NOAA Technical Memorandum ERL GLERL-27

# NEW OBSERVATIONS ON THE DAILY VARIATIONS OF NATURAL ICE ALBEDO

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Ann Arbor, Michigan
July 1980

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# NEW OBSERVATIONS ON THE DAILY VARIATIONS OF NATURAL ICE ALBEDO[1]

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Observations on the daily variation of ice albedo indicate a significant dependence of snow-ice and refrozen-slush-ice albedo on solar altitude under clear skies. Significant albedo variations were noted under variable cloudy conditions, but attempts to quantify these processes have been hampered by a lack of detailed data. Albedo variations of melting ice can be pronounced, and after substantial decay has occurred, the resultant albedo is a combination of ice and water reflectivity. Some measurements of near-infrared ice albedo indicate that diurnal variations are even more subtle in this spectral range than for the total solar spectrum and that many additional measurements are required to obtain even preliminary conclusions.

## 1. INTRODUCTION

A knowledge of the albedo of ice surfaces is critical for accurate representation of wintertime energy budgets. Such budgets are widely used as models for ice prediction, but many investigators have noted that errors in the albedo term have caused large errors in prediction dates. In an energy budget model used to produce a breakup forecast for the Buffalo, N.Y., Harbor, it was found that the least understood term and one that caused errors in the forecast date was ice albedo (personal communication, R. R. Rumer, 1977). Little is known of the daily variations in ice albedo, and in an area such as the Great Lakes, where many diverse types of ice exist, the problem is severely compounded.

Identification of ice types and ice extent by remote sensing is particularly valuable when large geographic areas must be covered. Application of such techniques is currently impossible because of a lack of ground truth for ice. Indeed, as emphasized by Hagman (1976). all that can be accomplished with satellite photographic transparencies is to distinguish between ice and water. A catalog of ground-based information on the albedo of various ice types according to the solar altitude, azimuth, and atmospheric conditions would fill a critical gap and would increase the usefulness of satellite ice imagery.

In early 1967, a study was conducted to obtain the total albedo (300-3000 nm) of various types of ice common to the Great Lakes (Bolsenga, 1969). It was found that albedo values ranged from 10 percent for clear ice to 46 percent for snow-ice. The study indicated, however, that diurnal variations occurred in the albedo, that different ice types would probably exhibit dif-

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ferent diurnal characteristics, and that the type and amount of cloud cover was a factor.

In a recent study, a preliminary assessment was made of the diurnal variation of albedo due to factors such as cloud type variation and surface melting (Bolsenga, 1978). The purpose of this paper is to define further the factors that influence the daily variation of ice albedo based on additional data.

## 2. TEST PROCEDURE AND INSTRUMENTATION

Ice albedo data were collected over clear, snow, and refrozen-slush-ice during the 1975-76 and 1976-77 winter seasons. The test site was a small inland lake located near Ann Arbor, Mich., (42°18'N, 83" 43'W). Incident and reflected total global radiation values were measured by factory calibrated Eppley high-precision spectral pyranometers (300-3000 nm). Only snow-free ice surfaces were studied since snow albedo'characteristics are relatively well known. If the field test areas were snow covered, the ice was shoveled and swept with a broom until the surface was snow free.

Sensors were mounted on a l-m-high tripod equipped with a horizontal crossarm extending outward from the tripod about 1.5 m for reflected bulb suspension. Pyranometer output was measured with a precision portable potentiometer during the 1975-76 season and an autographic recorder during the 1976-77 season. The output was transferred to computer cards on a measurement by measurement basis for the 1975-76 data and on a l-min-interval basis for the 1976-77 data. Local standard times of the measurements were converted to true solar times (TST) by computer, and corresponding solar altitudes and zenith angles calculated.

## 3. ANALYSIS

The daily variation of the albedo of a given area of ice was found to be caused by surface melting or refreezing, direct-diffuse incident radiation balance vs. ice composition, or cloud cover variations. Some variations are subtle and most are not fully understood. In this analysis the relationships are more fully defined based on the two winter seasons of data.

### 3.1 Total Solar Spectrum (300-3000 nm)

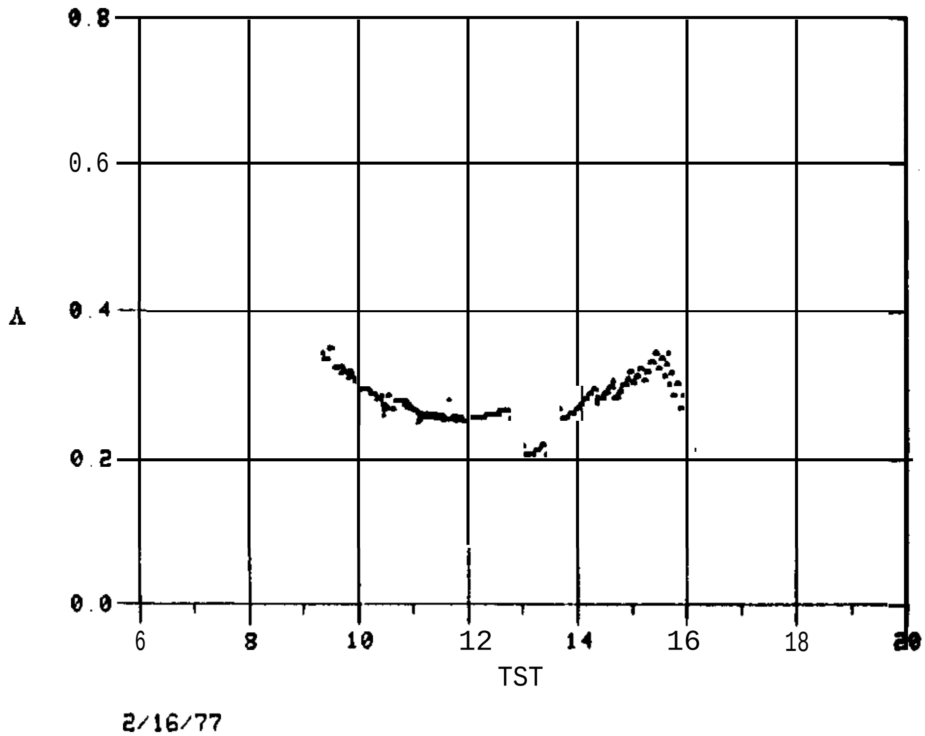
Significant daily variations of albedo with solar altitude were found to occur under clear skies with snow-ice or refrozen-slush-ice surfaces. The beam radiation component of the shortwave flux decreases with decreasing solar altitude and the diffuse component increases. Since the diffuse component is relatively rich in visible light and the albedo of snow-ice and refrozen slush is most probably higher in the visible spectrum than is clear ice, the albedo of the two ice types should vary significantly with solar altitude under clear skies. Figures 1 and 2 illustrate this condition by the characteristic "bowl" shaped pattern in the albedo vs. TST graphs. The stepped appearance exhibited in figure 1 is due to the 1-min-interval data extraction rate from the autographic charts. The ice consisted of nearly 4 cm of snow-ice overlying a total ice thickness of nearly 42 cm. The surface exhibited a slightly wavy appearance with numerous bubbles (figure 3). Skies were clear (0/10 coverage) on February 16, 1977. On February 17, 1977, skies were clear until late in the day, when some cloudiness was observed (2/10 cumulus).

In contrast, figures 4 and 5 show two snow-ice surfaces that exhibit a lack of diurnal variation due to cloudy skies. On January 15, 1976, (figure 4) from 0800 through 0908 TST, cloud coverage consisted of very thin, even cirrostratus and stratocumulus, varying from 8 to 10/10 coverage with albedo averaging 41.7 percent. From 0918 to 0946 TST a completely new cloud regime prevailed, consisting of a lower layer of stratocumulus (3/10) and a higher layer of cirrostratus (7/10) with albedo averaging 40.1 percent. From 0957 to 1228 TST another cloud regime (10/10 stratocumulus) prevailed. The solar beam was just visible through the clouds and the albedo averaged 40.6 percent. The highest variation of albedo between the different cloud regimes was only 1.6 percent. The data in figure 5 were taken under 10/10 stratocumulus clouds during most of the day. Cloud thickness as indicated by the incident radiation trace on the recorder was not uniform. Undulations in the albedo can probably be attributed to cloud thickness variations. The ice surface on February 14, 1977, is shown in figure 6.

Measurements of clear ice albedo, under both clear and cloudy skies, were made to verify that the above type of reflectivity variation is confined to snow-ice and slush-ice. Figure 7 shows the albedo pattern on a clear day (0/10 coverage) over clear ice with a "pebble grained" surface. The complete lack of a diurnal trend is impressive. Measurements under cloudy skies (10/10 coverage) also did not exhibit the "bowl" shaped patterns (figures 8 and 9). However, the albedo showed a general decrease of 5-10 percent over the day marked by a characteristic undulating pattern presumably caused by variations in cloud thickness. The general downward trend of albedo in both cases is unexplained. Air temperatures were well below freezing and beam radiation was lacking, which probably discounts the melting of frost or small amounts of snow on the ice surface. The range of the albedo, within each undulation, seems to be larger than that shown in figure 4 and previously reported by Bolsenga (1978) where he states:

> Differences in albedo due to changes in cloud cover were small. Measurements made under cumulus clouds of varying amounts and within clear-sky "windows" between the clouds showed albedo differences of only 1-2 percent. On one of the days of measurement the cloud cover varied from 8/10 to 10/10 cirrostratus and stratocumulus to 3/10 stratocumulus (lower layer) plus 7/10 cirrostratus (upper layer) and finally back to 10/10 stratocumulus. The largest variation of the average albedo between the different cloud regimes was only 1.6 percent.

Ultimately, it might be possible to relate certain albedo variations to cloud types. In figure 10, for example, prevailing cloud types are



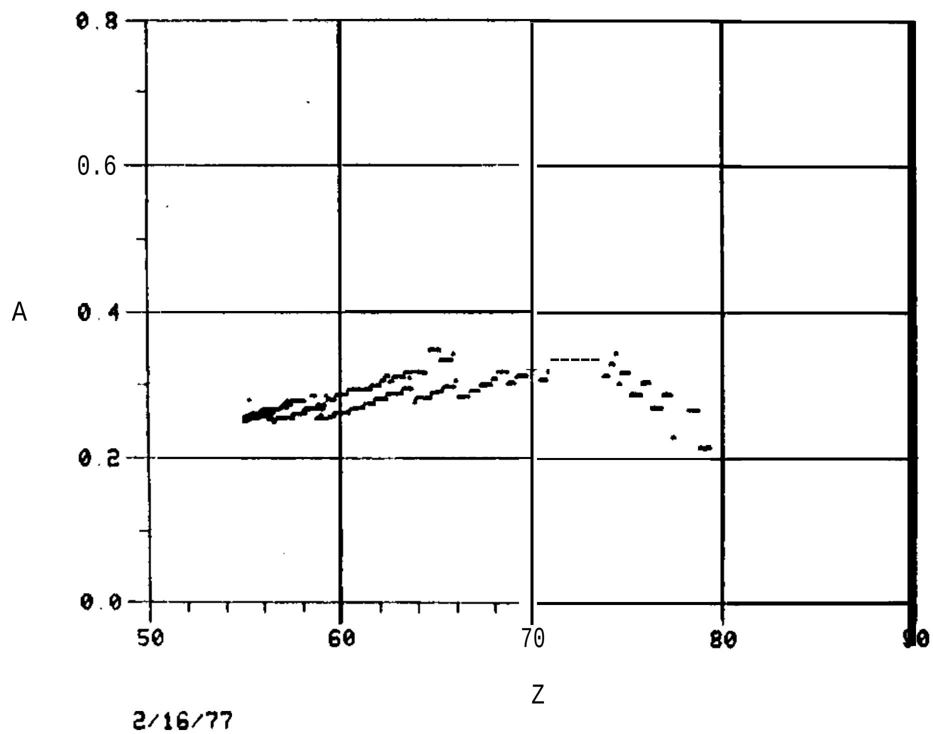




Figure 1.--*Albedo (A) vs. TST and zenith angle (Z) for a snow-ice surface under clear skies, February 16, 1977.*

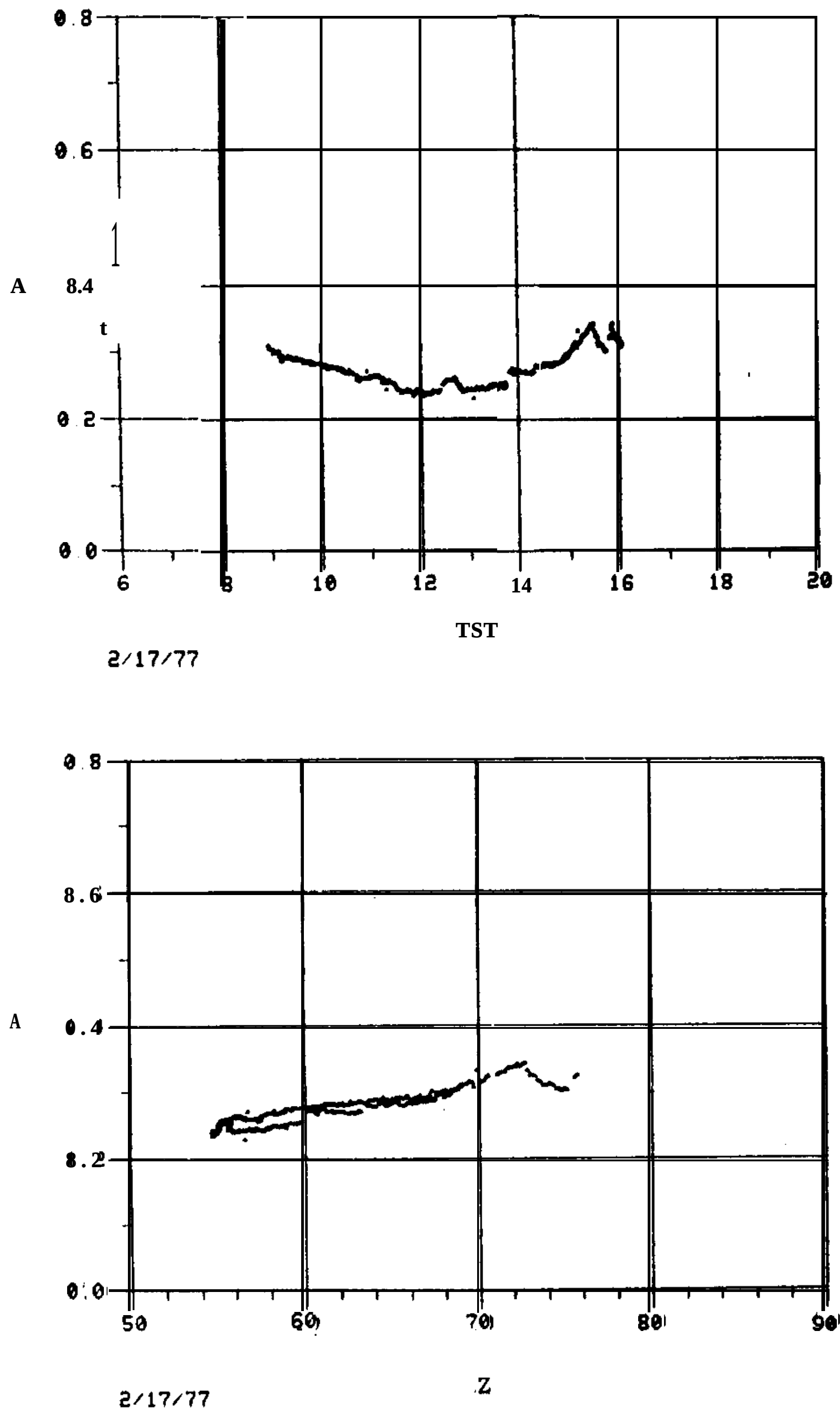



Figure 2.--*Albedo (A) vs. TST and zenith angle (Z) for a snow-ice surface under clear skies, February 17, 1977.*

