# *SOLAR RADIATION DATA ANALYSIS*

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# SOLAR RADIATION DATA ANALYSIS

by

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SOLAR RADIATION DATA ANALYSIS

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Under the Supervision of Professor Sanford A. Klein

This thesis reevaluates three fundamental concepts concerning the mathematical modeling of solar energy:

1) calculating solar radiation on a tilted surface from horizontal data;
2) analyzing the distribution of solar energy within a month; and
3) calculating the "utilizable energy" within a month.

One year of radiation data collected by Universities in San Antonio, Texas and in Albany, New York provided the basis for this study. Total solar insolation data were measured every minute and recorded on magnetic tape, for eight surface orientations. Normal incident beam radiation, various spectral ranges, and ambient conditions were also measured and recorded.

Modeling tilted surface radiation from horizontal data requires the calculation of a diffuse to total radiation fraction. The largest error in estimating monthly-average daily diffuse fractions from Erbs' [5] hourly diffuse fraction correlation was 10%. Typical errors were approximately 4%. Comparing individual hourly values from Erbs' correlation to data showed typical monthly RMS errors around 0.18, with a maximum RMS error of 0.32.

The isotropic hourly model, Hay [8] anisotropic hourly model, and hourly data values of tilted to horizontal surface radiation values were compared. For south-facing surfaces at a slope equal to the latitude, the isotropic model underestimated actual values by as much as 10%. In comparison, the Hay model provided better estimates of the radiation ratio for 23 of the 24 months studied. The worst performance was an underestimation by 6%. For all south-facing surfaces, the largest isotropic model errors occurred during winter months, with underestimations as large as 18%.

The distribution of solar energy within a month can be described by a "clearness frequency distribution". The minute clearness frequency distributions for hourly periods within a month show more variability in insolation levels than the presently used long-term hourly distributions. Variability in hourly distributions with the same monthly-average hourly clearness index indicates the potential need for modeling distributions with more than one independent parameter.

Monthly-average hourly and daily utilizability values calculated from hour data and Clark's [2] hourly correlation were compared to minute data values. An RMS error of 0.02 or less indicated a pair of approximately identical utilizability curves. Hour data values calculated for surface slopes equal to the latitude exceeded this RMS error for half of the months studied. Typically, surfaces receiving large amounts of normal incident beam radiation show the largest differences between hour and minute data values. Three versions of Clark's correlation were compared to the minute data values, to check for errors resulting from: the monthly-average hourly isotropic radiation ratio model; the symmetrical day insolation assumption; and a correlation modeled from long-term data versus a short-term data base. The largest source of error in Clark's correlation was typically from the isotropic radiation ratio model, using Erb's monthly-average daily diffuse fraction correlation.

# ACKNOWLEDGEMENTS

I wish to dedicate this work to the most important person in my life, Jesus Christ. Without His guidance and strength, I would have been lost. Also, without His creative world, there would not have been a topic to do my thesis on.

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## NOMENCLATURE

This list contains the major parameters used in this study. Others are defined locally.

| | |
|---|---|
| $a$ | Utilizability correlation parameter (Eq. 4.4) |
| $A$ | Hay's anisotropic index |
| $f$ | Cumulative frequency of occurrence |
| $G$ | Instantaneous insolation |
| $G_{sc}$ | Solar constant |
| $H$ | Total daily inolation on a horizontal surface |
| $H_d$ | Daily diffuse insolation on a horizontal surface |
| $H_T$ | Total daily insolation on a tilted surface |
| $H_o$ | Daily extraterrestrial radiation on a horizontal surface |
| $I$ | Total hourly insolation on a horizontal surface |
| $I_c$ | Critical hourly insolation level |
| $I_d$ | Hourly diffuse radiation on a horizontal surface |
| $I_{NIP}$ | Hourly normal incident beam radiation |
| $I_o$ | Hourly extraterrestrial radiation on a horizontal surface |
| $I_T$ | Total hourly insolation on a tilted surface |
| $J$ | Number of critical levels used in utilizability calculation |
| $k_T$ | Hourly clearness index |
| $K_T$ | Daily clearness index |
| $r_d$ | Ratio of hourly diffuse radiation to daily diffuse radiation |

$r_t$ Ratio of hourly total radiation to daily total radiation

$R$ Ratio of total hourly insolation on a tilted surface to that on a horizontal surface

$\tilde{R}$ Ratio of monthly-average hourly insolation on a tilted surface to that on a horizontal surface

$\bar{R}$ Ratio of monthly-average daily insolation on a tilted surface to that on a horizontal surface

$R_b$ Ratio of hourly beam radiation on a tilted surface to that on a horizontal surface

$X_c$ Critical insolation ratio

$X_m$ Minimum critical insolation ratio at which utilizability equals 0

$\beta$ Collector slope

$\gamma$ Azimuth angle

$\delta$ Declination

$\theta$ Angle of incidence

$\theta_z$ Solar zenith angle

$\rho$ Ground reflectance

$\phi$ (1) Latitude
(2) Monthly-average hourly utilizability

$\bar{\phi}$ Monthly-average daily utilizability

$\omega$ Hour angle

$\omega_s$ Sunset hour angle

An overbar '¯' indicates monthly-average

# INTRODUCTION

Energy received from the sun permeates all aspects of our lives. It affects the weather and our resulting conversations, provides energy for plants, provided the stored energy in fossil fuels, can be used to heat or cool buildings, contributes to building cooling loads, and can even generate electricity. Clearly, solar energy contributes to our lives regardless of our philosophy on "alternative energy sources".

This thesis reexamines solar insolation models which are used in solar process design applications and system evaluations. Chapter 1 discusses the two year data base, while the remaining chapters discuss the three major topics investigated: Chapter 2 - estimating tilted surface radiation from horizontal data; Chapter 3 - analyzing the insolation profile during a month; and Chapter 4 - estimating the energy above a given threshold level. Because of the short-term data base, conclusions concerning long-term model performances - accuracy over a 10 year or longer period - could not be made. However, a Recommendation section has been included to indicate areas for future research.

Calculating radiation on a tilted surface from horizontal data requires methodologies for handling beam, diffuse, and ground reflected radiation. For hourly models, methods for predicting beam and ground reflected components are well defined. However, predicting the diffuse radiation component is an area still receiving much attention. Chapter 2 investigates two areas concerning diffuse radiation: 1) the fraction of diffuse radiation to total radiation; and 2) the isotropic versus Hay's [8] anisotropic distribution model. Hay's hourly anisotropic model breaks diffuse radiation into an isotropic component and a circumsolar component, based on the ratio of terrestrial to extraterrestrial normal incident beam radiation. The tilted surfaces studied include the following orientations: slope equal to latitude; south-facing vertical; east and west-facing vertical; and north-facing vertical.

Insolation levels can be defined in terms of a "clearness index", or the ratio of terrestrial to extraterrestrial total radiation. The cumulative daily distribution of clearness indexes within a month form patterns that are fairly similar for a given monthly-average clearness index. The comparison of minute data distributions for hourly periods, hour data distributions, and existing long-term distributions is discussed in Chapter 3. Daily distributions calculated from hour data are also compared to existing long-term distributions.

The ratio of total solar energy above a given threshold or "critical" level to total solar energy is called "utilizability". This concept is useful for analyzing active solar systems, where the critical level is the energy required to make-up collector losses and the energy exceeding this level is the net gain of the system. For passive systems, the energy below the critical level is useful and the energy above the critical level has to be discarded to prevent overheating. In this context, utilizability is referred as "unutilizability".

Chapter 4 discusses the comparison of monthly-average hourly and daily utilizability values calculated from minute data, hour data, and Clark's [2] monthly-average hourly correlation. The monthly-average hourly utilizability comparison is for noon to 1 p.m. Clark's correlation was derived from a combined 61 year horizontal radiation data base from 3 locations. To develop the correlation for south-facing surfaces, Clark calculated tilted surface radiation values from the hourly isotropic radiation ratio model and Erbs' [6] hourly diffuse fraction correlation. Using the monthly-average hourly isotropic radiation model and Erbs' monthly-average daily diffuse fraction correlation, Clark's correlation is dependent only on the monthly-average daily clearness index for a given surface orientation and location.

All time referenced in this thesis represents true solar time, and not local standard time for the area investigated. Both San Antonio and Albany are located in the northern hemisphere, and therefore "south-facing surfaces" also imply surfaces facing the sun during mid-day hours. Similarly, north-facing surfaces imply surfaces receiving no direct sunlight during mid-day hours.

# 1. RESEARCH DATA SOURCE

## 1.1 Overview

This study utilized two years of existing meteorological data from San Antonio, Texas and Albany, New York. The data were collected as part of the Solar Energy Meteorological Research and Training Site Program (SEMRTS), conducted on behalf of the U.S. Department of Energy. Readings were taken on a minute-by-minute time scale for 20 different instruments and recorded on magnetic tapes. Global or Total radiation instruments included: Horizontal; Tilt = Latitude, Latitude + 10°, and Latitude - 10° south-facing orientations; and vertical surfaces facing North, South, East, and West. Other radiation instruments included: Normal Incident (Direct Beam); Diffuse; Infra-Red; Ultra-Violet; and various other spectral ranges. Also recorded were ambient and dewpoint temperatures, along with wind speed and direction.

The data tapes were arranged in a form of the Researchers Cooperator Format [27]. A file contained a month of data, and a record held 60 minutes of data for one instrument. Each record consisted of a 27-character header, and sixty 9-character minute data groups. As a means of quality control, each measured data point was compared to theoretical limits and various continuity checks through programs in the data acquisition systems. Therefore, a minute data group included a seven digit data value, and a two digit flag indicating the validation of that data value. Table 1.1 shows an example of a minute data record, with an explanation of the record header.

Four types of validation flags were observed in these tapes:

"11" = measured data, unvalidated;

"12" = measured data, considered valid;

"13" = measured data, considered bad;

"99" = missing data.

The "valid data" criteria is described in an Inter-Office Memorandum [16] from the Solar Energy Research Institute (SERI), which administrated the data collection. Only the "11" and "12" flagged data values were accepted for the work presented here. Generally, the "11" flags were only found during night hours, where the radiation instrument readings would be due to background "noise" or miscalibration. Typical instrument accuracy is ±5% [5].

The last three characters in the header represented an exponent multiplier to convert the integer data values to real numbers. The units were the same as for the SOLMET data tapes [32], i.e. $KJ/m^2$ for irradiation instruments.

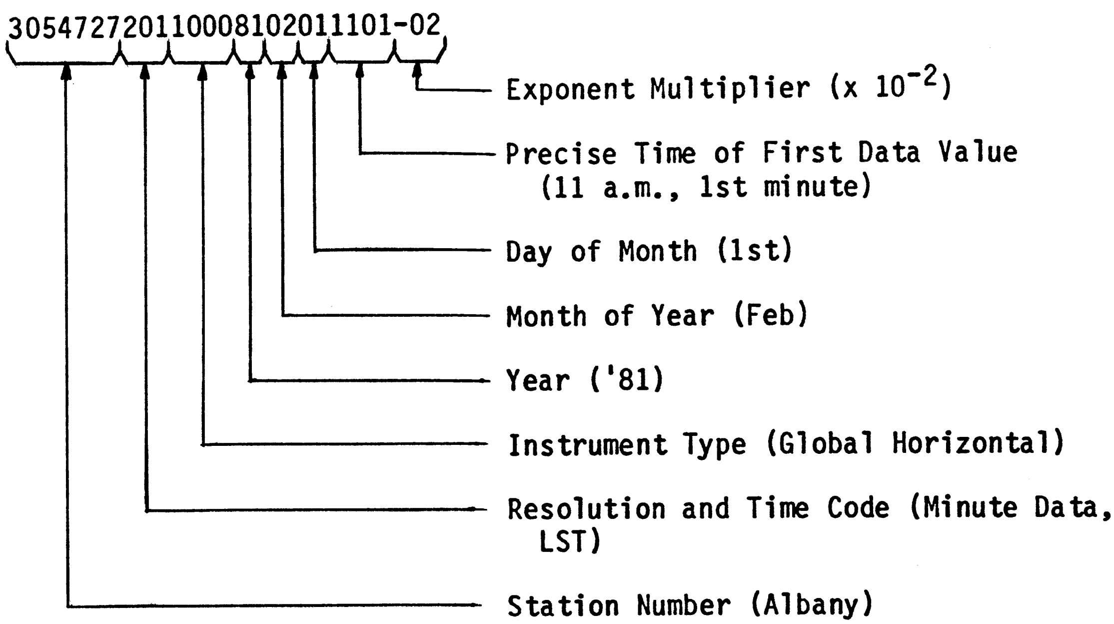
To compare minute data results to the more common hour data results, hour data tapes were made from the minute data. To be consistent with the minute tapes, a file contained a month of data, and a record held 24 hours of data for one instrument. Each record consisted of a 27-character header, and twenty-four 9-character hour data groups. Once again, each data group contained a seven digit data value, and a two digit flag. In making the hour tapes, the data

TABLE 1.1

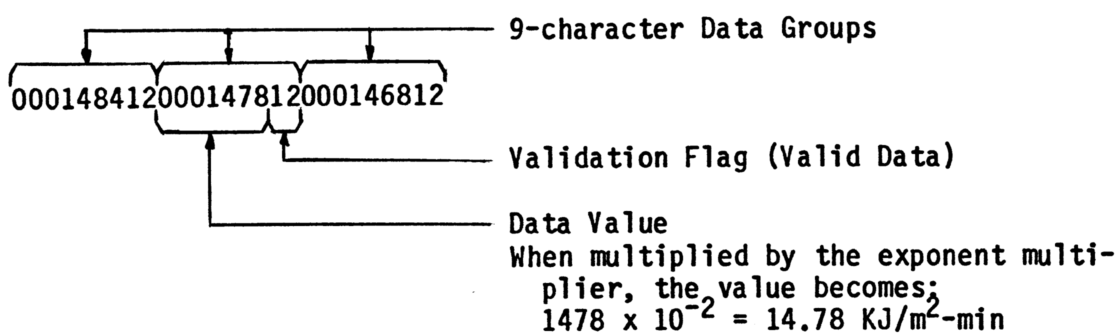
Minute Data Record Example

The numbers below are from a data record from the Albany Minute Tape.

Header:




Data Groups:



was also converted from Local Standard Time (LST) to True Solar Time (TST).

To compensate for "bad" or missing data, all sums were normalized to a sixty-minute value. A new two-digit flag was then written for each hour data point, indicating the number of "good" minute data values used in generating the hourly sum. Hours with completely missing data where filled with 9's and given a "00" flag.

## 1.2 San Antonio, Texas Data

The San Antonio, Texas data was taken by Trinity University in San Antonio, between April 1981 and March 1982. The tilted radiation instrumentation included: 20° south, 30° south, and 40° south. Table 1.2 shows a summary of the radiation data available for this study.

Besides beam and diffuse radiation, tilted pyranometers also receive radiation reflected from the ground, proportional to the local albedo or ground reflectivity. Typical albedo values are around 0.2, but may be as high as 0.7 for fresh snow. To reduce this variability in ground reflectance, Trinity University used flat black plates to produce artificial horizons for the tilted pyranometers [31]. This resulted in a low, year round value, estimated to be 0.05.

The diffuse radiation was measured by a pyranometer with a shadow band. The accuracy of this method versus other methods of obtaining diffuse data has been an ongoing debate [16]. Since the shadow band blocks out more radiation than just the beam, correction methods must be applied to the data [4,20]. Hogan and Loxsom [14]

TABLE 1.2

SAN ANTONIO, TX DATA

Data collected by Trinity University

Latitude = 29.5°

Longitude = 98.5°

Radiation Data Available for This Study

| Instrument I.D. Number | Variable Measured* and Orientation | Instrument [31] |
|---|---|---|
| 1000 | Global, Horizontal | Eppley PSP** |
| 1260 | Global, 20 South | " |
| 1360 | Global, 30 South | " |
| 1460 | Global, 40 South | " |
| 1920 | Global, 90 North | " |
| 1940 | Global, 90 East | " |
| 1960 | Global, 90 South | " |
| 1980 | Global, 90 West | " |
| 2010 | Direct Normal Beam | Eppley NIP*** |
| 3000 | Diffuse, Horizontal | Eppley PSP w/Shadow Band |

* Global instruments were filtered with a 0.295-2.80 μm pass band

** PSP = Precision Spectral Pyranometer

*** NIP = Normal Incident Pyrheliometer

showed that diffuse values from the corrected shadow band method are more accurate than calculated values from global horizontal and normal incident radiation data. However, in a more recent study using a larger data base, Huang [15] found the value of diffuse radiation calculated from normal incident and global radiation data to be more accurate than the shadow band measurements. For this work, the diffuse radiation measurements were ignored in favor of calculated values from the global and normal incident data.

In converting the minute data from LST to TST, the equation of time conversion factor [5] was calculated for the first day of each month only. This will cause a slight error for the following days in those months where the equation of time changes rapidly over the month. The worst cases are December and September, where the change in the equation of time conversion factor is 13 minutes and 11 minutes, respectively. This error is considered minor for mid-day calculations. In all cases, local standard time in San Antonio leads the true solar time.

### 1.3 Albany, New York Data

The Albany, New York data was taken by State University of New York at Albany, between August 1980 and July 1981. The tilted radiation instrumentation included: 33° south, 43° south, and 53° south. Through the use of shielding baffles, the ground reflectivity for their instrumentation was reduced to 0.00 [30]. Table 1.3 shows a summary of the radiation data available for this study.

TABLE 1.3

ALBANY, NY DATA

Data collected by State University of New York at Albany

Latitude = 42.7°

Longitude = 73.8°

Radiation Data Available for This Study

| Instrument I.D. Number | Variable Measured and Orientation | Instrument [31] |
|---|---|---|
| 1000 | Global, Horizontal | Eppley PSP* |
| 1460 | Global, 33 South | " |
| 1560 | Global, 43 South | " |
| 1660 | Global, 53 South | " |
| 1920 | Global, 90 North | " |
| 1940 | Global, 90 East | " |
| 1960 | Global, 90 South | " |
| 1980 | Global, 90 West | " |
| 2010 | Direct Normal Beam | Eppley NIP** |
| 3000 | Diffuse, Horizontal | Eppley PSP w/Shading Disk |
| 3001 | Diffuse, Horizontal | Eppley PSP w/Shadow Band |
| 3002 | Diffuse, Horizontal | Calculated from Instrument 1000 and 2010 |

* PSP = Precision Spectral Pyranometer

** NIP = Normal Incident Pyrheliometer

Three sets of diffuse radiation data were recorded: data measured by a pyranometer with shadow band; pyranometer with shading disc; and calculated values from global and normal incident data. A spot check of all three methods showed the corrected shadow band values to be the largest, while the shading disc and calculated values were approximately equal to each other. To be consistent with the San Antonio data analysis, the calculated data values were used for diffuse radiation.

For the Albany hour tape, the equation of time conversion factor to change the data from LST to TST was calculated for every day of each month. This eliminated the minor source of error mentioned for the San Antonio hour tape. The difference in LST and TST varied from local time leading the solar time, to solar time leading the local time. For programming reasons, local and solar times were considered equal for any differences less than 2 minutes.

# 2. RADIATION ON TILTED SURFACES

## 2.1 General Discussion

Long-term horizontal radiation data are available for most parts of the country. The most unexplicit are maps showing trends of average daily radiation for a given month [23]. For specific locations, the weather service frequently document the long-term monthly-average daily horizontal radiation [2]. The SOLMET program utilized 23 years of data to provide an hourly profile of horizontal radiation values over a "typical" year, for 26 U.S. locations [32]. The data were "rehabilitated" to account for instrument error from degradation, and other long and short term errors. The SOLMET program also included estimates of hourly horizontal radiation profiles for an additional 222 locations, based on related meteorological data.

In comparison, long-term data for tilted surfaces are scarce. Since most solar energy designs incorporate tilted surfaces, "radiation ratio" mathematical models are used to convert horizontal data into the corresponding tilted values. A "radiation ratio" is the ratio of radiation on the tilted surface, to the radiation on a horizontal surface. This ratio can then multiplied by the known horizontal radiation to obtain the desired radiation on the tilted surface.

Typical models find the radiation ratio on a tilted surface for hourly periods R, monthly-average hourly periods $\tilde{R}$, and monthly-average daily periods $\bar{R}$. The accuracy of these radiation ratios depends on the methodology for handling the beam, diffuse, and reflected components of solar irradiation. Presently, the major issue concerning the radiation ratio is the handling of diffuse radiation. Within this diffuse radiation discussion, two questions have arisen:

1) What is the percentage of diffuse to total insulation, and
2) Assuming this percentage is known, what is the distribution of diffuse radiation from the various parts of the sky?

For the following section it will be assumed that the percentage of diffuse radiation is known.

## 2.2 Isotropic Model Description

The simplest radiation ratio models incorporate an isotropic diffuse radiation assumption, first suggested by Hottel and Woertz [13]. This approach assumes diffuse radiation is uniformly distributed from all parts of the sky, regardless of weather conditions.

### 2.2.1 Hourly Isotropic Model

The hourly isotropic model calculates the radiation ratio for a specific hour. To define this ratio, the components required to calculate the radiation on a tilted surface will first be shown.

The diffuse radiation on a tilted surface is the diffuse radiation on a horizontal surface times the "sky-view factor" - the portion of the sky "in view" of the tilted surface. Defining $\beta$ as the surface slope, the sky-view factor is $(1 + \cos\beta)/2$. Therefore, the diffuse component can be written as:

$$\text{Diffuse} = I_d\,(1 + \cos\beta)/2\ , \qquad (2.1)$$

where $I_d$ is the diffuse radiation.

The ground reflected radiation also incorporates an isotropic assumption. Defining $\rho$ as the ground reflectivity, the reflected component is:

$$\text{Reflected} = \rho I \; (1 - \cos \beta)/2 \; . \tag{2.2}$$

where $(1 - \cos \beta)/2$ is the ground-view factor for the tilted surface.

The beam component is found by multiplying the beam radiation on a horizontal surface, $I_b$, by the ratio of beam radiation on the tilted surface to the horizontal surface, $R_b$. On an instantaneous basis, this beam ratio is a function only of geometry, as shown in Eq. (2.3).

$$R_b = \frac{G_{bT}}{G_b} = \frac{G_{bn} \cos(\theta)}{G_{bn} \cos(\theta_z)} = \frac{\cos(\theta)}{\cos(\theta_z)} \tag{2.3}$$

where equations for $\cos(\theta)$ and $\cos(\theta_z)$ can be found in Duffie and Beckman [5].

For a given period of time, the beam ratio numerator and denominator need to be integrated with respect to time. Since beam radiation is attenuated by the earth's atmosphere, the amount of atmosphere or beam "path-length," becomes important. As the position of the sun changes throughout a day, the path-length changes, making the beam ratio a function of the atmospheric transmittance.

For hourly periods, Hottel and Woertz [13] suggested treating $R_b$ as a constant, with the middle of the hour being used for the calculation. This is a reasonable approximation for mid-day hours, since the change in beam path-length is minimal, and a fair approximation for hours close to sunrise and sunset, where the change in beam path-length is more pronounced.

Horizontal beam radiation is the difference between global horizontal radiation and horizontal diffuse radiation: $I_b = (I - I_d)$. Calculating the beam radiation in this manner allows use of any one of the numerous diffuse radiation models, opposed to the limited number of beam radiation sources. These diffuse radiation models will be discussed latter in more detail. Using the horizontal and diffuse radiation terms, the beam component can be written as:

$$\text{Beam} = (I - I_d)R_b \tag{2.4}$$

Combining all three radiation components, the radiation on a tilted surface is:

$$I_T = I_d \left(\frac{1 + \cos \beta}{2}\right) + (I - I_d)R_b + \rho I \left(\frac{1 - \cos \beta}{2}\right) \tag{2.5}$$

Dividing Eq. (2.5) by the global horizontal radiation produces the hourly isotropic radiation model:

$$R = \frac{I_d}{I} \left(\frac{1 + \cos \beta}{2}\right) + \left(1 - \frac{I_d}{I}\right) R_b + \rho \left(\frac{1 - \cos \beta}{2}\right) \tag{2.6}$$

The hourly radiation model is useful for detailed analysis of a solar process. An example of this application is TRNSYS [37] - a transient system simulation program - which models time dependent solar operations. This program is useful for estimating both short and long-term performances.

### 2.2.2 Monthly-Average Hourly Isotropic Model

The monthly-average hourly radiation ratio is the ratio of the monthly-average hourly tilted radiation to the monthly-average hourly horizontal radiation.

$$\tilde{R} = \frac{\bar{I}_T}{\bar{I}} \tag{2.7}$$

It is used as an "average" hourly radiation ratio over a given month. The model is derived by integrating Eq. (2.5) over a month, and then dividing by $\bar{I}$. The hourly diffuse fraction becomes a monthly-average hourly diffuse fraction, $\bar{I}_d/\bar{I}$, while the other terms remain the same due to their dependence only on geometry. The monthly-average hourly isotropic model is therefore:

$$\tilde{R} = \frac{\bar{I}_d}{\bar{I}} \left(\frac{1 + \cos \beta}{2}\right) + \left(1 - \frac{\bar{I}_d}{\bar{I}}\right)R_b + \rho \left(\frac{1 - \cos \beta}{2}\right) \tag{2.8}$$

The monthly-average hourly radiation model is useful for "quick" simulations of a solar process. An example of this application is FCHART [36], a long-term performance design program used for modeling solar heating systems. FCHART produces fairly accurate long-term results, but without the expense of running a detailed simulation program such as TRNSYS.

### 2.2.3 Monthly-Average Daily Isotropic Model

The monthly-average daily radiation ratio is the ratio of the monthly-average daily radiation on a tilted surface to a horizontal surface.

$$\overline{R} = \frac{\overline{H}_T}{\overline{H}} \tag{2.9}$$

The model is derived by integrating the monthly-average hourly tilted surface radiation over all daylight hours in a month. Therefore, the diffuse fraction term becomes the monthly-average daily diffuse fraction, $\overline{H}_d/\overline{H}$. The beam ratio becomes the ratio of the monthly-average daily beam radiation on the tilted surface to that on a horizontal surface, $\overline{H}_{bT}/\overline{H}_b$. As discussed in Section 2.2.1, this is a function of the atmospheric transmittance. To obtain an estimated value, Liu and Jordan [21] suggested neglecting the effect of the atmosphere. In this case, $\overline{R}_b$ is the ratio of the monthly-average daily extraterrestrial radiation on the tilted surface to that on a horizontal surface. This assumption is correct only for south-facing surfaces during the solar equinox [22].

Using $\overline{H}_d/\overline{H}$ and $\overline{R}_b$, the monthly-average daily radiation ratio can be written as:

$$\overline{R} = \frac{\overline{H}_d}{\overline{H}} \left(\frac{1 + \cos \beta}{2}\right) + \left(1 - \frac{\overline{H}_d}{\overline{H}}\right) \overline{R}_b + \rho \left(\frac{1 - \cos \beta}{2}\right) \tag{2.10}$$

The monthly-average daily radiation model is useful for approximate calculations of solar irradiation on a tilted surface. These approximations can then be used in an economic analysis to determine if a solar process has economic potential, before the expense of a detailed design is made.

## 2.3 Diffuse Fraction Calculation

The three radiation ratio models shown are all functions of their respective diffuse fractions. As mentioned in Chapter 1, the method for obtaining diffuse insolation data is still being discussed. This raises the question, what methodology for obtaining the diffuse fraction should be used?

The hourly diffuse fraction $I_d/I$, can be obtained in several ways. Diffuse data can be measured by a pyranometer with a shadow band; pyranometer with a shading disc; or calculated from global and beam data. Using global horizontal radiation and normal incident beam radiation $I_{NIP}$ data, the diffuse radiation on a horizontal surface is:

$$I_d = I - I_{NIP} \cos (\theta_z) \quad . \qquad (2.11)$$

The diffuse fraction can then be found by dividing Eq. (2.11), or the actual measured diffuse insulation, by the horizontal radiation.

However, diffuse data of any kind is generally not available for most locations. To overcome this data deficiency, many correlations have been developed from available diffuse data, to estimate the diffuse fraction. Most of these correlations [6] are functions of the "clearness index" - the ratio of global terrestrial to global extraterrestrial radiation on a horizontal surface. This clearness index will be discussed in more detail in Chapter 3.

Diffuse fraction correlations are limited to the accuracy of their data base. Modeling the diffuse fraction around one independent parameter has also been questioned. In a study utilizing almost three years of global and direct radiation data from 33 U.S. sites, Garrison [7] found the diffuse fraction to actually be a function of five independent parameters: global solar irradiance; solar elevation (beam path-length); surface albedo; atmospheric precipitable water; and atmospheric turbidity. However, a diffuse fraction correlation as a function of these five parameters has yet to be developed. Also, except for global solar irradiance, these parameters are generally not available.

The monthly-average hourly and daily diffuse fractions can also be found from data when it is available. Monthly-average values can be calculated by summing the daily contributions to the diffuse and global components. The ratio of the sums becomes the monthly-average short-term value. For long-term values, an average can be taken of the monthly-average diffuse fractions.

However, due to the lack of data, correlations must once again be relied upon for most locations [5]. These monthly-average diffuse fraction models have been developed by correlating the results of monthly-average diffuse fractions calculated from a data base, to the monthly-average clearness index. Another approach for monthly-average daily diffuse fractions was first shown by Liu and Jordan [21]. They developed a correlation between the monthly-average diffuse fraction and monthly-average clearness index, by relating the daily components of the diffuse fraction to the long-term average distribution of the daily clearness index. This approach was also the method used by Erbs [6] to develop his diffuse fraction correlations, which will be discussed in more detail in Section 2.6.

As mentioned in the beginning of Chapter 2, part of the diffuse radiation discussion is the calculation of the diffuse to global radiation ratio. All of the correlations developed do work fairly well for calculating this ratio, for their given data base. However, judging on the limited diffuse data, the findings by Garrison [7], and the diversity of models developed, the diffuse fraction question has yet to be completely answered.

The following section on anisotropic radiation models assumes the diffuse to global fraction is known. Based on this "known" break-up, the issue in question is: what is the distribution of diffuse radiation from the various parts of the sky?

## 2.4 Anisotropic Model Descriptions

In 1966, Norris [25] compared the isotropic model, an anisotropic model, and one year's worth of data from Highest, Australia. The anisotropic model was developed by Morse and Czarnecki [24], and assumed that a major portion of the diffuse radiation emanates from the area surrounding the sun. This "circumsolar" diffuse radiation can then be treated as beam radiation in the isotropic model. The data base included total and diffuse radiation on both horizontal and 60° tilted surfaces. Norris concluded that both models were actually incorrect, and that real data should be taken in the location of interest. However, when averaged over a month, he felt that the distribution of diffuse radiation is isotropic.

During the last 10 years, this question has been reevaluated. Many reports conclude that the pure isotropic assumption is inappropriate [9,14,19,26]. Hay [10] concluded that the degree of anisotropic diffuse radiation varied from complete beam in the absence of atmospheric scattering, to complete isotropy under thick overcast clouds. Because of this recent work, new models for predicting the radiation ratio have been developed. Most incorporate various coefficients to modify the isotropic model, while a few take drastically new approaches. The following sections provide a short overview of some of the more notable anisotropic work recently done.

### 2.4.1 Klucher's Model

Klucher [19] used a data base of 6 months and 3 orientations (Horizontal, 37° and 60° south-facing) for comparison to the isotropic model, and to Temps and Coulson's [33] anisotropic-clear-sky model. The Temp and Coulson model considers anisotropic effects from both "horizon brightening" and circumsolar diffuse radiation under clear sky conditions. Both models had advantages under cloudy and clear weather conditions respectively, but neither were satisfactory for all cases. Consequently, Klucher developed an anisotropic correction factor for diffuse radiation on a tilted surface, to account for the degree of clearness. His model reduces to the isotropic case under heavy overcast conditions, but otherwise incorporates a fraction of the Temps and Coulson model.

