\phi_i - \beta) - a \sin 2\beta\right]}$$

$$I_u^o = \frac{I \sin 2(\phi_i - \beta) + U}{c \sin 2(\phi_i - \beta) - a \sin 2\beta}$$

c) Q, U combination

$$I_p^o = \frac{Q \sin 2\beta + U \cos 2\beta}{-b \sin 2\phi_i}$$

$$I_u^o = \frac{Q \sin 2(\phi_i - \beta) - U \cos 2(\phi_i - \beta)}{a \sin 2 \phi_i}$$

The degree of polarization was then calculated from

$$P = \frac{I_p^o}{I_u^o + I_p^o}$$

using combination a), b) or c), above. The uncertainty in the value of P resulting from uncertainty in reading the raw data was estimated for each of the three combinations of equations for each set of data from which a value of P was obtained. Usually one or two of the three sets of equations produced a very large uncertainty in P due to the evaluation of the difference between two nearly equal numbers in the calculation of I_p^o or I_u^o. The value of P having the least uncertainty was selected to be the value used in the data analysis.

FIELD SELECTION

Analysis of the field data was begun by first selecting those bare fields reported in the ground truth (Ref. 1) study as wet or moist and then by selecting a dry bare field of the same or similar soil type for each of the wet fields During the flights over the ground truth sites, a mark had been inserted into the data recordings and/or a voice comment was made into a tape recorder whenever the field of view included a road. By doing this, the identification of the data with the corresponding fields was facilitated by comparing the pattern made by these marks with the pattern of roads on a detailed map of the area and, in addition, it assured that no data recorded during the viewing of a road were used in the polarization-soil moisture analysis. After the elimination of several fields for which the field of view of the polarimeter fell partially upon roads bordering the fields, the total number of fields or combination of fields used for data analysis amounted to 20, with most of these fields having been flown over and providing data four times.

DATA ANALYSIS

The degrees of polarization calculated from the photopolarimeter data for these fields are given in Table 1. The list of phase angles given in this table for each polarization measurement was scanned to choose groups of data for which the phase angles were similar, thereby selecting data which could be expected to share a common polarization-soil moisture relationship. No data were plotted for phase angles less than 65° because it is known from previous work (Ref. 3) that the sensitivity of the polarimetry technique is low at small phase angles. Each group of data so selected was plotted in Figures 4 through 8 in which the degree of polarization of light reflected from the fields is plotted against percent soil moisture as given by the ground truth study. On each graph the solid line, estimated by eye, was drawn to represent the polarization-soil moisture relationship best fitting the plotted points with exceptions as noted below. The slope of this line at low moisture levels is known to have a nearly constant value (Ref. 3) and this fact was used in plotting the solid line at the lowest moisture levels. The phase angles and fields represented on Figures 7 & 8 are essentially the same; therefore the lines drawn on these two graphs were deliberately made identical. Phoenix field #84 was very moist when it was first observed on March 11 and it is evident when the data are plotted against time, as they have been in Figure 9, that the surface of that field dried as the day progressed and that the polarimeter measured the moisture at the surface as this drying was taking place. The ground truth specimens were taken for this field on March 11 at 13:30 and it is the degree of polarization of this time, 13:30, taken from the curve in Figure 9, that was used to plot a point at 31% moisture and through which the solid lines were drawn in Figures 7 and 8. The data marked 83/84 in Figure 8 were taken on March 13 at 13:13 and 13:39 and, apparently, the surface of the fields had again dried to the te afternoon levels of March 11 after having been under the influence of the Sun for more than half a day.

On each of these graphs the number of each field and a number representing its soil type, as given in Table 1, are given beside and within each point, respectively. In some cases, the numbers of two fields are given for a data point where the two fields meet and when there was neither a road nor ditch between the two fields nor was there any significant difference between the two fields in the ground truth report. The scatter of the data points on these graphs is best discussed by dividing the comments into two categories; scatter in the soil moisture measurements and scatter in the polarization measurements, as follows.

SCATTER IN GROUND TRUTH DATA

All the soil surface moisture data reported herein have been derived from samples taken by removing a specimen layer of soil down to a depth of 1/4 inch, which represents a compromise between a desire to sample the surface to as shallow a depth as possible, to represent only the soil viewed by the polarimeter, and the difficulty encountered in removing a thin layer from coarse soils. An estimate of the uncertainty which may be expected in duplicating a soil surface moisture measurement may be made from the duplicate samples reported for Phoenix fields #55, #57, #67 and #86 in the ground truth report, Airborne Microwave Radiometric Data Analysis, submitted to NASA, Goddard Space Flight Center by Biospherics Inc., June, 1972, under Contract No. NAS5-21674. Table 2 summarizes the data given in this report for the 0-1/4 inch samples taken from these fields. As may be expected, this table illustrates that the samples taken from a very dry field tend to vary very little one from another and that samples taken from a more moist field tend toward greater variation. The data in Table 2 suggest that uncertainty in moisture measurements on the moderately moist fields may be estimated to be + or - 2% moisture and to be larger for more wet fields. Examination of the points plotted for fields #11, #12 and #16 on Figures 4, 5 and 6 indicates a systematic departure from the solid line and suggests that the uncertainty at these moisture levels may be as great as + or - 5% moisture. Note that the data for all of these points were obtained on the same day and, because each field was sampled only once each day, the moisture value given for one field on one graph is the very same value given for the same field on the other two graphs.

SHORT TERM FLUCTUATIONS DUE TO MOTION OF FIELD OF VIEW

An estimate was made of the uncertainty which may exist in the calculated values of degree of polarization due to motion of the aircraft. Because the Stokes parameters are determined by the subtraction of two electrical signals obtained one after the other 0.05 sec apart, each dependent upon the light reflected from the earth for its magnitude, changes in the intensity of light during the 0.05 sec period, no matter what the cause, will result in some error in the subtraction and, hence in the degree of polarization calculated from the Stokes parameters. By examination of light intensity data recorded along with the Stokes parameter information the average variation or fluctuation of the light intensity over a 0.05 sec interval was estimated to be + or - 1/2%. Applying this to the data for a typical field, Imperial Valley #2, the calculated degree of polarization and corresponding uncertainty may be stated as $7.7 \pm 0.5\%$. Thus the short term, 0.05 sec variations in intensity do not produce a sufficiently large variation in polarization to account for much of the scatter which the data exhibit.