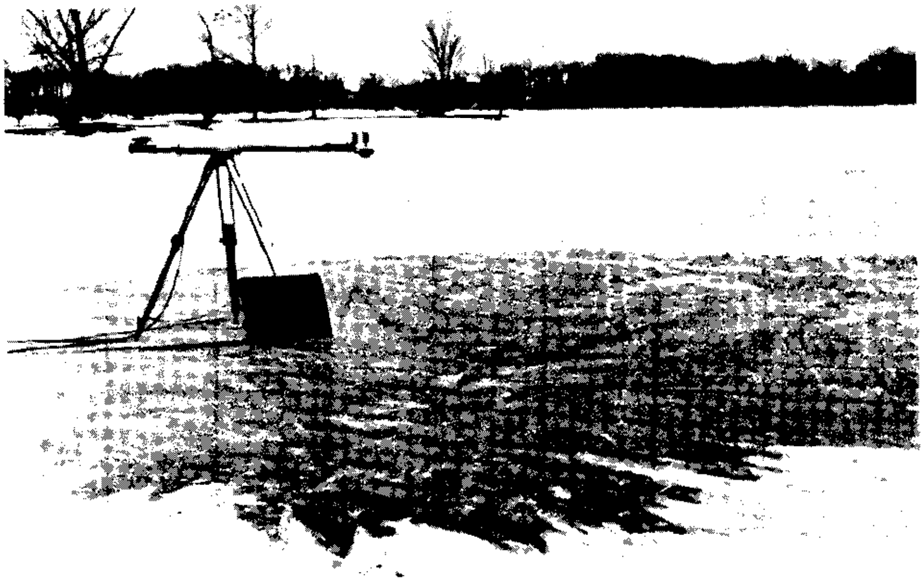


**Figure 3.**--*View of the snow-ice surface and the radiometer configumtion for the measurements shown by figures 1 and 2.*

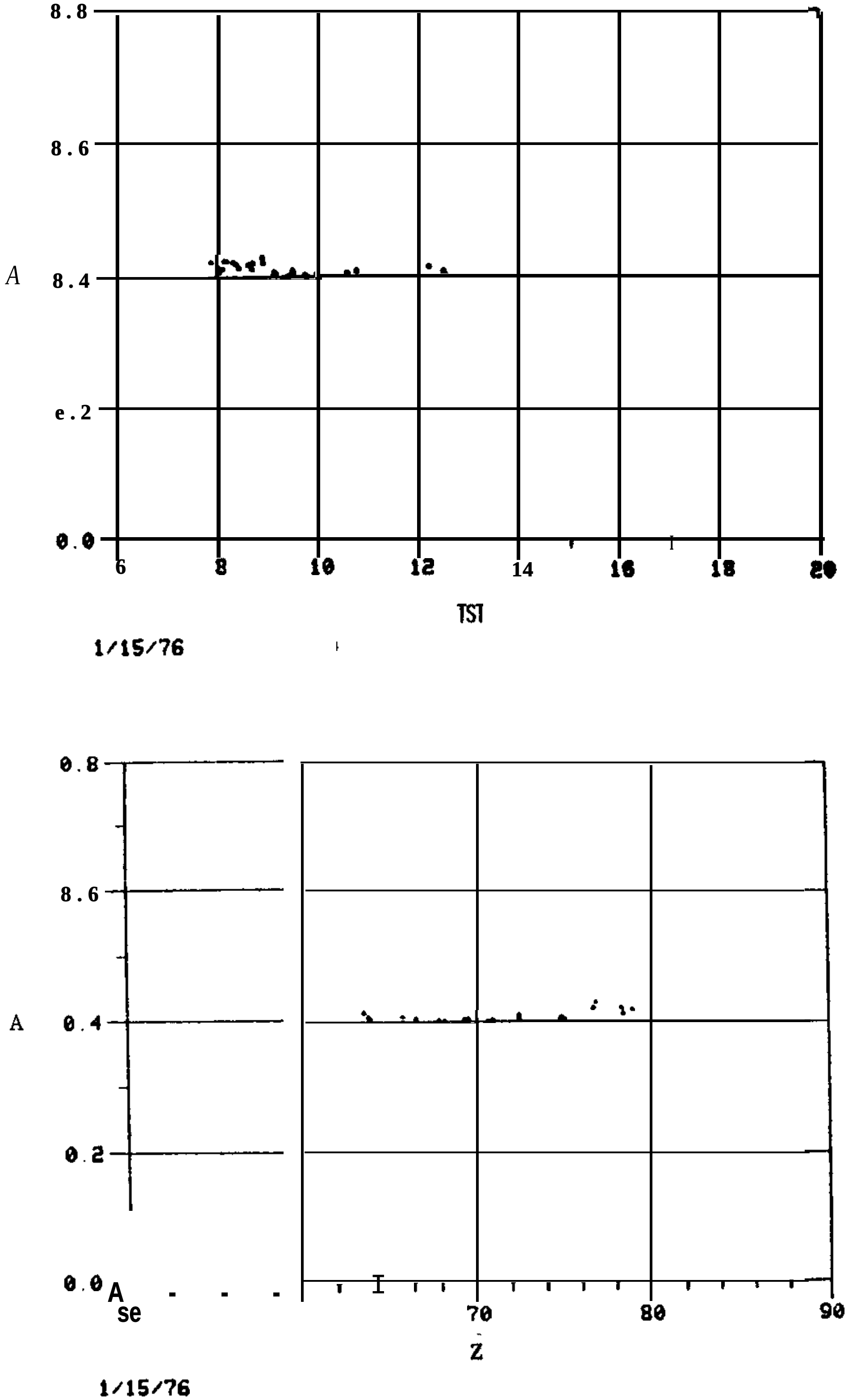



Figure 4.--*Albedo (A) vs. TST and zenith angle (Z)* for a *snow-ice* surface *under cloudy skies, January 15, 1976.*

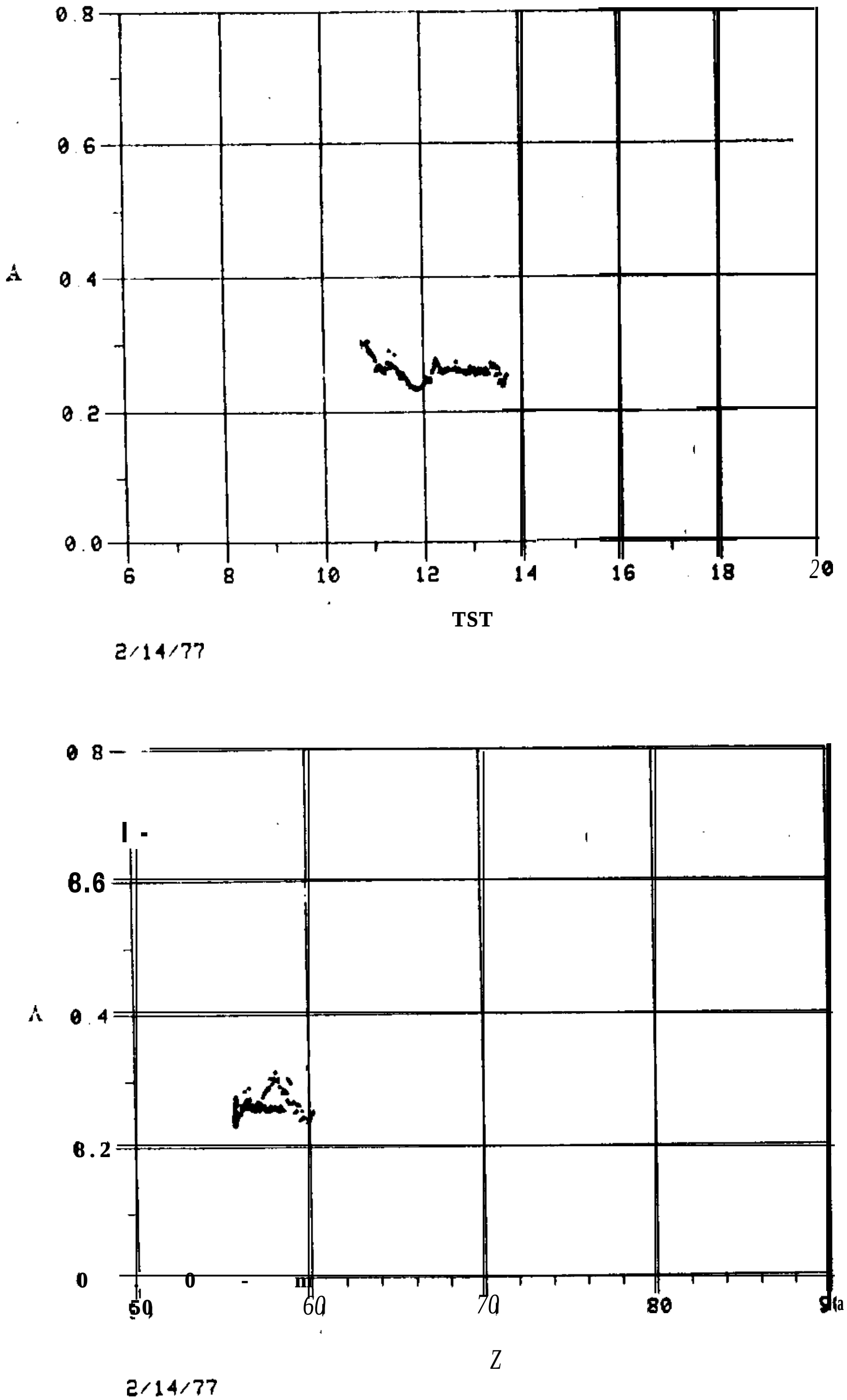



Figure 5.—*Albedo (A) vs. TST and zenith angle (Z) for a snow-ice surface under cloudy skies, February 14, 1977.*

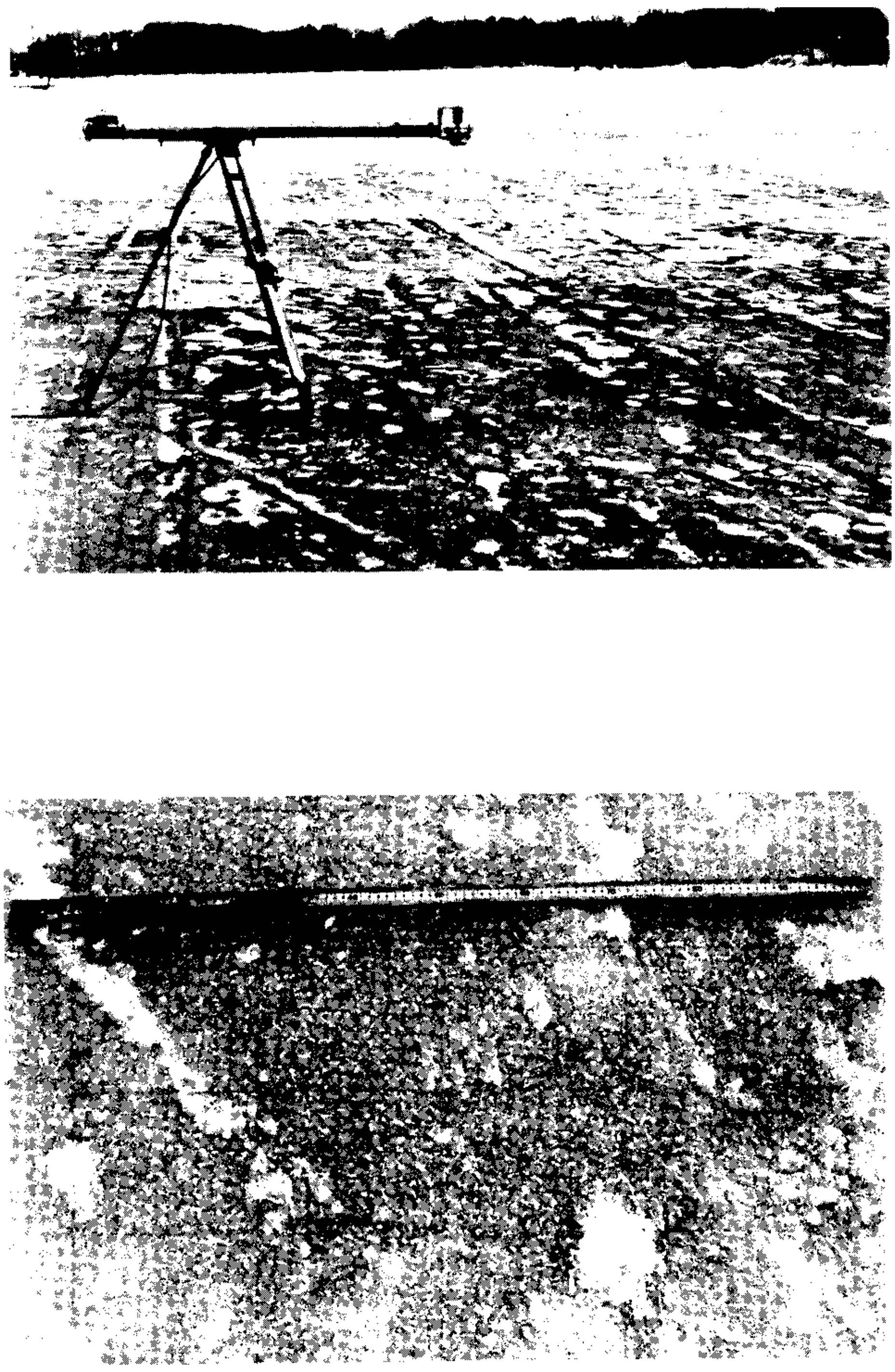


Figure 6.--Overall and closeup view of ice surface on February 14, 1977.