### 2.4.2 Hay's Model

Hay [8] found the isotropic hourly model leads to significant short and long term errors compared to actual data. Taking an approach similar to Robinson [29] and to Revfeim [28], he broke the diffuse radiation into isotropic and circumsolar components. However, he allowed the ratio of isotropic to anisotropic diffuse radiation to vary, depending on an anisotropy index [9]. His original model for this index was partially a function of the optical air mass. Later, he modified this to be the ratio of normal incident beam radiation to the extraterrestrial normal incident radiation [8]. Under conditions of heavy overcast, the normal incident radiation approaches zero, returning the radiation ratio model to the isotropic case.

The evaluation of his model utilized 6 years of data for three south-facing surfaces from both Vancouver, British Columbia and Toronto, Ontario. Data from vertical north, east, and west facing surfaces were also used from Vancouver.

### 2.4.3 Herzog Models

Herzog [11] used existing minute data from the SEMRTS program, to develop correction factors for the hourly isotropic model and the monthly-average daily isotropic model. His models were developed for south facing tilted surfaces and vertical surfaces facing north, south, east, and west. The data base included: San Antonio, Texas (27 months, 7 tilts); Albany, New York (55 months, 7 tilts); and Atlanta, Georgia (46 months, 1 tilt).

For the hour model, Herzog empirically developed an anisotropic to isotropic diffuse insolation ratio to account for circumsolar and horizon brightening diffuse radiation. In the same manner as Klucher and Hay, this ratio is used as a correction factor in the diffuse radiation component of the isotropic model. It is a function of the hourly clearness index, angle dependent parameters, and time of year. Three different hourly correction factors were developed to account for differences in radiation characteristics during the winter, equinox, and summer seasons.

Using his hourly results and probability theory of the clearness frequency distribution (see Chapter 3), Herzog also developed a correction factor for the isotropic monthly-average daily radiation ratio model. Two versions of the correction factor were developed based on zero and nonzero values of the monthly-average daily beam fraction, as defined by Klein and Theilacker [18].

#### 2.4.4 Perez Model

Perez et al. [26] took a different approach to calculating the diffuse radiation component on a surface. They developed a "geometrical sky hemisphere description" to help parameterize the various characteristics of diffuse radiation. This resulted in a matrix equation with three independent variables used to calculate the radiation ratio. The model was then compared to data for seasonally representative months from data from Trappes, France; Carpentras, France; San Antonio, Texas; and Albany, New York.

At present, the matrix variables are not written as continuous functions, but are defined by one of over 200 "sky condition categories". Consequently, this model is inconvenient to implement at this point in time.

## 2.5 Past Comparisons of Radiation Ratio Models

All of the anisotropic models presented have advantages and disadvantages. All of them were developed from relatively short term data, which may limit their universal application. Also, most have been developed only for hourly radiation ratio models, which limits their use to detailed analysis. Herzog did develop a monthly-averaged daily model, but no monthly-averaged hourly models were found, as required for use in Clark's utilizability correlation (see Chapter 4). Klucher's model was developed only from south-facing orientations, and Herzog's hourly model has three different forms depending on the time of year. Perez's model can not be used without knowing the matrix elements for the desired locations.

The four anisotropic hourly models discussed do have one major strength in common: under the conditions tested by their authors, the respective anisotropic model usually provided closer results to tilted surface insolation levels, than the isotropic model. The comparative study done by Norris [25] was the only contrary report found. When evaluated over a monthly period, he found the hourly isotropic model was better than the anisotropic model developed by Morse and Czarnecki [24].

Many studies have been made of these anisotropic models. Hogan and Loxsom [14] made an independent comparison of the isotropic, Hay, and Klucher models, to three winter months of SEMRTS data from San Antonio, Texas. Their comparison was for 20°, 30°, 40° south-facing surfaces, and vertical north, south, east, and west surfaces. They concluded:

1) none of the models can accurately predict insolation on vertical surfaces; and
2) the Klucher model produced the most consistently correct results for these data.

Studies using larger data bases have found different results. Huang [15] used 27 months of SEMRTS data from San Antonio, Texas at the same orientations as Hogan and Loxsom. Once again, the isotropic, Hay, and Klucher models were compared. However, Huang found the Hay model to be the most accurate during the winter for all tilts, and in the summer for small tilts. The isotropic model was best for one condition - vertical surfaces during summer months, while the Klucher model was best during the summer for tilts between 20 and 40 degrees. On an annual basis, Huang concluded that the Hay model was best, although it exceeded ±5% of the measured values for vertical surfaces.

Perez et al. [26] compared their model and the isotropic, Hay, and Klucher models to their data base, showing that their model was best. They also pointed out that the Hay model underestimates on clear days for surfaces away from the sun, due to its lack of a horizon brightening consideration. In comparison, the Klucher model overestimates for surfaces not facing the sun.

Hay and McKay [8] made a comparison of eight models, including the isotropic, Klucher, Hay, and Perez models, to their Vancouver data base. They too discussed the positive and negative attributes of all of the models evaluated. Many of the models gave excellent results under certain conditions, but generated poorer results for the other cases. The exception was the Hay model, which consistently produced small short and long term errors for all slope orientations.

## 2.6 Radiation Ratio Analysis from Present Data

### 2.6.1 Diffuse Fraction Comparison

Existing diffuse fraction correlations were developed from limited data bases. Since the SEMRTS data included normal incident beam radiation - which can be used to calculate diffuse radiation, a comparison was made of correlation versus data derived monthly-average daily diffuse fractions. These diffuse fractions were calculated from: hourly data; Erbs' [6] hourly diffuse fraction model; and Erbs' [6] monthly-averaged daily diffuse fraction model. Comparing the monthly-average daily values was considered a fair method for evaluation of hourly diffuse fractions over typical ranges, i.e. all daylight hours, and monthly variations in radiation data. Erbs' monthly-average daily diffuse fraction was included as a check of a "quick" calculation method. As a measure of the individual hourly errors between the data and Erbs' hourly diffuse fractions, the RMS error was also calculated.

A closer look at the normal incident beam (NIP) data revealed some problems. As discussed in Chapter 1, all data contained a two-digit flag indicating the quality of that data value. The NIP data were flagged as being missing or invalid for a large percentage of the hours within most months, especially for San Antonio. Some hours were found with only 1 to 20 minutes of valid NIP data while 60 valid minutes of global data were found. Since an explanation could not be envisioned as to why data would be randomly invalid within an hour, only hours with 60 valid minutes of both global and NIP data were used for the diffuse fraction comparison. Due to instrument accuracy problems and "pre-dawn" light, hours surrounding a sunrise or sunset were also neglected. These hours contain very little insolation and therefore introduce negligible error by neglecting them.

The decision to use only hour values with 60 valid minutes greatly limited the number of allowed NIP data, as shown by Table 2.1. The number of global horizontal hour values with 60 valid minutes is also shown by Table 2.1. Overall, the hours of valid San Antonio NIP data only represented 49% of the potential daylight hours during the year. The Albany NIP data were better at 68%. The worst month was October in San Antonio, where only 39 hours out of the potential 310 hours of complete daylight contained valid NIP data. Fortunately, the hours of valid horizontal data for San Antonio and

TABLE 2.1

Number of hours used in $\overline{R}$ calculation.

Notes:

1. Only hours with 60 "good" minutes of data were used.
2. Only "complete" daylight hours were used. Part hours caused by a sunrise or sunset were neglected.

**SAN ANTONIO, TX DATA**

| Month | Daylight Hours in month | Hours of "Good" Horizontal data | Hours of "Good" NIP Data |
|---|---|---|---|
| January | 310 | 294 | 209 |
| February | 280 | 262 | 156 |
| March | 328 | 322 | 220 |
| April | 360 | 354 | 138 |
| May | 372 | 359 | 188 |
| June | 360 | 311 | 84 |
| July | 372 | 364 | 219 |
| August | 372 | 370 | 236 |
| September | 340 | 325 | 241 |
| October | 310 | 308 | 39 |
| November | 300 | 279 | 71 |
| December | 302 | 302 | 178 |
| Total | 4014 | 3850 | 1979 |
| % of Daylight Hours | | 96% | 49% |

**ALBANY, NY DATA**

| Month | Daylight Hours in Month | Hours of "Good" Horizontal Data | Hours of "Good" NIP Data |
|---|---|---|---|
| January | 248 | 240 | 190 |
| February | 276 | 269 | 148 |
| March | 328 | 316 | 192 |
| April | 360 | 357 | 213 |
| May | 428 | 409 | 336 |
| June | 420 | 414 | 316 |
| July | 434 | 421 | 336 |
| August | 388 | 374 | 288 |
| September | 340 | 329 | 238 |
| October | 310 | 301 | 215 |
| November | 244 | 236 | 148 |
| December | 248 | 230 | 134 |
| Total | 4024 | 3896 | 2754 |
| % of Daylight Hours | | 97% | 68% |

Albany were 96% and 97% respectively, of the potential daylight hours.

Erbs' hourly diffuse fraction is a function of the hourly clearness index $k_T$, where:

$$\frac{I_d}{I} = 1.0 - 0.09\, k_T \qquad \text{For } k_T \leq 0.22$$

$$\frac{I_d}{I} = 0.9511 - 0.1604\, k_T + 4.388\, k_T^2 - 16.683\, k_T^3 + 12.336\, k_T^4 \qquad \text{For } 0.22 < k_T \leq 0.80 \tag{2.12}$$

$$\frac{I_d}{I} = 0.165 \qquad \text{For } k_T > 0.80$$

$k_T$ was calculated for each valid hour, using global horizontal data and an analytical equation for the hourly horizontal extraterrestrial radiation, $I_o$ [5]:

$$I_o = \frac{12 \times 3600}{\pi} G_{sc}\left[1 + 0.033 \cos\left(\frac{360\, n}{365}\right)\right]\left[\cos\phi \cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{2\pi(\omega_2 - \omega_1)}{360} \sin\phi \sin\delta\right] \tag{2.13}$$

where $G_{sc}$ = the solar constant, and n = day of the year.

The hourly diffuse fractions were multiplied by the actual global horizontal insolation, to obtain the horizontal diffuse radiation. The diffuse and global values were then separately summed for the month. The ratio of the total diffuse to total global insolation produced the monthly-average daily diffuse fraction. The data derived monthly-average daily diffuse fraction was similarly found, by dividing the total valid diffuse value by the total valid global value.

Erbs' monthly-average daily diffuse fraction is a function of the monthly-average daily clearness index $\overline{K}_T$.

$$\frac{\overline{H}_d}{\overline{H}} = 1.317 - 3.023\ \overline{K}_T + 3.372\ \overline{K}_T^2 - 1.760\ \overline{K}_T^3 \tag{2.14}$$

$$\text{for } 0.3 \leq \overline{K}_T \leq 0.8$$

The monthly-average daily clearness index was found by summing both the horizontal global data values and the calculated horizontal extraterrestrial values over all valid daylight hours in the month. The ratio of these sums produces the monthly-average daily clearness index.

Figures 2.1 and 2.2 show the results of the monthly-average daily diffuse fraction calculations for San Antonio and Albany, respectively. Figure 2.1 shows an equal number of overestimations as underestimations of the monthly-average daily diffuse fraction found by Erbs' hourly correlation. The worst errors are around 10% of the maximum diffuse fraction (The maximum diffuse fraction = 1.0). However, for seven of the months, the error in the predicted value of $\overline{H}_d/\overline{H}$ is less than 3%. Considering instrumentation accuracy of ±5% [5], these values are excellent. As expected, the simpler monthly-average daily correlation had a larger error than the hourly correla-

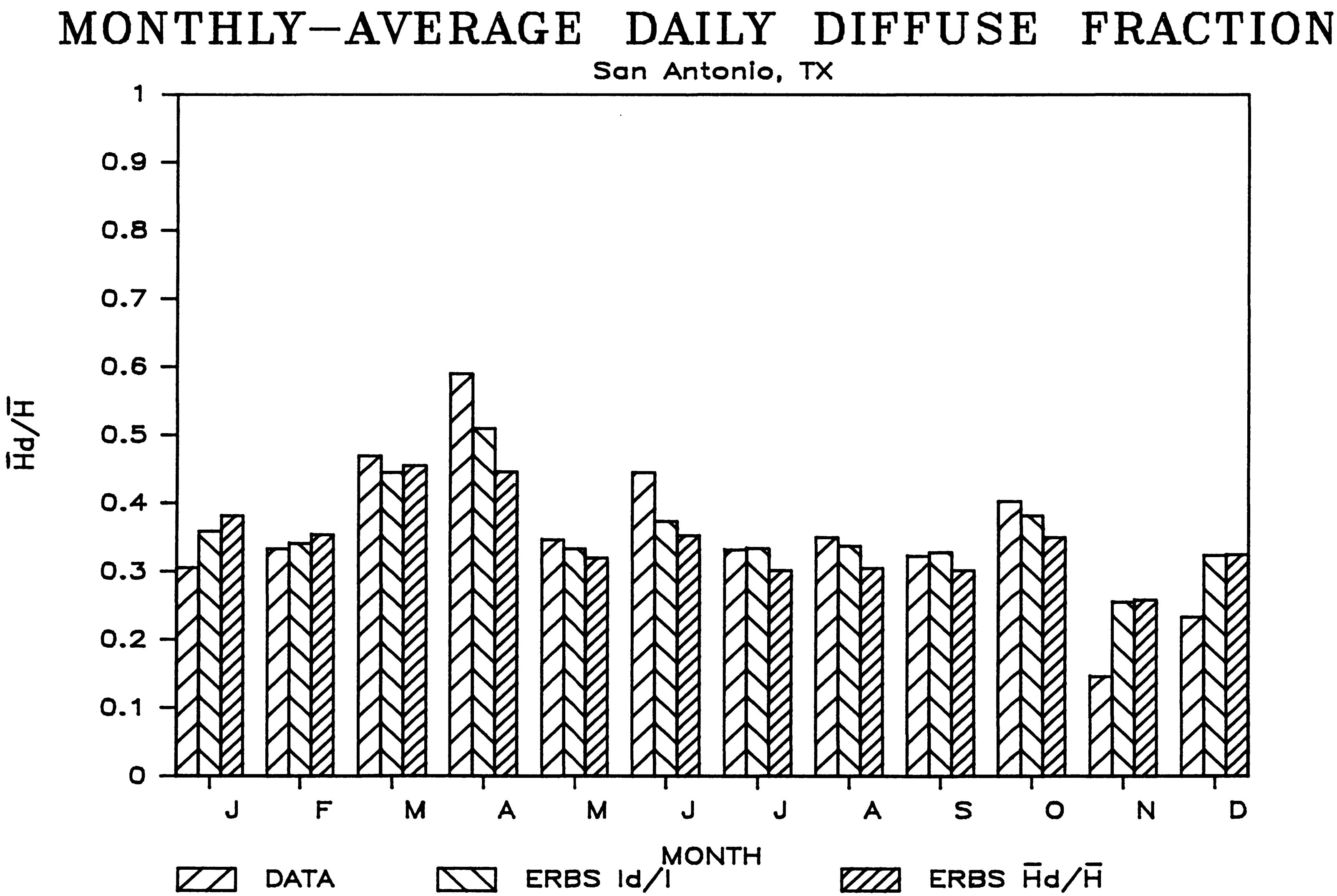



Figure 2.1: Monthly-Average Daily Diffuse Fractions for San Antonio, TX.

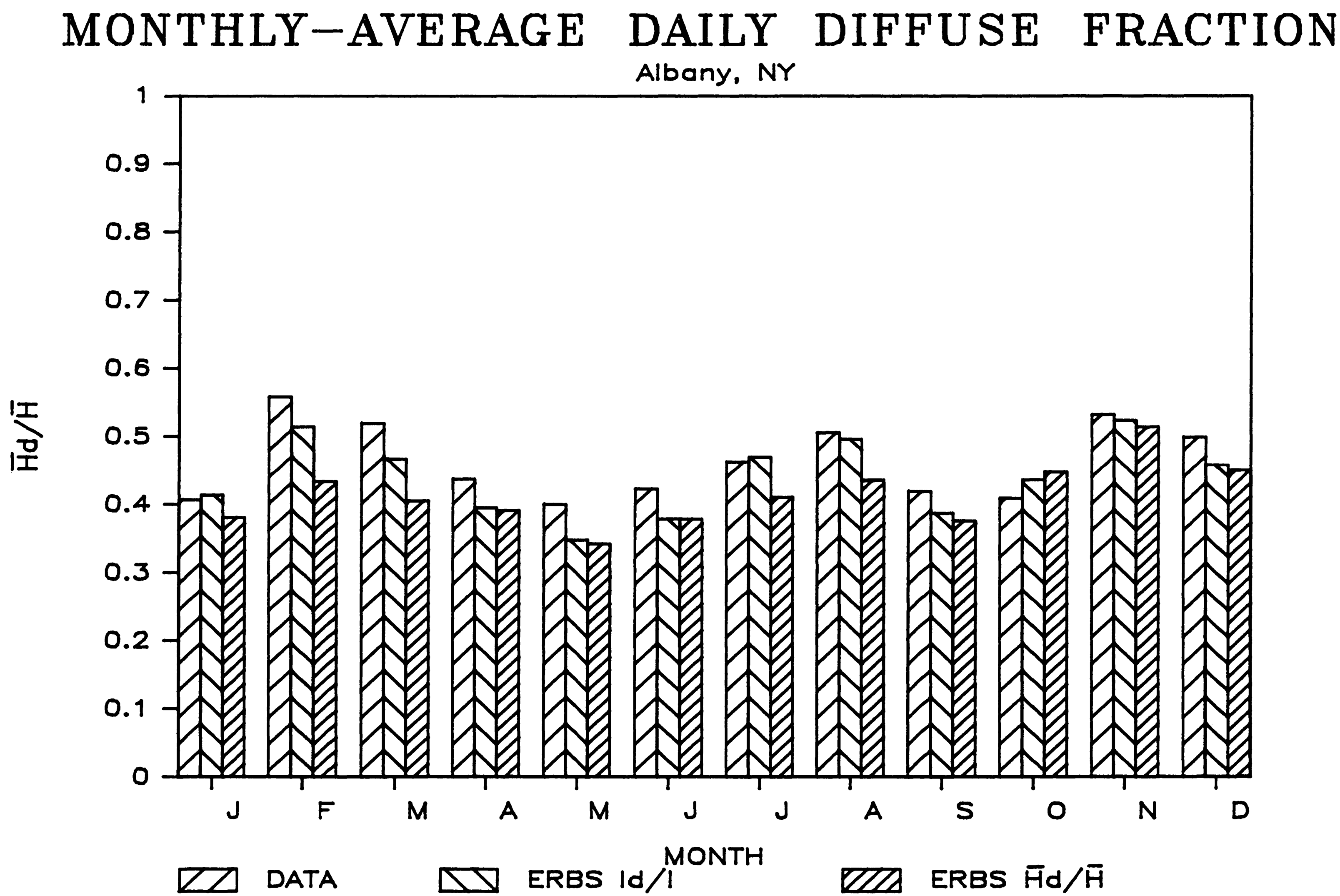



Figure 2.2: Monthly-Average Daily Diffuse Fractions for Albany, NY.

tion. The poorest case is an overestimation by 11% of the maximum fraction.

Figure 2.2 - Albany - shows smaller errors than found for San Antonio. In most cases, Erbs' hourly model underestimates the data value, usually by 4 to 5% of the maximum fraction. The few cases of overestimation are all less than 3%. Once again, Erbs' monthly-average daily correlation produces larger errors than the hourly model, the poorest being an underestimation by 12%.

Overall, the monthly-average daily diffuse fractions compare fairly well. However, as a measure of the differences between individual hourly diffuse fractions found from data and Erbs' hourly correlation, an RMS error was calculated. As applied here, the RMS error is defined as:

$$\text{RMS error} = \sqrt{\frac{\sum^{n} \left( \frac{I_d}{I}\Big|_{\text{data}} - \frac{I_d}{I}\Big|_{\text{Erbs}} \right)^2}{n - 1}} \tag{2.15}$$

By summing the squares of the individual errors, the RMS error places more weight on larger differences. Therefore, a large RMS error indicates poor agreement between data and correlation hourly diffuse fractions.

Table 2.2 shows the RMS error between Erbs' hourly diffuse fraction and the hourly diffuse fraction calculated from the data. The RMS error shows the individual hourly value comparison is not always favorable. The poorest comparison is in Albany, where the RMS error is 0.322. The poorest RMS error for San Antonio is 0.227. Also

TABLE 2.2

Comparison of Monthly-Average Daily Diffuse Fractions

Note: $\% \text{ Change} = [(\frac{\bar{H}_d}{\bar{H}}\Big|_{model} - \frac{\bar{H}_d}{\bar{H}}\Big|_{data})/1.0] \times 100$ .

**San Antonio, TX**

| MONTH | % CHANGE Erbs Hourly vs. Data | % CHANGE Erbs $\bar{H}_d/\bar{H}$ vs. Data | RMS ERROR |
|---|---|---|---|
| January | 5.3% | 7.6% | 0.177 |
| February | 0.8 | 2.1 | 0.134 |
| March | -2.5 | -1.4 | 0.103 |
| April | -8.0 | -14. | 0.117 |
| May | -1.3 | -2.6 | 0.140 |
| June | -7.1 | -9.2 | 0.110 |
| July | 0.2 | -3.0 | 0.119 |
| August | -1.2 | -4.5 | 0.139 |
| September | 0.5 | -2.1 | 0.147 |
| October | -2.1 | -5.3 | 0.124 |
| November | 10. | 11. | 0.183 |
| December | 9.1 | 9.2 | 0.227 |

**Albany, NY**

| MONTH | % CHANGE Erbs Hourly vs. Data | % CHANGE Erbs $\bar{H}_d/\bar{H}$ vs. Data | RMS ERROR |
|---|---|---|---|
| January | 0.7% | -2.6% | 0.113 |
| February | -4.4 | -12. | 0.122 |
| March | -5.2 | -11. | 0.124 |
| April | -4.2 | -4.6 | 0.223 |
| May | -5.2 | -5.8 | 0.322 |
| June | -4.4 | -4.4 | 0.286 |
| July | 0.7 | -5.2 | 0.148 |
| August | -1.0 | -7.0 | 0.215 |
| September | -3.2 | -4.3 | 0.285 |
| October | 2.7 | 3.9 | 0.215 |
| November | -0.8 | -1.8 | 0.189 |
| December | -4.1 | -4.9 | 0.264 |

shown is a summary of the percent change between the correlations and the data values of $\overline{H}_d/\overline{H}$ (percent of maximum fraction).

Due to the limited data base, especially for San Antonio, only nonconclusive statements can be made. A comparison was made of the percent changes in $\overline{H}_d/\overline{H}$ to the percent of potential daylight hours utilized, but no correlation was found. Consequently, even though data were lacking, these deficiencies do not appear to affect the overall results. For the two years studied, the monthly-average daily diffuse fractions calculated by Erbs' correlations were usually fairly accurate. Erbs' hourly correlation usually gave the best results, while Erbs' monthly-average daily correlation typically gave slightly poorer results. However, large RMS errors indicate poor hourly agreement between Erbs' hourly correlation and data. Whether this hourly inaccuracy is due to "atypical" data, or inherent error in Erbs' correlations due to one parameter modeling, is unknown.

### 2.6.2 Model Selection

As discussed in the isotropic model section (Section 2.2), there are many needs for accurate models to calculate insolation levels on tilted surfaces. For detailed analysis, hourly models are the most widely used. At present, the TRNSYS [37] simulation program developed by the University of Wisconsin Solar Energy Laboratory, uses the hourly isotropic model for its calculation of hourly insolation levels on sloped surfaces. As a generic check for potential improvement in hourly radiation ratio calculations, radiation ratios calculated from the data were compared to results from one anisotropic hourly model, and from the isotropic model. Also compared was the monthly-average hourly isotropic model, which is used in Clark's hourly utilizability correlation (See Chapter 4). These comparisons were made using hourly diffuse fractions calculated from both Erbs correlations and from the available NIP data.

Since this was a generic investigation, only one anisotropic model was evaluated. The Perez model was not considered since the matrix elements have not been generalized for various locations. The seasonal Herzog models involved a degree of complexity that was beyond the present interest in anisotropic models. Including seasonal variations in an anisotropic model should be considered only after being convinced of the need for an anisotropic model. This left the Klucher and Hay anisotropic models to choose from. From the reports studied, the Hay model seemed to have the best accuracy under most conditions. As a bonus, it was also the most algebraically simple. Therefore, Hay's anisotropic hourly model was selected as the best suited for this investigation.

### 2.6.3 Methodology for Comparison

Hourly radiation ratios were used to calculate the monthly-average daily radiation ratio. To accomplish this, the calculated hourly radiation ratios were multiplied by the actual horizontal radiation, giving the insolation levels on the tilted surfaces. The tilted and horizontal insolations were then summed for all daylight hours over every day of the month, to obtain monthly values. By dividing the total tilted insolation by the total horizontal insolation, the monthly-average daily radiation ratio was obtained. This method is similar to the algorithm used by TRNSYS.

As in the diffuse fraction comparison (section 2.6.1), hours with a sunrise or sunset were neglected. Also, only hours composed of 60 "good" minutes of data were considered. To insure equal weighting of the radiation ratio numerator and denominator, the summations were skipped if either horizontal or tilted data were invalid. Due to different total hours with valid data for each tilted instrument, the tilted insolation and the horizontal insolation summations were made separately for each slope. Summations using data derived diffuse fractions also included a check for valid NIP values.

The monthly-average hourly model is based on the "average day" of the given month, as defined by Duffie and Beckman [5]. Therefore, summation of the hourly values was only required over the complete daylight hours of this day. Interest in this model developed from its use in Clark's Utilizability correlation.

Hay's modification to the hourly isotropic model can be written as:

$$R = \frac{I_d}{I}(1 - A)\left(\frac{1 + \cos\beta}{2}\right) + \left(1 - \frac{I_d}{I}(1 - A)\right)R_b + \rho\left(\frac{1 - \cos\beta}{2}\right) \quad (2.16)$$

where A is the anisotropic index. Hay defined his anisotropic index as the ratio of normal incident beam radiation to the normal extraterrestrial incident radiation. Multiplying both terms by the cosine of the zenith angle converts the index from normal values to horizontal values, or:

$$A = \frac{I_{NIP} \cos \theta_z}{I_o} \tag{2.17}$$

Since $I_{NIP}\cos(\theta_z)$ equals the beam radiation on a horizontal surface, this term can be rewritten as:

$$I_{NIP} \cos(\theta_z) = I - I_d \, . \tag{2.18}$$

Substituting Eq. (2.18) into (2.17) and multiplying the numerator and denominator by I, gives:

$$A = \frac{(I - I_d)}{I} \left(\frac{I}{I_o}\right) \tag{2.19}$$

Recognizing $I/I_o$ as the hourly clearness index $k_T$, Hay's anisotropic index can be rewritten as:

$$A = \left(1 - \frac{I_d}{I}\right) k_T \tag{2.20}$$

This is now in a form that can use the hourly diffuse fraction.

The monthly-average hourly isotropic model shown in Eq. (2.8) requires a monthly-average hourly diffuse fraction. This hourly diffuse fraction can be calculated from Erbs' monthly-average daily diffuse fraction - Eq. (2.14), using the ratios $r_d$ and $r_t$:

$$\frac{\bar{I}_d}{\bar{I}} = \left(\frac{r_d}{r_t}\right)\left(\frac{\bar{H}_d}{\bar{H}}\right) \tag{2.21}$$

where $$r_d = \frac{\text{hourly diffuse radiation}}{\text{daily diffuse radiation}}$$

and $$r_t = \frac{\text{hourly total radiation}}{\text{daily total radiation}}$$

The $r_d/r_t$ ratio is a function of the hour angle $\omega$, and the sunset hour angle $\omega_s$ [5]. Dividing out common terms, $r_d/r_t$ can be written as:

$$\frac{r_d}{r_t} = \frac{1}{a + b\cos(\omega)} \tag{2.22}$$

where $$a = 0.409 + 0.5016\sin(\omega_s - 60),$$

and $$b = 0.6609 - 0.4769\sin(\omega_s - 60).$$

Equations (2.8), (2.14), and (2.21) provide a simple method to calculate $\bar{R}$ from monthly-average hourly correlations, based only on $\bar{K}_T$ and geometry. The horizontal radiation component of $\bar{K}_T$ was calculated from actual data, over all valid hours of horizontal data.

### 2.6.4 Comparison of Monthly-Average Daily Radiation Ratios

Figures 2.3 through 2.22 show the results of the monthly-average daily radiation ratio calculations. These graphs and their discussions are broken into four groups: slope = latitude; slope = 90°S; slope = 90°E and slope = 90°W; and slope = 90°N orientations. Each

FIG. 2.3 R̄'s (Id/I FROM ERBS' CORR.)

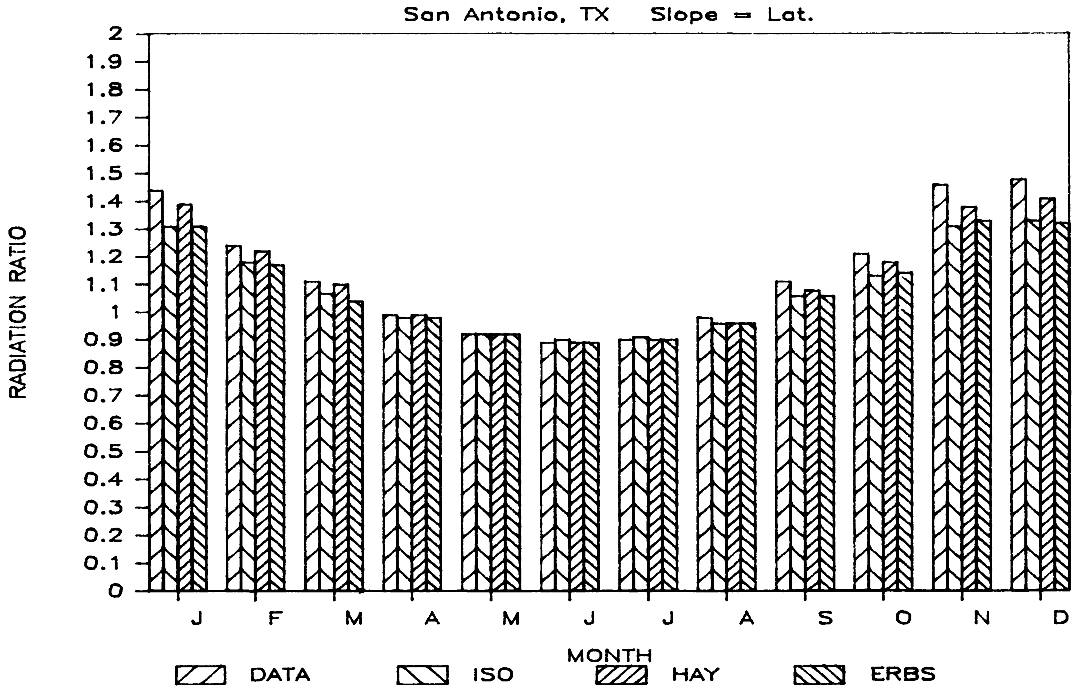



FIG. 2.4 R̄'s (Id/I FROM NIP DATA)

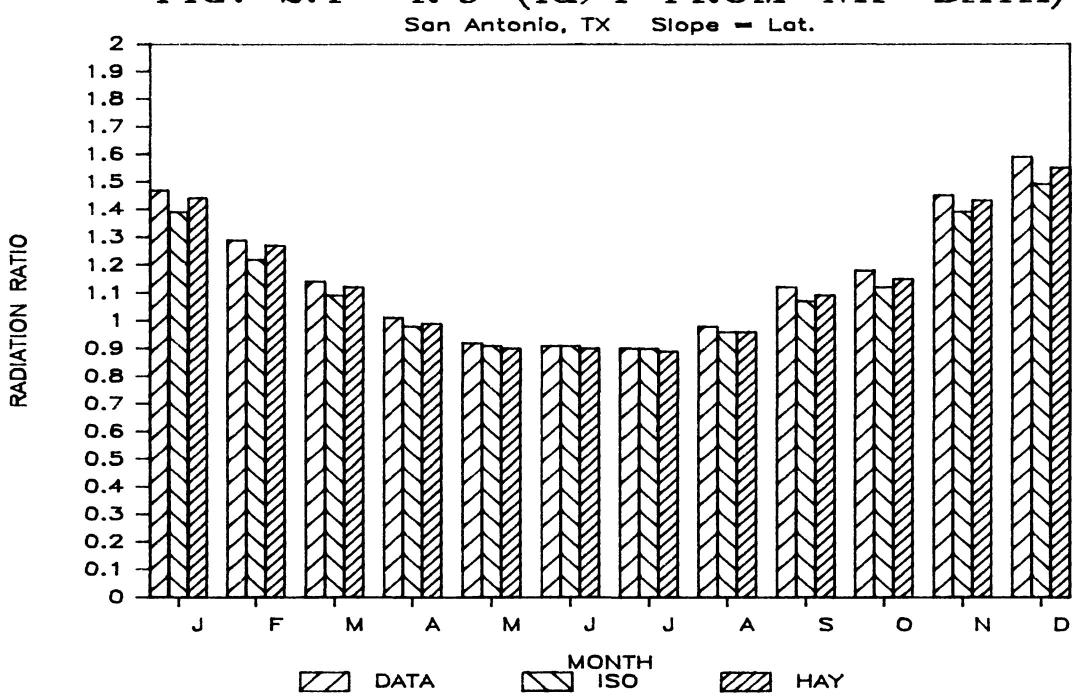


FIG. 2.5 $\bar{R}$'s (Id/I FROM ERBS CORR.)