LONG TERM VARIATIONS DUE TO MOTION OF FIELD OF VIEW

The change in intensity from the time the Stokes parameters are measured once until the next time they are measured was found to average 6% with an extreme change of 12% in one case. The time interval between these measurements is 1.3 sec and the ground speed of the aircraft was typically 400 feet/sec which means that a distance of about 500 feet would have been travelled during that period between measurements. The distance travelled during the measurement of I, Q and U, for comparison, is about 100 feet. As may be seen from the color photographs taken during the flights, each bare field is essentially all the same color with many variations in the intensity of that color, presumably due to variations in moisture content, with the wetter soils appearing darker than the drier soils. Adopting a value of 10% to represent a typical variation in intensity within any one field and assuming that this variation is due entirely to changes in amount of moisture in the soil, an estimate may be made of the resulting variation in observed polarization. Reference 4 gives data concerning the reflectivity and polarization for wet and dry loam and for these data at the phase angles reported herein it shows that when the reflectivity decreases by 60%, as a dry loam is made moist, the degree of polarization increases by about 140%. Assuming a similar relationship exists between reflectivity and polarization for the soil in Imperial Valley field #2, a 10% decrease in intensity, hence reflectivity, would increase the polarization from the observed value of 7.7% to a value of approximately 9.4%. Using this calculation as a guide, a pair of dotted lines has been drawn in Figures 4 through 8 corresponding to a 10% maximum intensity variation from one dotted line vertically to the other, due to variations in moisture content and it may be seen that most of the data points fall within or close to the band formed by these two lines. This indicates that most of the scatter is due, in addition to variations in ground truth measurements, to actual variations in the soil moisture from one part of a field to another part of the same field.

CORRELATION COEFFICIENTS

In order to facilitate comparison of this work with that reported by Schmugge, Gloersen and Wilheit in Ref. 7, correlation coefficients were calculated for the data in figures 4 through 8. The coefficient is defined as (Ref. 6)

$$k_{PM} = \frac{\Sigma (P_i - \bar{P})(M_i - \bar{M})}{\left[\Sigma (P_i - \bar{P})^2 \cdot \Sigma (M_i - \bar{M})^2\right]^{1/2}} \qquad (3)$$

in which P_i and M_i are the individual values of polarization and moisture for each data point and $\bar{P}$ and $\bar{M}$ denote their average values. These coefficients are listed in Table 3 in the column headed with the words "For data points" and are given for each of the figures, except for Figure 8. The data for Figure 8 were obtained under essentially the same conditions as were those for Figure 7, except that they were obtained later in the day. Therefore the data (uncorrected) for Figure 8 were included with those for Figure 7 (also uncorrected) in a correlation coefficient calculation to determine to what extent the drying of the fields would degrade the correlation. It is known that the relationship between P and M is non-linear (Ref. 3) so that the correlation coefficients for the Polarization/Moisture data could never exceed some value less than unity, the exact value depending upon the degree of non-linearity. In order to assess the limiting values of the linear correlation coefficient as applied to the data in the present work, another column entitled "For solid line" is given in Table 3. This gives the linear correlation coefficients derived from equation (3) for sets of hypothetical data uniformly distributed along the solid line in each figure. These latter numbers represent a maximum value for the linear correlation coefficient for each set of data. A similar non-linear relation may be seen in Ref. 7 between soil moisture and microwave emissivity which is presumably due to the different indices of refraction for free water and for water bound to soil particles and to variation in the amounts of free and bound water in the soil.

It may be seen by comparison of the empirical and maximum values of the linear correlation coefficient that, in general, good correlation was obtained. A similar comparison could be performed with the data in reference 7.

REMOTE IDENTIFICATION OF BARE FIELDS

The fields selected for analysis in this report had been reported in the ground truth report as bare, or very nearly bare which facilitated the initial data reduction efforts by concentrating these efforts on these fields for which the polarization-soil surface moisture technique is applicable. However, the same discrimination could have been made without the aid of the ground truth work by observing the ratio of light intensities measured at two different colors as measured by the polarimeter and noting the variation of this ratio with varying amounts of vegetative coverage of the fields. These ratios were calculated for several typical fields and are listed in Table 4. It may be seen that a discrimination level of about 0.70 for the I (8914):I (6406) ratio could have sorted out the essentially bare fields from those significantly covered by foliage. Intensity information at 5560Å was also recorded and the ratio I (5560):I (6406) is also given in Table 4 but it may be observed that this ratio is not as sensitive an indicator of the presence of foliage as is the I (8914):I(6406) ratio. An interesting point is to be noted in the data given for Phoenix field #78. The ratios given for this field appear to vary with the time of day at which the intensities were measured, suggesting that shadowing of portions of the field, either by plants or the soil, itself, in the form of clods or furrows, may significantly affect these ratios.

SUMMARY

The degree of polarization of sunlight at 6400Å reflected from cultivated fields in agricultural test areas in southwestern U.S. has been measured from an aircraft flying over these areas at an altitude of 2000 feet. Soil specimens taken from these fields on the day of the over-flights provided data concerning the moisture content of the fields to which the polarization data were compared. The results show that it is practical to measure the moisture content at or near the surface of the soil by airborne polarimetric instrumentation.

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LIST OF REFERENCES

1. Work Performed in Support of Photopolarimeter Experiment, BIOSPHERICS INC., June 1, 1972

2. Radiative Transfer, S. Chandrasekhar, Dover Publications, New York, 1960.

3. Polarization of Light Reflected by Moist Soils, E. H. Stockhoff and R. T. Frost, Seventh International Symposium on Remote Sensing of Environment, May, 1971, University of Michigan.

4. Earth Resources Target Signature Characterization and Experiment Development, D. E. Shaw et al, General Electric Company TIS 69SD5, April, 1969.

5. Experiment S-046, Visible Radiation Polarization Measurements, Space Sciences Laboratory, General Electric Company final report for contract UCLA 50772-0/NASA NAS 9-7267, January, 1968.

6. Applied Regression Analysis, N. Draper and H. Smith, John Wiley & Sons, Inc., New York, 1966.

7. Remote Sensing of Soil Moisture with Microwave Radiometers, T. Schmugge, P. Gloersen and T. Wilheit, NASA/Goddard report X-G52-72-305, August, 1972.

8. Effects of Surface Reflection on Planetary Albedo, K. L. Coulson, E. L. Gray and G. M. B. Bouricius, Icarus 5, 139-148 (1966).

TABLE 1

	Ground Truth Data				Polarimeter Data		
Field Ident.	Soil Type	Surface Moisture Description	Moisture (by dry weight) 0-1/4 in. depth	Local Time	Deg. of Pol.	Phase Angle	Local Time
March 1?, 1972							
IV 1 *	3 *	DSMU *	8.5%	7:00	5.8%	80.4°	10:03
					5.6	74.5	10:33
					7.4	114.3	16:10
					7.8	119.7	16:37
IV 2	3	DSMU	3.7	7:20	7.8	80.3	10:03
					8.3	74.0	10:33
					9.2	114.2	16:10
					8.7	119.7	16:37
IV 7	3	MS	13.0	8:25	6.4	80.1	10:03
					6.5	73.0	10:33
					6.3	114.3	16:11
					7.0	120.2	16:37
IV 8	3	MS	11.0	9:15	7.8	80.0	10:04
					6.7	73.0	10:33
					7.3	114.4	16:11
					6.9	120.3	16:37
IV 11	3	F	22.7	9:40	13.9	79.0	10:04
					11.9	73.0	10:34
					21.2	115.4	16:11
					18.0	120.6	16:38
IV 12	3	F	26.3	9:55	13.0	78.9	10:04
					12.3	72.5	10:34
					21.6	115.5	16:11
					17.2	120.9	16:38
IV 15	3	DSMU	2.2	10:30	6.9	79.5	10:04
					5.7	71.3	10:34
					11.5	115.7	16:11
					12.0	120.7	16:38
IV 16	3	F	30.2	10:40	11.6	79.0	10:04
					10.2	71.5	10:34
					16.0	115.4	16:11
					15.1	120.9	16:38

*See end of table for explanation of abbreviations, etc.