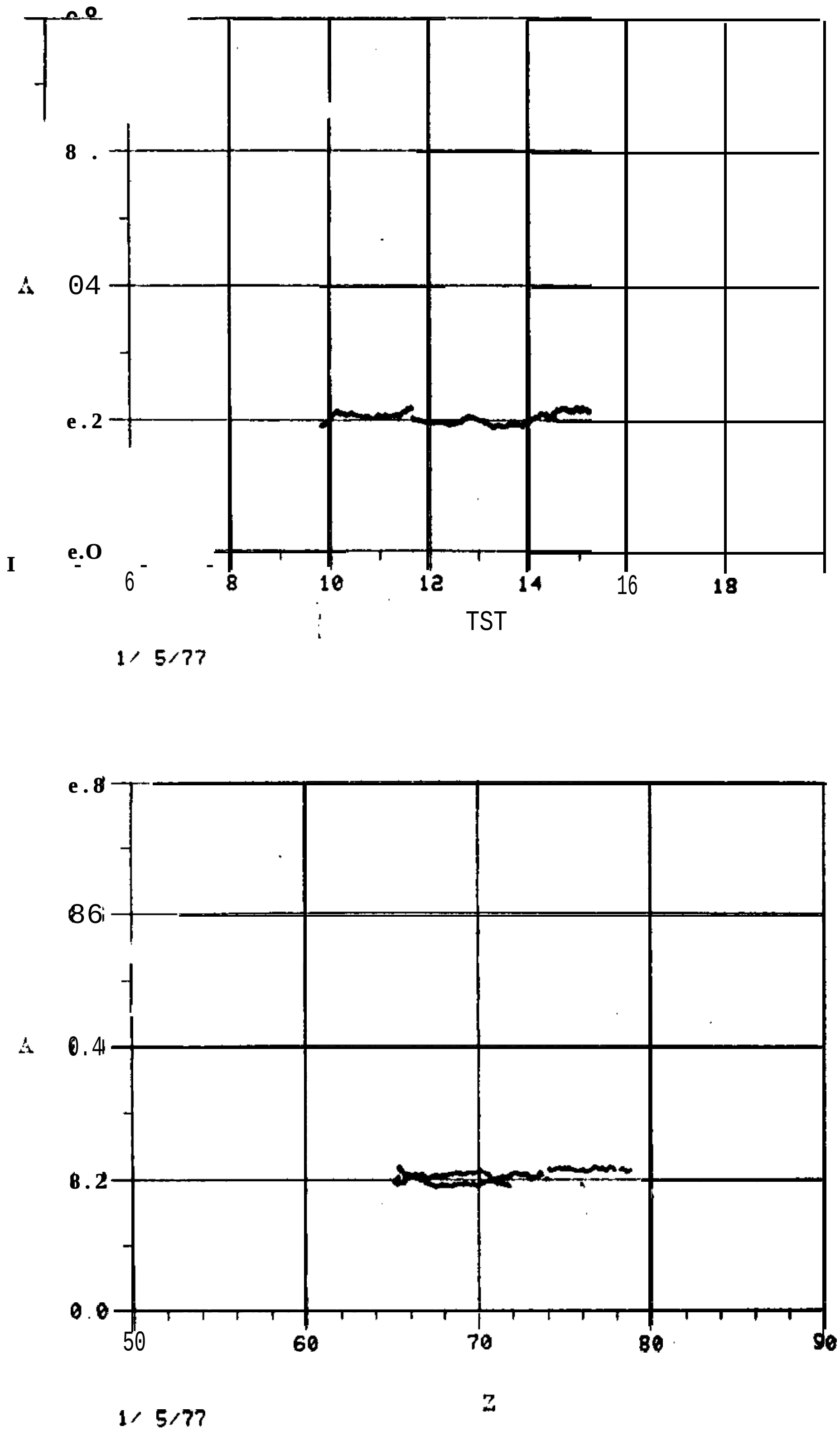
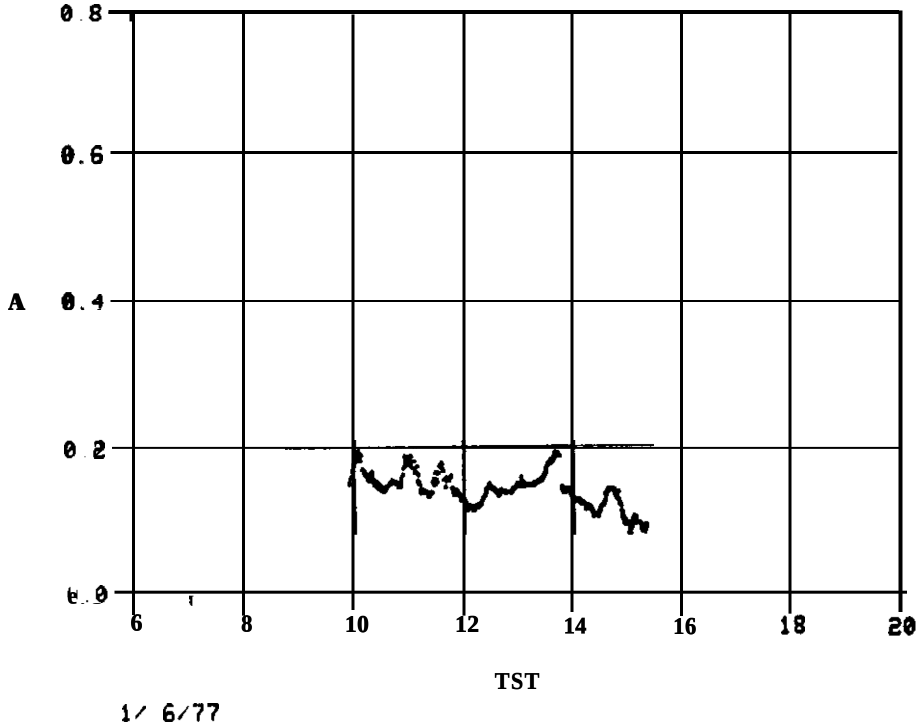



Figure 7.--*Albedo (A)* ve. TST and zenith *angle (Z)* for *clear ice* under clear skies, January 5, 1977.



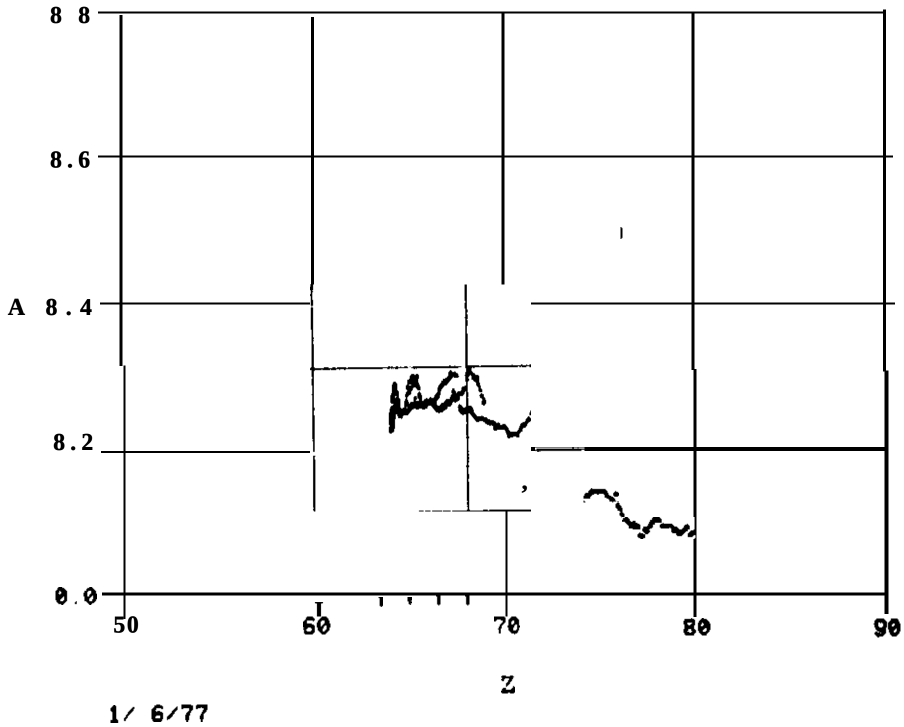




Figure 8.--*Albedo (A) vs. TST and zenith angle (Z) for clear ice under cloudy skies, January 6, 1977.*

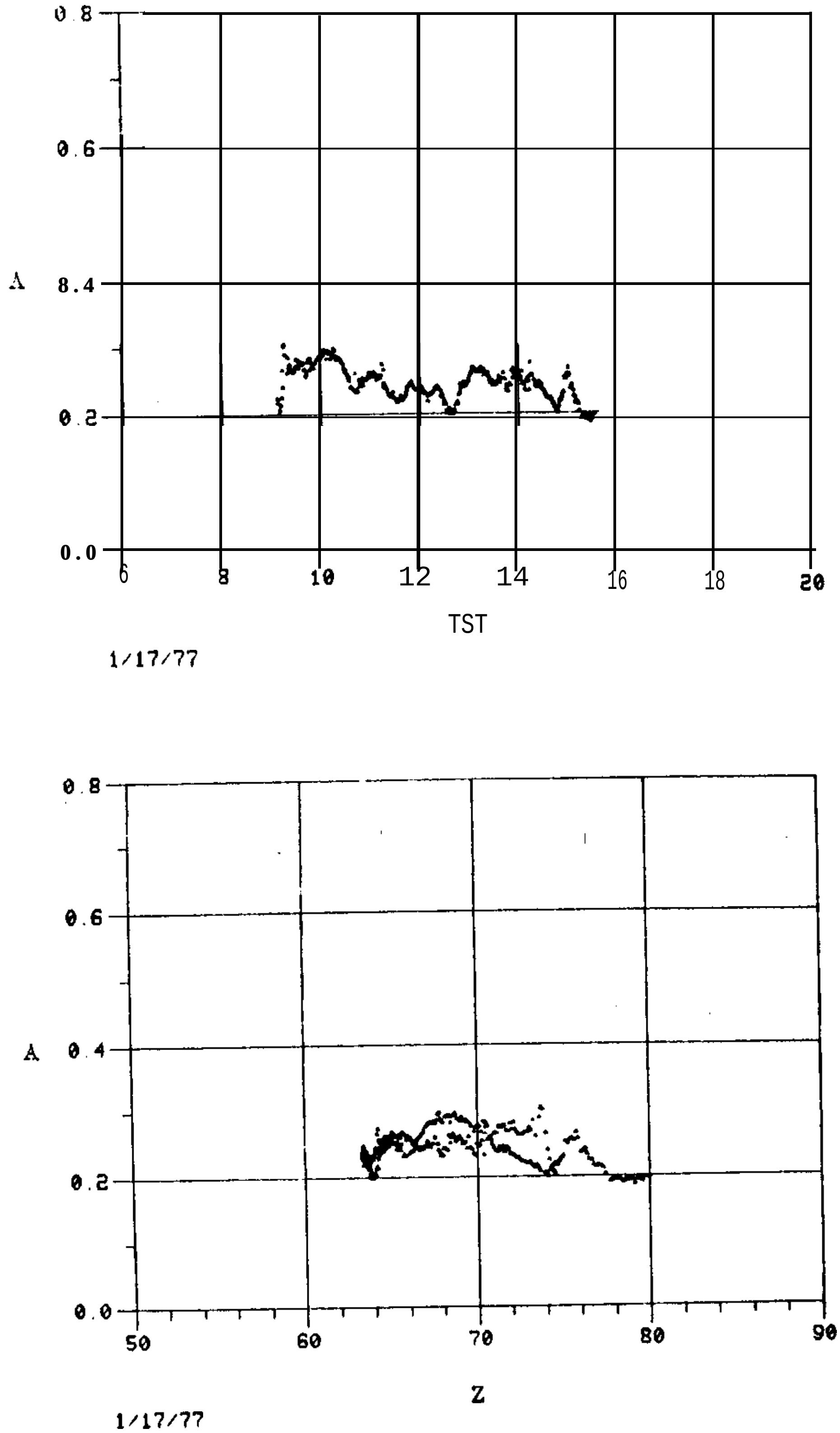



Figure 9.--*Albedo (A) vs. TST and zenith angle(Z)* for dear *ice under cloudy skies,* January *17, 1977.*