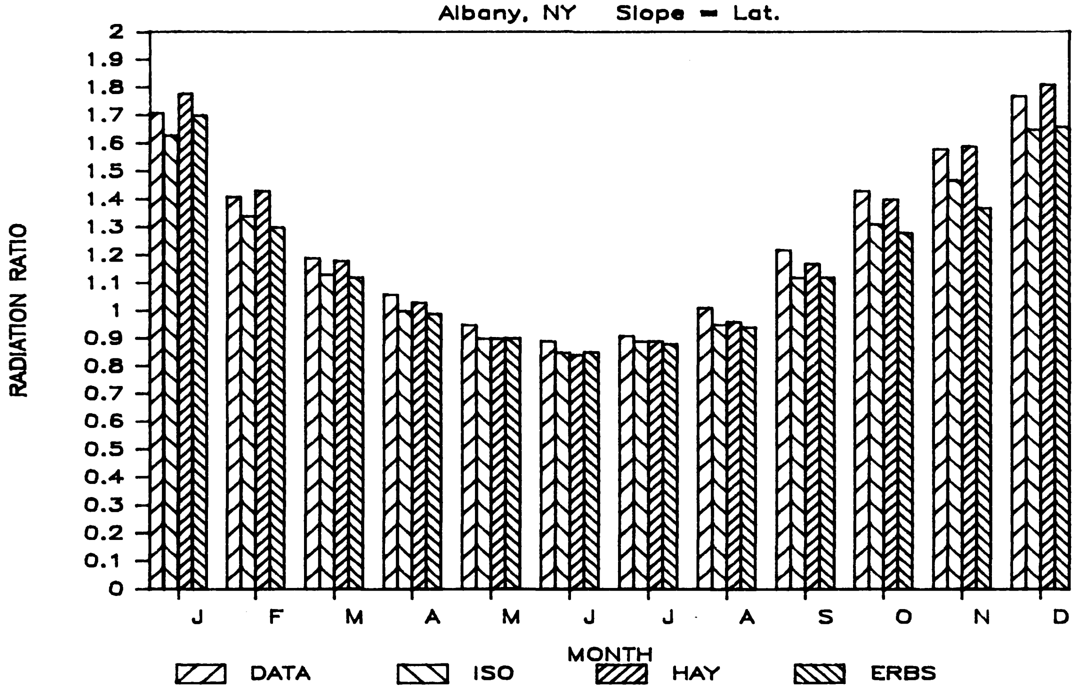



FIG. 2.6 $\bar{R}$'s (Id/I FROM NIP DATA)

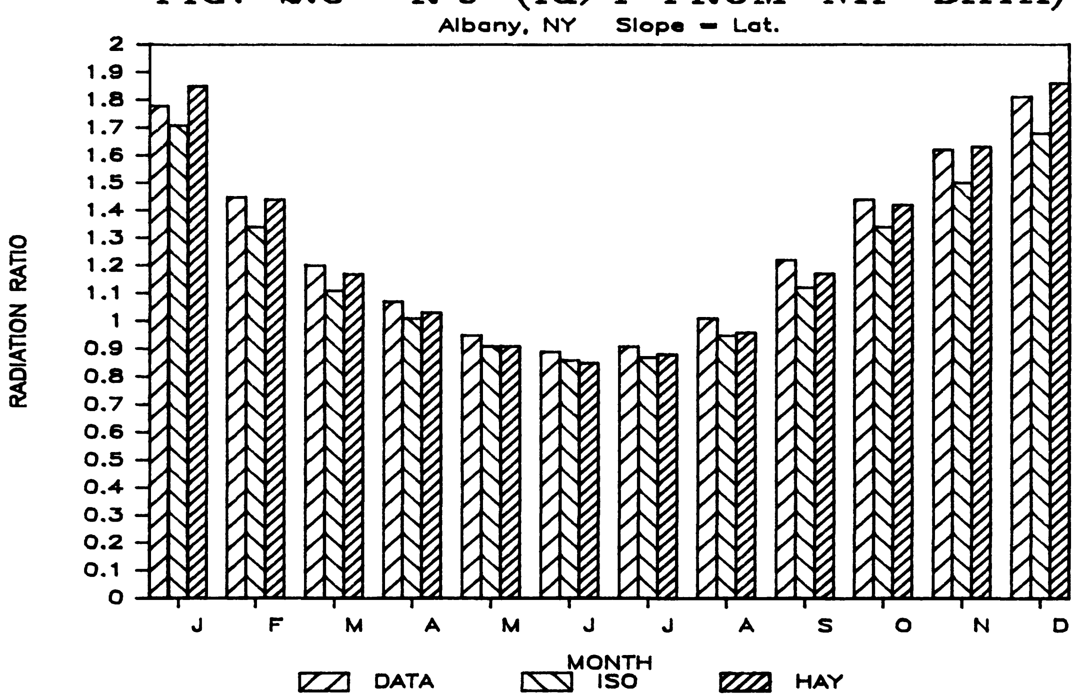


FIG. 2.7 $\bar{R}$'s (Id/I FROM ERBS CORR.)

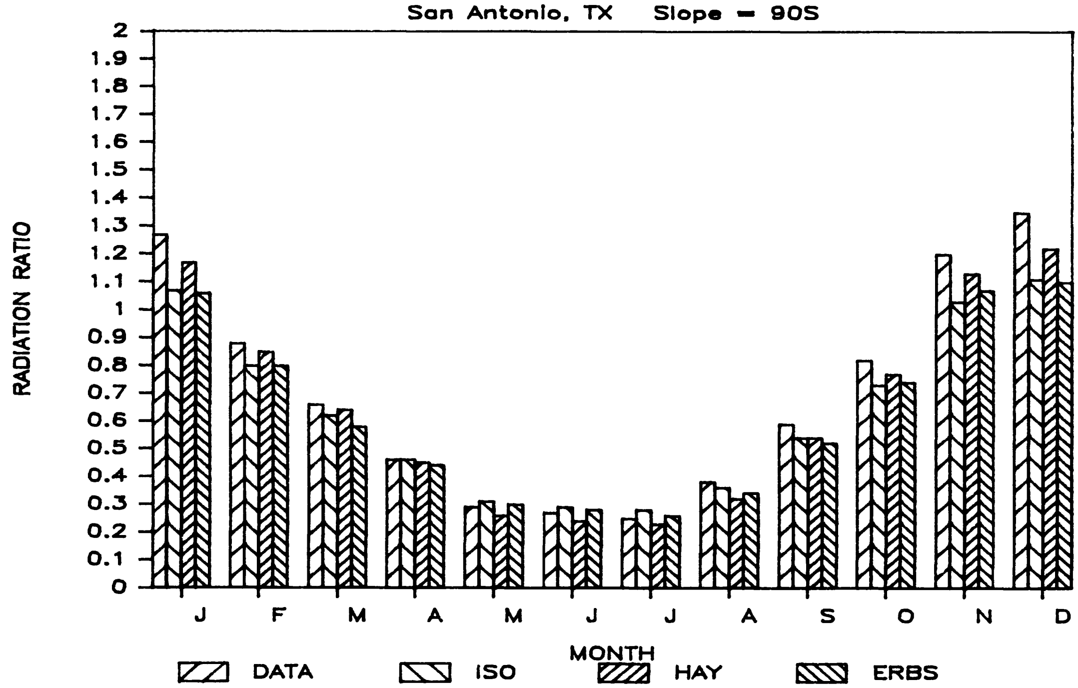



FIG. 2.8 $\bar{R}$'s (Id/I FROM NIP DATA)

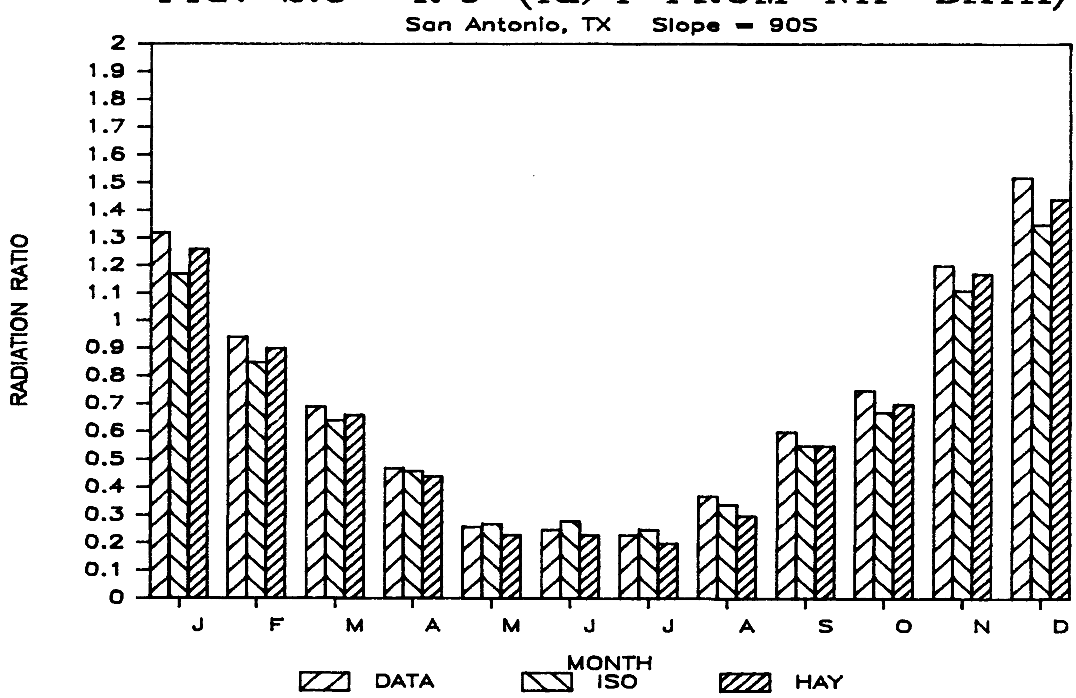


FIG. 2.9 $\bar{R}$'s (Id/I FROM ERBS CORR.)

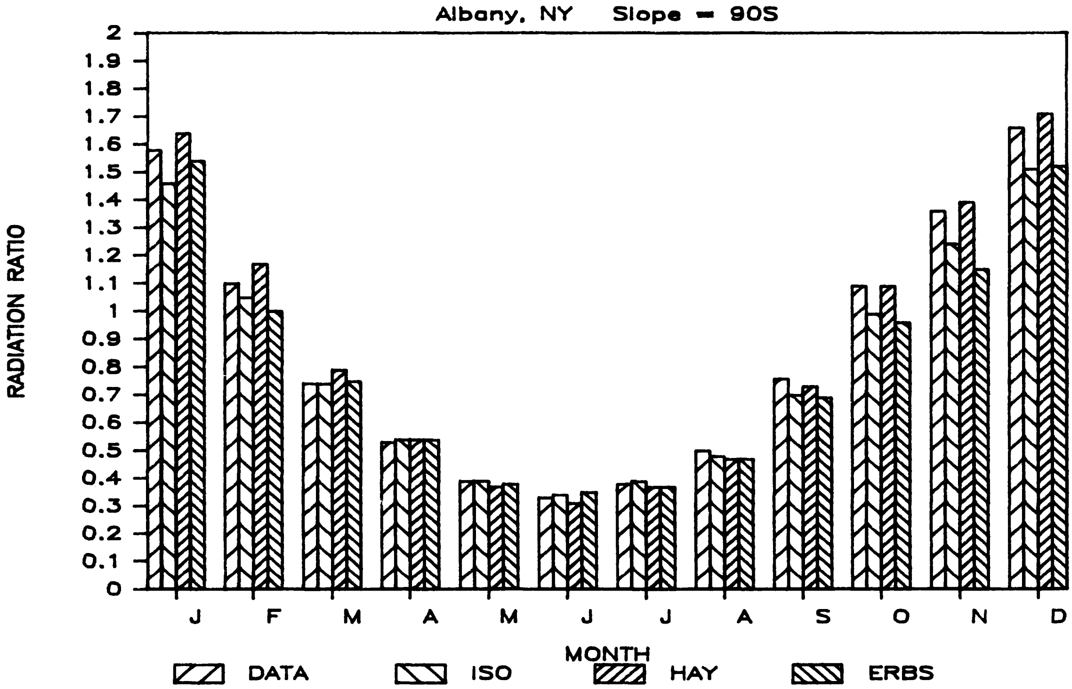



FIG. 2.10 $\bar{R}$'s (Id/I FROM NIP DATA)

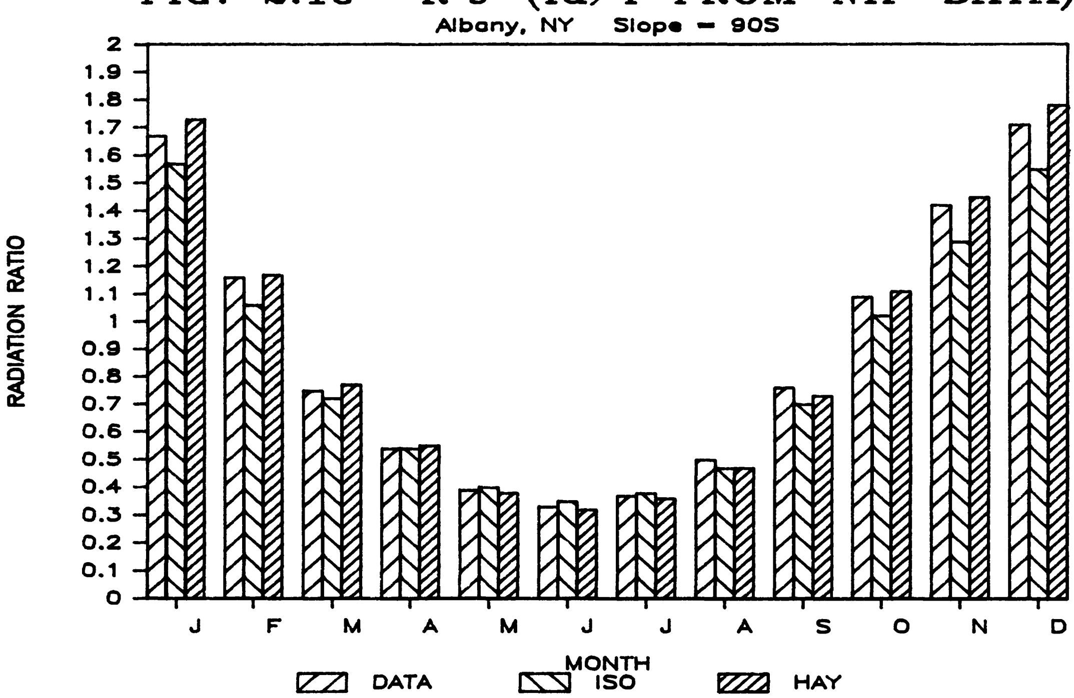


FIG. 2.11 $\bar{R}$'s (Id/I FROM ERBS CORR.)

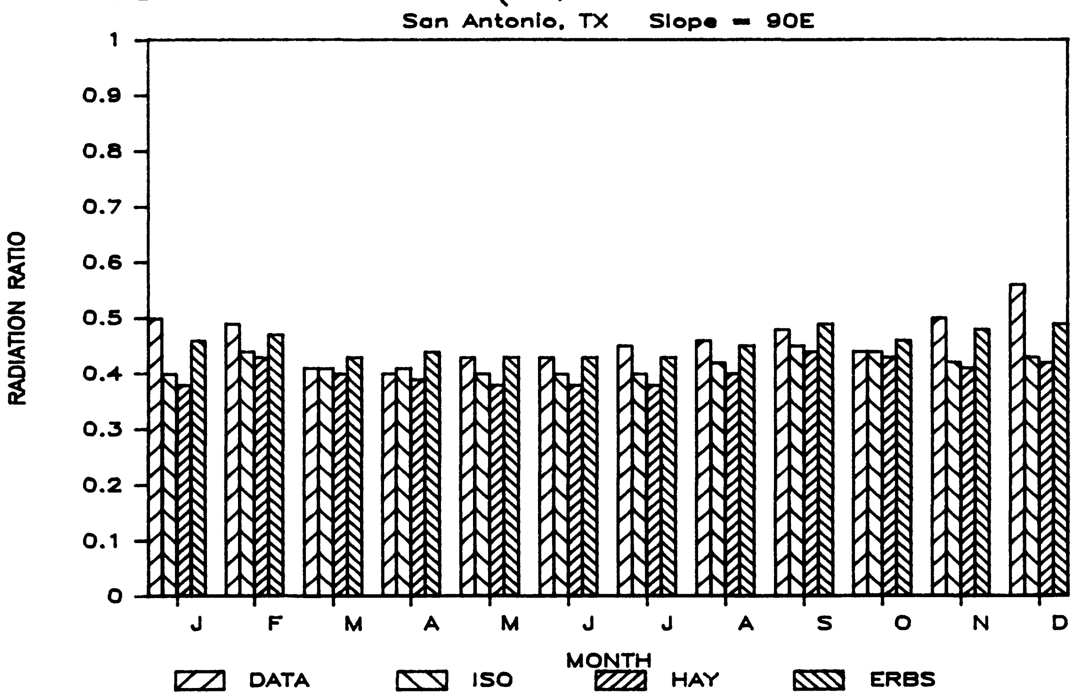



FIG. 2.12 $\bar{R}$'s (Id/I FROM NIP DATA)

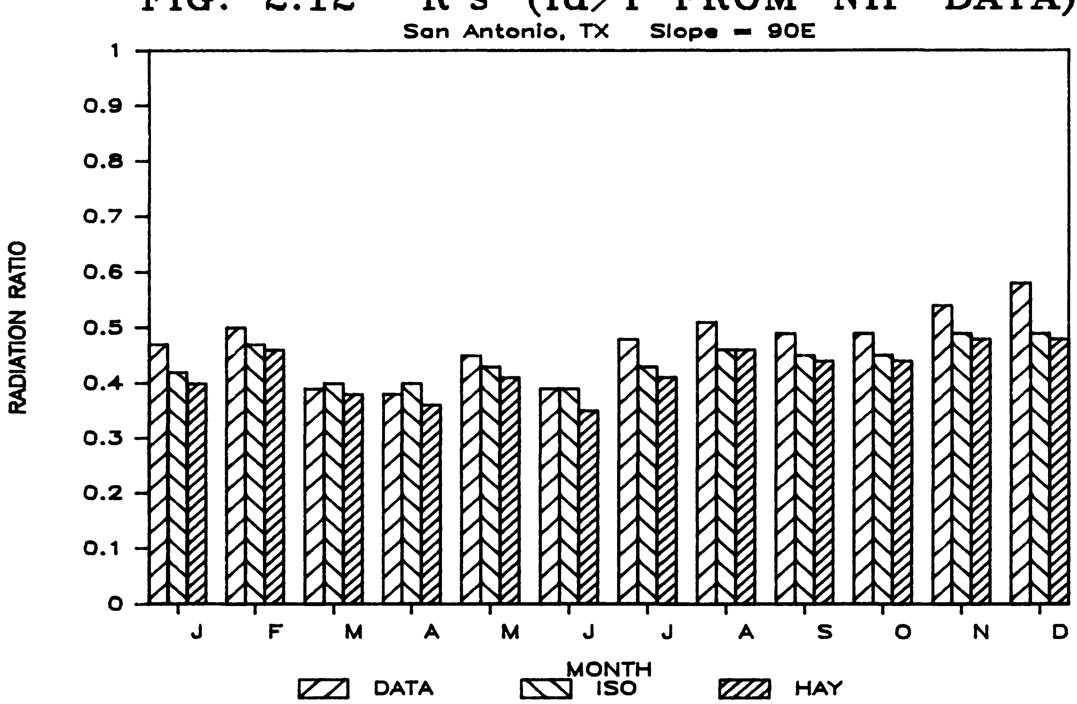


FIG. 2.13 $\bar{R}$'s (Id/I FROM ERBS CORR.)

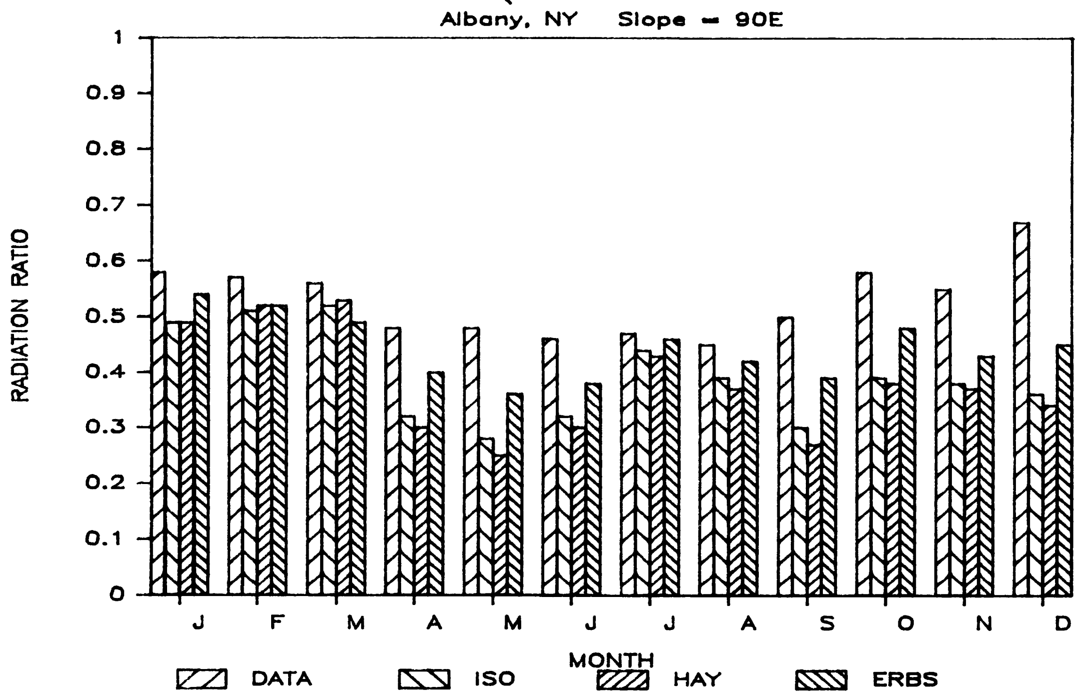



FIG. 2.14 $\bar{R}$'s (Id/I FROM NIP DATA)

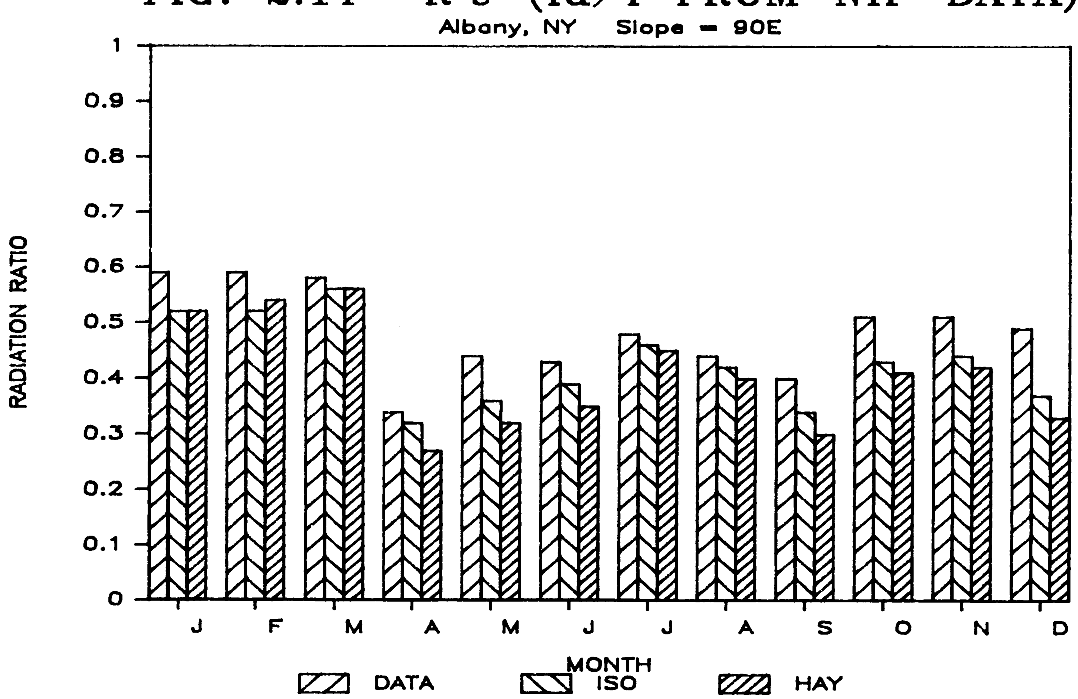


FIG. 2.15 $\bar{R}$'s (Id/I FROM ERBS CORR.)

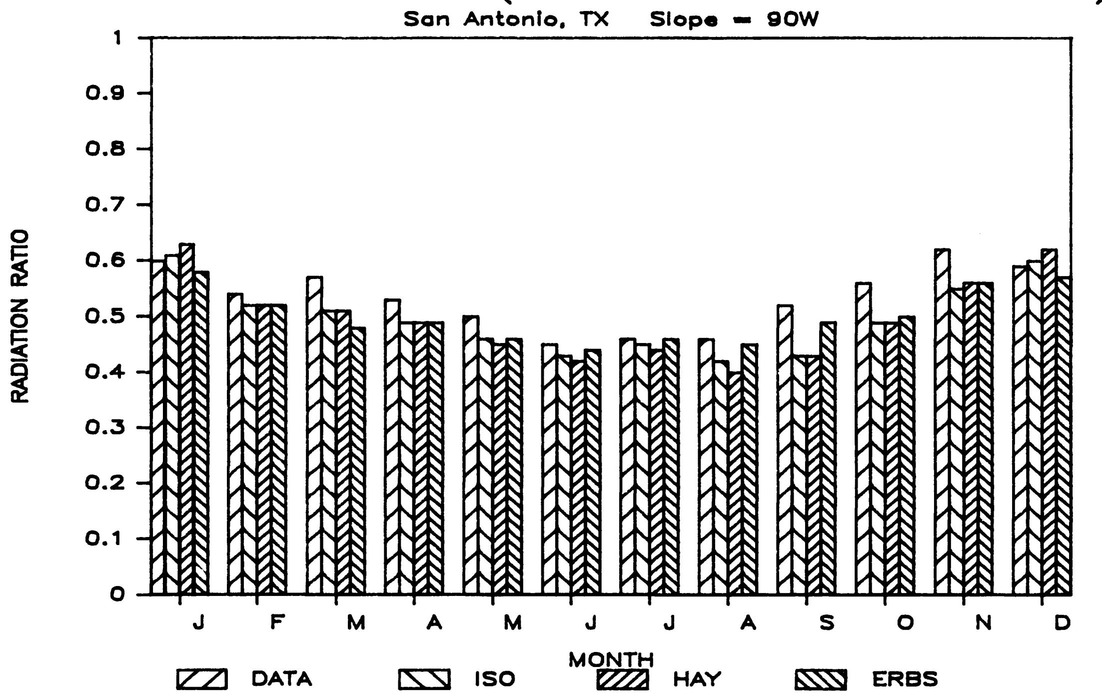



FIG. 2.16 $\bar{R}$'s (Id/I FROM NIP DATA)

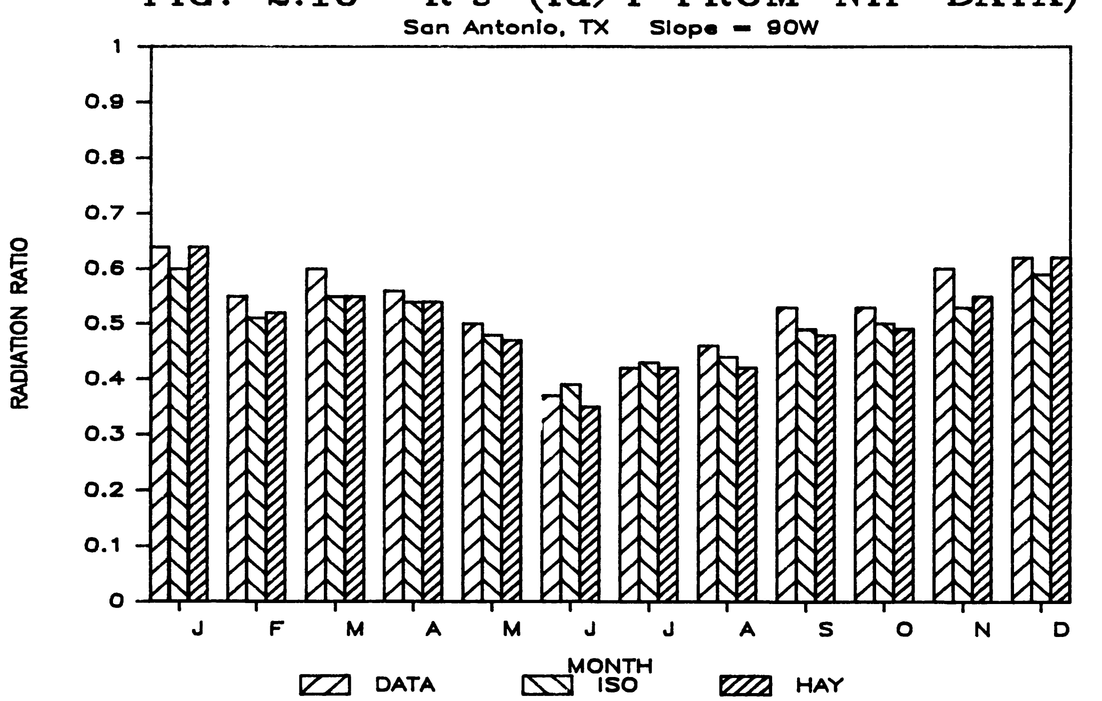


FIG. 2.17 $\bar{R}$'s (Id/I FROM ERBS CORR.)