TABLE 1 (Cont'd.)

IV 23	4	W	17.9	12:40	7.6	79.7	10:05
					6.8	71.6	10:36
					8.3	115.2	16:13
					10.1	120.8	16:39
P 45/46	5-2/2	D	1.4	13:33	5.0	55.1	12:36
					4.0	49.5	13:05
					0.4	25.4	15:48
					7.4	107.3	16:16
P 47	2	D	0.7	13:40	4.2	55.2	12:36
					3.6	49.8	13:05
					0.7	26.0	15:48
P 53/54	2	D	2.5	10:45	5.4	56.0	12:35
					4.9	49.3	13:04
					0.4	26.1	15:47
					9.2	106.7	16:16
P 60/61	3/3-5	DSMU		11:08	2.9	52.4	16:06
P 61	3-5	DSMU	3.2	11:15	6.7	81.6	12:29
P 67/68	3-5	DSMU	3.3	13:00	6.6	82.7	12:29
					6.8	80.4	12:58
					7.9	85.8	15:40
					2.4	53.0	16:07
P 71/72	3	TWFD	18.0	9:53	9.8	82.4	12:28
					8.7	79.9	12:58
					10.7	85.6	15:40
					3.0	52.7	16:07
P 73/74	3	DSMU	13.1	10:23	7.8	82.8	12:28
					7.2	80.8	12:58
					10.1	85.4	15:40
					3.2	52.2	16:07
P 84	5	W	30.9	13:30	24.4	82.1	12:28
					25.1	81.8	12:57
					13.5	85.0	15:39
					3.0	52.2	16:07
P 90	5	DSMU	6.7	14:15	7.6	81.6	12:27
					6.8	82.3	12:56
					6.8	85.2	15:39
					1.4	51.8	16:06
P 91	4-5	DSMU	3.3	13:30	7.5	81.8	12:56
P 95	1-5-4	W (a)	18.4	11:10	No. 16.0	81.4	12:27
					So. 7.3	81.4	12:27
					No. 13.4	82.6	12:56
					So. 9.8	82.8	12:56

TABLE 1 (Cont'd.)

March 13, 1972

P 45/46	5-2/2	D	1.4%	14:39	3.3%	46.5°	13:20
					2.8	40.8	13:47
P 47	2	D	0.9	14:51	2.2	46.5	13:20
					1.1	41.0	13:47
P 53	2	D	32.4 (b)	11:24	4.1	47.0	13:19
					3.2	41.7	13:46
P 68	3-5	DSMU	64.3	14:10	6.1	81.5	13:14
					5.7	82.9	13:40
P 72	3	DSMU	16.7	9:45	7.3	81.5	13:14
					6.8	82.3	13:40
P 73/74	3	DSMU	4.8	10:23	6.7	81.5	13:14
					7.4	81.3	13:40
P 83/84	5	W	30.9	13:08	11.1	81.1	13:13
					11.4	81.0	13:39
P 90	5	DSMU	8.2	13:40	3.8	82.0	13:12
					4.9	80.7	13:39

Field Identification Key

IV	Imperial Valley
P	Phoenix

Soil Types Key

2	loam
3	sandy clay loam
4	sandy clay loam
5	clay loam

Surface Moisture Key

DSMU	Dry surface, moist underneath
MS	Moist surface
F	Flooded trenches
W	Wet surface
D	Very dry surface
TWFD	Trenches wet, furrows dry

(a) South dry; North wet

(b) The northern end of P 53 was wet but the polarimeter's field of view fell only upon the southern end which was reported to be dry.

TABLE 2

Average Value of Soil Moisture	Absolute Value of Difference Between Two Samples From Same Field
2%	0%
3-4%	0.7%
7%	4%

TABLE 3

Correlation Coefficients

Figure No.	For data points	For solid line
4	0.81	0.93
5	0.85	0.93
6	0.74	0.89
7	0.91	0.91
7 + 8	0.75	0.91

TABLE 4

Field Ident.		Soil Type	Degree of Vegegative Coverage	Ratios of Light Intensity I (8914Å) / I (6406Å)	I (5560Å) / I (6406Å)
IV	1	3	0 %	0.6	0.7
	11	3	0	0.6	0.7
	12	3	0	0.6	0.7
	15	3	0	0.6	0.6
	16	3	0	0.5	0.6
P	10	2	0	0.6	0.5
	45/46	5-2	0	0.6	0.6
	47	2	0	0.6	0.6
	53/54	2	0	0.6	0.6
	67/63	3-5	0	0.5	0.6
	73/74	3	0	0.6	0.6
	84	5	0	0.5	0.6
	90	5	0	0.6	0.6
	95	1-4-5	0	0.5	0.6
IV	2	3	1	0.6	0.6
	7	3	1	0.6	0.6
	8	3	1	0.6	0.7
	23	4	10	0.9	0.7
P	78	3	50	2.3*	0.9
				4.4**	1.3
				2.6***	1.0
	77	-	100	10.8	1.9
				9.6	1.6