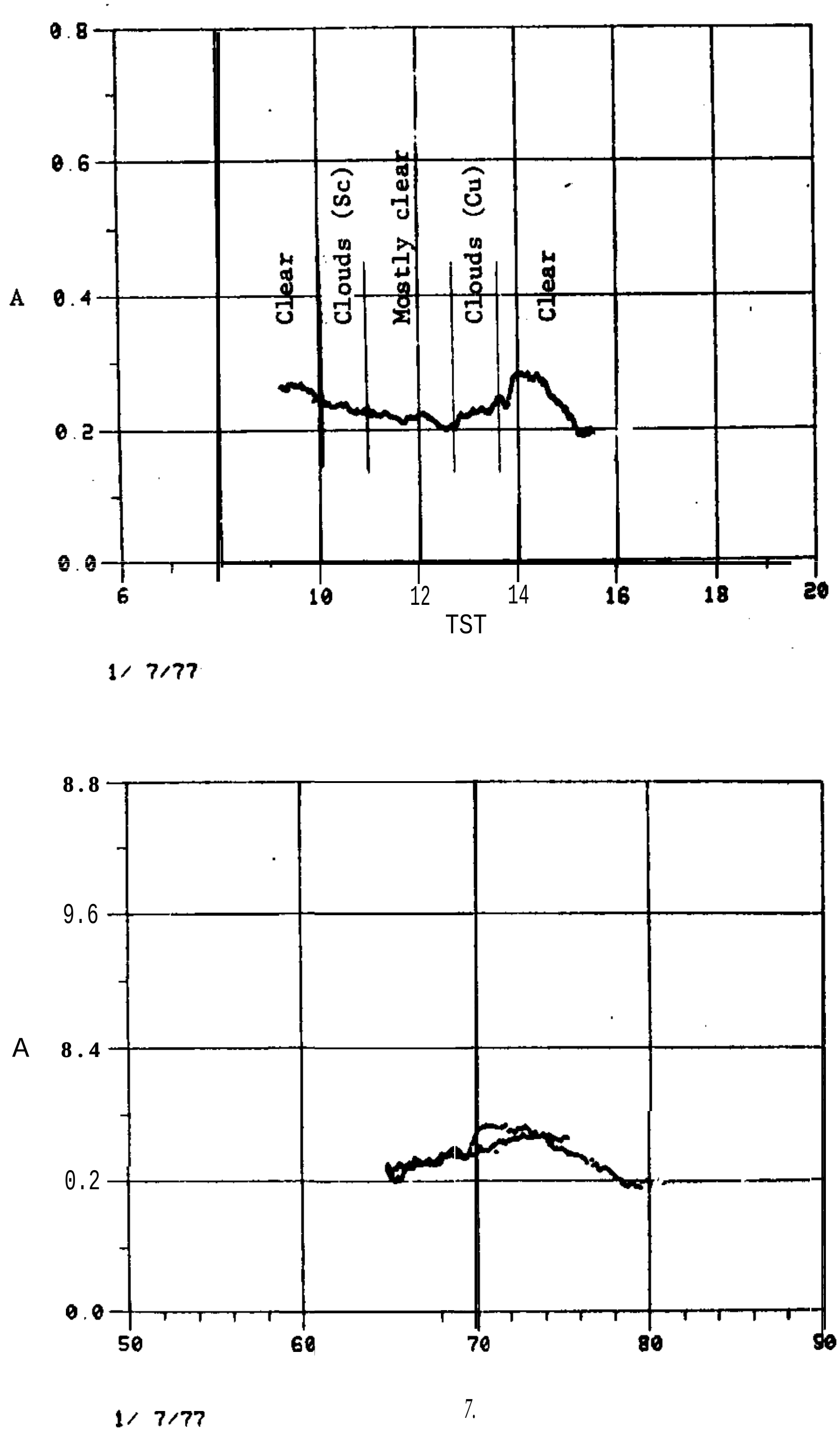



Figure 10.--*Albedo(A) ve. TST and zenith angle(Z)* for *clear ice on a variable cloudy day with cloud periods and types marked, January 7, 1977.*

marked in a time series of albedo measurements over a clear ice surface. The cloud periods were noted from the radiometer traces and the cloud types from Detroit Metropolitan Airport data (with a suitable allowance for time lag due to the distance between the two sites). Note that the stratocumulus clouds in the morning seemed to exert little effect on the albedo when compared to the cumulus clouds later in the day. The significant rise in albedo just before 1400 TST was also noted in another case (Bolsenga, 1978) when a variable cloudy pattern changed to nearly clear skies (6 percent albedo increase) over a refrozen-slush-ice surface. In another case (figure 11) 1/10 stratocumulus prevailed until 1130 TST, after which cloudiness increased to the 6-8/10 level (stratocumulus) for the remainder of the day. Some brief periods of nearly clear skies prevailed early during the afternoon.

It appears that a detailed study of cloud composition coupled with the albedo variations will be required for a complete understanding of these phenomena. Albedo patterns on variable cloudy days present complex situations, which are not easily unraveled. The problems involved are primarily due to the type of data considered here. It is felt that the albedo variation is a complex function of the spectral composition of the incident radiation as influenced by various types of cloud layers and the associated spectral composition of the reflected radiation as influenced by the type of ice. Spectral albedo measurements are clearly necessary and additional information on cloud properties, such as droplet size and water content, are desirable.

One of the most dramatic daily variations in ice albedo can be produced by mild conditions causing melting of the ice. Figure 12 shows the albedo vs. TST and zenith angle for a case study completely reported by Bolsenga (1978) where the ice surface was refrozen slush. Water was observed to occupy the interstitial spaces between small protruding grains of the ice surface during the period of lowest albedo. A thin, even layer of clouds prevailed during the measurements.

In a less dramatic situation (figure 13), solid snow ice had become moist by midday, causing a steady decrease in albedo of nearly 10 percent. Maximum temperature measured at the site was 8.3°C. Variable cloudiness (7-10/10 coverage) prevailed until 1400 TST, when the sky became clear. The rise in albedo after 1400 TST is due to the direct-diffuse incident radiation balance interacting with the snow-ice. The solar altitude-albedo variations due to melting effects are indicated by the top curve in figure 13b and direct-diffuse interactions are apparent in the lower curve.

A series of measurements were taken on 3 consecutive days when a combination of refrozen slush and clear ice deteriorated under mild weather conditions. Air temperatures during measurement periods at the Detroit Metropolitan Airport averaged 4.6°C on March 7, 1977; 13.4°C on March 8, 1977; and 15.2°C on March 9, 1977. On March 7, 1977, cloud cover remained at 6/10 stratocumulus throughout most of the day. On March 8, 1977, cloud cover remained at 3/10 cirrus throughout the day. On March 9, 1977, 3/10 cirrostratus in the morning increased to about 7/10 near the middle of the day. Near the end of the day the cloud cover decreased to 3/10 altostratus. Observer reports indicate a moist ice surface numerous times during the observations with standing water near, but not under, the reflected pyranometer.

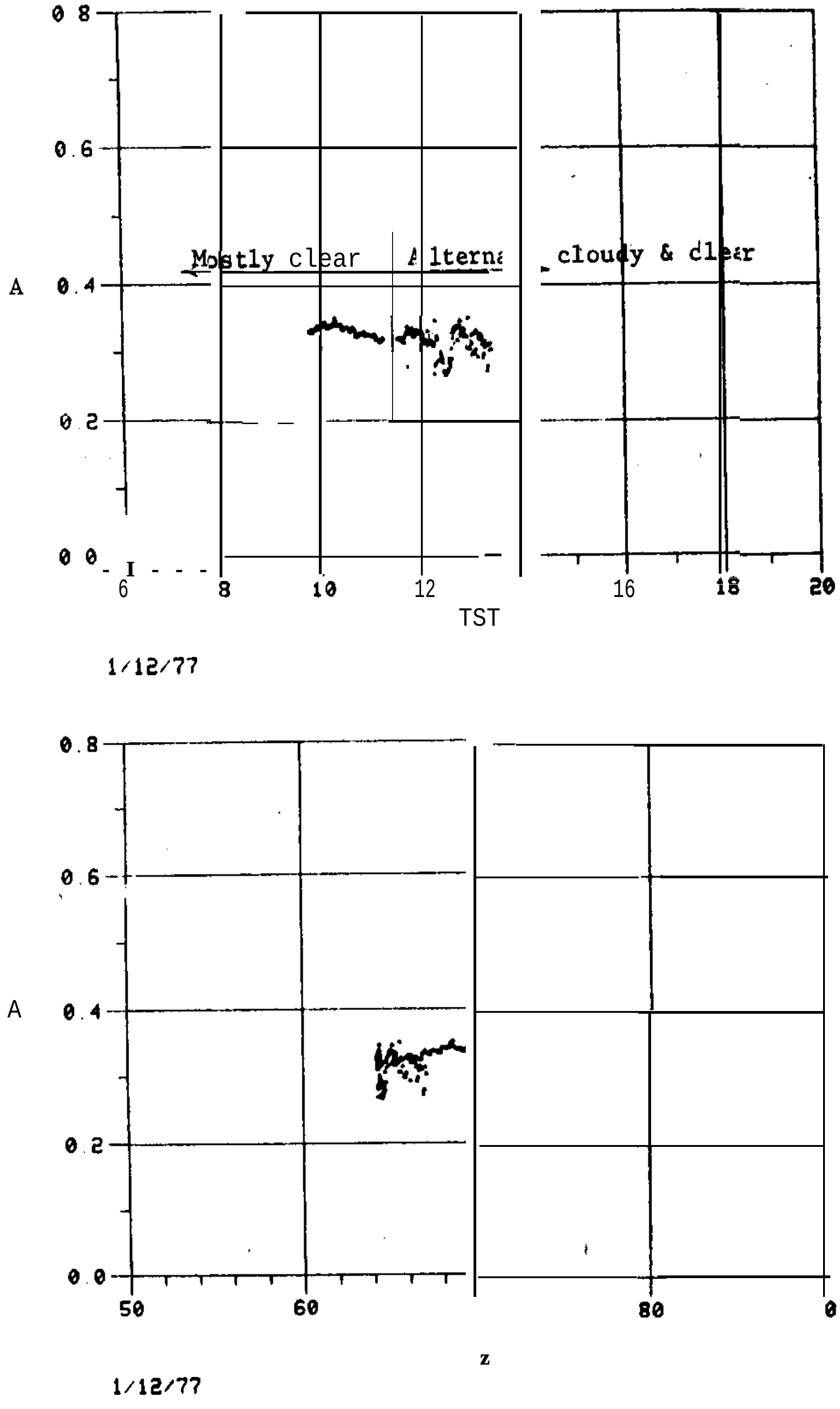



Figure 11.--*Albedo (A) vs. TST and zenith angle (Z) for clear ice on a variable cloudy day with cloud periods and types marked, January 12, 1977.*

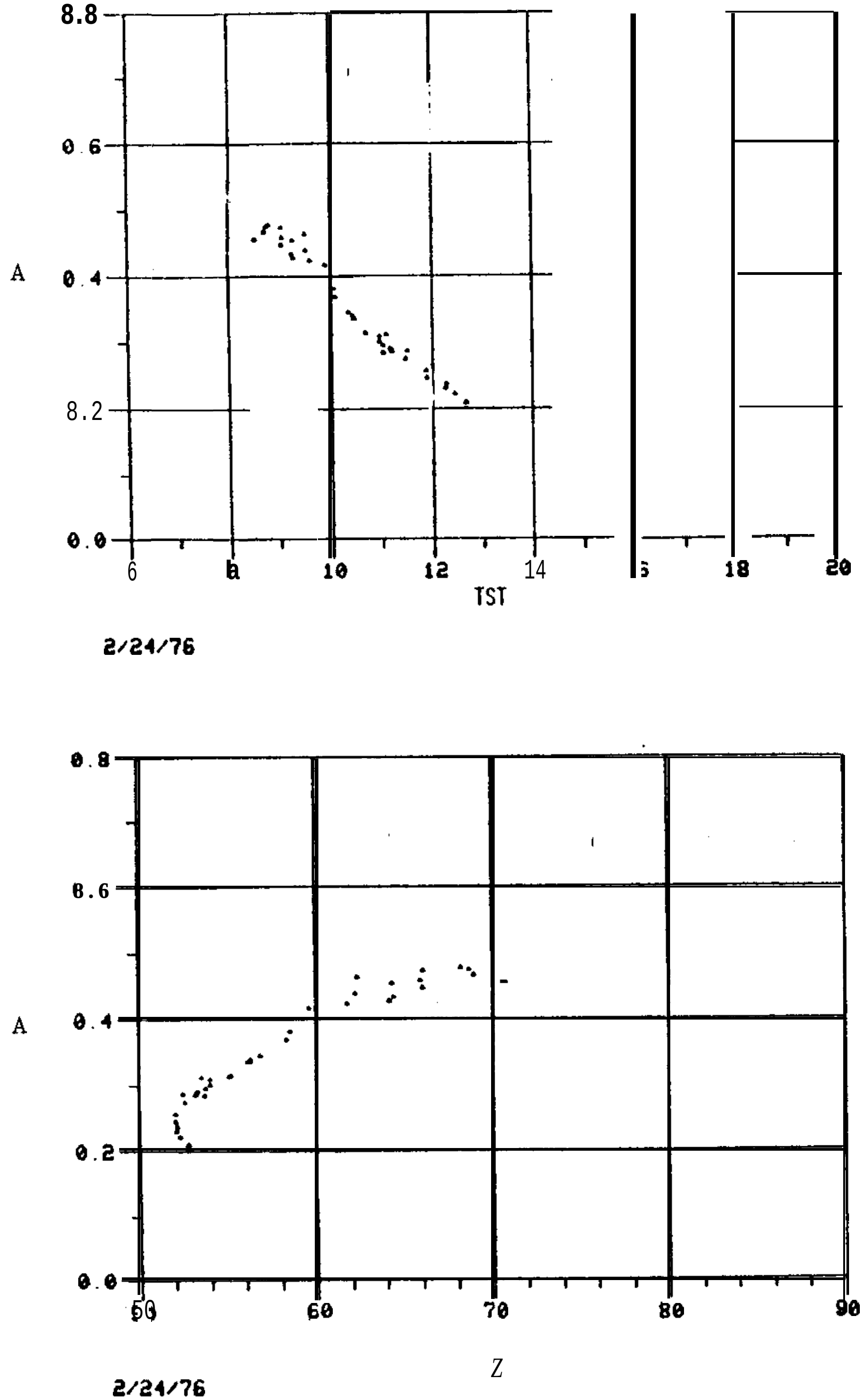
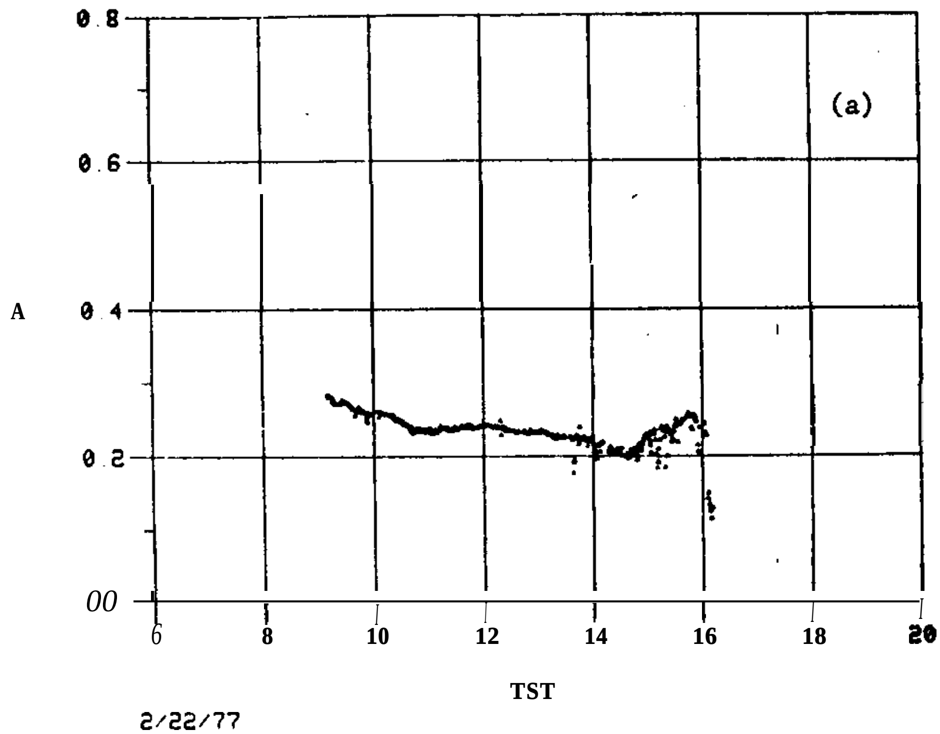