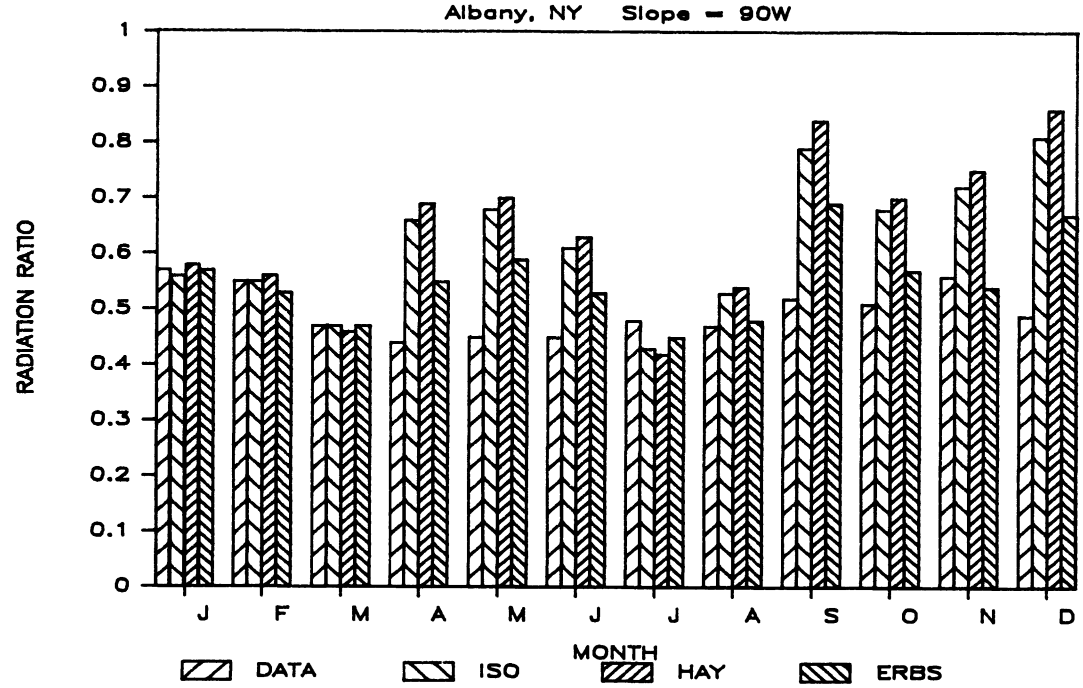



FIG. 2.18 $\bar{R}$'s (Id/I FROM NIP DATA)

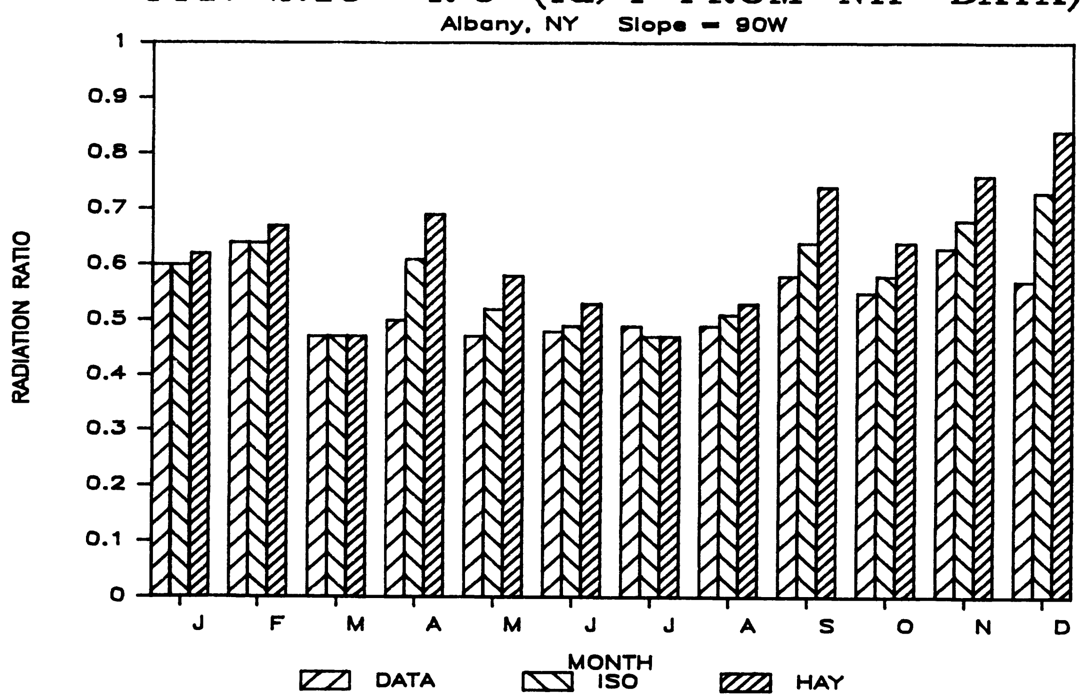


FIG. 2.19 R̄'s (Id/I FROM ERBS CORR.)

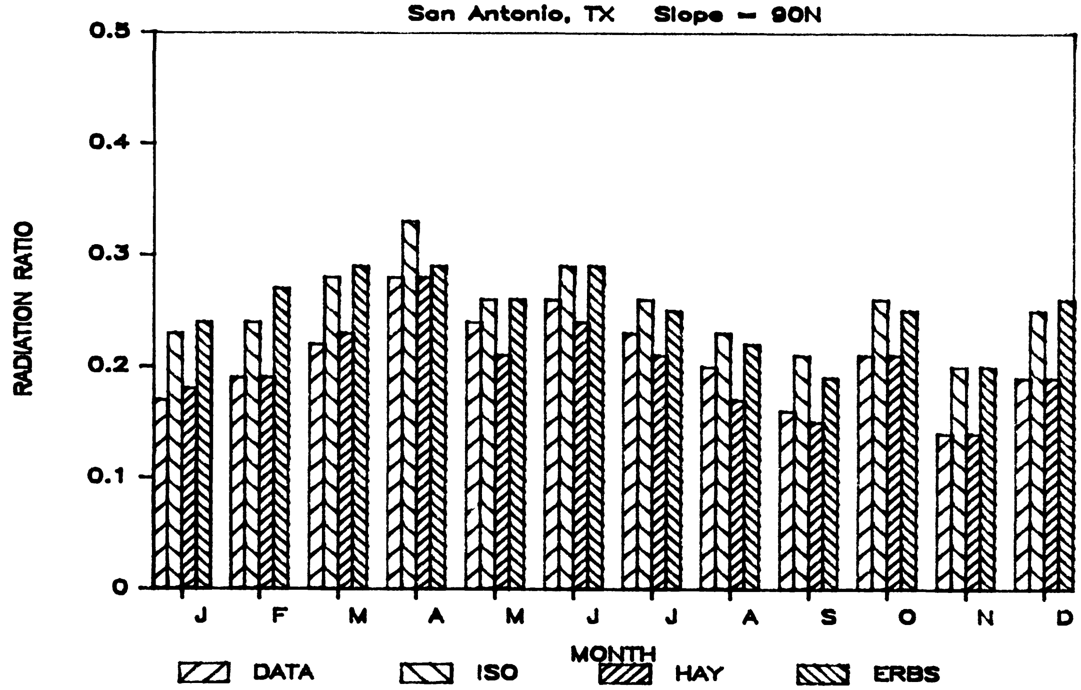



FIG. 2.20 R̄'s (Id/I FROM NIP DATA)

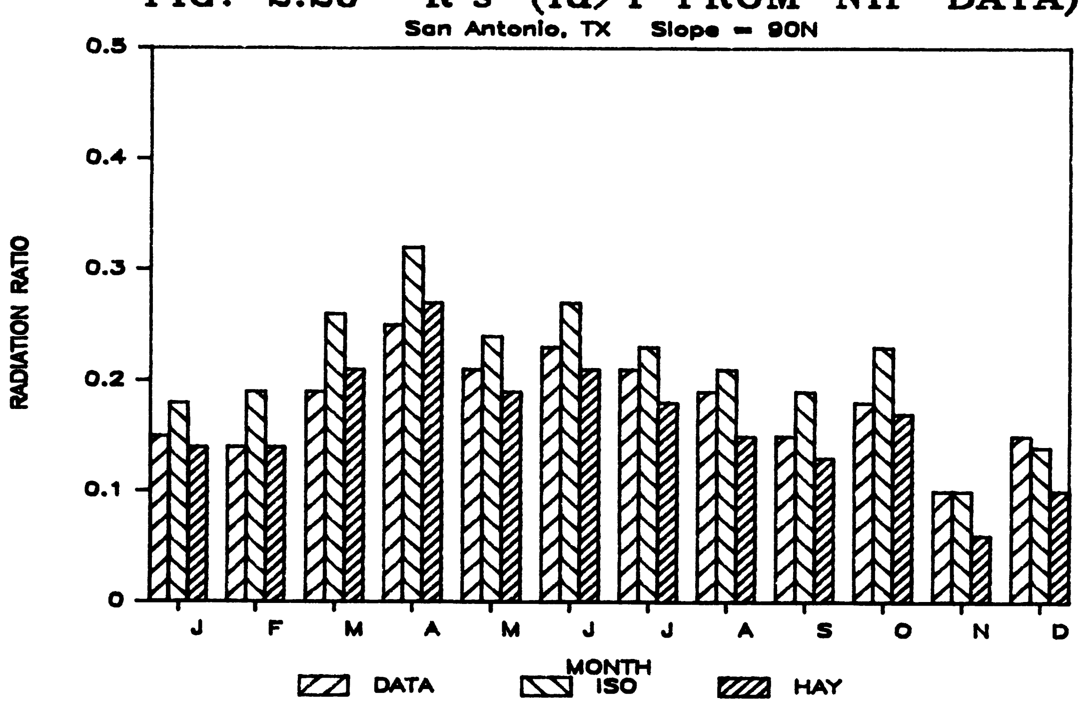


FIG. 2.21 R̄'s (Id/I FROM ERBS CORR.)

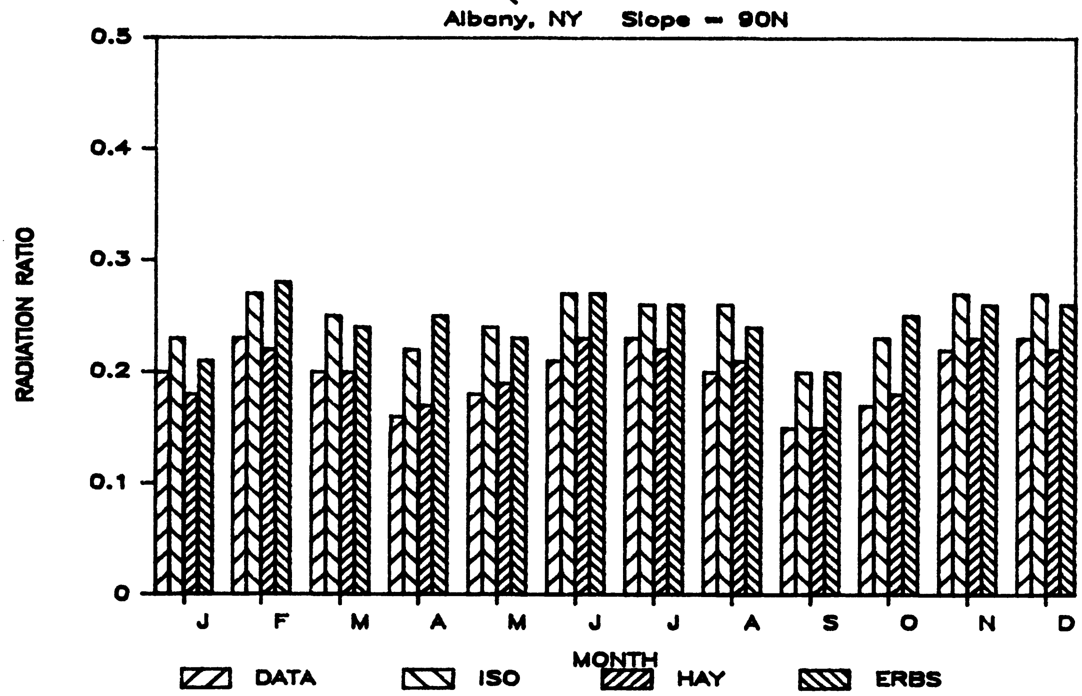
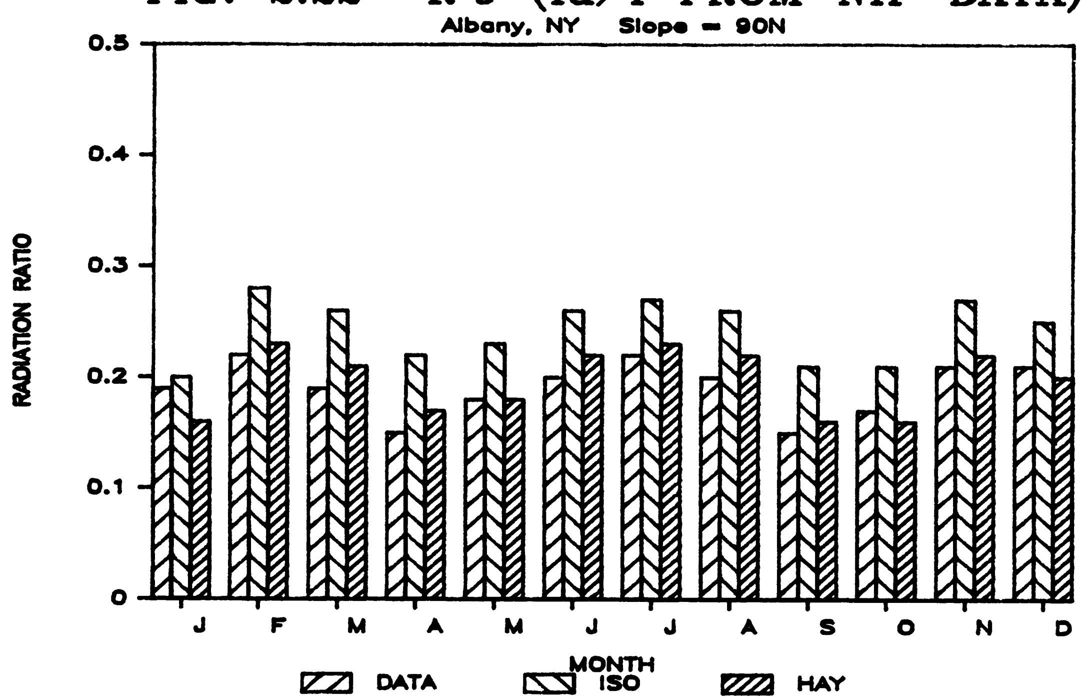



FIG. 2.22 R̄'s (Id/I FROM NIP DATA)



group contains the San Antonio and Albany results, as found from both Erbs hourly correlation and data derived hourly diffuse fractions.

The bar graph legends used in these comparisons are as follow:

Data = $\overline{R}$ calculated from actual insolation measurements;

Iso = $\overline{R}$ calculated from the hourly isotropic model, Eq. (2.6);

Hay = $\overline{R}$ calculated from the Hay hourly anisotropic model, Eq. (2.16);

Erbs = $\overline{R}$ calculated from the monthly-average hourly isotropic model, Eq. (2.8), using Erbs' monthly-average daily diffuse fraction, Eq. (2.14).

In general, the same trends between the various models for calculating $\overline{R}$ is seen using either diffuse fraction method. The values usually change slightly, as expected for methods using a different amount of data. Due to a large number of invalid NIP values, the number of hours used to calculate $\overline{R}$ from data derived diffuse fractions was relatively small. In comparison, the number of valid hours using Erbs' hourly diffuse fraction was approximately equal to the number of hours with valid global horizontal data. Consequently, it could not be determined if the difference in $\overline{R}$ values was caused by the methodology used for calculating the diffuse fraction, or from the change in the data base size.

In a few cases where the hourly isotropic and Hay anisotropic results were close, the "better" model would switch, depending on which method was used to calculate the diffuse fraction. However, considering the small differences between the isotropic and Hay results, both radiation ratio models can actually be considered equal for these limited cases.

Unless otherwise indicated, the following discussions will be centered around the results from the Erbs diffuse fraction method, since it incorporated the larger data base.

A. Surface Slopes Equal to Latitude

Slopes tilted at angles equal to the latitude probably have the largest engineering interest. For these slopes, graphs 2.3 through 2.6 show the Hay anisotropic model best matches the actual data values. Out of the 24 months studied, only once did it perform worse than the isotropic model. In that case, the difference in isotropic and anisotropic values was only 1.2%, while the difference between actual and anisotropic values was 6%. The worse performance for the Hay anisotropic model was this underestimation of 6% (June in Albany). For three of the Albany winter months, the Hay model overestimated the actual value by as much as 4%.

The isotropic model error was largest during the fall and winter months. In San Antonio, the isotropic model underestimated the data value by as much as 10% in both November and December, and by 8% in September and October for Albany. In comparison, the Hay model underestimated the data values by 5% for San Antonio, and 2 to 4% for Albany. In general, the isotropic model performed its best during the summer months, although it still underestimated by 4% during June (Albany). In all cases for surface slope equal to latitude, the isotropic model never overestimated the actual $\bar{R}$ values. This underestimation can be attributed to the lack of a circumsolar diffuse radiation component in the isotropic model.

The monthly-average hourly radiation ratio values using Erbs monthly-average daily diffuse fraction generally agreed with the hourly isotropic model values. In a few cases it gave poorer results, the worst being an underestimation of the actual value by 13%. A poorer performance is expected for any "quick" method, when compared to the numerically integrated hourly model values.

B. Surface Slopes at 90 South

Vertical surfaces probably have the largest architectural interest, due to windows. For these slopes, Figures 2.7 through 2.10, show similar results as the surface slopes equal to the latitude. In general, the Hay model better estimated the data $\bar{R}$ values. The isotropic model performed poorest during the winter, with underestimated values as large as 9% for Albany, and 18% for San Antonio. For those same months, the Hay model overestimated by 3% for Albany, and underestimated by 10% for San Antonio.

In a few summer cases, the isotropic model overestimated by as much as 12% (San Antonio), while the Hay model underestimated by 8% for the same month. However, these are large percentages of small radiation ratios, i.e. 0.25 for the case mentioned. Therefore, the effect of these errors on the resulting tilted insolation values are not significant, when compared to the magnitude of the initial horizontal insolation levels. Consequently, considering the overall minimal change in $\overline{R}$, both hourly methods can be considered equivalent for these cases.

The $\overline{R}$ values calculated from the monthly-average hourly isotropic model once again tended to closely match the hourly isotropic model values. The worst comparisons to the actual values were underestimations by 15% for November in Albany, and 19% for December in San Antonio.

C. Surface Slopes at 90° East and 90° West

Figures 2.11 through 2.18 show the $\overline{R}$'s calculated for surface slopes at 90° East and 90° West. For the east-facing surfaces, all models typically underestimated the actual values. This can be attributed to the lack of a horizon brightening diffuse radiation term. Typically, the isotropic model was usually slightly better than the Hay model, for both San Antonio and Albany. Surprisingly, the monthly-average hourly model tended to be the best of all three correlations.

The largest errors for the east-facing surfaces were during the winter months. The worst case was December in Albany, where both the isotropic and Hay models were low by 48%. In comparison, calculations using the NIP diffuse fraction showed a 39% error. However, the reduction in error using NIP data was accomplished by changing the magnitude of the data $\overline{R}$, and not the magnitude of the $\overline{R}$'s from the hourly isotropic and Hay models. Since the data $\overline{R}$ is a ratio of tilted insolation values to horizontal values, one or both of these values must have greatly fluctuated between the two diffuse fraction data bases. The hourly models require global horizontal data and either Erbs $I_d/I$ or data $I_d/I$. However, the magnitudes of the isotropic and Hay model $\bar{R}$'s remained fairly constant, and therefore the global horizontal and NIP values remained fairly consistent between both diffuse fraction data bases. By default, the tilted insolation data must have been the greatly fluctuating value. Since the east-facing data are the only large-scale varying values, instrument error is indicated for the winter months.

San Antonio also had larger errors in the hourly models during the winter months, but only in the 25% range - which is still a large error. The summer month values were better at approximately 10% underestimation for the hourly models. The $\bar{R}$ magnitudes between Erbs and the NIP diffuse fractions methods were similar.

The west-facing surfaces in San Antonio provided fairly good results for both hourly models. The exception was for September, where both the isotropic and Hay models underestimated the data result by 17%. However, in Albany both the isotropic and Hay models showed some drastic errors compared to the actual values. The worst case is for December, where the isotropic and Hay models overestimated by 65% and 76%, respectively. September also showed a severe overestimation with 52% and 62%. The isotropic and Hay models using the NIP diffuse fraction have slightly smaller winter time errors than the models using Erbs' diffuse fraction.

The reasons for these large $\bar{R}$ model errors in only the Albany west-facing results are unknown. The overestimation for a west-facing surface contradicts the horizon brightening theory, and the inconsistency between the west-facing and east-facing results are puzzling. Further investigation needs to be made, to see if these errors are from instrument failure, or if some other phenomenon is occurring.

D. Surface Slopes at 90° North

Figures 2.19 through 2.22 show the $\bar{R}$ results for surfaces sloped at 90° North. The first observation is the expected low magnitude of the monthly-average daily radiation ratios. In most cases, the actual $\bar{R}$ values are around 0.2 for both San Antonio and Albany. Therefore, any "large" errors result in small changes in the tilted surface values compared to the magnitudes of the initial horizontal radiation. However, the Hay model did give excellent estimates of the actual $\bar{R}$ values for most cases. In general, both the isotropic model and the monthly-average hourly model noticeably overestimated by equal amounts.

## 2.7 Conclusions

The $\bar{R}$'s analyzed represent a relatively small, and short term data base. Nonetheless, comments can still be made on the results obtained.

For the two locations studied, Erbs' hourly diffuse fraction correlation usually misestimated actual monthly-average daily diffuse fractions by 3 to 5% of the maximum fraction. The largest error was 10%. Comparison between Erbs' and data hourly diffuse fractions showed poorer agreement. Typical monthly RMS errors were around 0.18, the maximum being 0.32.

Hay's hourly anisotropic radiation ratio model usually provided better estimates of the actual monthly-average daily radiation ratio, then the isotropic hourly model. The best improvements by using the Hay model were for south-facing surfaces during winter months. For surfaces tilted at angles equal to the latitude, the isotropic model underestimated measured values as much as 10%, compared to 5% for the Hay model. For solar heating systems, these are the critical design conditions.

During summer months, both models provided closer results to actual data. Under a few conditions, the difference between the Hay model results and the isotropic model results is insignificant, due to the small $\overline{R}$ magnitudes. For east and west surfaces, the isotropic model was usually slightly better than the Hay model.

The Hay model is easy to implement, and provided no "practical" penalties.

# 3. CLEARNESS INDEX FREQUENCY DISTRIBUTIONS

## 3.1 General Description

The ratio of terrestrial to extraterrestrial radiation received on a horizontal surface is commonly called the "clearness index". This concept was originally developed by Liu and Jordan [21] under the title of "cloudiness index", since the value is largely dependent upon the amount of clouds. However, the ratio increases for increasing atmospheric clearness, and therefore many sources have referred to it as the clearness index.

The hourly clearness index is noted as $k_T$, where by definition:

$$k_T = \frac{I}{I_o} \tag{3.1}$$

An analytical equation for $I_o$ was previously given as Eq. (2.13). Similarly, the daily clearness index $K_T$ is defined as:

$$K_T = \frac{H}{H_o} \tag{3.2}$$

where the analytical equation for $H_o$ can be found in Duffie and Beckman [5].

Useful parameters are the monthly-average values of the hourly and daily clearness indexes. The monthly-average clearness index is the ratio of monthly-average terrestrial to extraterrestrial radiation for the hour or daily period, which can be found by summing the individual quantities over a month. The monthly-average hourly clearness index is defined as:

$$\bar{k}_T = \frac{(\sum^N I)/N}{(\sum^N I_o)/N} = \frac{\bar{I}}{\bar{I}_o} \tag{3.3}$$

where N = the number of days in a month. In similar fashion, the monthly-average daily clearness index is defined as:

$$\bar{K}_T = \frac{(\sum^N H)/N}{(\sum^N H_o)/N} = \frac{\bar{H}}{\bar{H}_o} \tag{3.4}$$

Liu and Jordan [21] found that the cumulative distributions of the daily clearness indexes formed similar curves for a given monthly-average daily value. These curves represent the fraction of time the daily clearness index is at or below a given value during a month. Figure 3.1 shows the Liu and Jordan curves, which were developed for the five monthly-average values shown.

Whillier [35] found the hourly distributions were also similar to the daily distributions. In a later study, Theilacker [34] showed the hourly distributions to be slightly "steeper" - a larger slope for part of the distribution - than the daily distributions. An increase in slope results in larger changes in the clearness index for a given increment of the fractional time. This increase in the clearness index corresponds to the higher probability of having one hour that is completely sunny or completely cloudy, than an entire day that is completely sunny or completely cloudy.

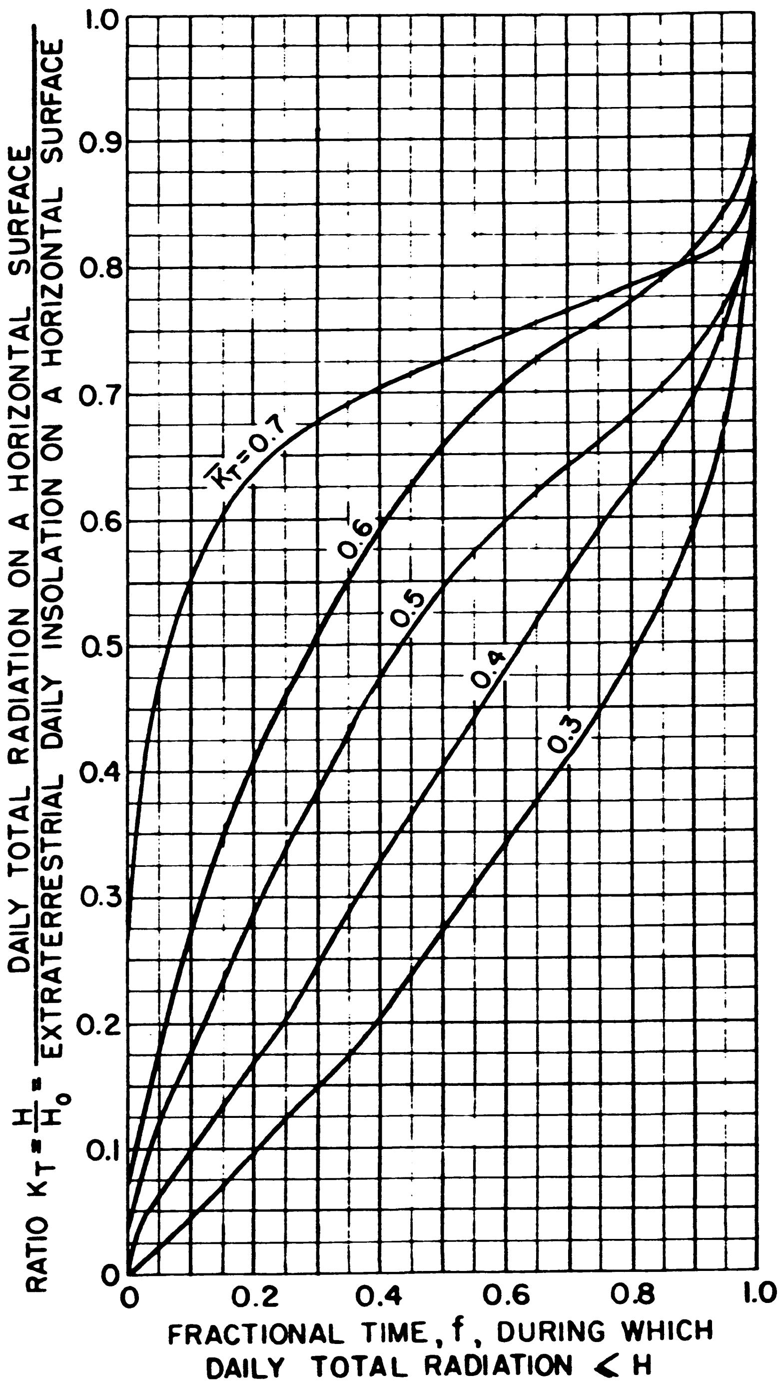



Figure 3.1: Liu and Jordan Cumulative Daily Clearness Frequency Distributions.
From Liu and Jordan [22]

Although the hourly distributions were slightly steeper than the daily distributions found by Liu and Jordan, Theilacker showed that they still had almost the same form. The exception was at fractional times approaching 1.0. Theilacker's curves had a flatter slope at these higher fractions, instead of the sudden approach to $k_T = 1$ as in the Liu and Jordan distributions. Theilacker also showed some seasonal and locational dependencies, but still within the same general curve shape. Although the hourly distributions did vary slightly from the daily distributions, generalized hourly distributions were not, and still are not available. However, Theilacker did conclude that the hour distributions could still be reasonably well represented by the Liu and Jordan curves.

Bendt et al. [1] compared the Liu and Jordan curves to a data base from 90 different locations. The two sets of daily clearness index curves were very similar, except at the high fractions. As shown in Theilacker's work, the Bendt data lacked the sudden change in slope at large fractional times. Next Bendt et al. developed a clearness distribution function based on probability theory for random insolation sequences. This distribution followed the data set extremely well, and also lacked the Liu and Jordan "tail" - the sudden increase in clearness indexes at high fractions.

For this present study, the Bendt distribution is used to compare the clearness frequency distribution from the San Antonio and Albany data. This decision is based on their use of a large data set, the better representation at high fractions, and the analytical form of the required equations.

Clearness indexes are used extensively as the independent parameter in many solar correlations. They are useful for describing atmospheric conditions, and therefore have been used to find diffuse to total insolation fractions - as shown in Chapter 2, and for finding utilizable energy - as shown in Chapter 4. Through insolation distribution assumptions [5], hourly insolation levels can be estimated from daily clearness indexes. The clearness frequency distributions are useful for calculating long-term insolation levels for a given month, based on monthly-average values. Because of its simplicity, atmospheric descriptiveness, and versatility, the clearness index has become one of the most important parameters in solar calculations.

## 3.2 The Bendt Frequency Distribution

The Bendt cumulative frequency distribution is a function of the desired clearness index $K_T$, a maximum clearness index $K_{max}$, and a theoretically derived parameter from statistical mechanics $\gamma$. The fractional time for a given $K_T$ was shown to be:

$$f(K_T) = \frac{\exp(\gamma K_{min}) - \exp(\gamma K_T)}{\exp(\gamma K_{min}) - \exp(\gamma K_{max})} \tag{3.5}$$

where $K_{min} = 0.05$. The $K_{max}$ term was found to be a function of the monthly-average clearness index, where:

$$K_{max} = 0.6313 - 0.267\ \overline{K}_T - 11.9\ (\overline{K}_T - 0.75)^8 \qquad (3.6)$$

The parameter $\gamma$ can be found by solving an integrated equation of a probability function for $\overline{K}_T$ [1], where:

$$\overline{K}_T = \frac{(K_{min} - \frac{1}{\gamma})\ \exp\ (\gamma K_{min}) - (K_{max} - \frac{1}{\gamma})\ \exp\ (\gamma K_{max})}{\exp\ (\gamma K_{min}) - \exp\ (\gamma K_{max})} \qquad (3.7)$$

Herzog [11] used Eqs. (3.6) and (3.7) to solve for $\gamma$ for every 0.05 increment of $\overline{K}_T$ between 0.3 and 0.7. He then derived the following equation for $\gamma$ based on $\overline{K}_T$:

$$\gamma = -1.498 + [1.184\ \Gamma - 27.182\ \exp\ (-1.5\ \Gamma)]/(K_{max} - K_{min}) \qquad (3.8)$$

where $\Gamma = (K_{max} - K_{min})/(K_{max} - \overline{K}_T)$ .