* 12:30 - 13:00, 3/11/72
** 15:40 - 16:00, 3/11/72
*** 13:10 - 13:40, 3/13/72

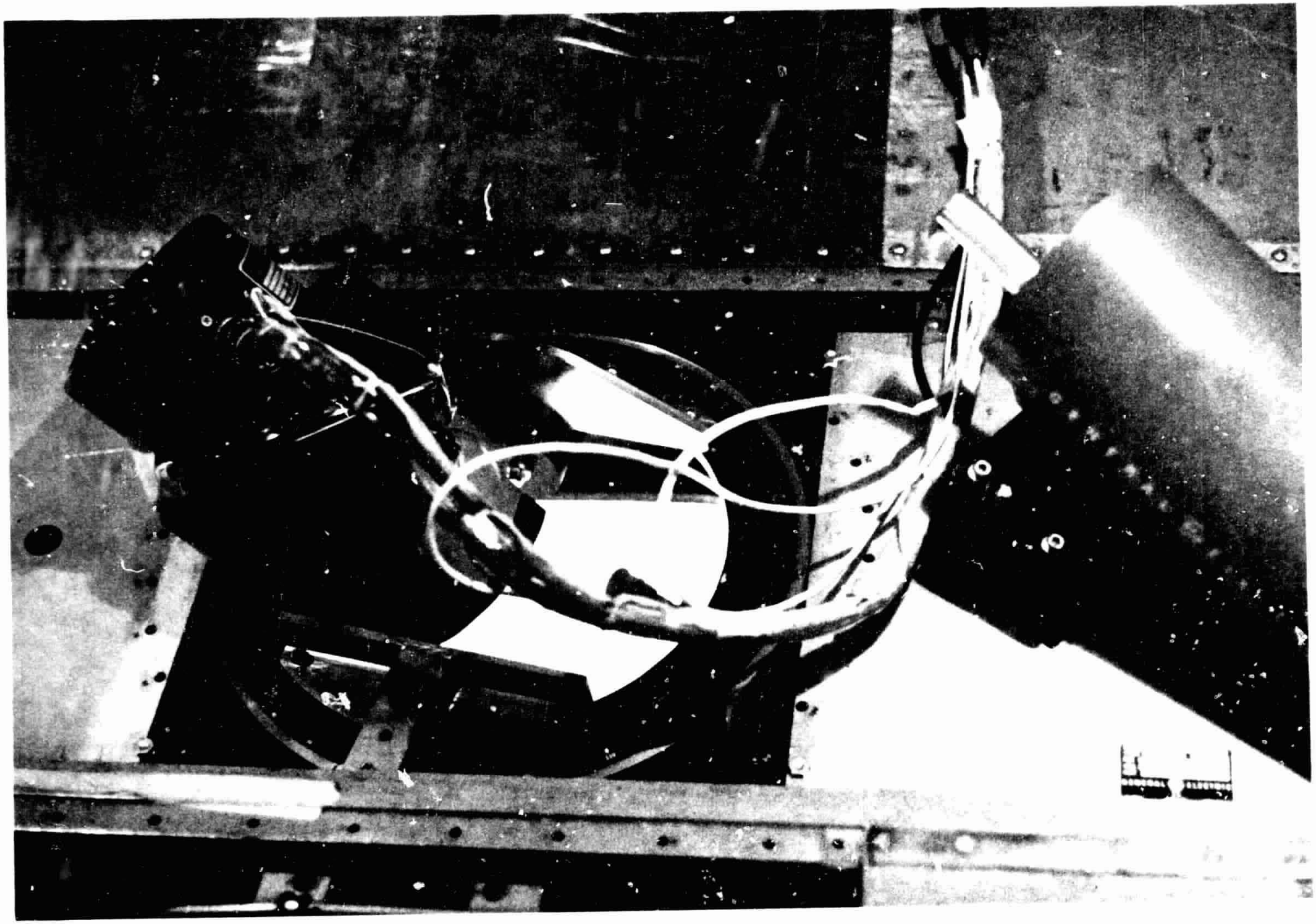


Figure 1. Photopolarimeter in Place Over a Window in the Floor of the Convair-990.

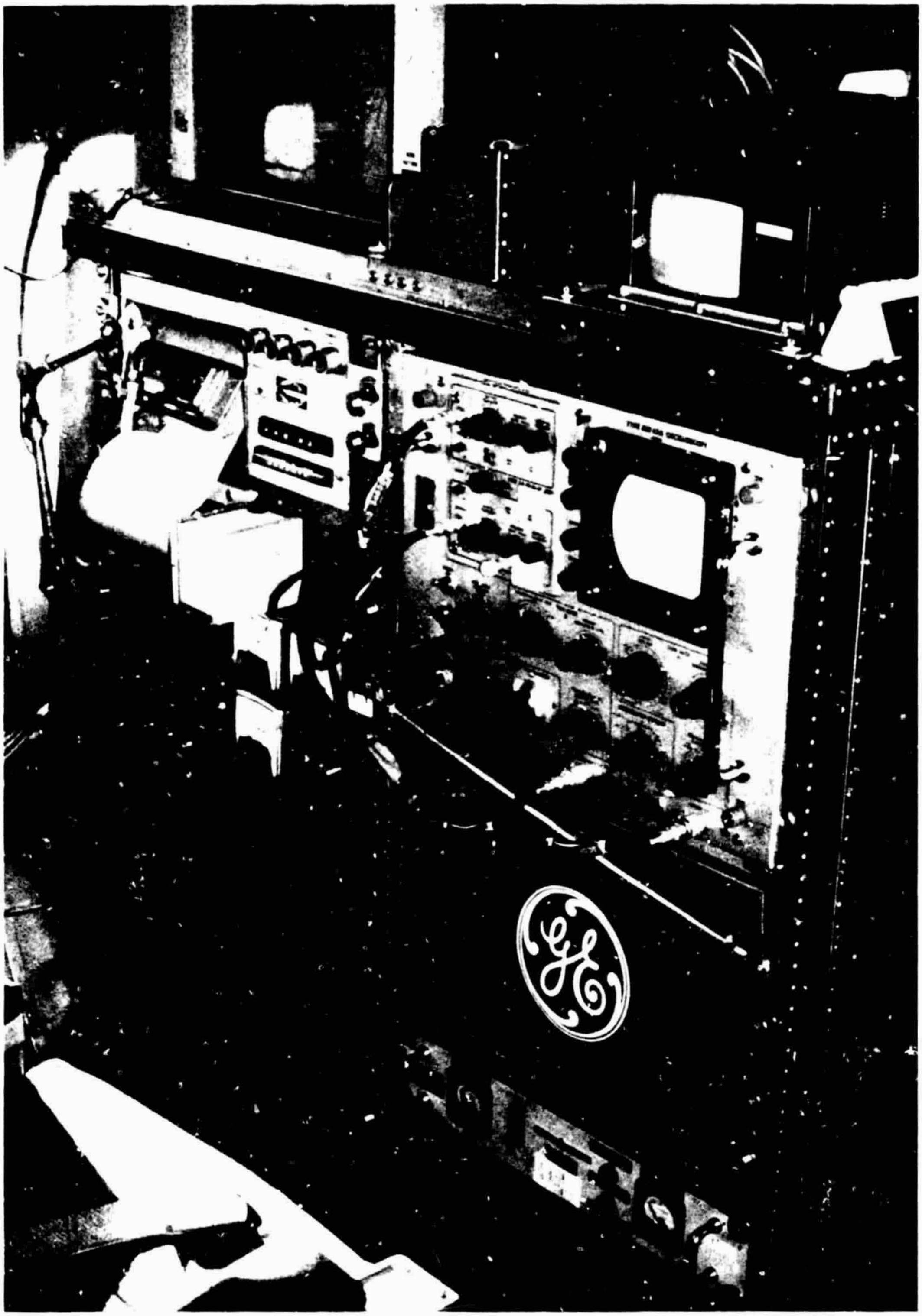
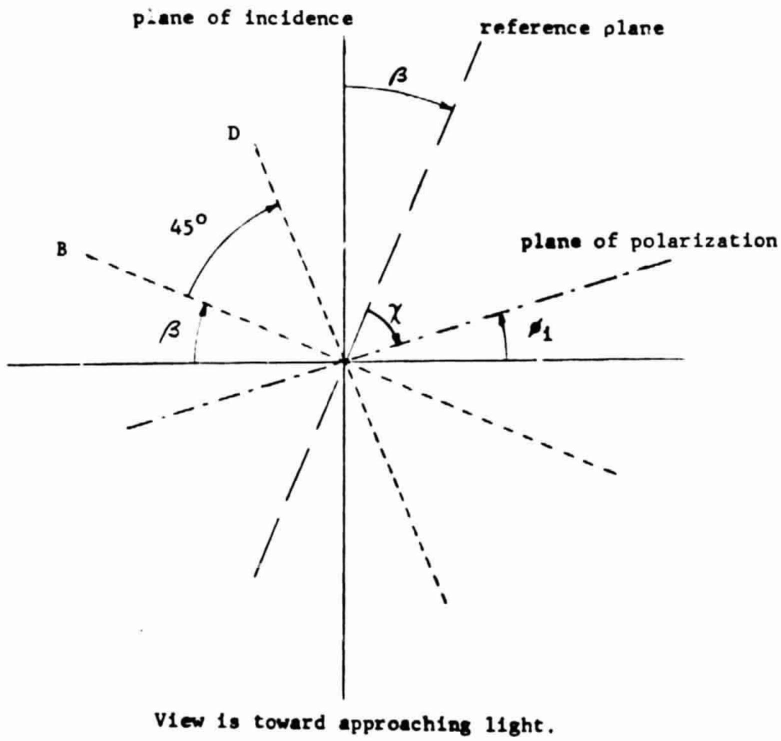