Figure 12.--*Albedo (A) vs. TST and zenith angle (Z)* for refrozen *slush ice during a period* of *melting, February 24, 1976.*



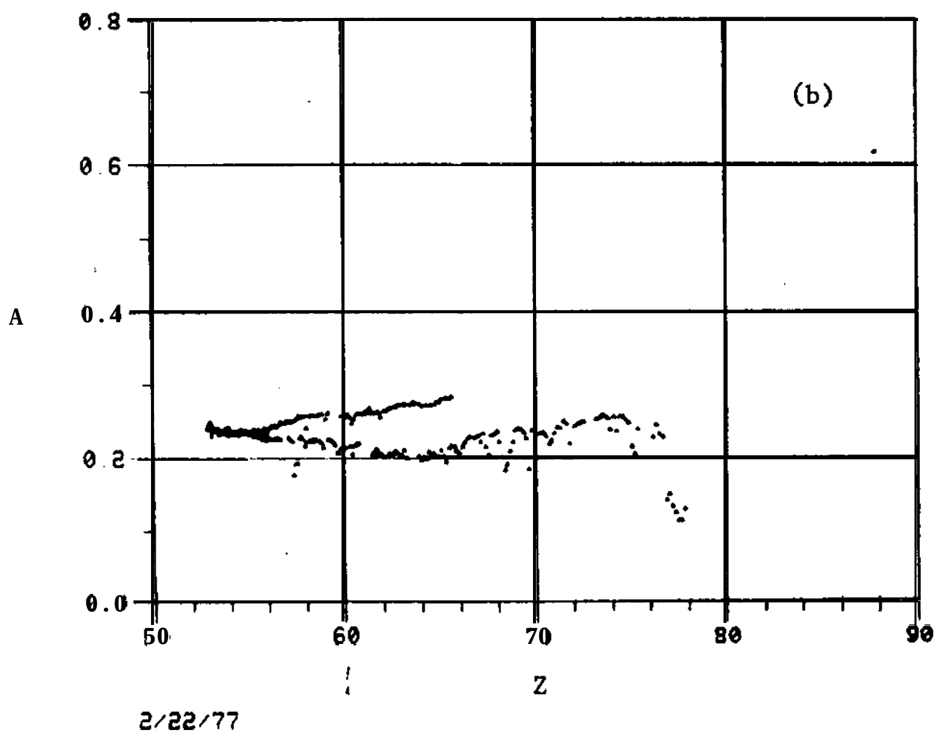




Figure 13.--Albedo (A) vs. TST and zenith angle (Z) for a snow-ice surface shooing a steady albedo decrease due to melting, February 22, 1977.

A series of photographs shows closeups of the ice surface and details the drainage of the surface water with time (figures 14-16). Albedo values during the middle of all days of measurement remained fairly constant in the range 4-9 percent (figures 17-19). Solar altitudes during the same midday periods ranged from about 35°-45°. Using the reflection law of Fresnel,

$$R = \frac{1}{2}\left[\frac{\sin^2(i - r)}{\sin^2(i + r)} + \frac{\tan^2(i - r)}{\tan^2(i + r)}\right], \qquad (1)$$

where

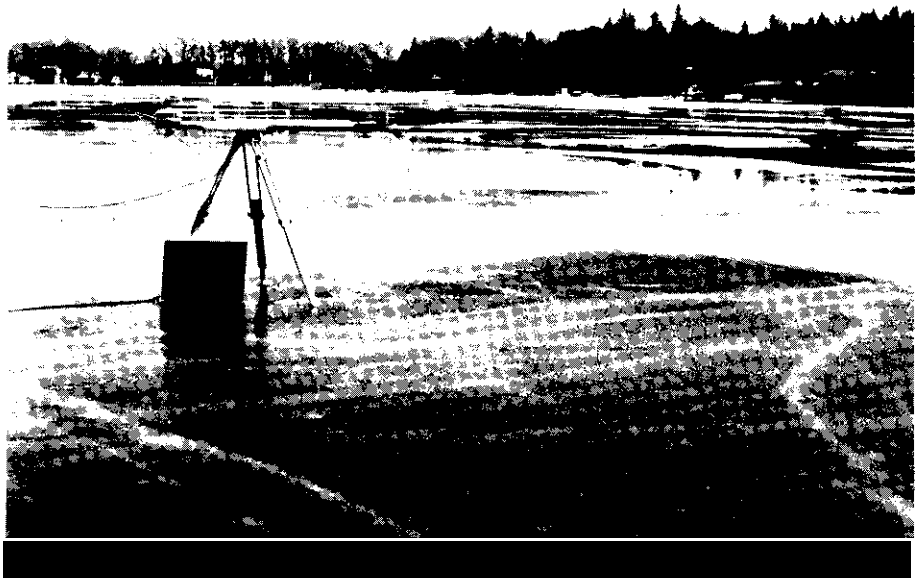
R = reflectivity,
i = angle of incidence,
r = angle of refraction, and

the reflectivity of a pure water surface at solar altitude 40" is 6.0 percent. The midday albedo values thus compare closely to the reflectivity of water. However, the dramatic increase in reflectivity of pure water at low solar altitude as indicated by the equation was not exhibited by the ice. Perhaps water lying in microscale depressions on the ice surface caused "Fresnel reflection" at high solar altitudes and normal ice reflection at low solar altitudes. (The reflectivity of clear ice at solar altitude 37° is 10 percent [Bolsenga, 19691.) Cloud cover variability seemed to have only a slight effect on the measurements.

## 3.2 Near Infrared Spectrum (700-3000 nm)

A limited number of measurements of near-infrared albedo were made by fitting the pyranometers with Schott RG-8 hemispherical filters with a lower sharp cutoff at about 700 nm. In some previous measurements (Bolsenga, 1978) near-infrared albedo averaged 34 percent over snow-ice, about 7 percent lower than total solar spectrum albedo. Measurements in this series were over clear ice and only averaged about 20 percent. No measurements were made of total solar spectrum albedo immediately before or after near infrared measurements, but comparison of the readings on January 17, 1977, (figure 9) to near infrared measurements on the next day (figure 20) provide a rough verification of a difference near 7 percent. All measurements (figures 20-23) were over the same ice surface, which consisted of about 38 cm of clear ice. Variable cloud conditions prevailed during all days of measurement with the exception of January 24, 1977, (figure 22). On that day 1/10 stratocumulus

Figure 14.--*Overall* view *and* closeup of ice *during melting period. Top view on March 7, 1977. Note absence of standing water (not yet developed).*



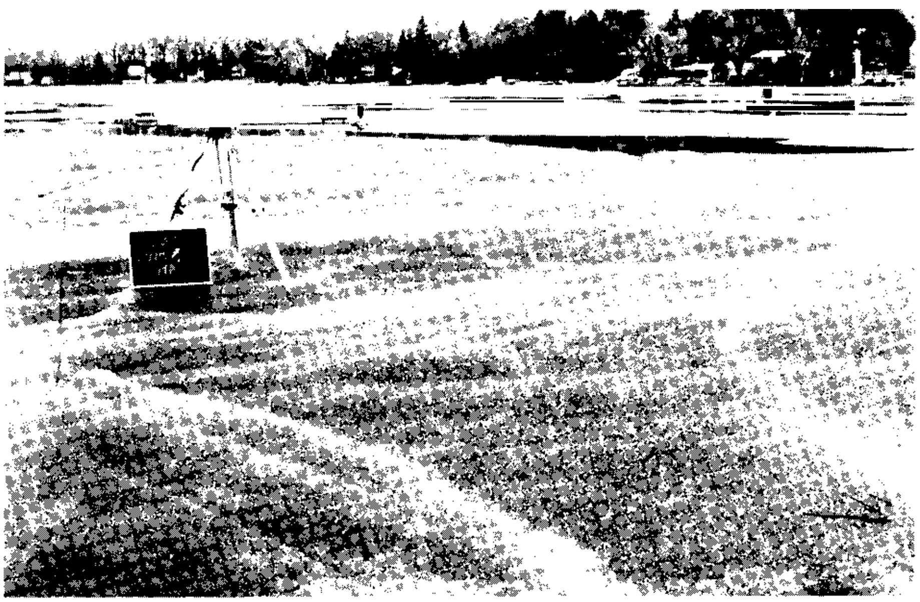


Figure 15.--Two overall views of the ice surface on March 8, 1977. The top photograph shows considerable standing water on the surface. The lower view was taken later in the day and indicates partial drainage of melt-water through the ice.

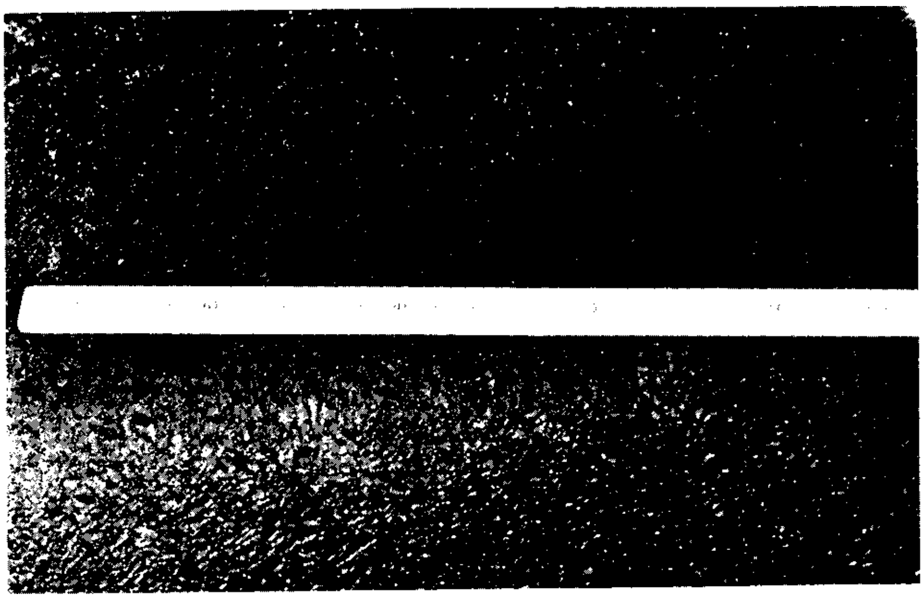


Figure 16.--Ice surface a *March 8, 1977, after met melt-water had drained through the ice and closeup view of ice* **cover (compare** *with figure 141.*

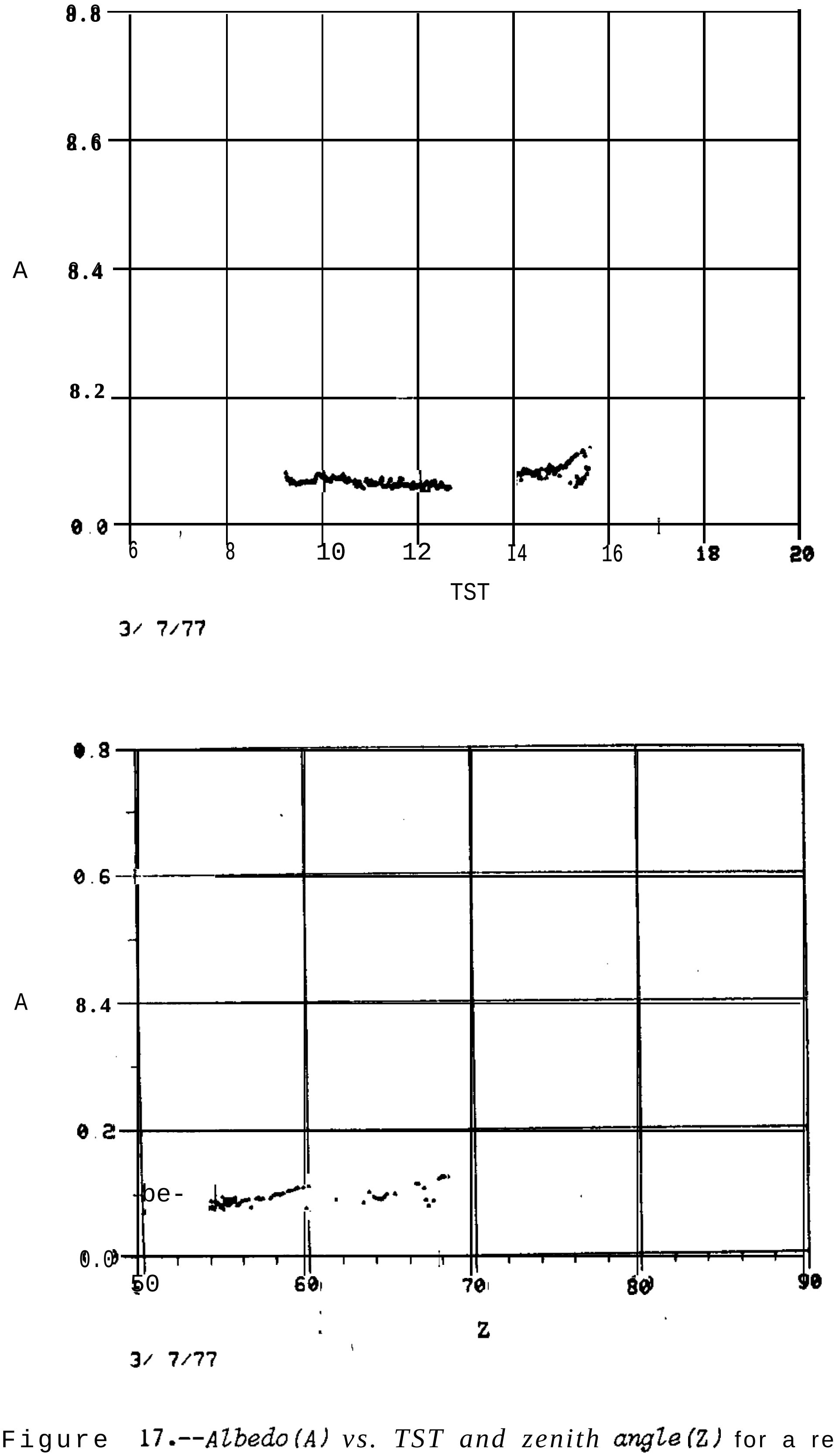



Figure 17.--*Albedo(A) vs. TST and zenith angle(Z)* for a refrozen *slush-clear ice combination during melting, March 7,1977.*