## 3.3 Frequency Calculation Methods from Data

Cumulative daily clearness frequency distributions show the fraction of time an individual daily clearness index is at or below a given value. Large fractional times indicate most days in the month are at or below a correspondingly large clearness index, while small fractional times indicate only a few days in the month are at or below the correspondingly small clearness index. Figure 3.1 shows this relationship between fractional time and daily clearness indexes. The relationship between fractional time and hourly clearness indexes are analogous to daily distributions.

The Albany and San Antonio hour data provided both daily and hourly clearness frequency distributions for a given month. The daily clearness frequency distributions were found by calculating the clearness index for each day and then sorting the indexes by increasing value. Since each clearness index represents one day, the cumulative fraction for a given clearness index is the day of the month, divided by the total number of days in the month. The hourly clearness frequency distributions were similarly made using the hourly clearness indexes for each day.

The cumulative frequency distributions for monthly-average hourly clearness indexes were also calculated using the minute data. Since most months have approximately 1860 minutes for a given hourly period, the "Bin Method" was used to simplify the output. Fifty "Clearness Index Bins" were created between 0 and 1, in 0.02 increments: i.e. Bin #1 was for $k_T$ = 0 to 0.02; Bin #2 was for $k_T$ = 0.02 to 0.04; etc. The clearness index was then calculated for each minute within the hourly period, and put into the appropriate bin. The cumulative number of clearness indexes was then found by summing the number of clearness indexes in each bin, along with the totals from each preceding bin. This gave the total number of clearness indexes at or below the clearness index for the midpoint of each bin. The cumulative fraction was then found by dividing the cumulative numbers for each bin, by the total number of clearness indexes. This method resulted in a workable number of points to describe the minute cumulative frequency distribution.

Short-term clearness indexes occasionally exceed 1.0, indicating that terrestrial radiation is exceeding extraterrestrial radiation for that period. Norris [25] suggested this peculiarity may be attributable to sunlight reflecting from the sides of clouds, concentrating the insolation over a small area. Since this phenomenon is rare, the clearness index scale on frequency distributions have always ranged between 0 and 1. In this study, any clearness indexes exceeding 1.0 were reset to 1.

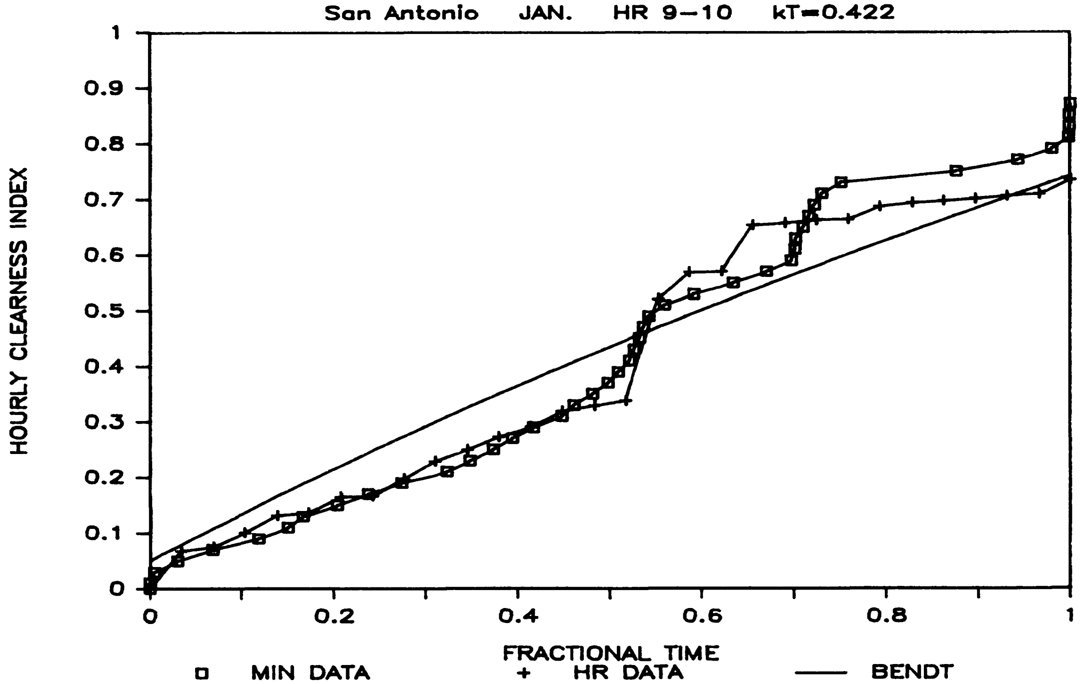
The area under a cumulative clearness frequency distribution curve must equal the monthly-average clearness index. Due to the number of significant digits used in the following distribution plots, the actual areas shown may have errors as large as ±2%.

### 3.4 Frequency Distributions for Hourly Periods

Figures 3.2 through 3.17 show some of the frequency distributions for a given monthly-average hourly clearness index. The graphs include minute and hourly clearness frequency distributions along with the Bendt correlation. The degree of superposition between the hour data and Bendt's correlation shows how closely the given month matches the accepted long-term average. Dissimilar curves indicate the hourly period within the month are not typical of long-term values. San Antonio and Albany both have some months that are similar to long-term distributions (Figs. 3.7-3.13 and 3.15) and other months that are dissimilar (Figs. 3.2-3.6 and 3.14). None of the hourly data distributions have the Liu and Jordan tail - $k_T$ approaching 1 at large fractional times.

# FIG. 3.2 kT FREQUENCY DISTRIBUTION

San Antonio JAN. HR 9—10 kT=0.422




# FIG. 3.3 kT FREQUENCY DISTRIBUTION

San Antonio JAN. HR 10—11 kT=0.490

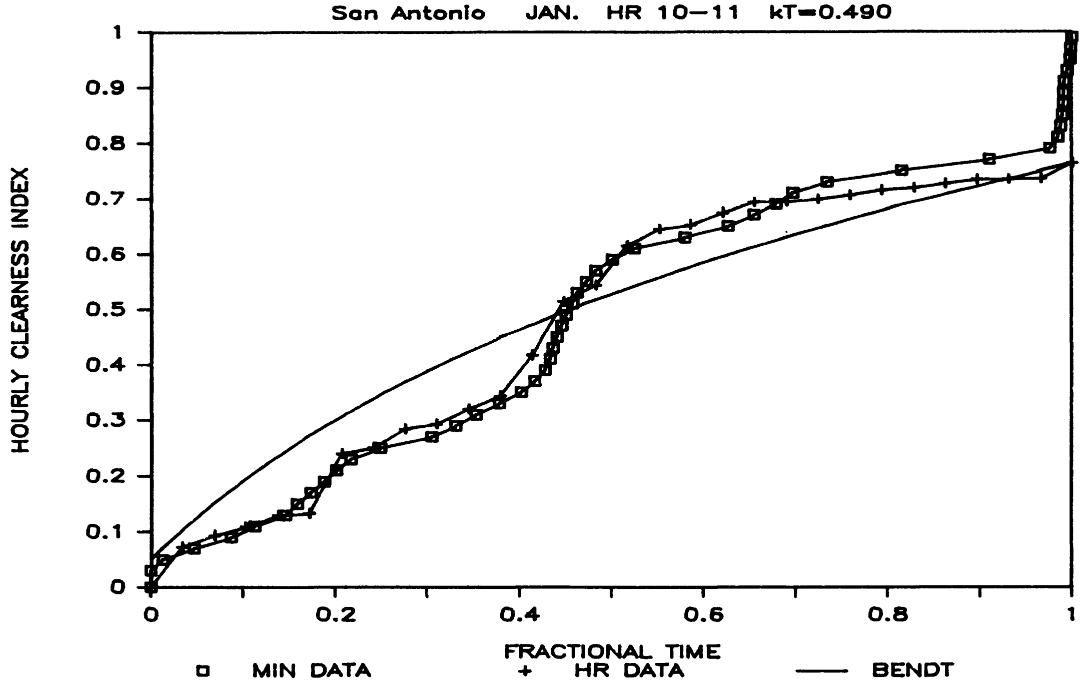


FIG. 3.4 kT FREQUENCY DISTRIBUTION

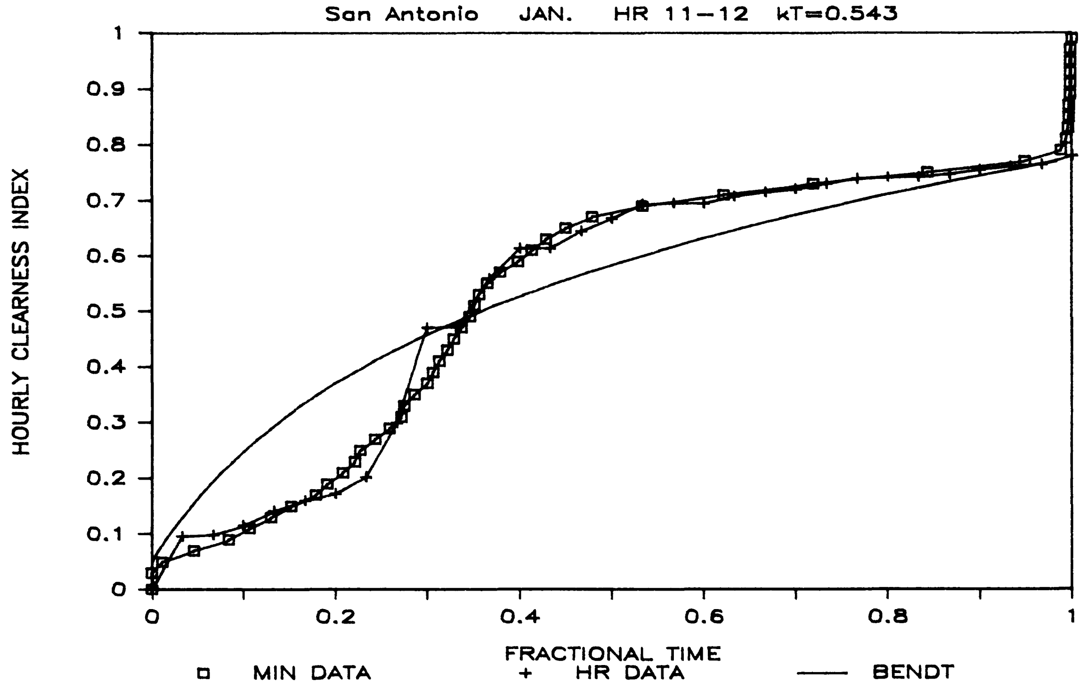
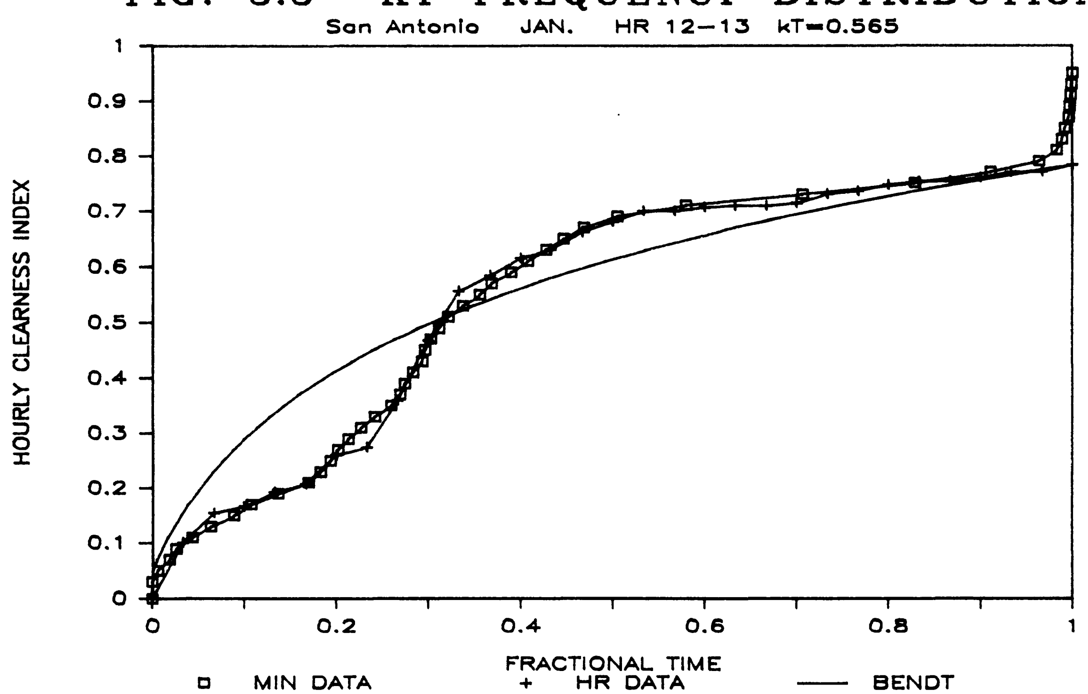
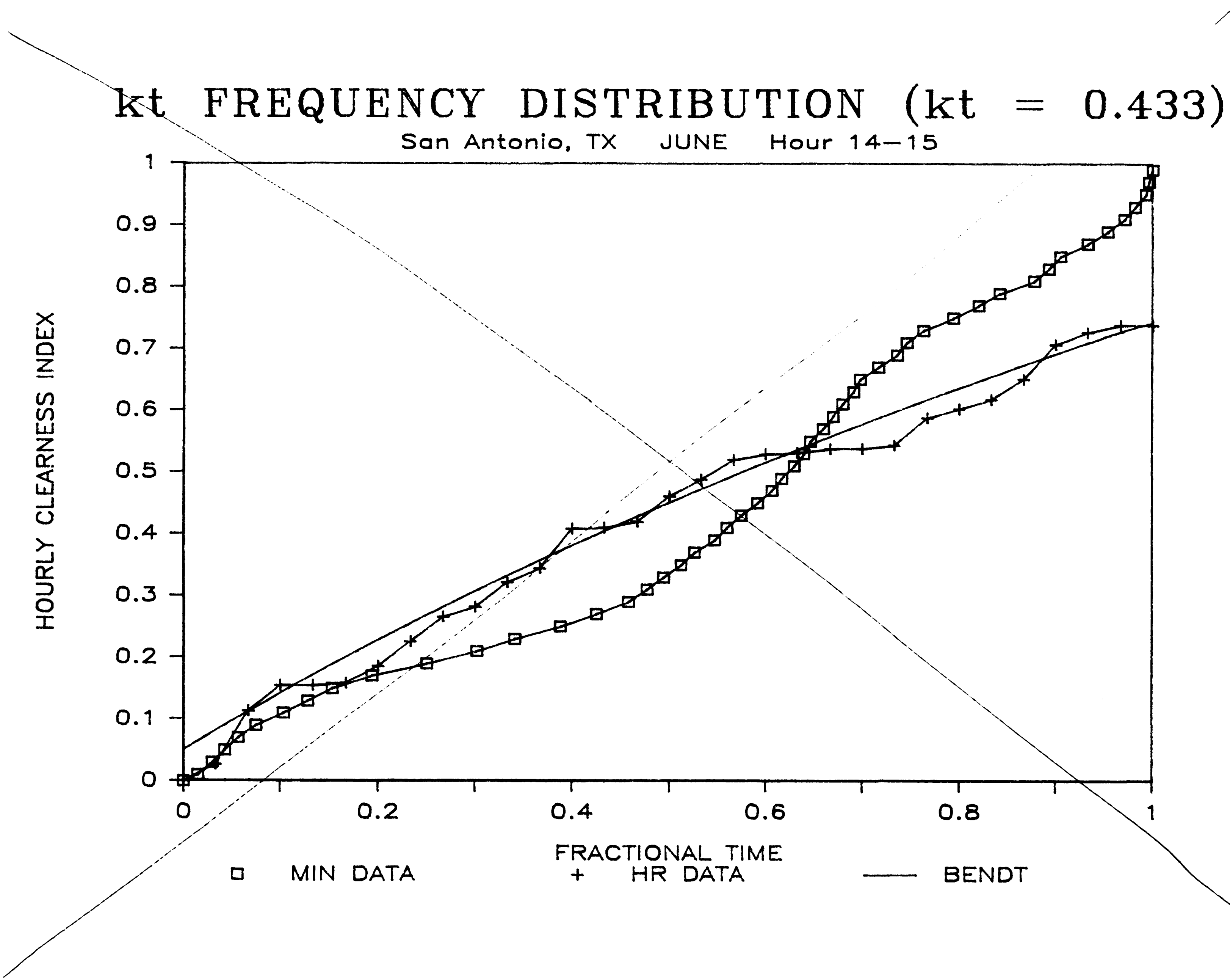


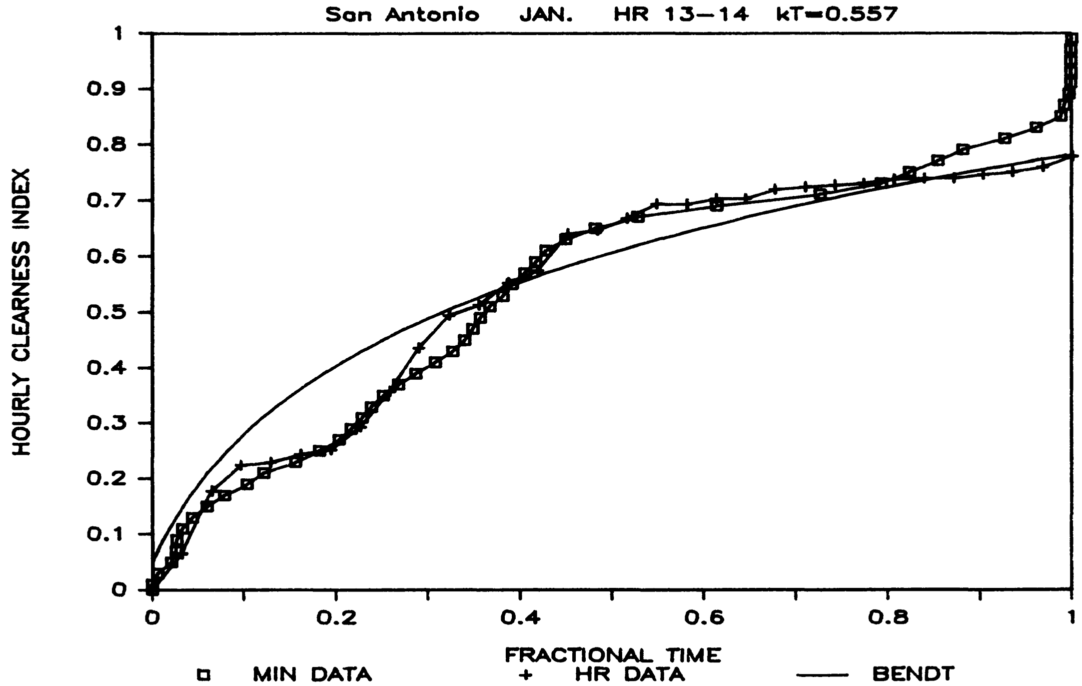

FIG. 3.5 kT FREQUENCY DISTRIBUTION



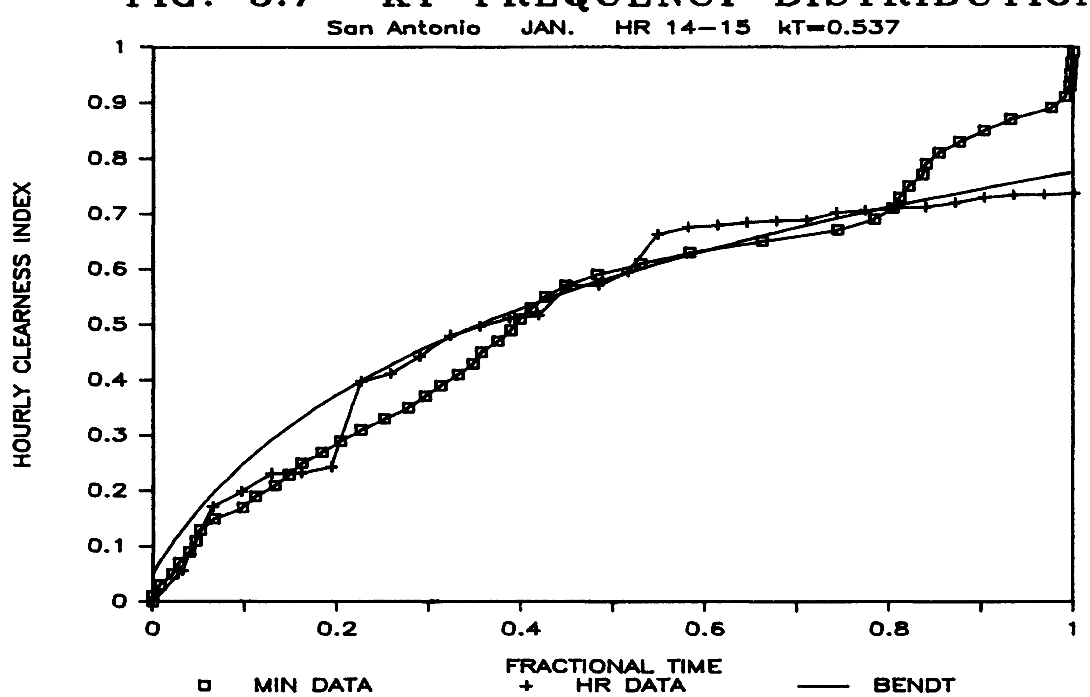


kt FREQUENCY DISTRIBUTION (kt = 0.433)
San Antonio, TX JUNE Hour 14–15
HOURLY CLEARNESS INDEX
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
FRACTIONAL TIME
MIN DATA
HR DATA
BENDT