Figure 2. Control Rack in Passenger Compartment



Plane of Incidence:	Plane defined by normal to window in aircraft and viewing direction.
Reference Plane:	Plane from which orientation of plane of polarization is measured.
Plane of Polarization:	Plane in which electric vector of light has its maximum value.

B: Plane of transmission of polarizing prism in one of the barrels of the photopolarimeter. This plane is normal to the reference plane.

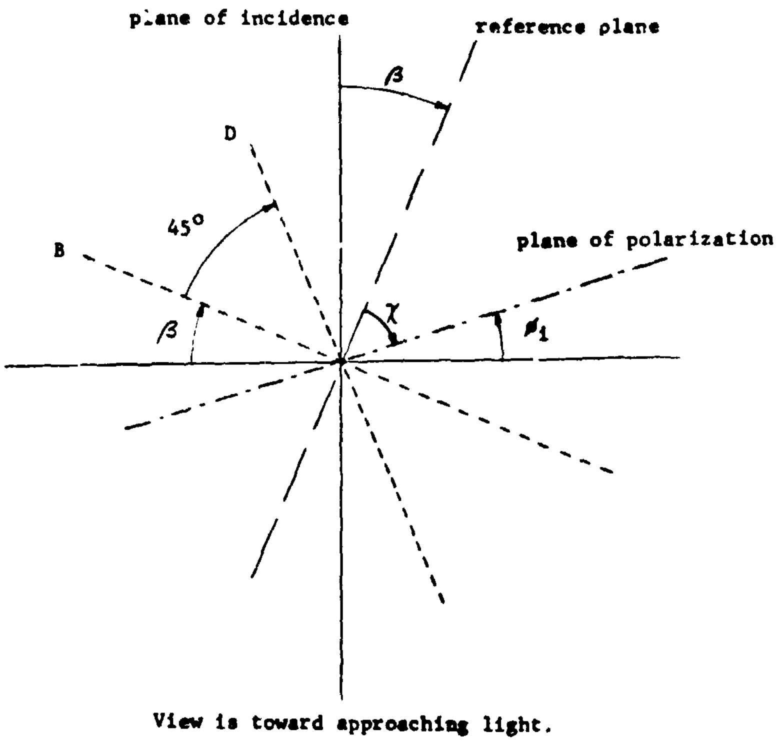
D. Plane of transmission of polarizing prism in another of the barrels of the photopolarimeter. (Plane of transmission means plane in which electric vector of light is completely transmitted.)

β: Arbitrary angle between photopolarimeter reference plane and normal to window. In the work reported here, $\beta = 22.5^{\circ}$.

ϕ_i: Angle indicating orientation of plane of polarization of light after having passed through aircraft window.

χ: Angle indicating orientation of plane of polarization relative to reference plane; used in general expression for Q & U.

Figure 3. Orientation of Planes Identified in the Discussion of Stokes Parameters



Plane of Incidence: Plane defined by normal to window in aircraft and viewing direction.

Reference Plane: Plane from which orientation of plane of polarization is measured.

Plane of Polarization: Plane in which electric vector of light has its maximum value.