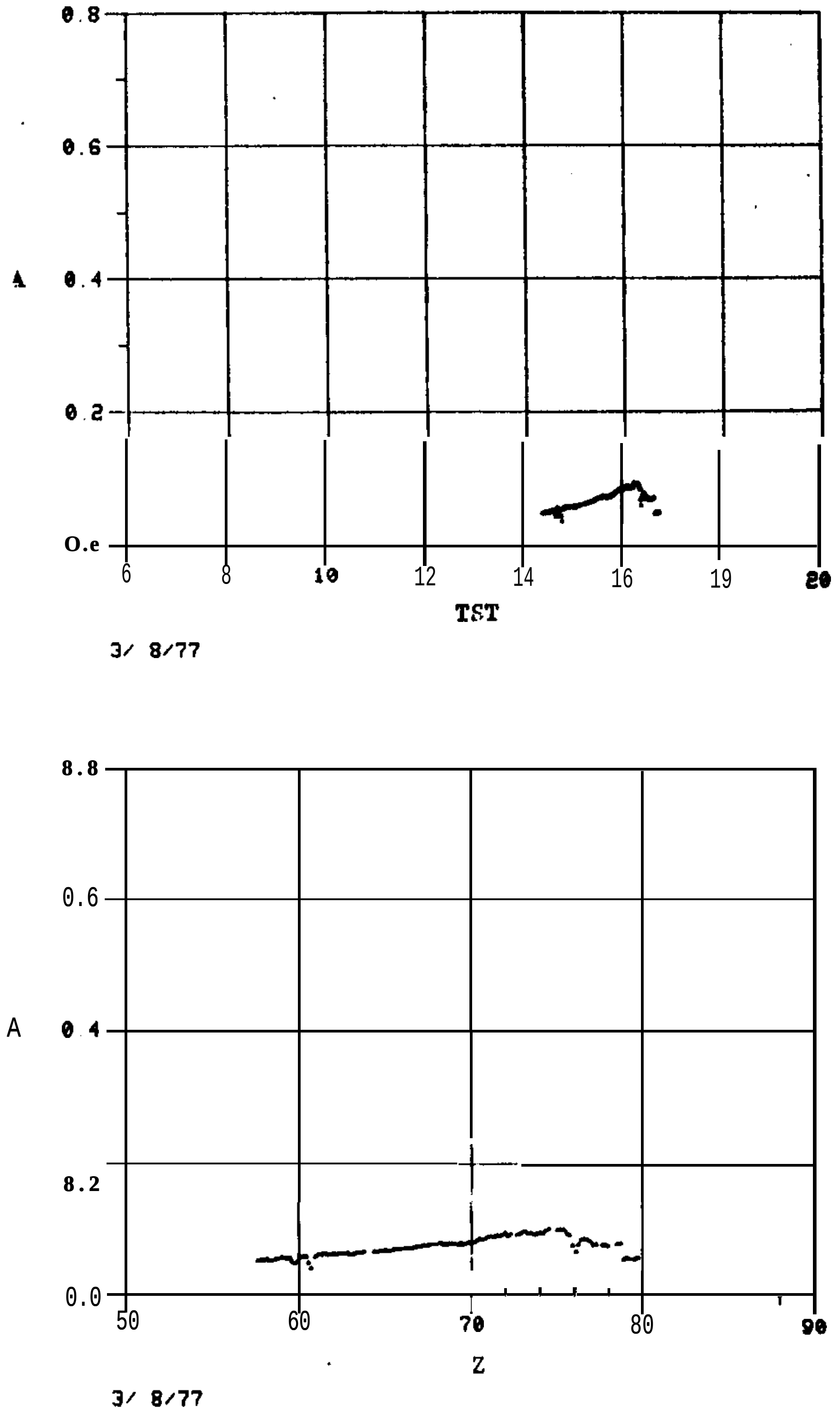



Figure 18.--*Albedo (A) vs.* TST *and zenith angle (Z) for a refrozen slush-clear ice combination during melting, March 8, 1977.*

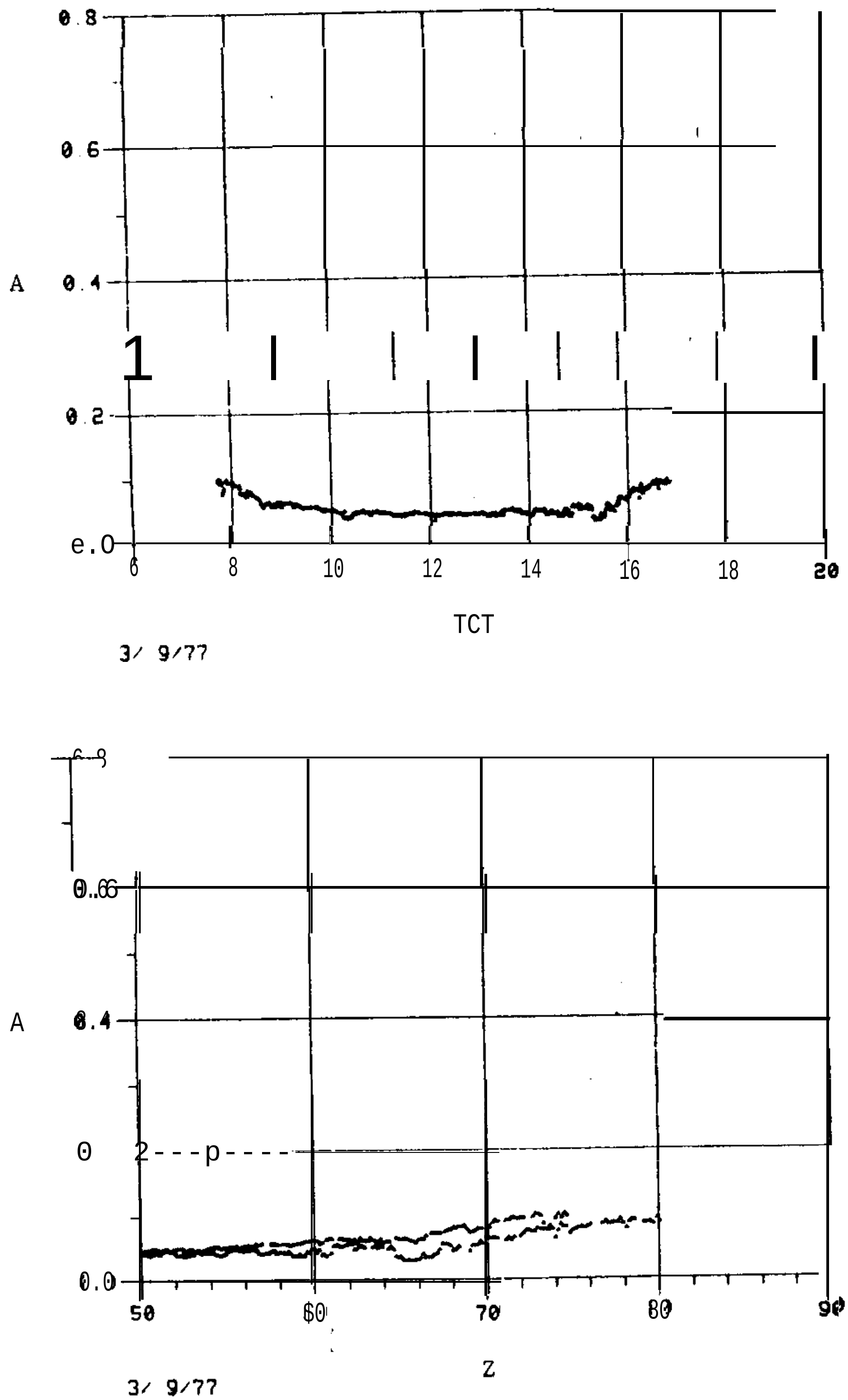



Figure 19.--*Albedo (A) vs. TST and zenith angle (Z)* for a *refrozen slush-clear ice combination during melting, March 9, 1977.*

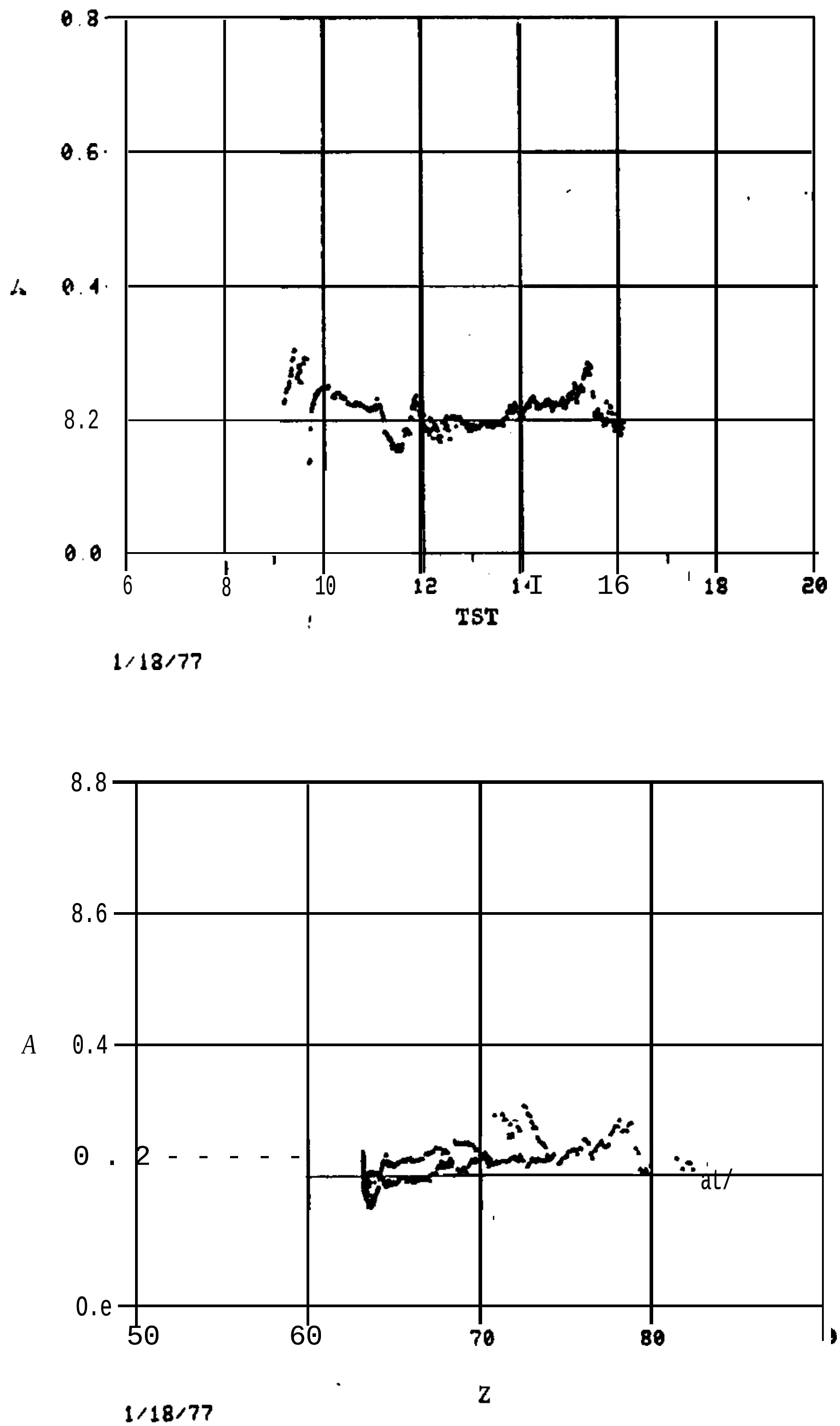
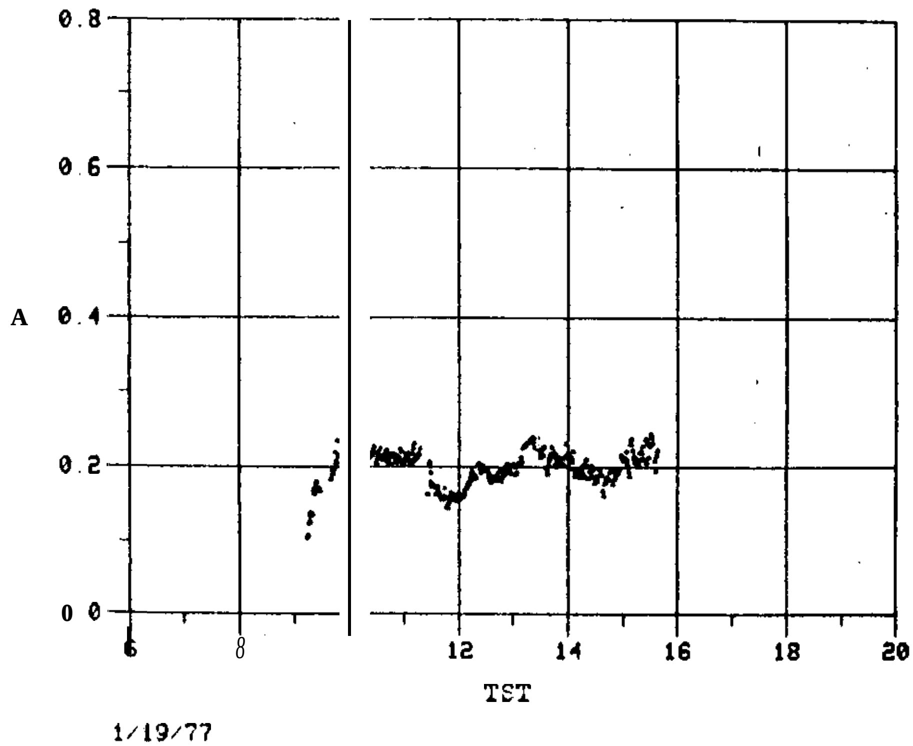



Figure 20.--Near infrared albedo (A) vs. TST and asnith angle (Z) for clear ice under variable cloudiness, January 18, 1977.