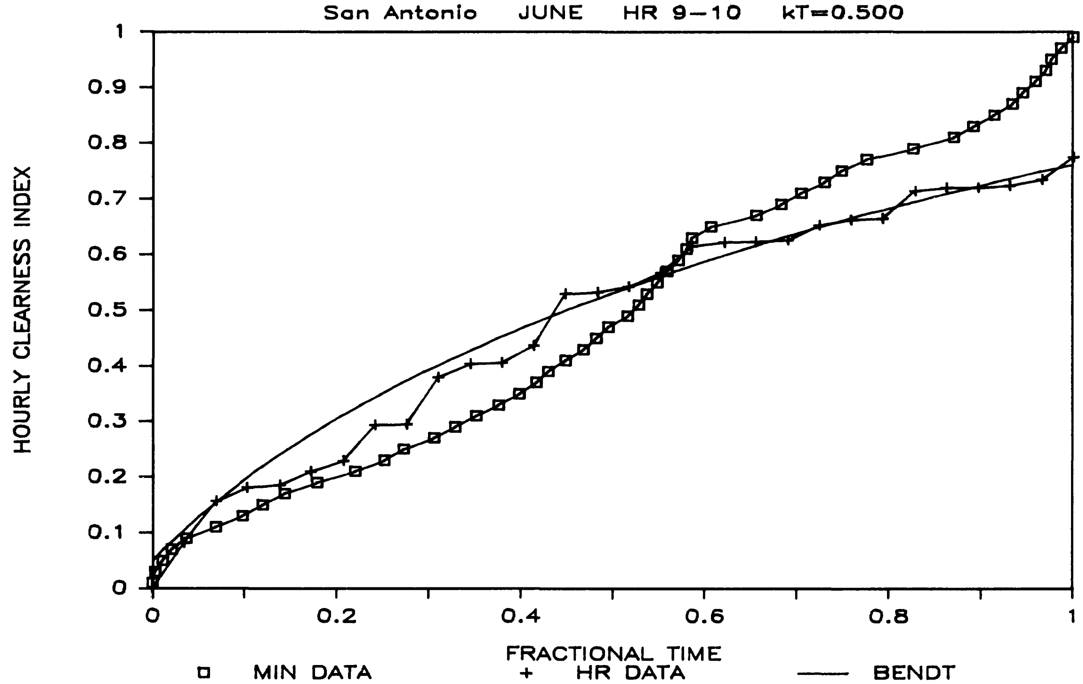
# FIG. 3.6 kT FREQUENCY DISTRIBUTION



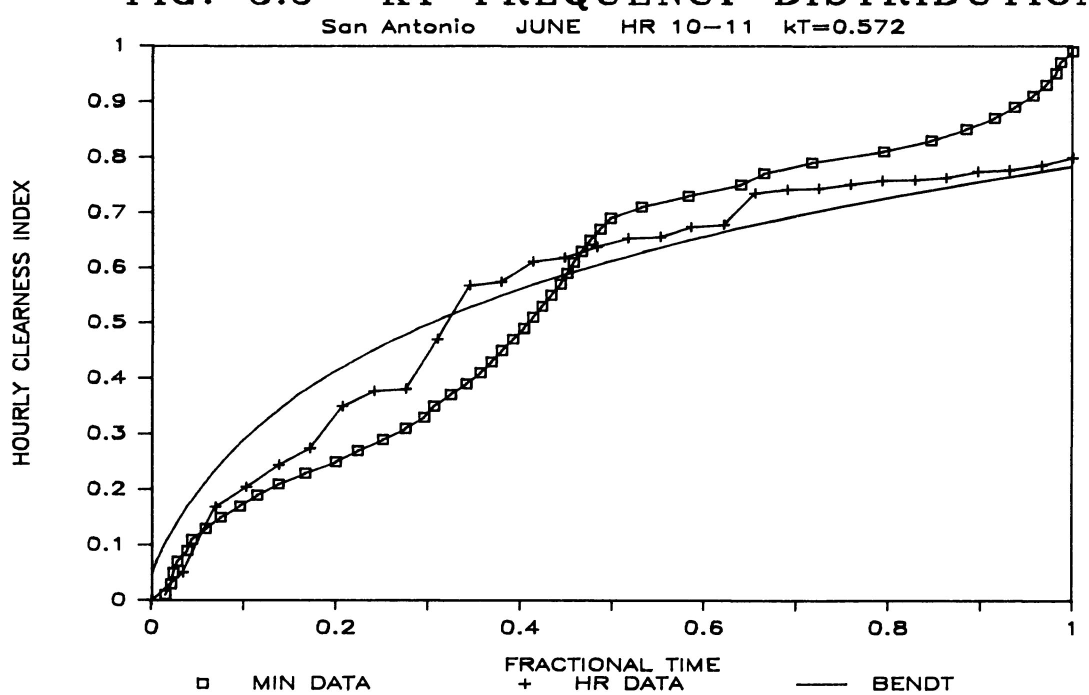

# FIG. 3.7 kT FREQUENCY DISTRIBUTION



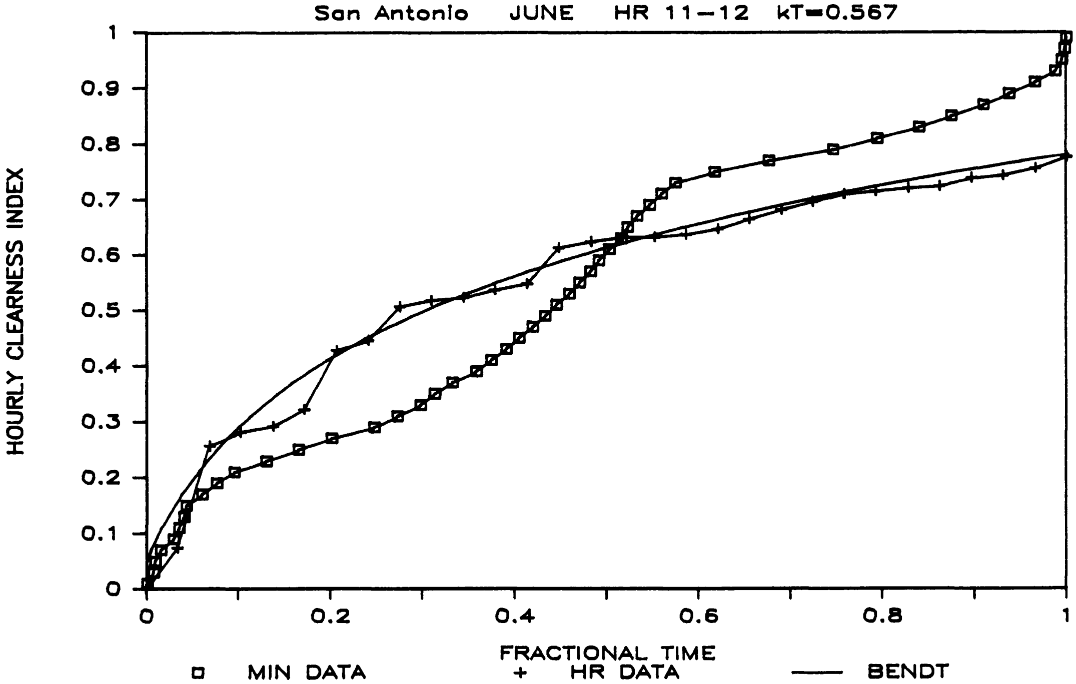
# FIG. 3.8 kT FREQUENCY DISTRIBUTION




# FIG. 3.9 kT FREQUENCY DISTRIBUTION



# FIG. 3.10 kT FREQUENCY DISTRIBUTION




# FIG. 3.11 kT FREQUENCY DISTRIBUTION

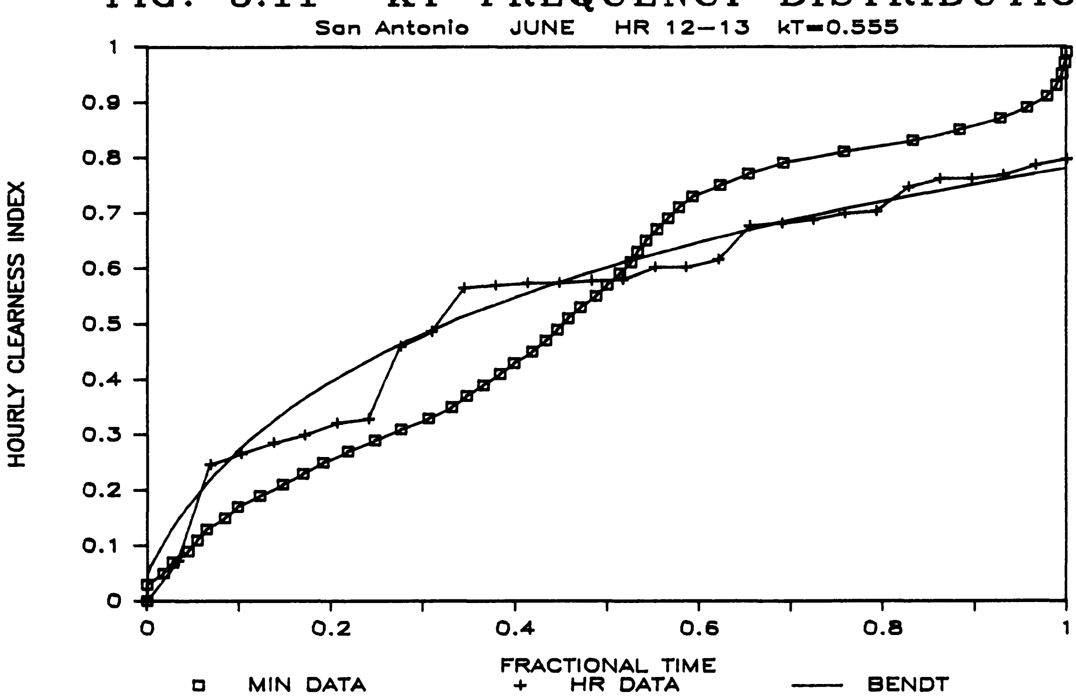


FIG. 3.12 kT FREQUENCY DISTRIBUTION

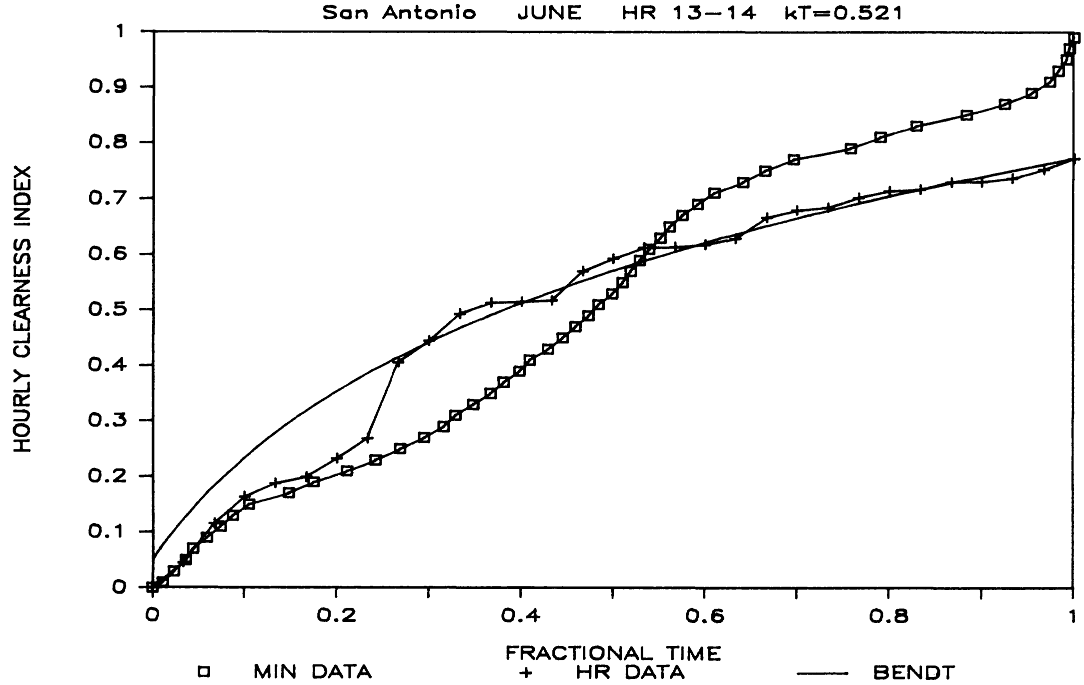



FIG. 3.13 kT FREQUENCY DISTRIBUTION

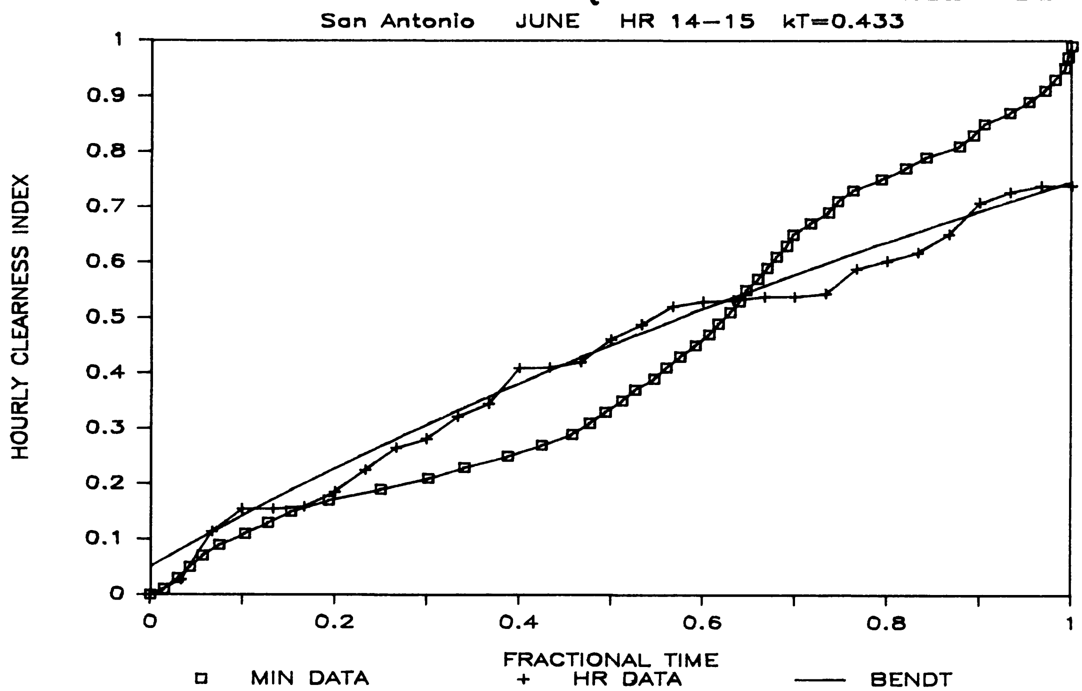


FIG. 3.14 kT FREQUENCY DISTRIBUTION

Albany, NY JUNE HR 16–17 kT=0.556

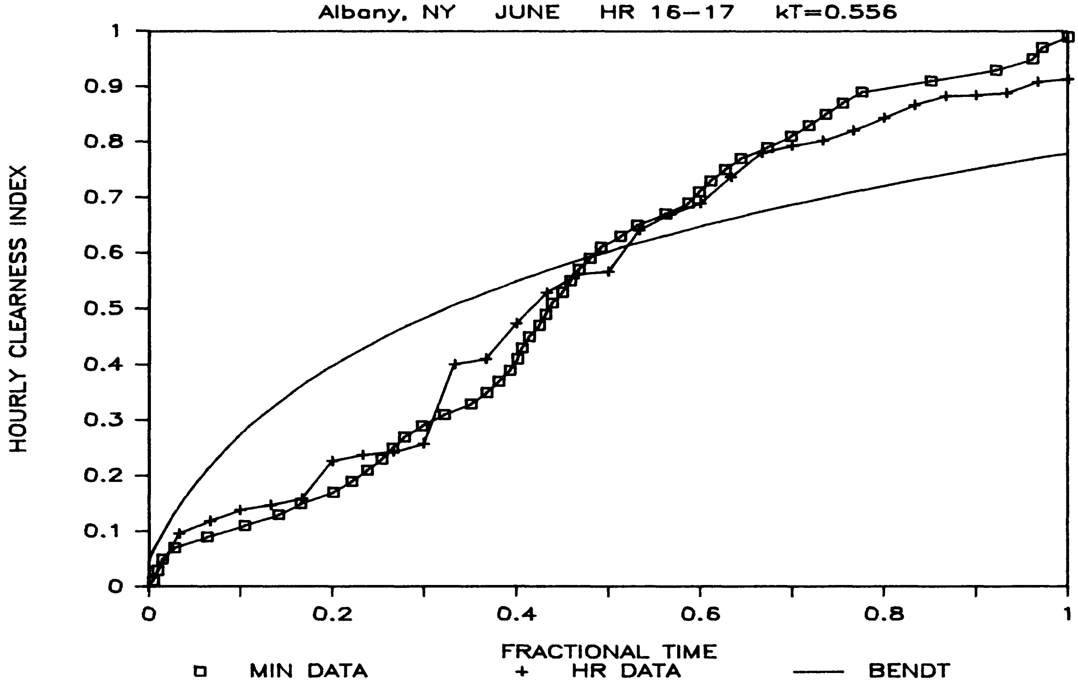
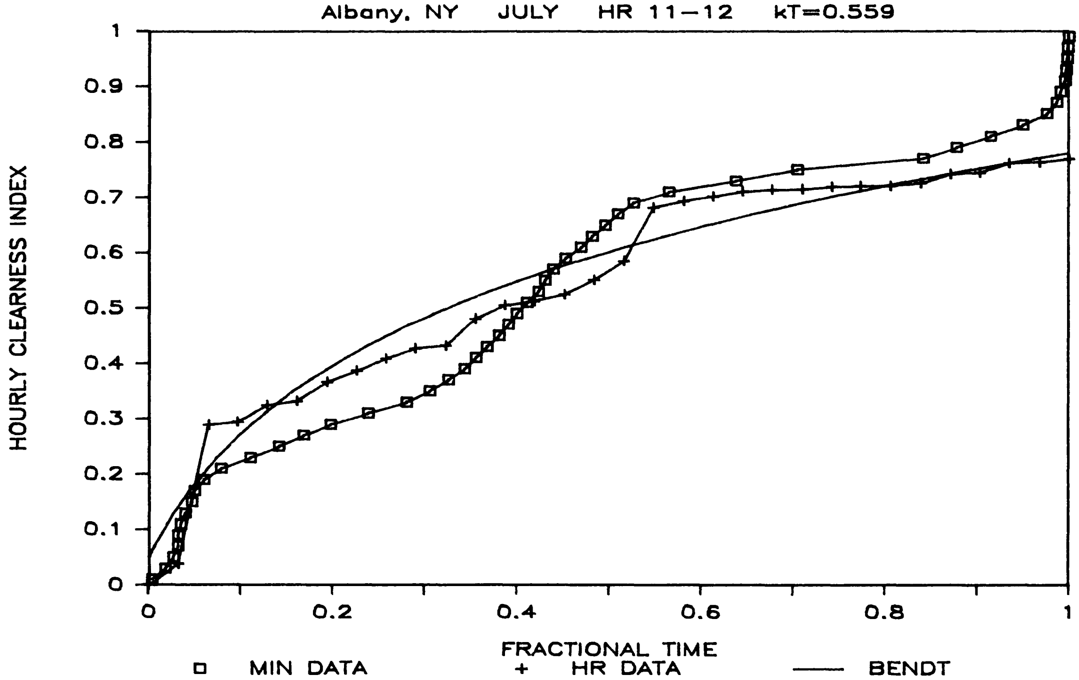
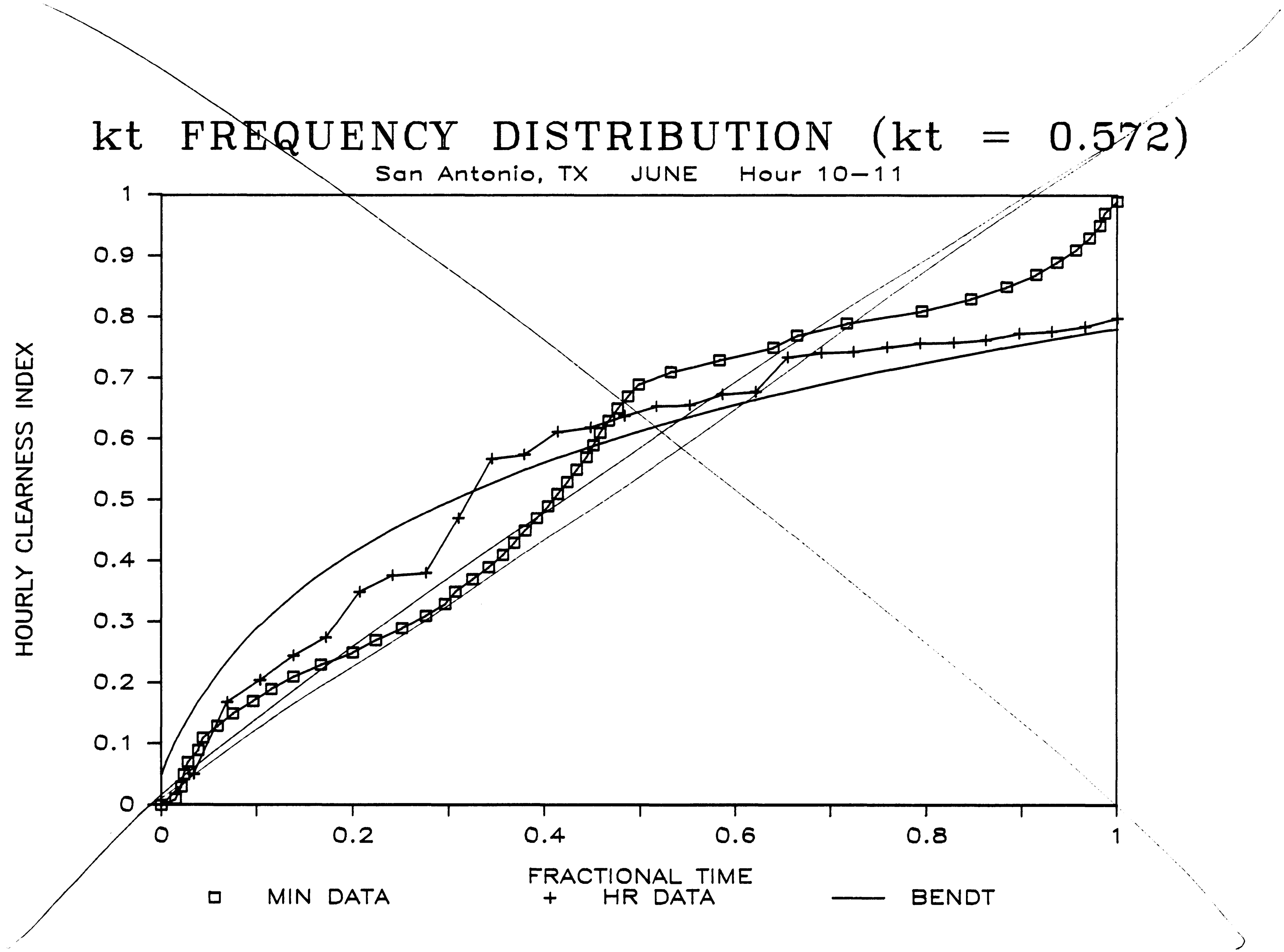



FIG. 3.15 kT FREQUENCY DISTRIBUTION

Albany, NY JULY HR 11–12 kT=0.559





kt FREQUENCY DISTRIBUTION (kt = 0.572)
San Antonio, TX JUNE Hour 10-11
HOURLY CLEARNESS INDEX
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
FRACTIONAL TIME
MIN DATA
HR DATA
BENDT

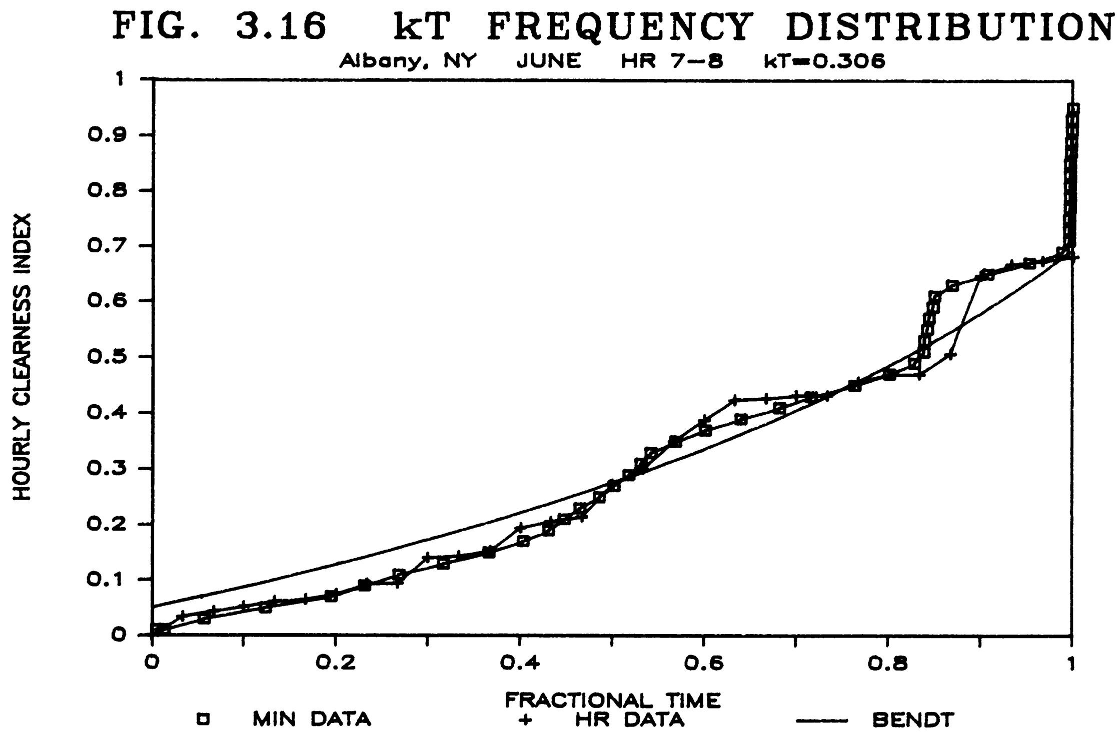


FIG. 3.16 kT FREQUENCY DISTRIBUTION
Albany, NY JUNE HR 7-8 kT=0.306
HOURLY CLEARNESS INDEX
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
FRACTIONAL TIME
MIN DATA
HR DATA
BENDT

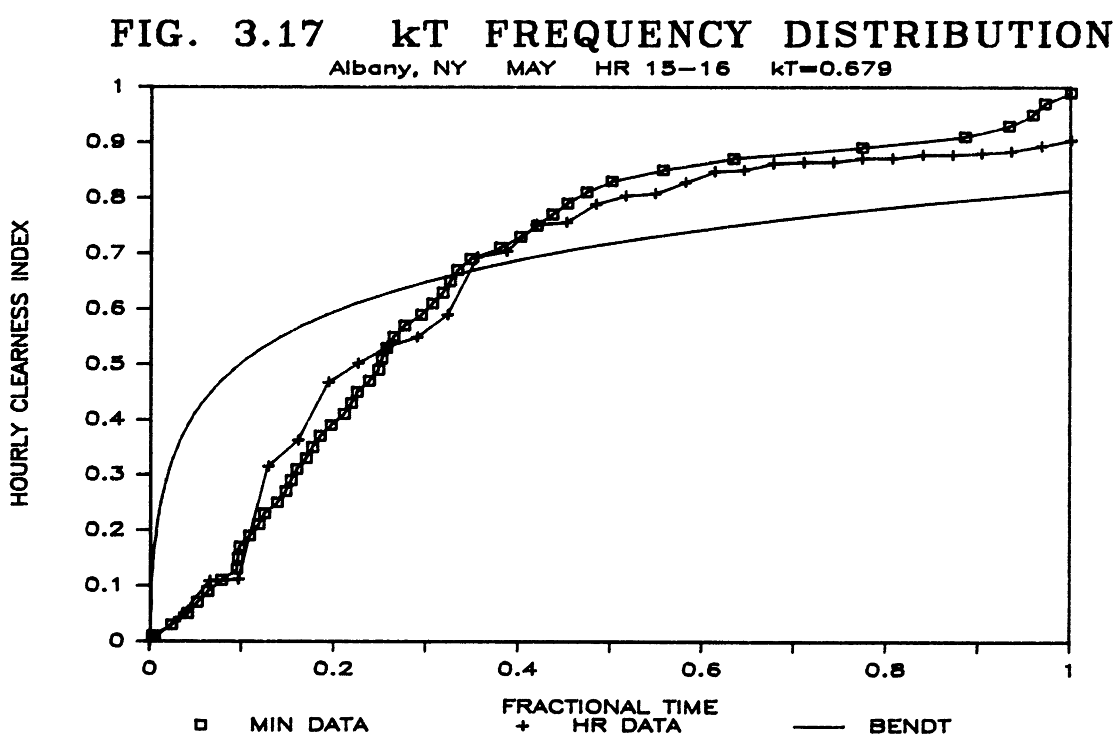


FIG. 3.17 kT FREQUENCY DISTRIBUTION
Albany, NY MAY HR 15-16 kT=0.679
HOURLY CLEARNESS INDEX
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
FRACTIONAL TIME
MIN DATA
HR DATA
BENDT

The minute clearness frequency distributions drawn for hourly periods give some unexpected results. The first surprise is the return of the Liu and Jordan tail. The monthly-average clearness indexes of the graphs shown range between 0.31 and 0.68, with hourly periods between 9 a.m. and 5 p.m. In every case, there is a sudden approach to $k_T = 1.0$. These large $k_T$ values indicate that within any hourly daylight period in a given month, there will always be some minutes where the terrestrial insolation approaches the extraterrestrial insolation.

The other observation is the degree of variability between the hour data and minute data. Figure 3.5 for San Antonio shows the hour data and minute data almost superimposed. Figure 3.11 shows the hour data and minute data with two very different shapes. Both of these graphs have very similar monthly-average hourly clearness indexes: 0.57 and 0.56, respectively.

The other hourly periods in San Antonio for the same months (Figs. 3.2-3.13) show the same trends: for January, the hour data and minute data are almost superimposed; for June, the two distributions are very different. Figures 3.14 and 3.15 for $\overline{k}_T = 0.56$ in Albany, show the same results. The two data distributions in Fig. 3.14 are very similar, while the two data distributions in Fig. 3.15 show a little more difference.

The two extreme $\overline{k}_T$ graphs (Fig. 3.16 - $\overline{k}_T = 0.31$ and Fig. 3.17 - $\overline{k}_T = 0.68$) do show practically superimposed hour data and minute data distributions, as expected. Low $\overline{k}_T$'s represent months where each day results in low hourly insolation levels, as in extremely cloudy conditions during the entire month. Under thick cloud conditions, the insolation level within an hour remains fairly constant. Therefore, a minute time-step will not provide new insolation information, and the resulting minute clearness frequency distribution coincides with the hourly clearness frequency distribution. For large $\bar{k}_T$'s, high hourly insolation levels are found for each day in the month - i.e. extremely clear conditions with no clouds, smog, fog, etc. Once again, the insolation level within an hour remains fairly constant, and the resulting hourly clearness frequency distribution coincides with the minute clearness frequency distribution.

The minute data distributions vary from noticeably differing from the hour data distributions, to superimposing with them. Since the hour data were generated by averaging measured minute values, the minute distributions better represent the actual solar insolation. This superposition variability between minute data and hour data has two implications:

1) hour time steps are sometimes too large to accurately represent insolation distributions, possibly due to intermittent clouds; and
2) Since the difference in distributions occurred for cases with the same monthly-average hourly clearness index, another independent parameter(s) must be involved in fully describing the distributions for hourly periods.

In the past, the monthly-average hourly clearness index has been used as the only independent parameter defining a frequency distribution. If the second implication is correct, then the clearness frequency distribution may not actually follow a known distribution defined only by $\overline{k}_T$, but possibly a distribution defined by $\overline{k}_T$ in conjunction with some other factor(s). This other independent parameter(s) is presently unknown, but may be one of the parameters found by Garrison [7] in his study of diffuse fractions: solar elevation; surface albedo; atmospheric precipitable water; and atmospheric turbidity (See Chapter 2).

The other independent parameter(s) could help explain a previous finding by Theilacker [34]. As part of a larger study on clearness indexes, Theilacker found the hourly clearness frequency distributions for Miami, Florida to have shapes "flatter" than the Liu and Jordan distributions. He attributed this to haze caused by the ocean environment, which would agree with Garrison's atmospheric precipitable water parameter. Theilacker concluded that climatic and locational parameters should be included in truly generalized distributions, but the improved accuracy through added correlation complexity would be undesirable. From an engineering point of view, the added correlation complexity may still be undesirable.

In an attempt to better understand the minute data distributions for monthly-average hourly clearness indexes, Figs. 3.18 and 3.19 were made to compare only the minute data distributions for the same $\overline{k}_T$. Figure 3.18 is for $\overline{k}_T$ = 0.56, and Fig. 3.19 shows $\overline{k}_T$ = 0.57.

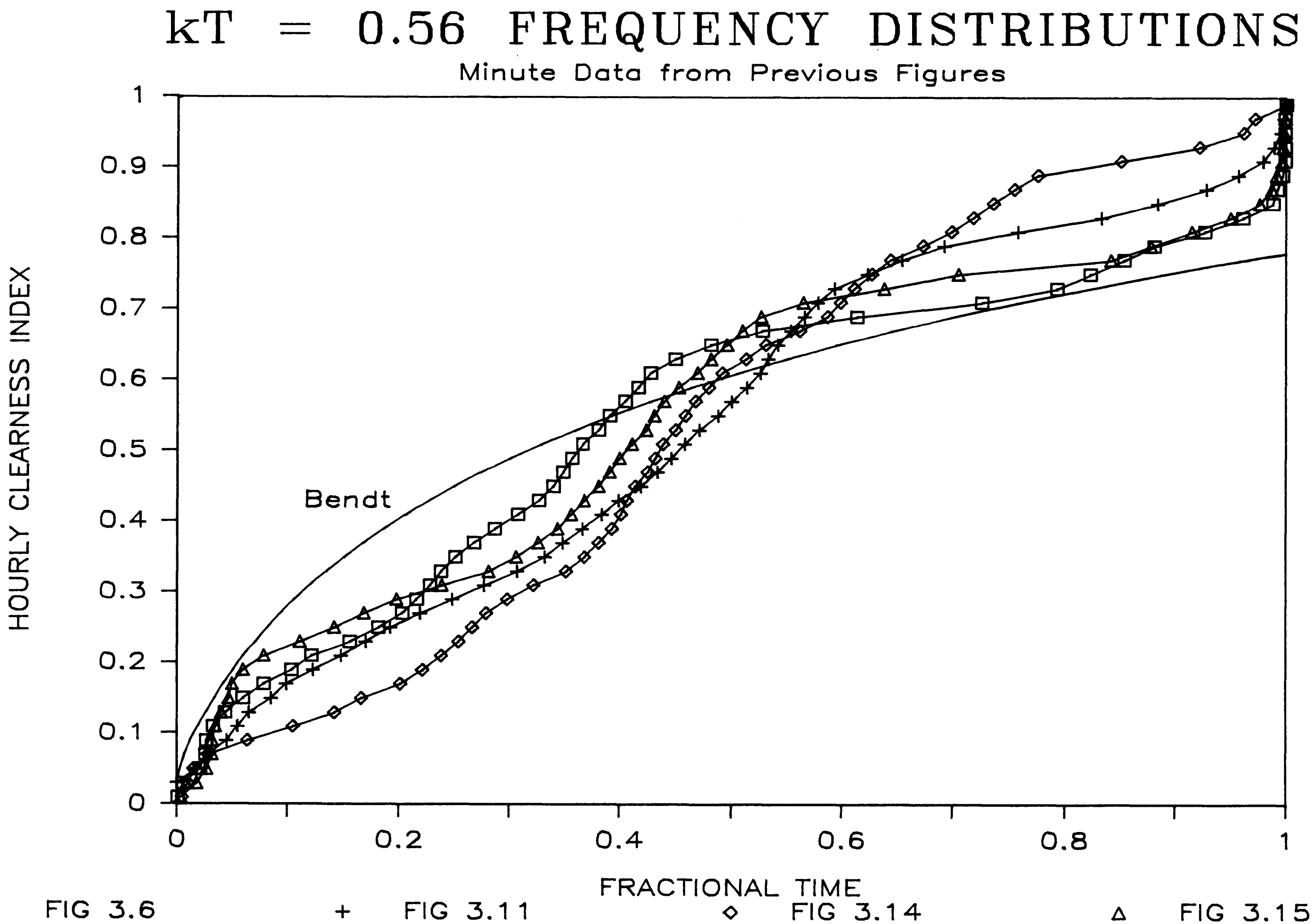



Figure 3.18: $\bar{k}_T$ = 0.56 Frequency Distributions.

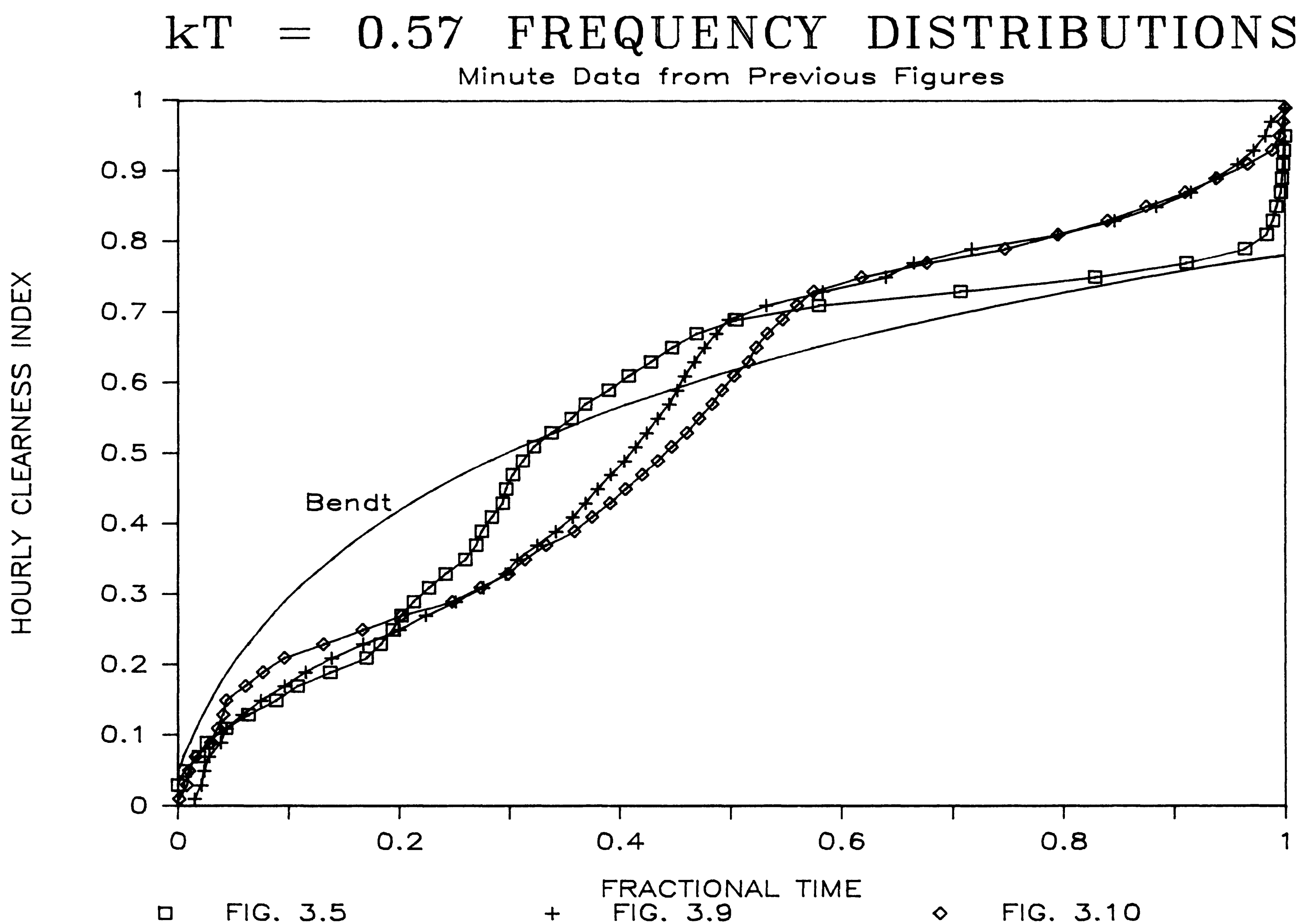



Figure 3.19: $\bar{k}_T$ = 0.57 Frequency Distributions.