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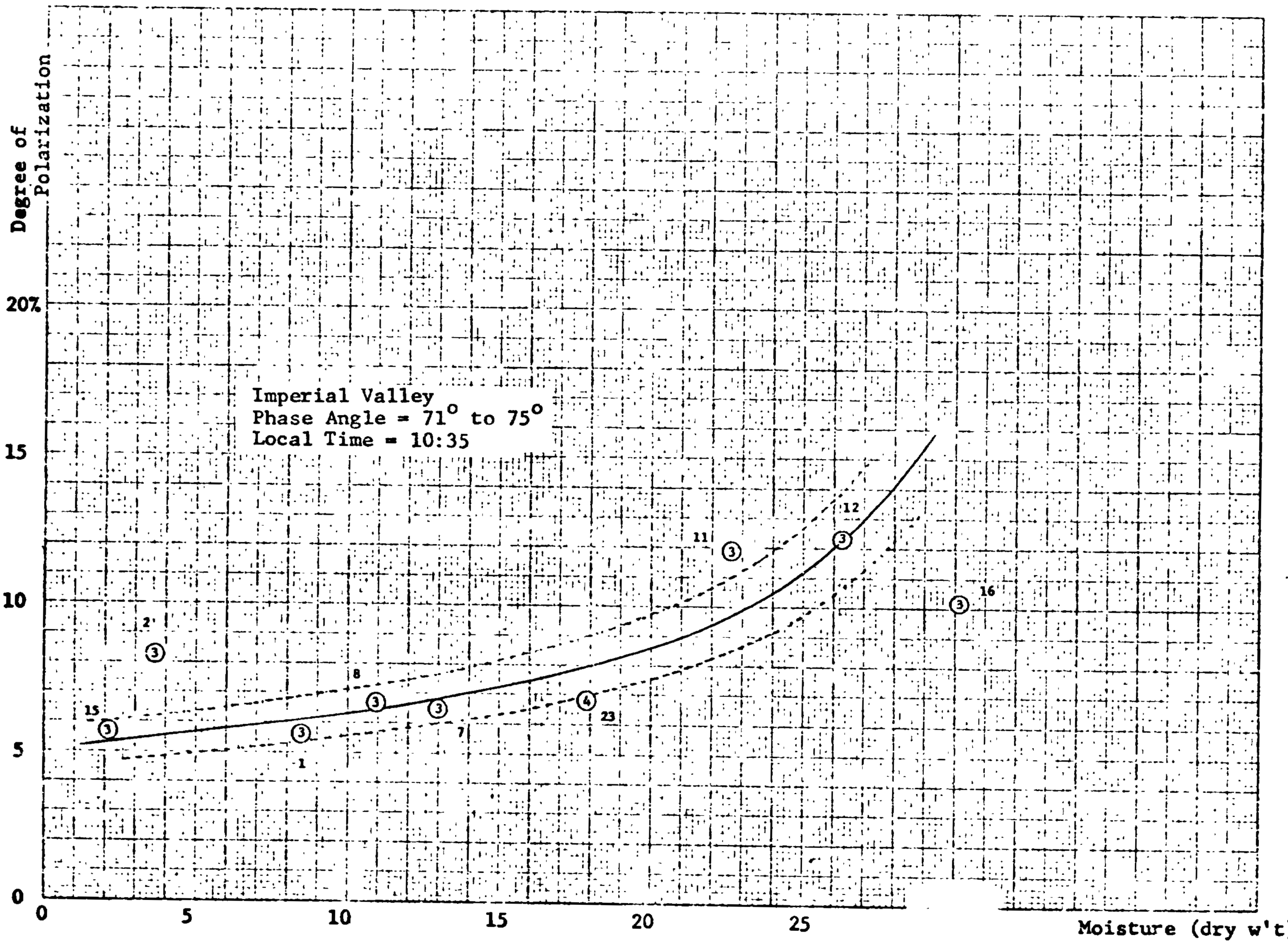

Figure 4. Degree of Polarization vs Soil Surface Moisture (0 - ½ inch)

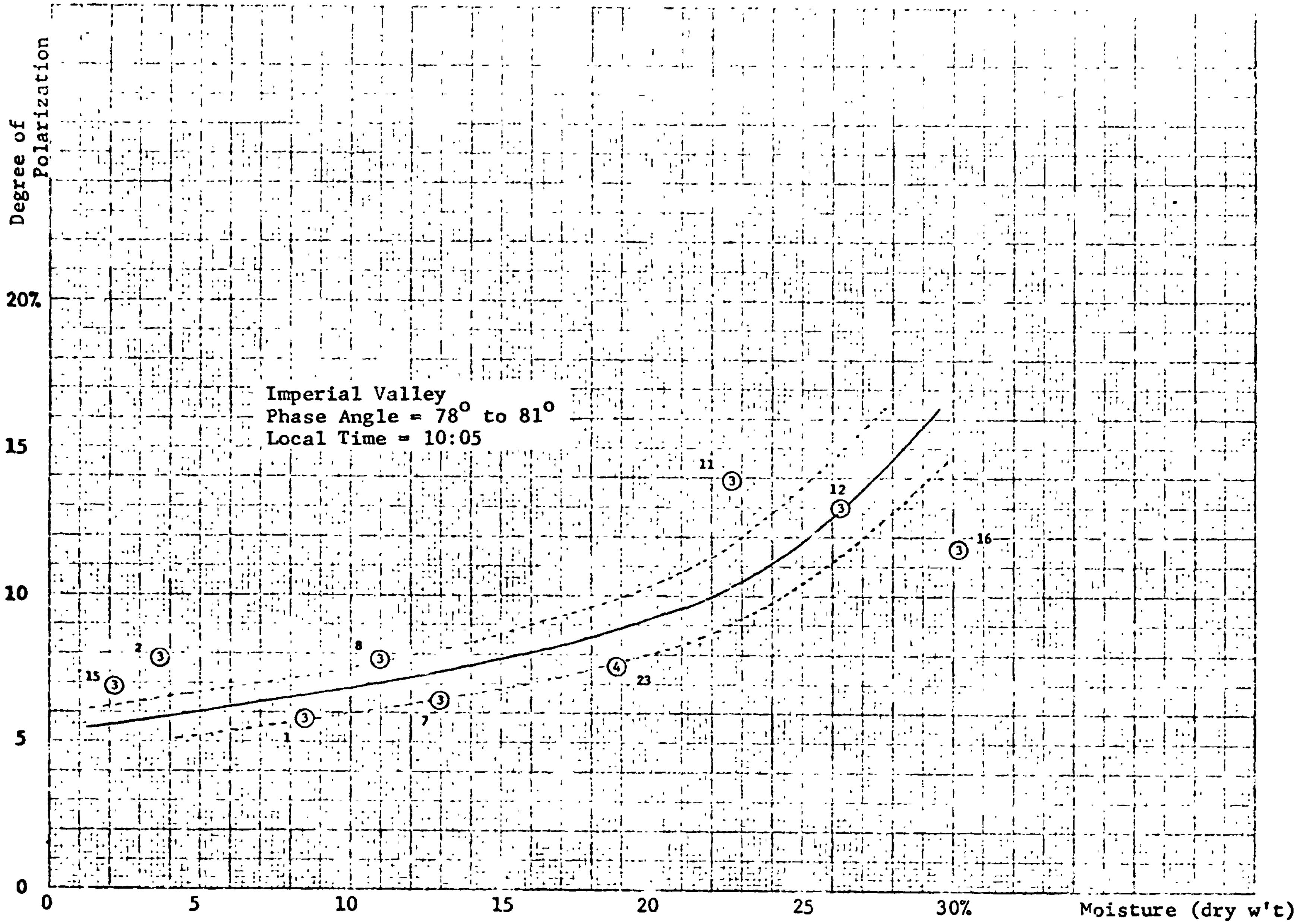

Figure 5. Degree of Polarization vs Soil Surface Moisture (0 - ½ inch)