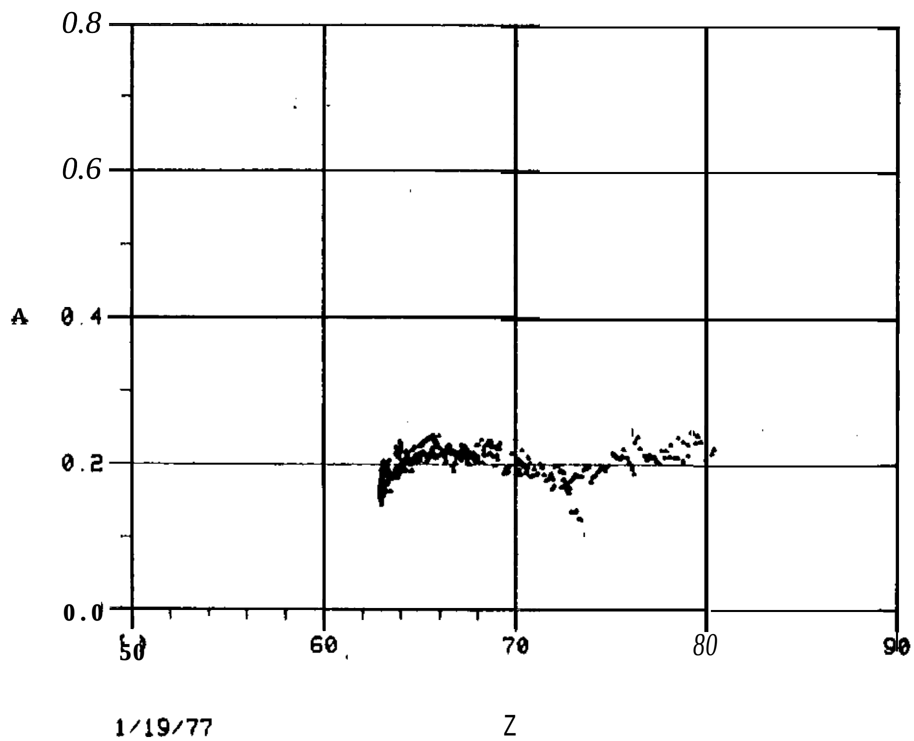
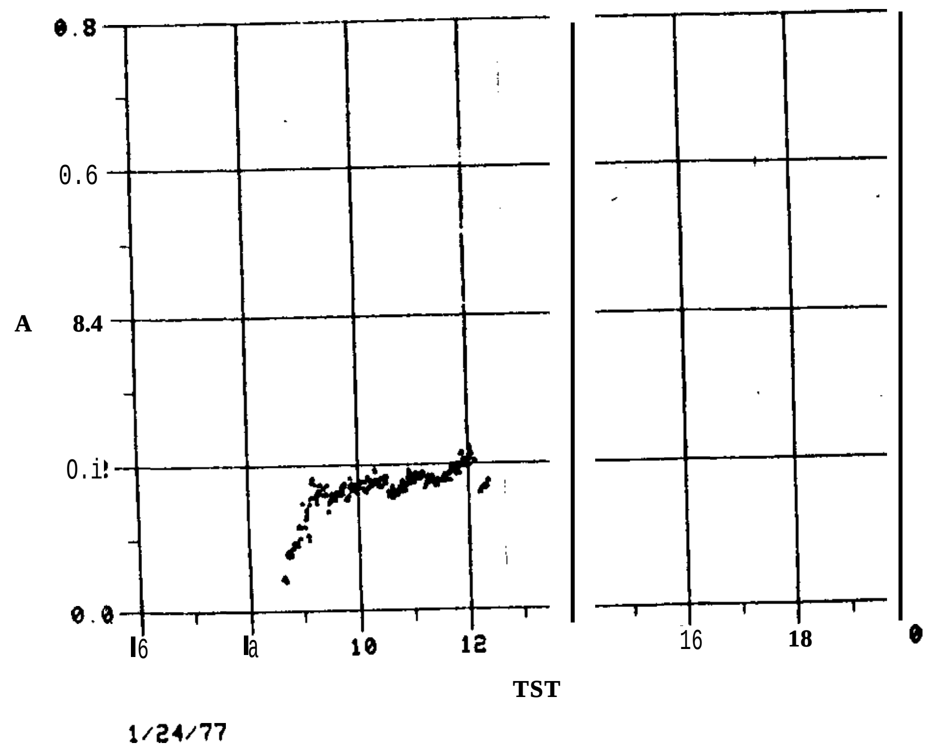




Figure 21.--Near infrared albedo (A) vs. TST and zenith angle (Z) for clear ice under variable cloudiness, January 19, 1977.



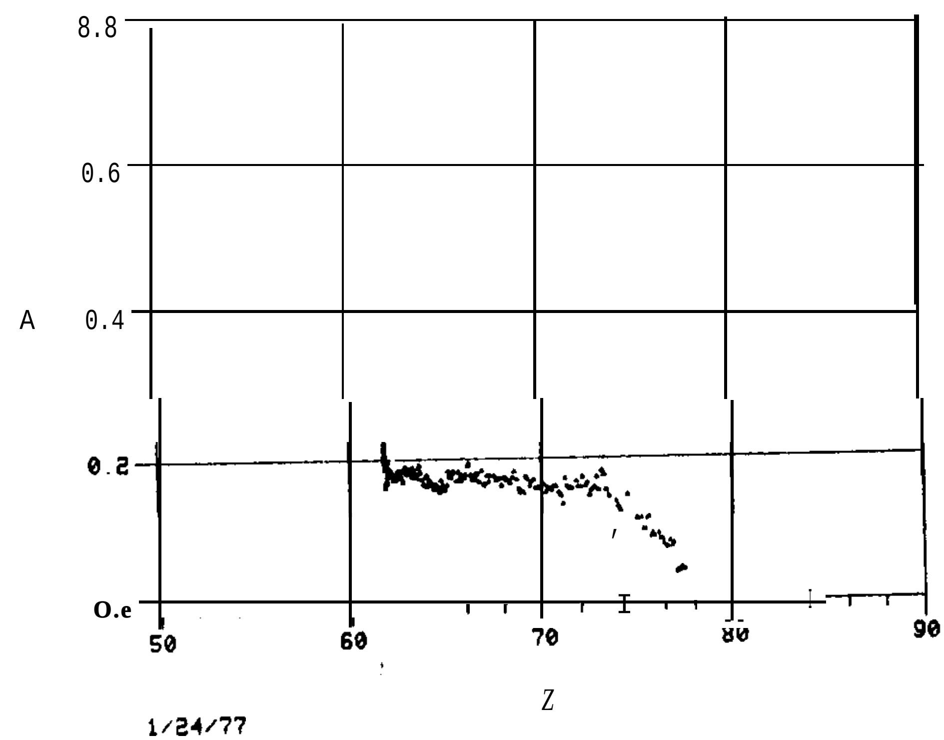
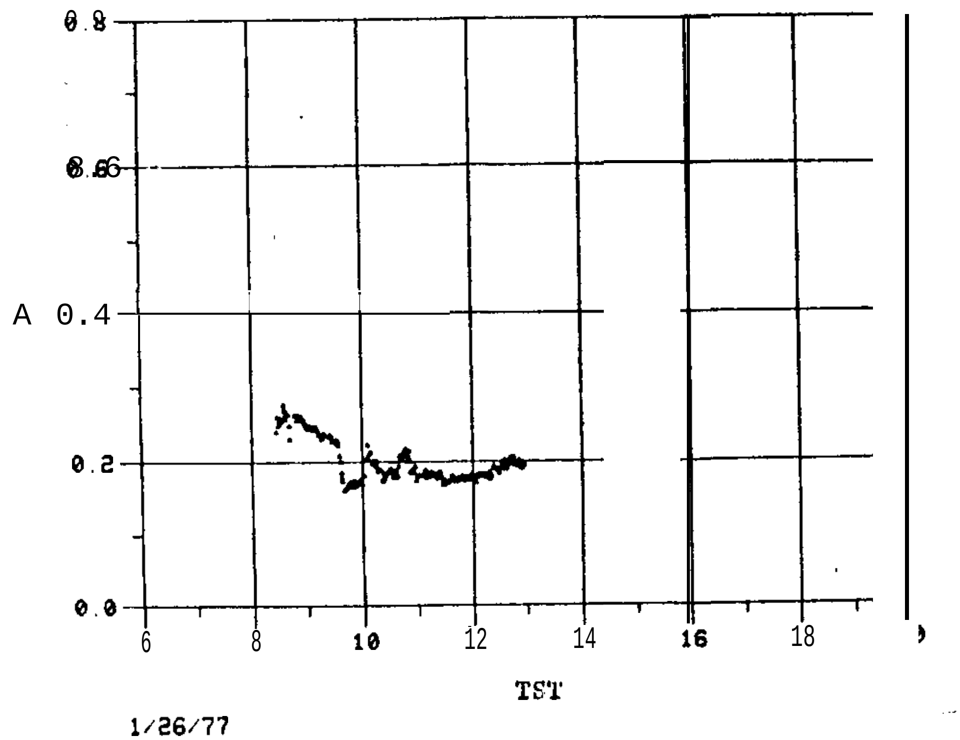




Figure 22.--Near infrared *albedo (A) vs. TST and zenith angle (Z) for clear ice under uniform (1/10) stratocumulus clouds,* January 24, *1977.*



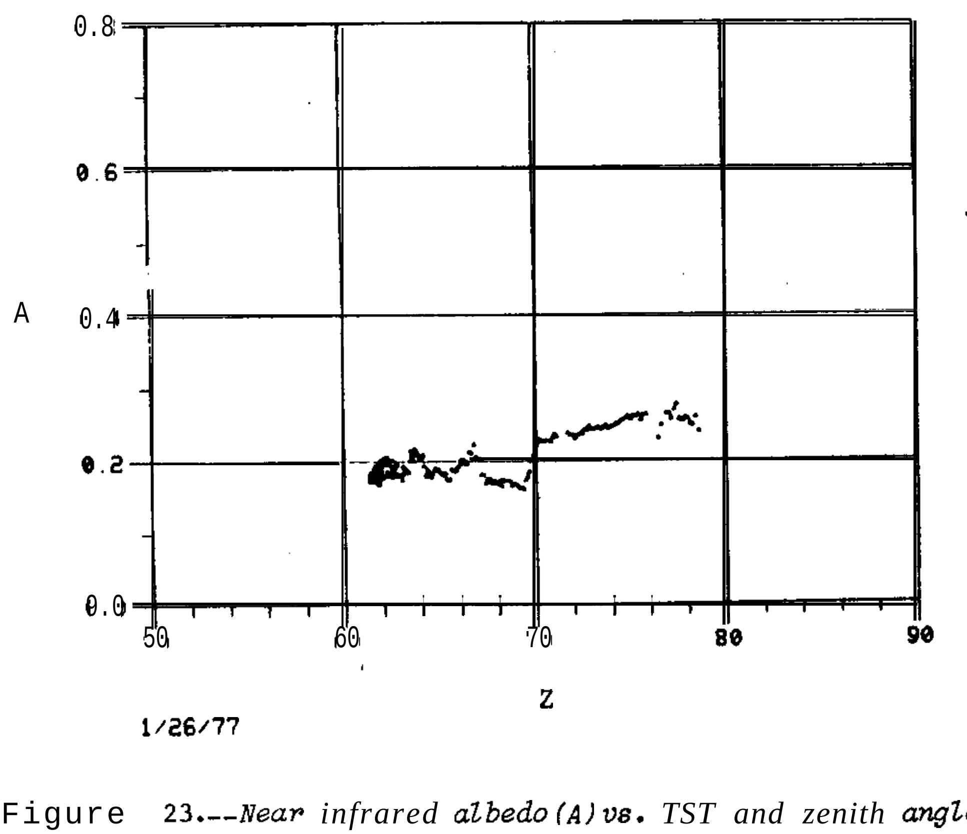




Figure 23.--*Near infrared albedo (A) vs. TST and zenith angle (Z) for clear ice under variable cloudy skies, January 26, 1977.*

clouds were reported during all hours of measurement.

One of the more prominent features of this measurement set is the significantly lower albedo values on the mornings of January 19 and 24, 1977, (figures 21 and 22) as compared to readings during the remainder of the day. The Eppley Corporation, manufacturer of the sensors, warns against measurements of total solar spectrum radiation at solar altitudes of $<10°$ because of low radiation levels that exceed the capability of the thermopile. These data have been deleted from all total solar spectrum albedo calculations in this report, but are included with the near infrared data for illustrative purposes. Nearly all of the measurements on both days were at solar altitudes $>10°$, but it is felt that low radiation levels combined with diminution of the flux caused by the filters caused incorrect readings of the inverted sensor. It should be noted that measurements at solar altitudes $<10°$ were taken on January 18, 1977, (figure 20). The lack of spurious readings in this case is attributed to higher incident and reflected readings due to differences in cloud cover from the other days of measurement.

It is difficult to ascribe any significant trends to the near infrared data based on only 4 days of information. Additional data are required during clear days over both snow-ice and clear ice. It does appear, however, that the daily range of values is somewhat smaller than what might be expected for total solar spectrum albedo.

## 4. QUANTIFICATION

One of the ultimate goals of this study is quantification of the phenomena involved to eliminate the expense of additional data collection for various efforts such as predictive modeling. Such investigations have been conducted by Idso *et al.* (1975). Idso and Reginato (1974). and Coulson and Reynolds (1971) for certain soil types and by Arnfield (1975) for a limited number of agricultural surfaces.

It is possible to fit mathematical expressions such as those derived in the above studies to the data given here, providing diurnal variations clearly attributable to solar altitude variations are exhibited. The expression suggested by Arnfield,

$$A = ae^{bz} \tag{2}$$

where $z$ = solar zenith angle,

was applied to the February 16 and 17, 1977, data with the results shown in table 1.

Plots of ln A vs. the zenith angle for the same periods are shown in figures 24, 25, 26, and 27. Additional plots of ln A vs. Z were completed for several other days of measurement. Most would have produced significantly different a and b values from those shown in table 1 owing

Table 1.--Constants computed for equation (2) for dates and times specified

| | | |
|---|---|---|
| February 16, 1977 | Afternoon | |
| | | a = 0.06 |
| | | b = 0.02 |
| February 17, 1977 | Morning | |
| | | a = 0.12 |
| | | b = 0.01 |
| | Afternoon | |
| | | a = 0.11 |
| | | b = 0.01 |

to the various ice types and conditions. Some indicated that equation (2) would not provide a representative fit (possibly because of the lack of data, cloud conditions, etc.).

Extreme caution must obviously be exercised in using such expressions. The diurnal nature of soil albedo is almost totally dependent on shading due to solar altitude variations coupled with the shape of individual soil particles. The size and shape of the individual agglomerates influence the degree of shading, and in turn the size of the particles depends on the soil type and moisture content at the time of plowing and the degree of breakup caused by single or repeated plowing passes. The diurnal nature of crop albedo is also almost totally due to shadowing effects caused by the stage of maturity for living crops or the state of decomposition of crop stubble. Thus, transfer of diurnal albedo variation analyses for any surface (such as soils) to ice is totally unfounded, except in the case of severely undercut or pitted ice surfaces. Certain variations due to shading will take place in ice even with the relatively smooth surfaces reported here, but they will be minor when compared to the variations mentioned earlier due to the direct-diffuse incoming radiation balance caused by solar altitude changes vs. the spectral reflectance properties of the particular ice type involved. Clearly spectral albedo measurements are necessary to provide an explanation for that type of diurnal variation. Metamorphism of an ice surface might also occur during a daily period, adding an additional dimension to the problem. In short, the relationships for ice and for soils and crops are mostly different. To say that mathematical expressions such as equation (2) can be applied to ice data, only implies that any equation of a certain type can ultimately be fitted to the data, *not* that the physicial processes (or the associated mathematical expressions) causing diurnal variations in ice, soils, crops, etc., are in any way the same.