Both graphs show some variability in the curve shapes. Although the data base is small, other independent parameters appear to be required to adequately define minute clearness frequency distributions for hourly periods within a month.

### 3.5 Frequency Distributions for Daily Periods

Figures 3.20 through 3.23 show some of the daily frequency distributions for a given monthly-average daily clearness index. The graphs are for San Antonio in January, San Antonio in June, Albany in June, and Albany in July. All four distributions have $\overline{K}_T$'s approximately equal to 0.5. Plotted with each graph is the generalized Bendt distribution for the same $\overline{K}_T$.

In all cases shown here, the data distributions follow the Bendt distribution fairly well. There are no large differences in shape, as there were in the minute data distributions. This implies the insolation levels during the months presented are somewhat close to "typical" distributions.

The other observation is the lack of the Liu and Jordan tail. This is in agreement with the Bendt distribution and Theilacker's observations. It also suggests that individual daily insolation levels do not approach extraterrestrial values. For the cases here, the maximum daily insolation levels are within 75% of the extraterrestrial values.

### 3.6 Conclusions

The clearness frequency distributions analyzed represent a small data base, and therefore no general conclusions can be made. How-

FIG. 3.20 KT FREQUENCY DISTRIBUTION

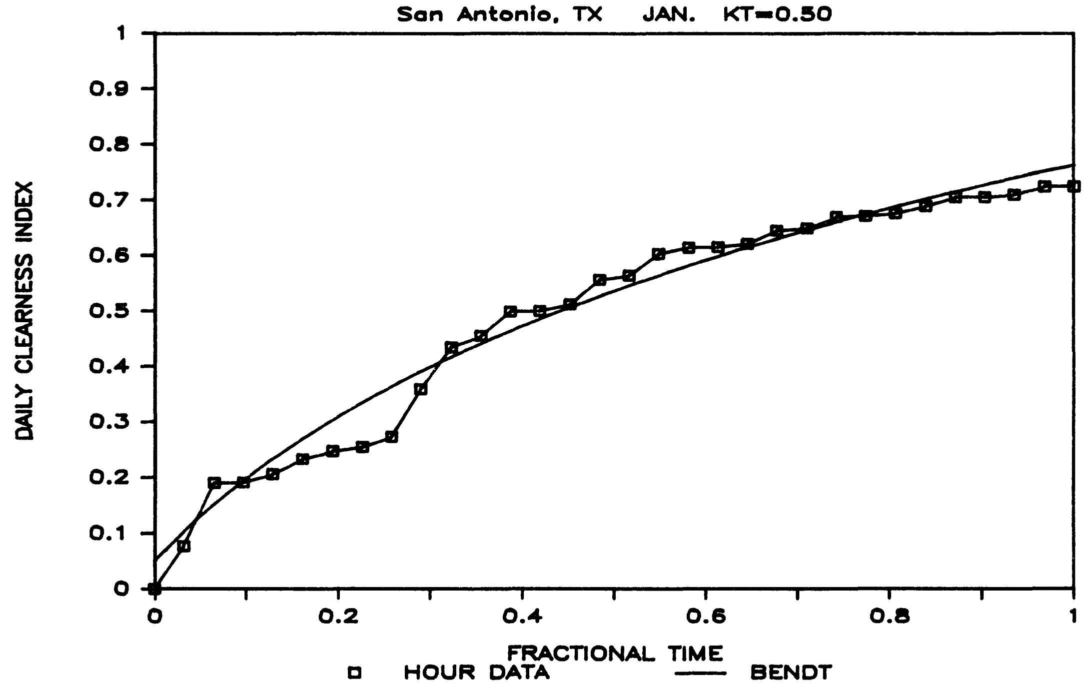



FIG. 3.21 KT FREQUENCY DISTRIBUTION

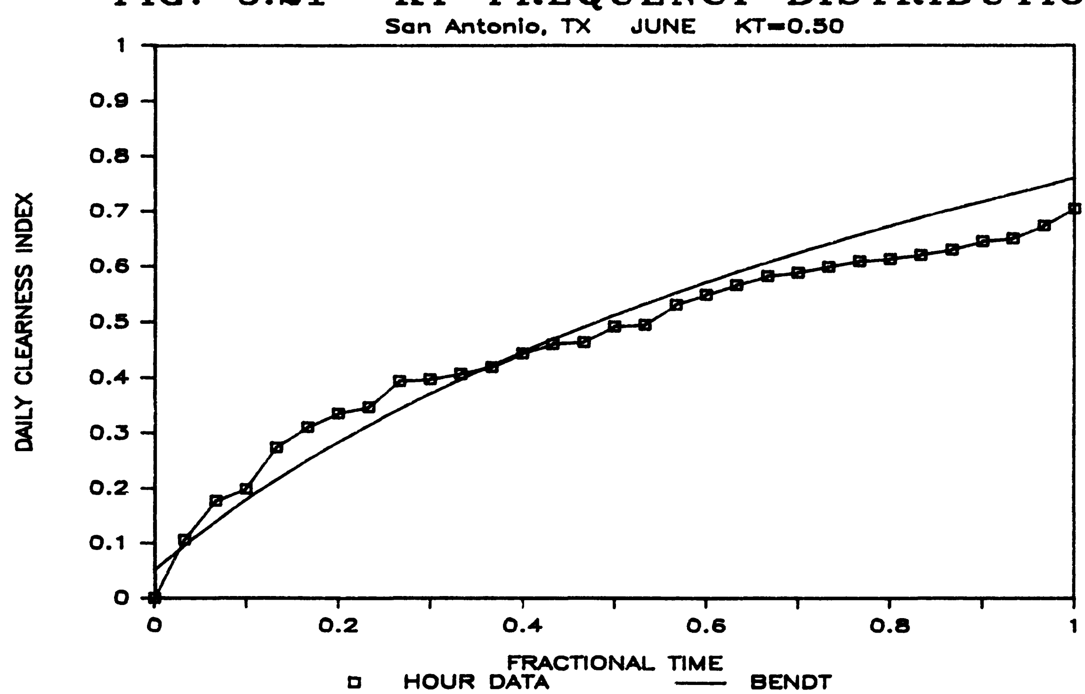


FIG. 3.22 KT FREQUENCY DISTRIBUTION

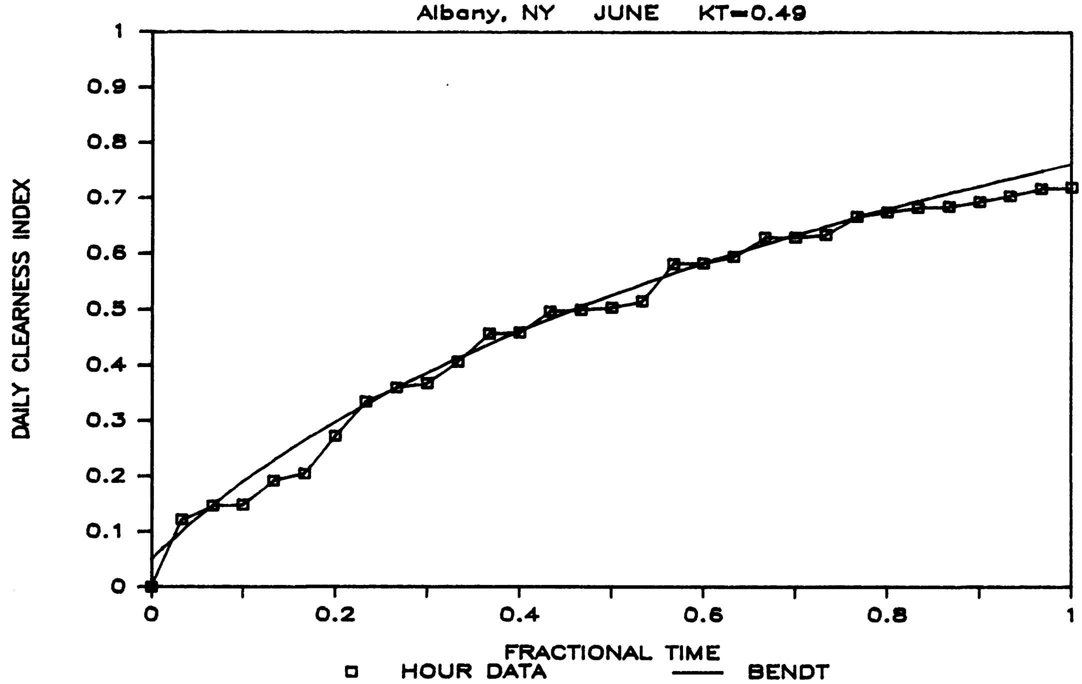
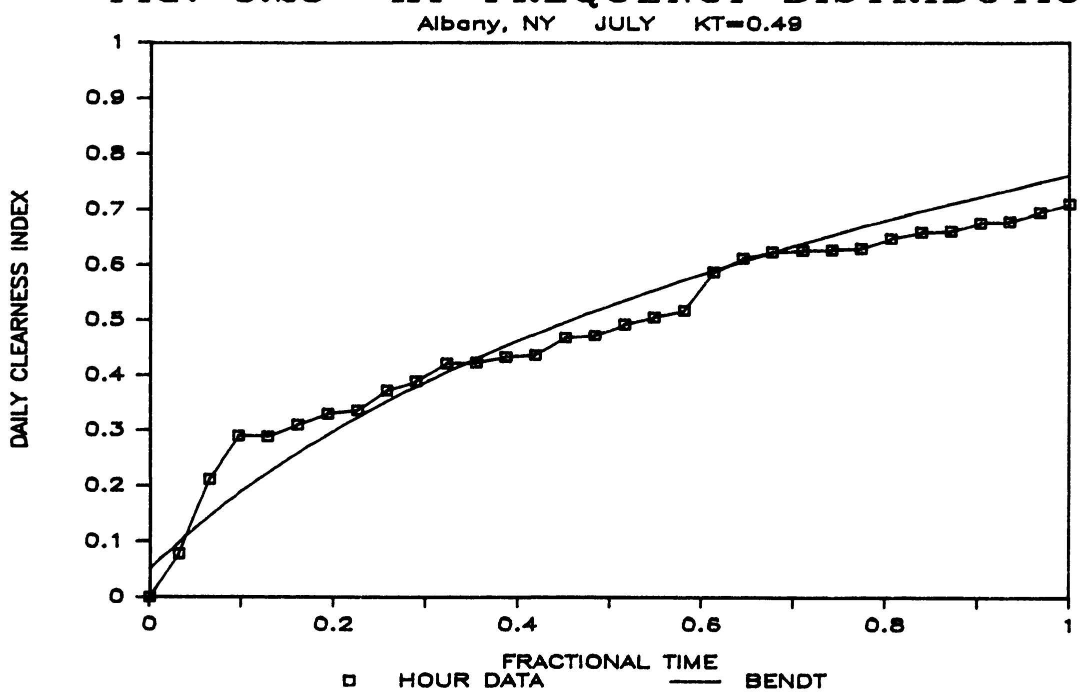



FIG. 3.23 KT FREQUENCY DISTRIBUTION



ever, the following implications were found:

1. Hourly data is occasionally too large of a time step to accurately represent actual insolation levels. Improvement can sometimes be made using minute data. The effect of using minute versus hour data for utilizable energy calculations is discussed in Chapter 4.
2. Minute clearness frequency distributions for hourly periods within a month show more variability in insolation levels than the generalized daily distributions presently used to describe hourly insolation levels. These generalized curves may need to be updated to accurately represent distributions for hourly periods.
3. Minute data distributions for hourly periods rapidly approach $k_T = 1.0$ at large fractional times. Therefore, individual minute insolation levels can approach extraterrestrial values.
4. The strong possibility of more than one independent parameter defining the clearness frequency distributions for hourly periods was shown. At present, this other parameter(s) is unknown, but may be one or more of the following: solar elevation; surface albedo; atmospheric precipitable water, or atmospheric turbidity.
5. The daily clearness frequency distributions calculated from hour data do approximately follow the Bendt et. al [1] clearness frequency distributions. The rapid approach to $K_T = 1.0$ at large fractional times as shown by Liu and Jordan [21] was not observed. Therefore, the maximum daily insolation will always be well below the extraterrestrial levels. For the cases shown

here, the maximum daily insolation values are below 75% of the extraterrestrial values.

# 4. UTILIZABILITY

## 4.1 Background on Utilizability

Utilizability is the ratio of energy above a given threshold or critical level, to the total incident energy. This critical level can be the energy required to maintain a collector plate at the fluid inlet temperature. Consequently, the incident solar energy above this level is the "useful" or "utilizable" energy for the desired goal. Since utilizability is a fraction of useful to total energy, it ranges between 0 and 1. Large utilizability values indicate a large percentage of the energy is available for the desired goal, while small utilizability values indicate a small percentage is available.

Utilizability values are usually given for long-term monthly average periods. Figure 4.1 shows the solar irradiation for a hypothetical three day month. The abscissa is time, while the ordinate is the irradiation on the surface. Each day represents one of three different kinds of days: hazy, clear, and cloudy. The horizontal line drawn through the curves indicates an arbitrary critical level, $I_c$. The cross-hatched areas represent the total energy above this critical level which can be used to heat a home, heat water, charge a battery, etc. On the cloudy day, the insolation is too low to contribute any useful energy for the desired goal. The clear day receives the most irradiation, and therefore has the largest area above the critical level.

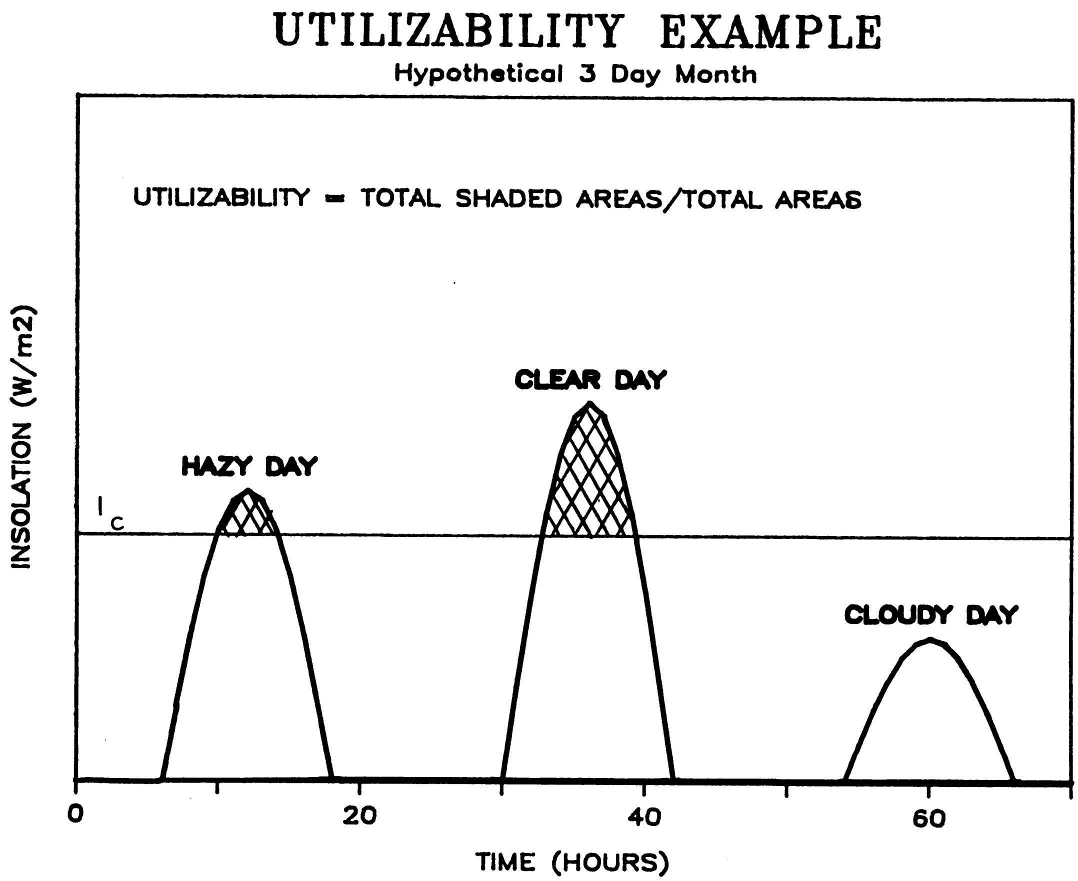



Figure 4.1: Utilizability Example for Hypothetical Month.

The distribution of hazy, clear, and cloudy days varies for every month. Months with all clear days will have high utilizability values for a given critical level, while months with all cloudy days will have low utilizability values. Months with a combination of hazy, clear, and cloudy days will have a higher utilizability than months with the same total irradiation, but with all hazy days. Figure 4.2 shows the same hypothetical 3 day month, in comparison to a month with all hazy days. The total areas under both sets of curves are equal. However, the month with the variable weather results in more energy above the critical level than the constant weather month.

Since utilizability depends on this distribution of hazy, clear, and cloudy days, it is considered as a solar radiation statistic. Using this statistic, the useful energy above a known critical level can be calculated, given the expected total irradiation for the month. This useful energy can then be used for design calculations.

The utilizability concept was first proposed by Whillier [35], as an approach to predict the long-term performance of flat-plate solar collectors. Since then, the utilizability concept has been expanded for many uses, as summarized by Klein and Beckman [17]. In general, utilizability is applicable for analysis of solar processes with constant critical levels or as theoretical limits for processes with variable critical levels.

Many correlations have also been developed to calculate the utilizability for a given critical level and surface orientation, usual-

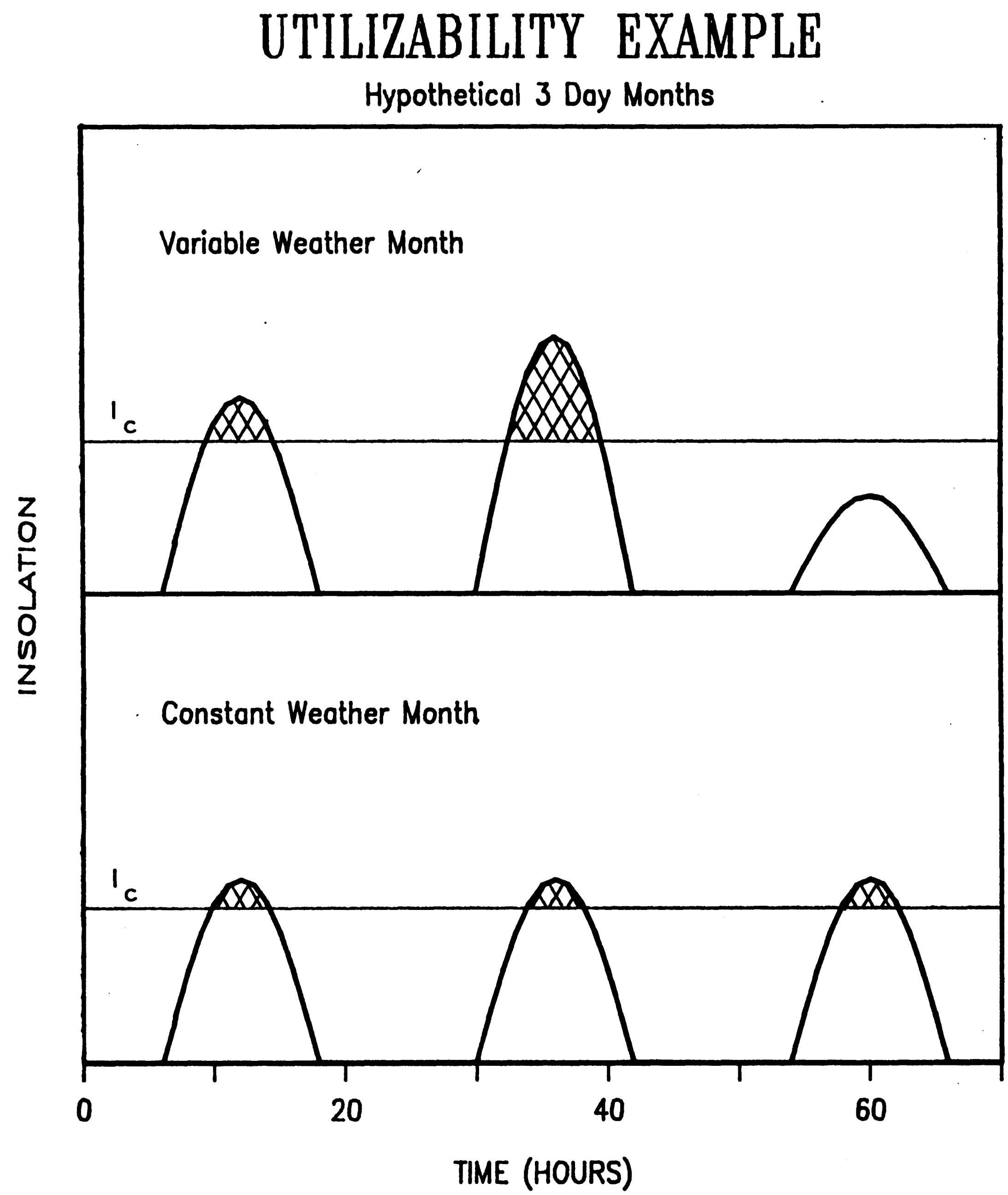



Figure 4.2: Utilizability Comparison Example for Two Hypothetical Months.

ly south-facing surfaces [17]. Because utilizability is a solar radiation statistic, correlations produce long-term monthly-average daily $\overline{\phi}$ values or long-term monthly-average hourly $\phi$ values.

## 4.2 Utilizability Calculation Methods

Utilizability correlations are useful engineering design tools for statistically calculating long-term energy above critical levels. The accuracy of these correlations are important, as both underestimating and overestimating usable energy is undesirable.

By nature of the utilizability concept, periods with large variation in insolation levels produce larger utilizability values than constant insolation values, as shown by Fig. 4.2. Therefore, the time-step that insolation is measured over also becomes important. Large time-steps average insolation levels over the given period, decreasing the effect of the larger values. Large time-steps therefore decrease the apparant utilizable energy that is above a given critical level.

Figure 4.3 shows the importance of the time-step in calculating the utilizable energy. Instrument A represents insolation measured in steps equal to 1 time unit. During the first unit of time, the insolation was above the shown critical level, indicating utilizable energy. Instrument B received the same total insolation, but measured this radiation with a time-step equal to 3 units. As is typical for radiation measuring devices, the insolation was averaged over the time-step. Even though both instruments are measuring the same insolation, instrument A recorded utilizable energy, while

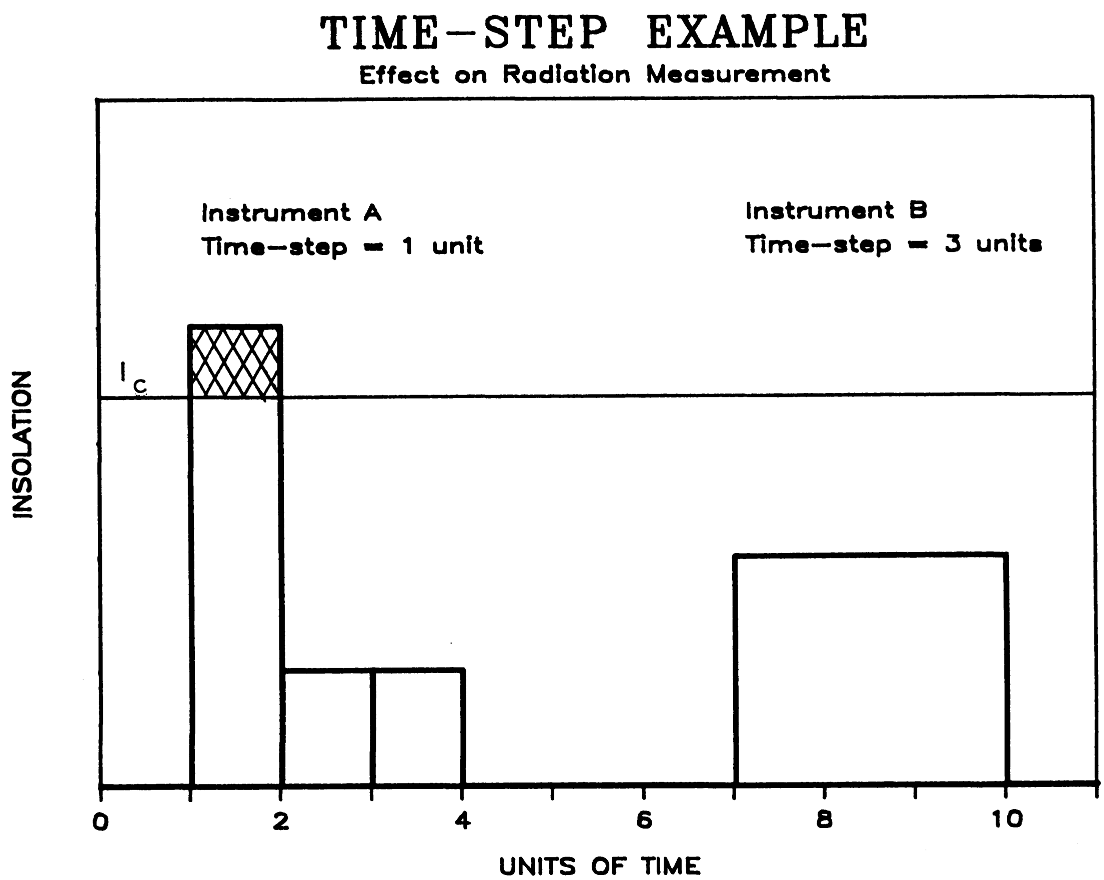



Figure 4.3: Generic Comparison of Time-Steps in Representing Radiation Data.

instrument B "washed out" the period of high insolation and therefore shows no utilizable energy.

Existing correlations were developed from hour data, but as shown above and in Chapter 3, hour data is not always an accurate representation of actual insolation levels. The SEMRTS data provides valuable information about insolation on a minute-by-minute basis. The SEMRTS data also provides insolation information for surfaces at several orientations. Therefore a comparison was made of monthly-average hourly and monthly-average daily utilizability values calculated from hour data, minute data, and Clark's [2] monthly-average hourly correlation.

#### 4.2.1 Utilizability From Data

For a given surface, utilizability is the summation of all insolation above a critical level divided by the summation of the total insolation. For monthly-average hourly utilizability, this can be written as:

$$\phi = \frac{\sum^{N} (I_T - I_c)^+}{\sum^{N} I_T} \tag{4.1}$$

where $(I_T - I_c)^+$ implies positive values only, and N = days in month [17]. Similarly, monthly-average daily utilizability can be written as:

$$\bar{\phi} = \frac{\sum^{N} \sum^{hrs} (I_T - I_c)^+}{\sum^{N} \sum^{hrs} I_T} \tag{4.2}$$

Both functions are easily programmed to process real data. For this study, both the minute data and the hour data were used to calculate utilizability. For the minute data, an extra summation was required to account for the 60 minutes that constitute an hour.

4.2.2 Clark's Correlation

Many algorithms exist for calculating the utilizability on south-facing surfaces. Some methods analytically integrate energy levels represented by long-term clearness frequency distributions, and then calculate monthly utilizability for a given critical level [17]. Clark [2] took a different approach by directly correlating calculated values of hourly utilizability obtained from many years of hourly horizontal insolation data. The resulting correlation was for monthly-average hourly utilizability for all surface orientations.

Clark's data base consisted of 23 years from Madison, Wisconsin; 23 years from Albuquerque, New Mexico; and 15 years from Seattle, Washington. In a comparison to numerically integrated data values, Clark's method had a root mean square error of 5% [17]. Consequently, due to its accuracy, surface versatility, and algebraic simplicity, it was chosen as the existing algorithm to compare with data values.

Clark defined his correlation in terms of the critical insolation ratio $X_c$, and the "minimum" critical insolation ratio $X_m$. The critical insolation ratio is a common dimensionless expression for the critical level divided by the monthly-average radiation on the surface, or

$$X_c = \frac{I_c}{\bar{I}_T} \tag{4.3}$$

$X_m$ is therefore the minimum critical insolation level where the utilizability equals 0. Using these ratios, the hourly utilizability correlation was expressed as:

$$\phi = \begin{cases} 0 , & X_c \geq X_m \\ (1 - (X_c/X_m))^2 , & X_m = 2 \\ |a| - \sqrt{a^2 + (1 + 2a)((X_m - X_c)/X_m)^2} , & \text{otherwise} \end{cases} \tag{4.4}$$

where $$a = \frac{X_m - 1}{2 - X_m}$$

After attempts to derive equations for $X_m$ from general equations, Clark empirically found the minimum critical level to best be represented by:

$$X_m = 1.85 + 0.169 \frac{\tilde{R}}{\bar{k}_T^2} - 0.0696 \frac{\cos \beta}{\bar{k}_T^2} - 0.981 \frac{\bar{k}_T}{(\cos \delta)^2} \tag{4.5}$$

For a given location, orientation, and critical level, the required input parameters for Clark's correlation are the monthly-average hourly clearness index, $\bar{k}_T$ and monthly-average hourly radiation ratios, $\tilde{R}$. As shown in Chapter 2, $\tilde{R}$ can be correlated to the monthly-average hourly clearness index, making $\bar{k}_T$ the only independent parameter. Since utilizability is usually desired for more than one hour, algorithms use the monthly-average daily clearness index, $\bar{K}_T$ along with the $r_d/r_t$ relation presented in Chapter 2, to estimate $\bar{k}_T$. The $\bar{K}_T$, $\bar{k}_T$ relation is as follows:

$$\bar{k}_T = \frac{r_t}{r_d} \bar{K}_T \tag{4.6}$$

where $r_t/r_d$ equals the reciprocal of Eq. (2.13).

Insolation levels and the resulting utilizability vary from year to year. Clark's correlation was developed from 61 years of data, and therefore represents long-term or average utilizability levels. Long-term $\bar{K}_T$'s are used in design applications to estimate average utilizability for a given location. However, the Albany and San Antonio data sets represent only one year periods. To allow comparison between data and Clark utilizability values under "identical" short-term conditions, clearness indexes calculated from the data base were used.

To investigate the different sources of error in Clark's correlation, three different approaches were devised. The $\bar{k}_T$ algorithm using $r_t/r_d$ assumes symmetrical insolation levels about noon. Due to actual asymmetries found in the data, the first approach used $\bar{k}_T$'s calculated from the data. The monthly-average hourly radiation ratios were calculated from the isotropic model (Eq. 2.8), with Erbs' $\bar{H}_d/\bar{H}$ correlation (Eq. 2.14) and the $r_d/r_t$ relation as shown in Chapter 2.

Method two used the actual monthly-average daily clearness indexes, along with the $r_t/r_d$ relation to calculate the $\bar{k}_T$'s. This approximates typical usage of Clark's correlation with the symmetrical insolation level assumption, but still under "identical" monthly-average daily conditions. The isotropic model was still used to calculate $\tilde{R}$.

Method three used the actual monthly-average hourly clearness index again, along with actual monthly-average hourly radiation ratios. This eliminates any error from radiation ratio assumptions and modeling, and therefore is considered the most accurate version of Clark's correlation used in this study.

4.2.3 Critical Level Calculation

Due to varying amounts of radiation a surface receives during a year, appropriate critical levels for each surface were calculated for each month. Calculating new monthly critical levels allows the same number of utilizability values under all conditions, which is required for RMS error comparisons (see Section 4.2.4).