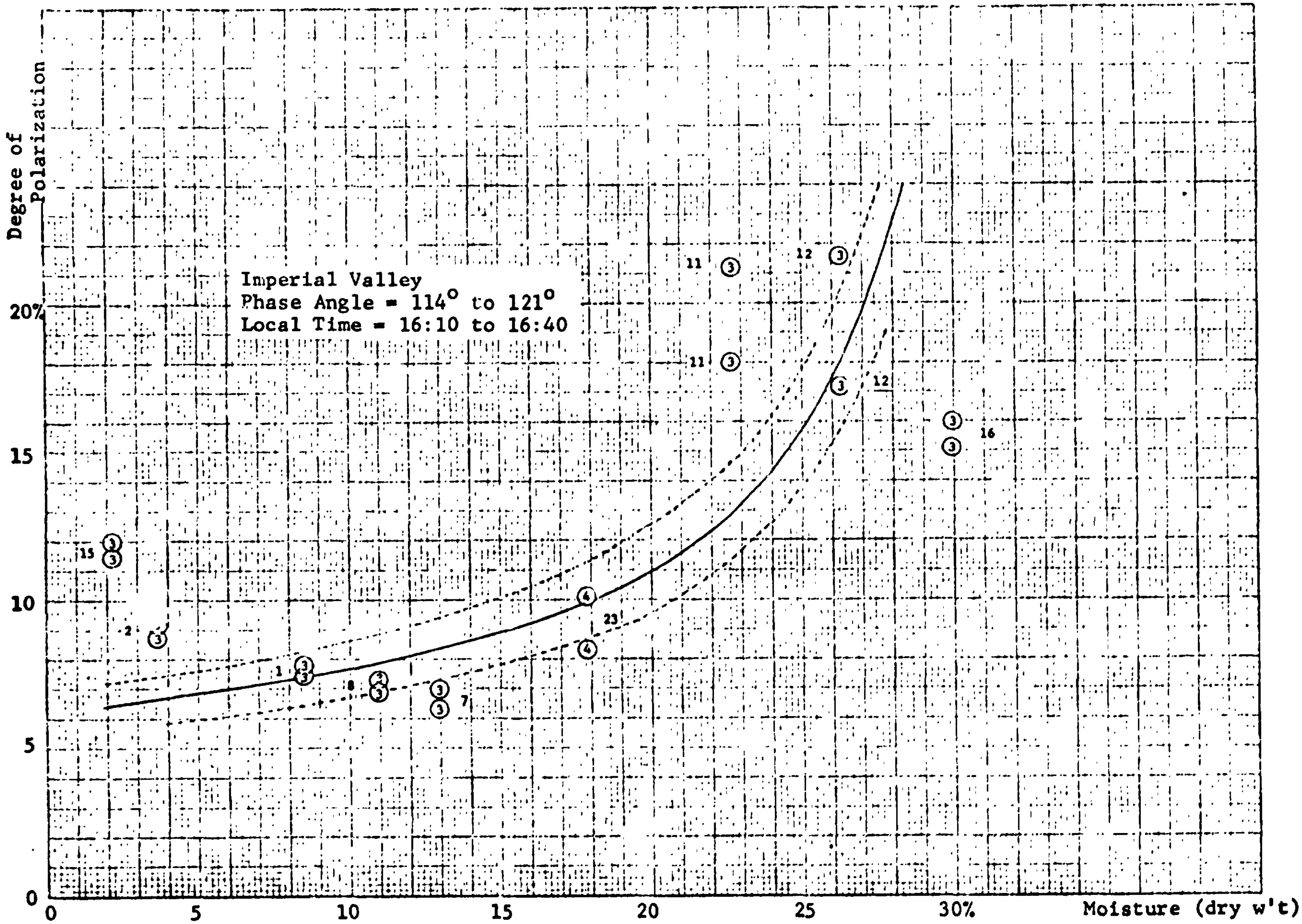

Figure 6. Degree of Polarization vs Soil Surface Moisture (0 - ¼ inch)

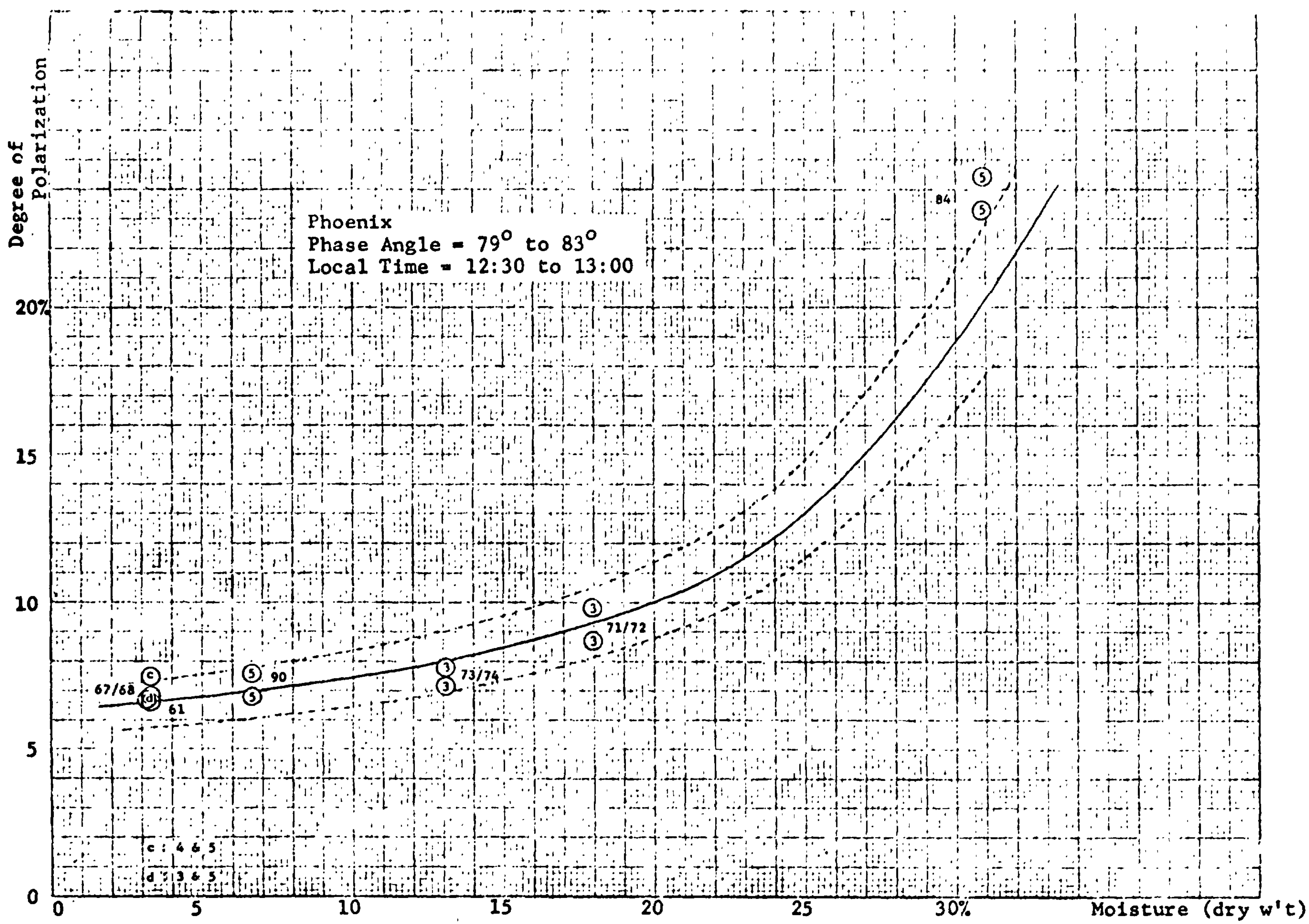

Figure 7. Degree of Polarization vs Soil Surface Moisture (0 - ¼ inch)