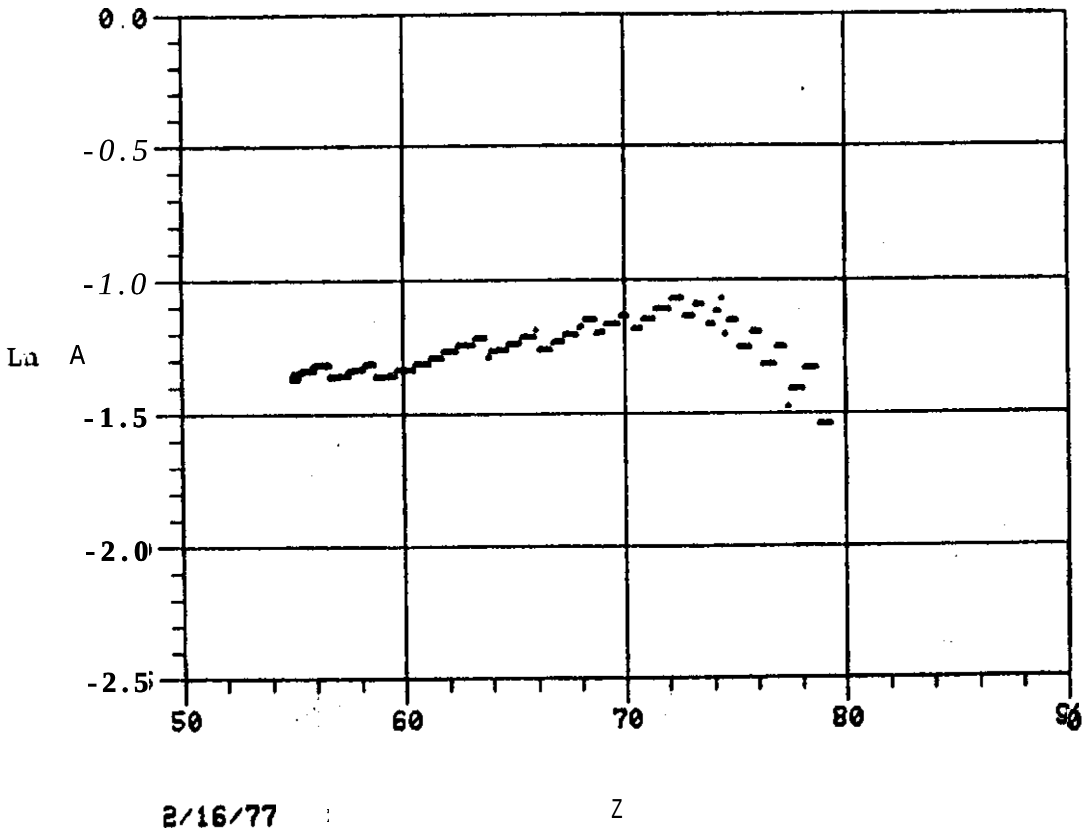



Figure 24.--*Ln A vs. zenith angle (Z) for afternoon data on February 16, 1977.*

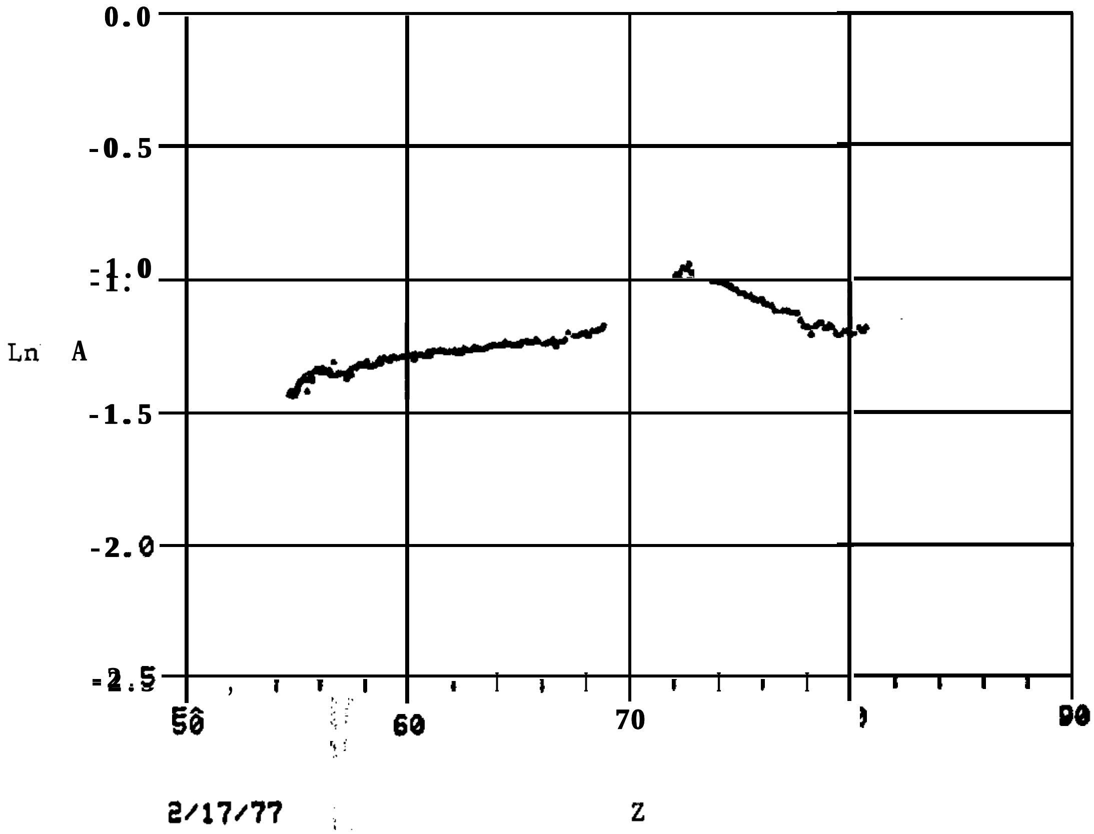



Figure 25.--*Ln A vs. zenith angle (Z) for morning data on February 17, 1977.*

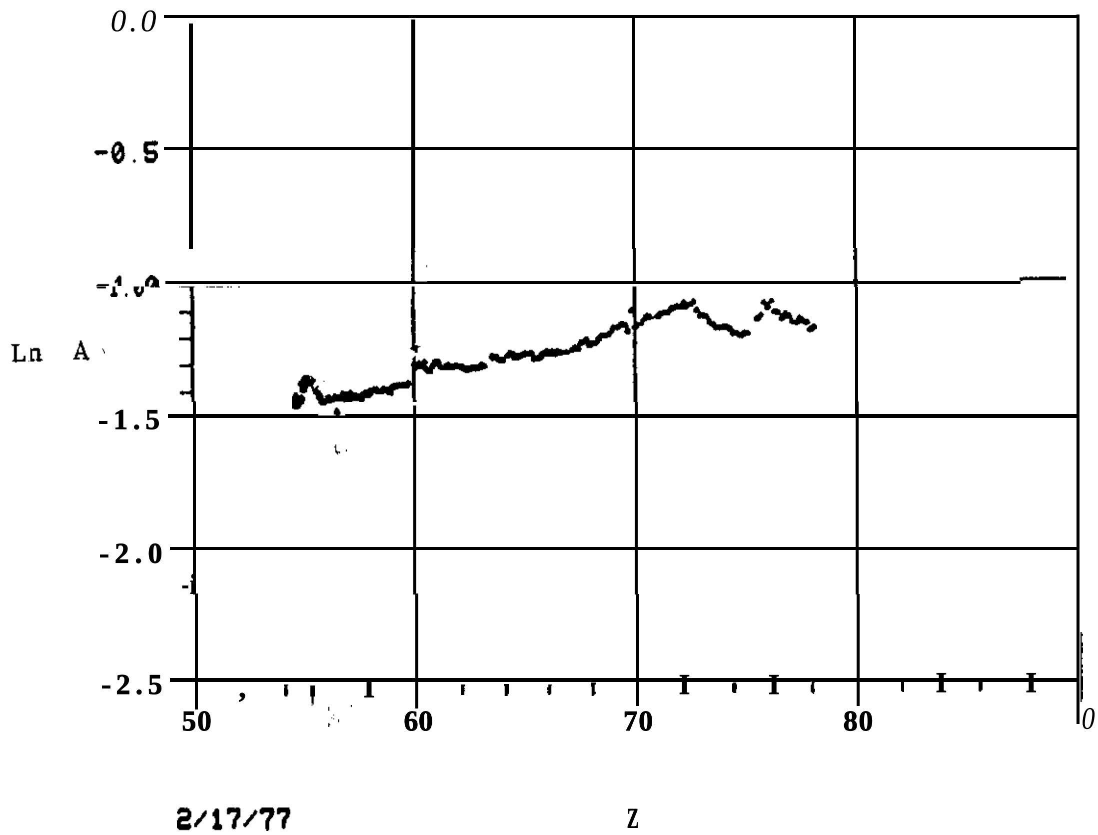



**Figure** 26.--*Ln A vs. zenith angle (Z) for afternoon data on February 17, 1977.*

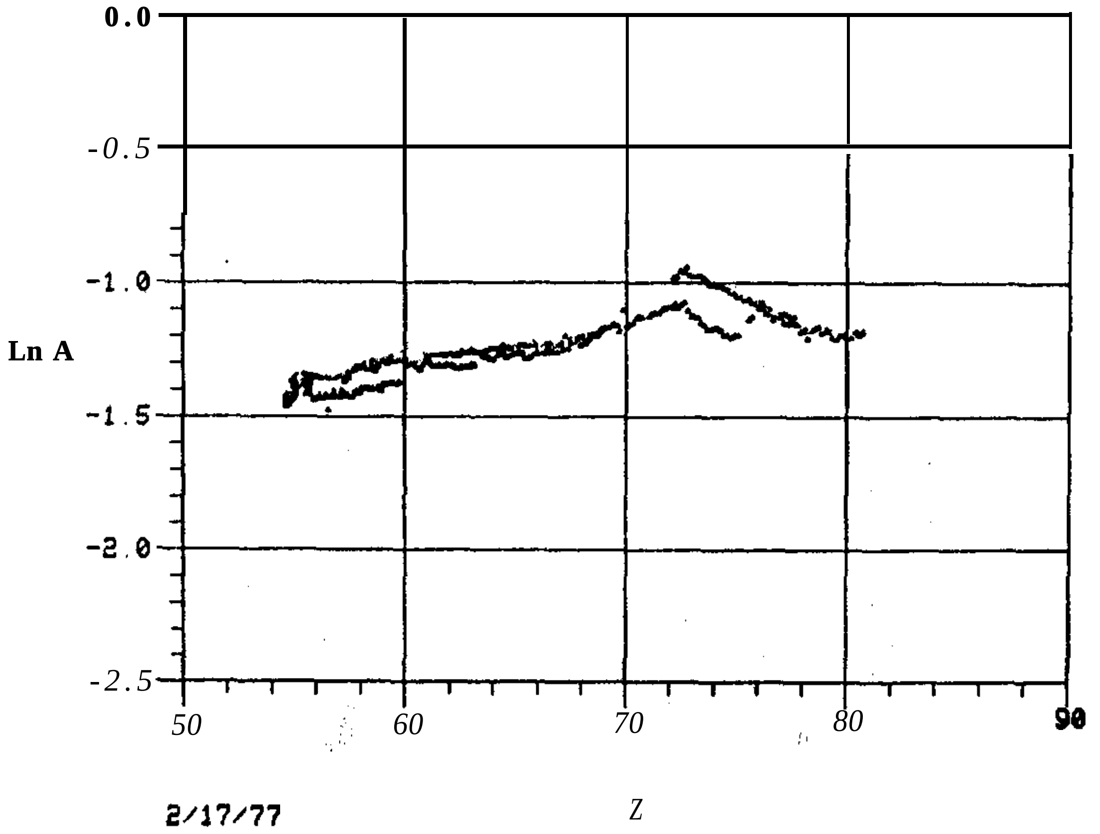



**Figure 27.**--*Ln A vs. zenith* **angle** *(Z)* **for** *morning* **and afternoon** *data* **on February** *17, 1977.*

Thus, for quantification of these phenomena, collection of extensive new information is necessary in order that physical explanation accompany development of equations for various types of ice. Until such a study is conducted, information such as that given in table 1 is not only extremely premature but also misleading.

## 5. CONCLUSIONS

Under certain atmospheric conditions and with certain ice types the daily variation of ice albedo is pronounced. The albedo of snow-ice or refrozen-slush-ice was found to vary significantly and in a characteristic manner under clear skies. The variation is attributed to changes in the spectral balance of the incoming radiation interacting with these types of ice surfaces. When beam radiation was absent (cloudy skies), diurnal variation was absent. Measurements over clear ice did not exhibit the variations shown by the snow-ice or slush-ice, but the evidence is not conclusive because of lack of data.

Albedo measurements under variable cloudy skies showed corresponding albedo variations, but a quantitative assessment of this phenomena must await detailed measurements of the physical properties of the clouds coupled with spectral incident and reflected radiation measurements.

Pronounced daily variations in albedo occur when a solid ice cover deteriorates owing to mild weather. After the albedo drops significantly, it stabilizes at a low level approximately equal to the albedo of a plane water surface at high solar altitudes.

Four days of measurements of near-infrared albedo showed a smaller daily range than what might be expected for total albedo in comparable situations. The lower radiation levels obtained owing to the filters employed emphasized the need for caution regarding measurement accuracy. Many additional near infrared data are required to obtain even a general idea of the diurnal patterns involved.

Some preliminary attempts at quantification of the relationships found for total ice albedo indicate that meaningful efforts must await analysis of additional data to firmly define the physical relationships involved.

The observations of this study, as well as other works cited, have emphasized the need for spectral reflectance measurement of Great Lakes ice. Accordingly, two scanning spectrophotometers have been recently acquired and configured for field use. Analysis of some of the data shows significant results. After additional data collection, results will be provided in the open literature.


## 6. ACKNOWLEDGMENT

Many thanks are due to Professor S. I. Outcalt of the University of Michigan for several stimulating discussions on this material.

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