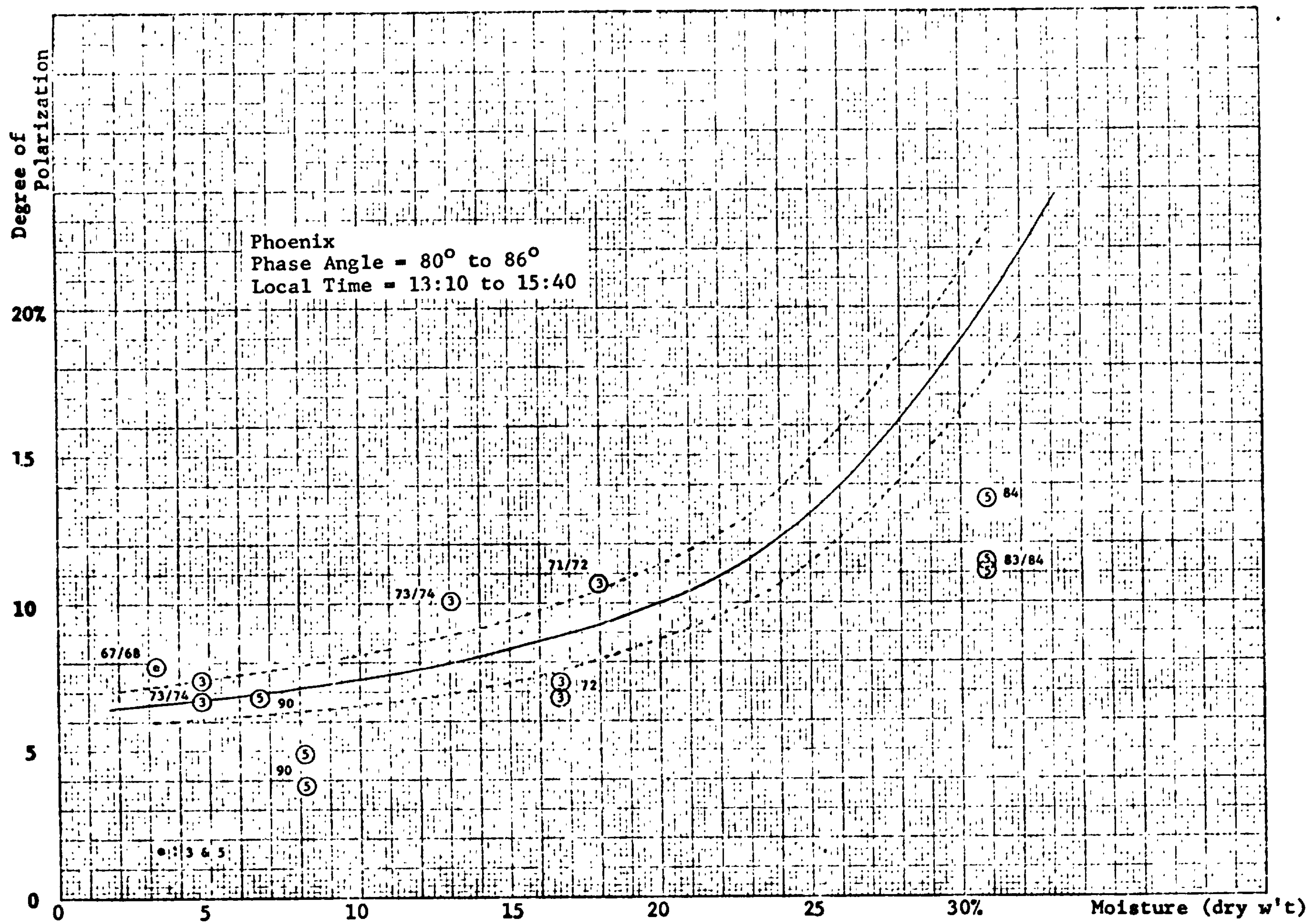

Figure 8. Degree of Polarization vs Soil Surface Moisture (0 - ¼ inch)

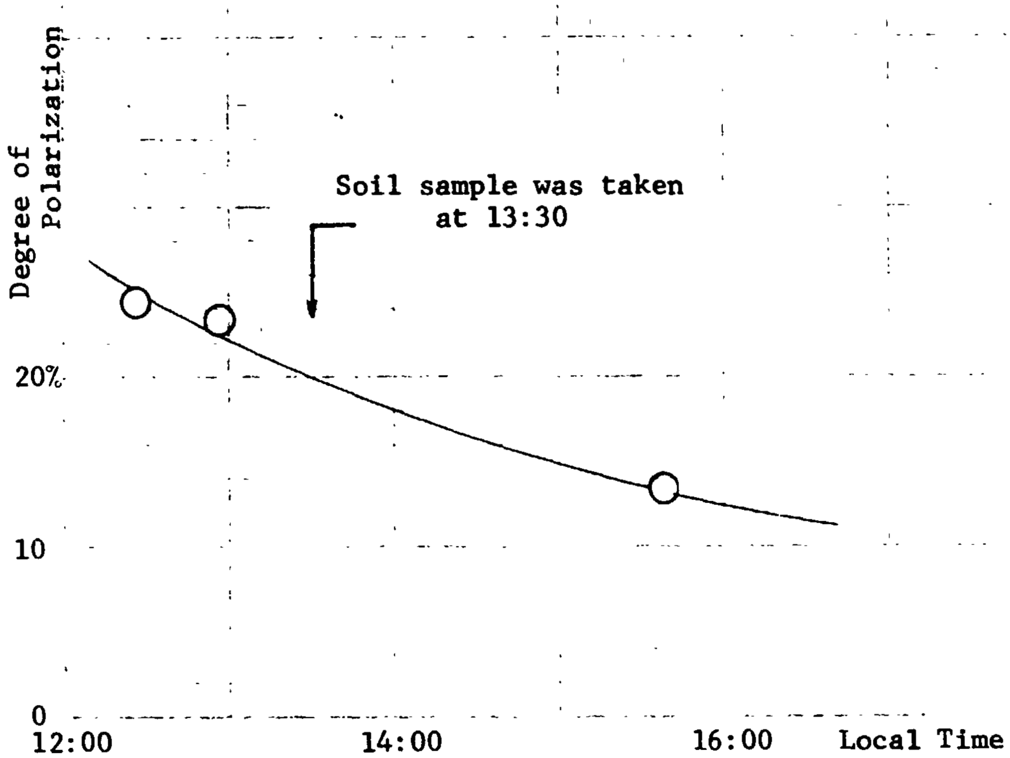

Figure 9. Degree of Polarization vs Local Time for Phoenix Field No. 84 on March 11, 1972