Eleven critical levels were calculated for each surface, based on a percentage of the maximum noon-time irradiation. An approximation of the noon-time radiation was derived by multiplying the horizontal extraterrestrial irradiation $I_o$ (see Eq. 2.13) by the noon-time value of $R_b$,

$$I_{noon} = I_o R_b \big|_{noon} = I_o \left.\frac{\cos(\theta)}{\cos(\theta_z)}\right|_{noon} \qquad (4.7)$$

For noon, $w_1$ = -7.5° and $w_2$ = 7.5°. Since these are small angles, sin ($w_2$) - sin ($w_1$) approximately equals $w_2 - w_1$, which equals 0.262 radians. Also, the earth-sun distance correction term can be approximated by 1.03. Consequently, the horizontal extraterrestrial equation can be rewritten as:

$$I_o = 13{,}750\ G_{sc}(1.03)(0.262)[\cos(\phi)\cos(\delta) + \sin(\phi)\sin(\delta)] \quad (4.8)$$

where for this application, $\phi$ equals the latitude. Now, $\cos(\theta_z)_{noon} = \cos(\phi)\cos(\delta) + \sin(\phi)\sin(\delta)$. Therefore, combining Eqs. (4.7) and (4.8),

$$I_{noon} = 13{,}750\ G_{sc}(1.03)(0.262)\cos(\theta)$$

or,

$$I_{noon} = 5{,}020\ \text{Kw/m}^2 \cos(\theta)\ . \quad (4.9)$$

To aid in the computer programming, the same critical levels were used for both daily and hourly utilizability calculations. For J varying between 1 and 11, the critical level equation was:

$$I_c = 495\ (\text{KJ/m}^2)\ K_{max}\ C\ (J - 1). \quad (4.10)$$

$K_{max}$ was a polynomial equation equal to the Bendt et al. [1] $K_{max}$ term described in Chapter 3, where:

$$K_{max} = 0.2075 + 2.771\, \overline{K}_T - 4.750\, \overline{K}_T^2 + 2.917\, \overline{K}_T^3 \qquad (4.11)$$

and C is a variable defined by the surface orientation. For horizontal and most south-facing surfaces:

$$C = \cos\,(\theta)_{noon}\ .$$

Otherwise, for

| | |
|---|---|
| East & West surfaces: | $C = 0.7\ K_T$ (Albany) |
| | $C = 0.8\ K_T$ (San Antonio) |
| North surfaces: | $C = 0.3\ K_T$ |
| South surfaces, | |
| for $\cos\,(\theta)_{noon} < 0.3$: | $C = 0.3$ |

These critical levels allowed 8 to 11 non-zero daily utilizability values and 6 to 11 non-zero hourly utilizability values to be calculated for all conditions. Usually, 10 to 11 non-zero values resulted. For each case considered, only the first zero utilizability values were included in the RMS error comparisons. The other zero utilizability values provided redundant information, and therefore were considered invalid for RMS error calculation.

4.2.4 RMS error Calculation

With a total of 24 months of data, each with 8 global radiation measuring instruments and various methods of calculating the hourly and daily utilizability, it is necessary to find a systematic and efficient approach for comparing the results. Because of its small time step, the utilizability calculated from minute data is the most accurate of all methods used for this study. Consequently, all of the other methods were compared to the minute data results. To aid in this comparison, the RMS error was calculated using all valid utilizability values. As used here, the RMS error is:

$$\text{Utilizability RMS Error} = \sqrt{\frac{\sum_{I_c=1}^{J} (\phi_A - \phi_B)^2}{J - 1}} \qquad (4.12)$$

where $\phi_A$ is the minute data utilizability, and $\phi_B$ is the utilizability from one of the other four methods.

A large RMS error represents a pair of extremely different utilizability values, while a small RMS error represents a pair of virtually identical utilizability values. To find a cut-off RMS error value between identical and unidentical utilizability values, RMS error values were compared to graphs of the utilizabilities versus critical levels. Based on these comparisons, an RMS error of 0.02 or less represents an approximately identical set of utilizability values for the given range of critical levels. Figure 4.4 shows an example of minute data and hour data utilizability values having an RMS error of 0.02.

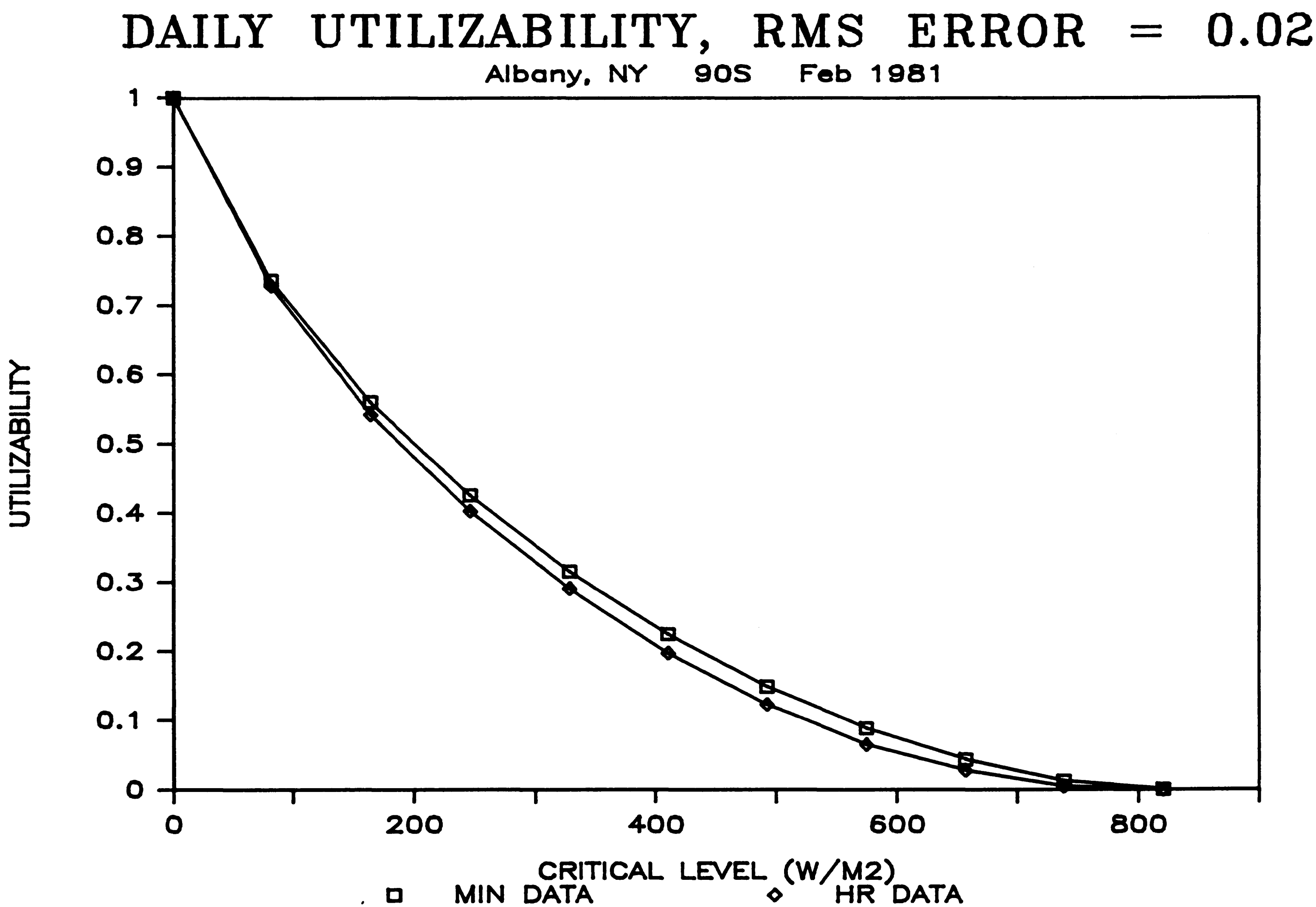



Figure 4.4: Utilizability Example of a 0.02 RMS error.

In Fig. 4.4, the utilizability from the minute data is greater than the utilizability from the hour data, as previously discussed. Also, at a critical level equal to 0 $W/m^2$, both methods show a utilizability equal to 1, indicating that all of the energy is "utilizable". Due to this common "starting point" of 1, deviation between utilizability values calculated from any two methods occurs at nonzero critical levels.

### 4.2.5 Utilizability Method Abbreviations

Five methods of calculating utilizability were used in this study. Two methods used only measured data: minute data, or hour data. The other three methods utilized a form of Clark's correlation, as discussed in Section 4.2.2. To avoid confusion, the RMS error graphs presented in the following sections used label abbreviations to designate the appropriate method. The following key describes these abbreviations:

MN = Numbers from Minute Data

HR = Numbers from Hour Data

CL(k) = Numbers from Clark's correlation, with actual $\bar{k}_T$ input

CL = Numbers from Clark's correlation, with actual $\bar{K}_T$ input

CL(kR) = Numbers from Clark's correlation, with actual $\bar{k}_T$ and $\tilde{R}$ input

The RMS error between any two methods is therefore designated by hyphenating the two abbreviations.

## 4.3 Monthly-Average Hourly Utilizability

Monthly-average hourly utilizability is useful for analysis of solar processes where critical levels change during the monthly-average day. Defining independent critical levels for each monthly-average hour may yield a better prediction of the solar process performance, then assuming a constant critical level during the entire monthly-average day.

To find areas for improving $\phi$ correlations, results from the five calculation methods previously discussed were compared. Due to the number of surfaces studied, the comparisons have been categorized by surface orientation. All comparisons are for the hour 12-13.

### 4.3.1 South-Facing Surfaces at Slope Equal to Latitude

Figures 4.5 and 4.6 show the $\phi$ RMS error for the five methods of calculating utilizability during hour 12-13. Figure 4.5 is for San Antonio, while Fig. 4.6 is for Albany. The acceptable $\phi$ RMS error of 0.02 has been drawn in for reference. Within each of these bar graphs are several points of interest worth discussing.

#### A. Hour Data versus Minute Data:

For both San Antonio and Albany, the $\phi$ RMS error between the minute data and hour data exceeded 0.02 for seven of the twelve months. In a few cases, the difference between the hour data and minute data values are very noticeable: 0.041 for March in Albany, and 0.054 for June in San Antonio.

Figures 4.7 and 4.8 show the utilizability values for one month with an extremely low and with a high RMS error, respectively.

FIG. 4.5 UTILIZABILITY RMS ERROR

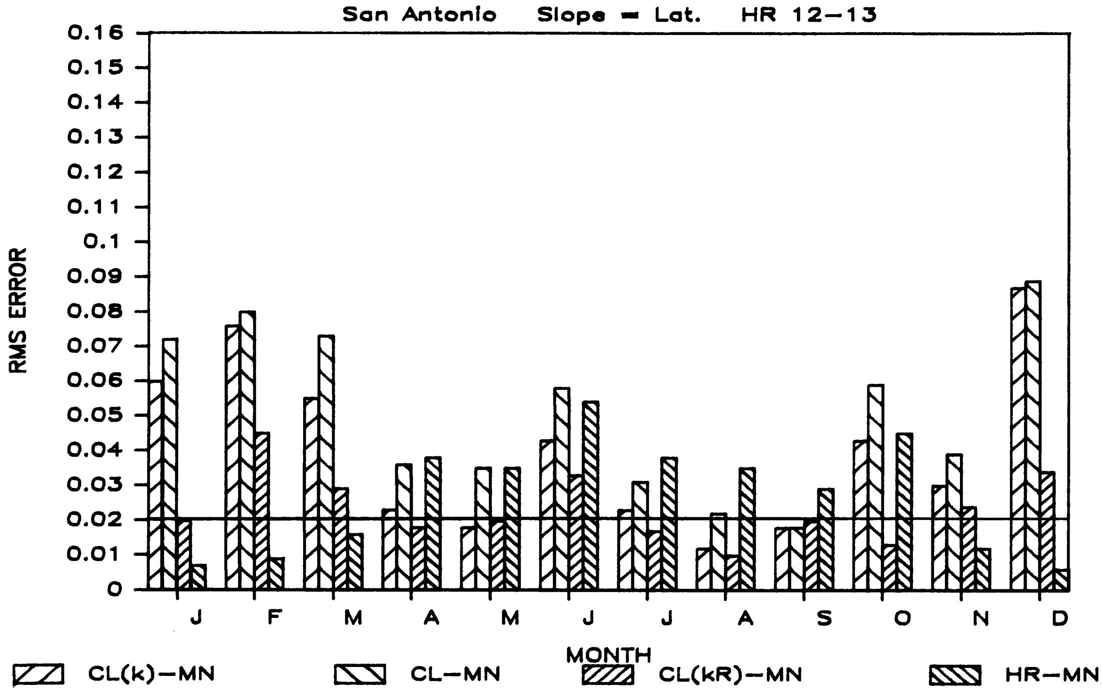
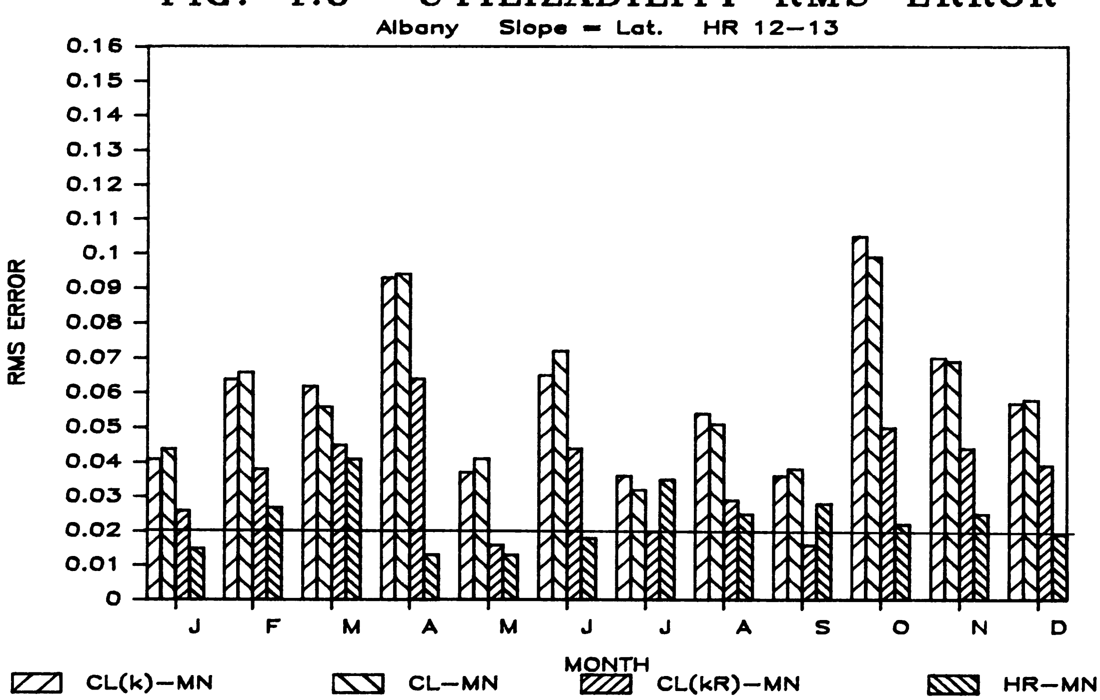



FIG. 4.6 UTILIZABILITY RMS ERROR



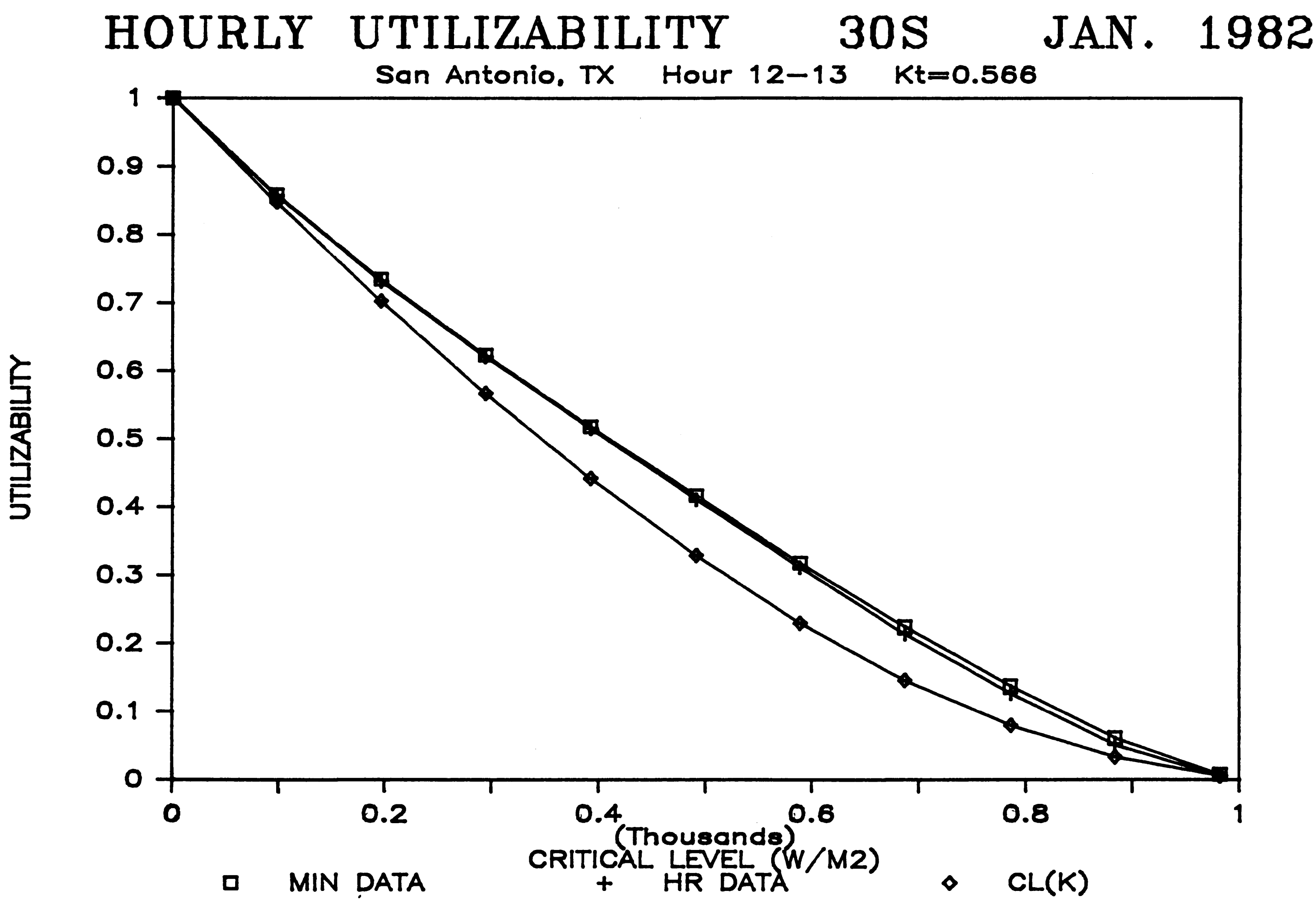



Figure 4.7: Monthly-average Hourly Utilizability Values.

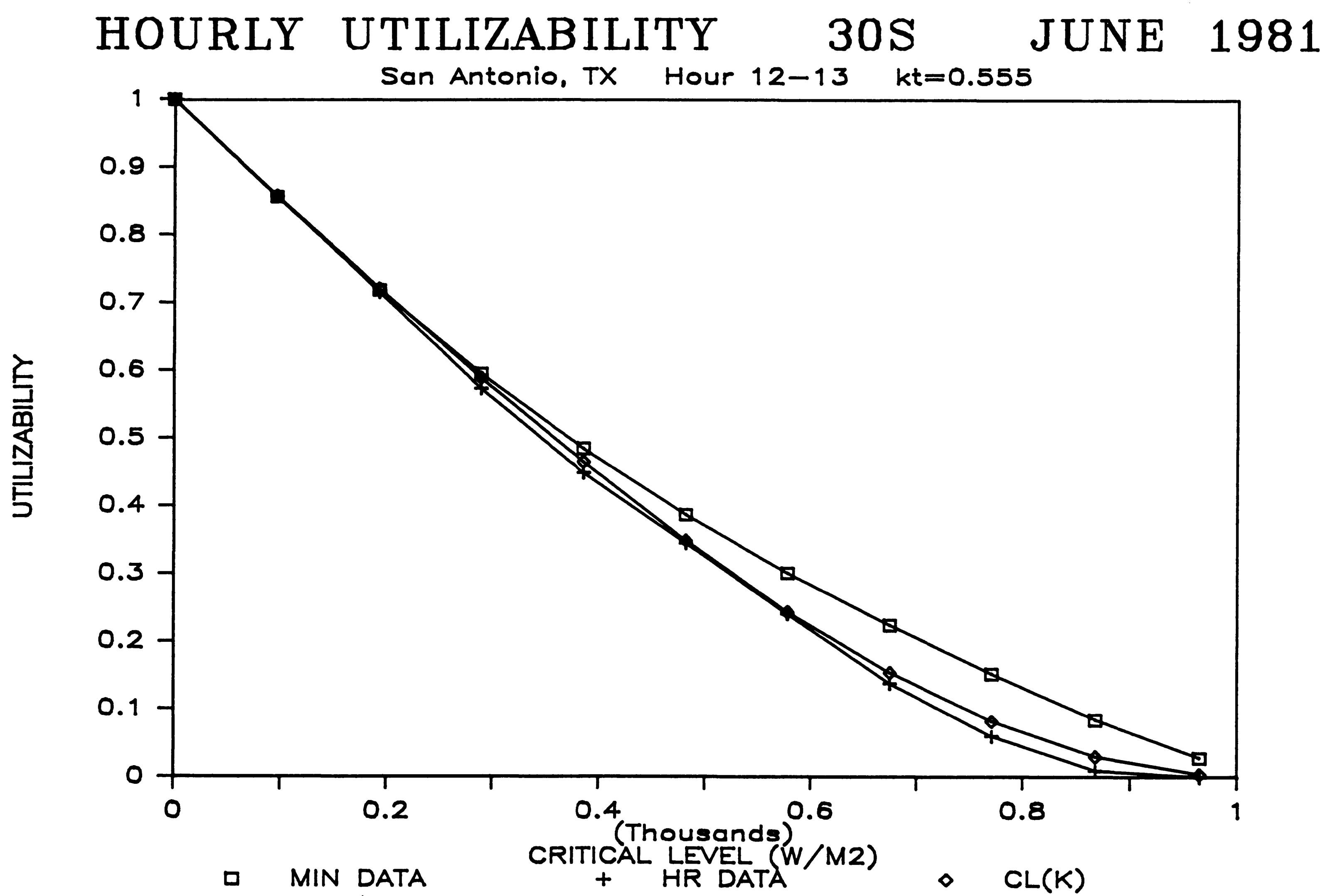



Figure 4.8: Monthly-average Hourly Utilizability Values.

Figure 4.7 is for San Antonio in January, and Fig. 4.8 is for San Antonio in June. Both utilizability graphs show values calculated from the minute data, hour data, and Clark's correlation using actual $\bar{k}_T$'s. The minute data versus hour data $\phi$ RMS error for San Antonio in January is 0.007, which is very acceptable. As seen in Fig. 4.7, the hour data and minute data utilizabilities are almost coincident. The Clark utilizability values will be discussed later.

In contrast, the minute data versus hour data $\phi$ RMS error for San Antonio in June (Fig. 4.8) is a very large 0.054. For June, the minute data provides valuable insolation information that was lost in the hour data. At a critical level of 400 $W/m^2$, the minute data shows an approximate 9% increase from the hour data in utilizable energy.

The importance of using minute data for south-facing $\phi$ calculations is related to the differences between the minute data and hour data clearness frequency distributions discussed in Chapter 3. The clearness frequency distribution is a form of insolation profile for the given month. Therefore, the "steeper" the frequency distribution (more variability in insolation), the larger the utilizability.

Figure 3.11 shows the difference in clearness frequency distributions between the minute data and hour data for June in San Antonio for the hourly period 12-13. The minute data distribution is much steeper than the hour data distribution, and as expected, the utilizability from the minute data in Fig. 4.8 is much larger than the utilizability from the hour data. Similarly, Fig. 3.5 - January in

San Antonio - show almost identical distributions from both the minute data and hour data for the 12-13 hour period. As expected, the utilizabilities calculated from the minute data and hour data are also almost identical.

B. Clark Methods versus Minute Data:

Figures 4.5 and 4.6 also show the $\phi$ RMS error between the three Clark methods and the minute data. In most cases, the utilizability calculated from Clark's correlation using actual $\bar{k}_T$'s, CL(k)-MN, is significantly different than the utilizability calculated from the minute data. These large RMS errors are surprising, considering the insolation conditions are suppose to be identical, as defined by $\bar{k}_T$. The reasons for these differences in utilizability values may be threefold:

1) the minute data clearness frequency distributions for hourly periods do not coincide with the long-term hourly distribution built into Clark's correlation;
2) Clark's correlation poorly represents long-term hourly data; and
3) the isotropic radiation model used in Clark's correlation is inaccurate.

Clark's correlation was not derived from known long-term frequency distributions, although it was fitted to long-term hour utilizability data that would have represented these distributions. As shown in Chapter 3, the minute data clearness frequency distributions for hourly periods are always different from the generally accepted long-term distributions. Therefore, the differences between minute data clearness frequency distributions for hourly periods and long-term hourly frequency distributions, will account for some of the differences between Clark's utilizability values and minute data values.

The theory of Clark's correlation not accurately representing long-term distributions can not be substantiated. Using actual $\overline{K}_T$'s and $\tilde{R}$'s in Clark's correlation eliminates "outside" sources of errors. Therefore, the $\phi$ RMS errors shown by the CL(kR)-MN bars represent the errors from minute data not representing long-term hourly distributions along with inherent correlation errors. These two sources of errors can not be separated. Figures 4.5 and 4.6 show the net effect of the minute data and correlation errors are below the allowed 0.02 RMS error in 10 of the 24 months studied. For other months, these RMS errors are significant, especially in Albany. However, without a larger data base, conclusive statements concerning the long-term accuracy of Clark's correlation can not be made.

While the CL(kR)-MN error bars representing these minute data and correlation errors are sometimes significant, the CL(kR)-MN $\phi$ RMS errors are the smallest of the three Clark methods, indicating that another source of error is also present.

Comparing the CL(k)-MN RMS error bars to the CL(kR)-MN bars on Figs. 4.5 and 4.6, show the largest error in Clark's correlation is usually caused by using the isotropic radiation model with Erbs' $\overline{H}_d/\overline{H}$ model. The CL(k)-MN error bars typically are substantially the larger of the $\phi$ RMS error bars shown. Only on two occasions, March and September in San Antonio, did the $\phi$ RMS error increase by using the actual R's. For both of these cases, the increase was small, and the $\phi$ RMS error was still within the acceptable 0.02 range. The other 22 months show large reductions in the $\phi$ RMS error with the use of the correct radiation ratio in Clark's correlation. This finding supports the need to improve the monthly-average hourly radiation ratio model.

Figure 4.7, January in San Antonio, includes the CL(k) utilizability values along with the previously discussed minute data and hour data values. The 0.06 RMS error reflects the underestimation of minute data $\phi$ by Clark's correlation using the isotropic model.

Comparing the $\phi$ RMS error bars between CL(k)-MN and CL-MN shows the effect of using the $r_t/r_d$ correlation between daily and hourly values. For San Antonio, using $\overline{K}_T$'s and $r_t/r_d$ usually caused noticeable increase in the $\phi$ RMS error, implying the distribution of $\overline{k}_T$'s within the monthly-average day did not represent the long-term distributions. Since Clark's correlation is dependent on $\overline{k}_T$, the incorrect estimation of $\overline{k}_T$ caused erroneous calculation of the utilizability. For Albany, the RMS error occasionally decreased, but never significantly. Compared to the other RMS errors for both San Antonio and Albany, the largest error in Clark's correlation is still caused by using the monthly-average hourly isotropic radiation model with Erbs' $\overline{H}_d/\overline{H}$ correlation.

## 4.3.2 South-Facing Vertical Surfaces

Figures 4.9 and 4.10 show the $\phi$ RMS errors for south-facing vertical surfaces in San Antonio and Albany, respectively. The same trends that are found for south-facing surfaces equal to latitude, can also be seen here. The hour data and minute data occasionally give different results as shown by the HR-MN bars, but the differences are usually slightly smaller than the differences for slope equal to latitude. Most of the hour data versus minute data errors are around the acceptable 0.02 RMS error. As shown in the slope equal to latitude $\phi$ RMS errors, the differences between using $\overline{k}_T$ and $\overline{K}_T$ in Clark's correlation, CL(k)-MN versus CL-MN, is usually negligible.

For San Antonio, the largest source of error in Clark's correlation is the radiation ratio model, as is seen by comparing CL(k)-MN to CL(kR)-MN. The largest RMS error shown by CL(k)-MN occurs during winter months where the RMS error may be as high as 0.145. This pattern of large utilizability errors during winter months corresponds to the large winter $\tilde{R}$ errors found in the isotropic radiation ratio analysis in Chapter 2. During winter months when the sun is low in the sky, the normal component of beam and circumsolar diffuse radiation increases on vertical south-facing surfaces. Since the isotropic model lacks a circumsolar diffuse radiation component, the underestimation of radiation increases, which decreases the estimation of utilizable energy. The estimation of $\overline{H}_d/\overline{H}$ is also large during winter months, as shown in Fig. 2.1. This overestimation of

FIG. 4.9 UTILIZABILITY RMS ERROR

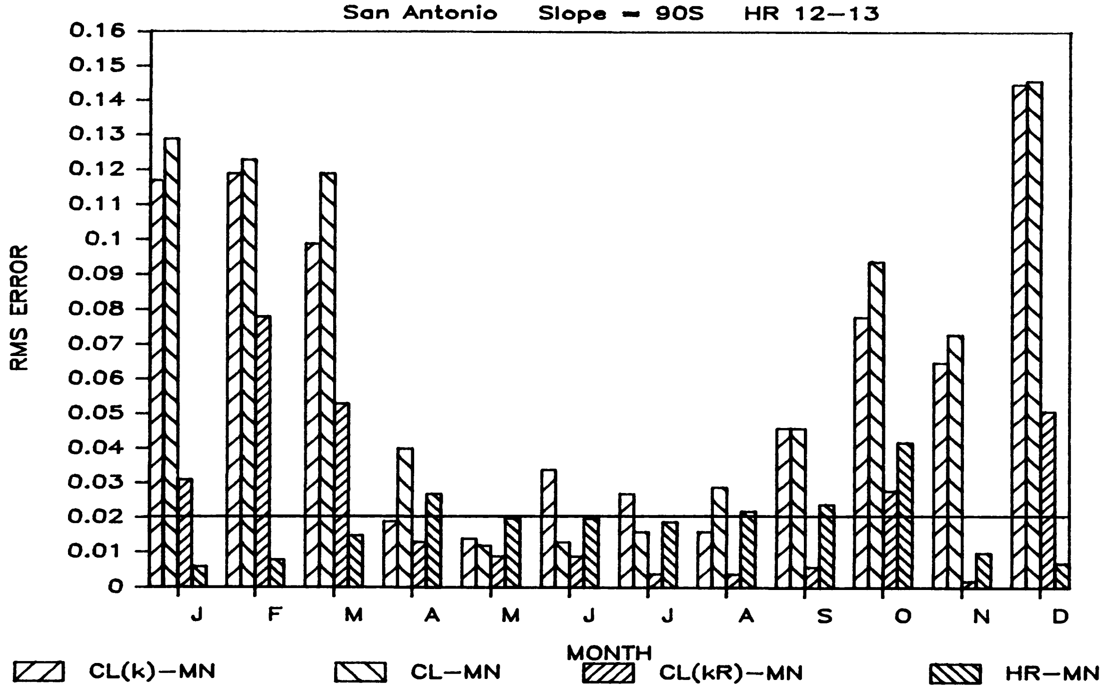
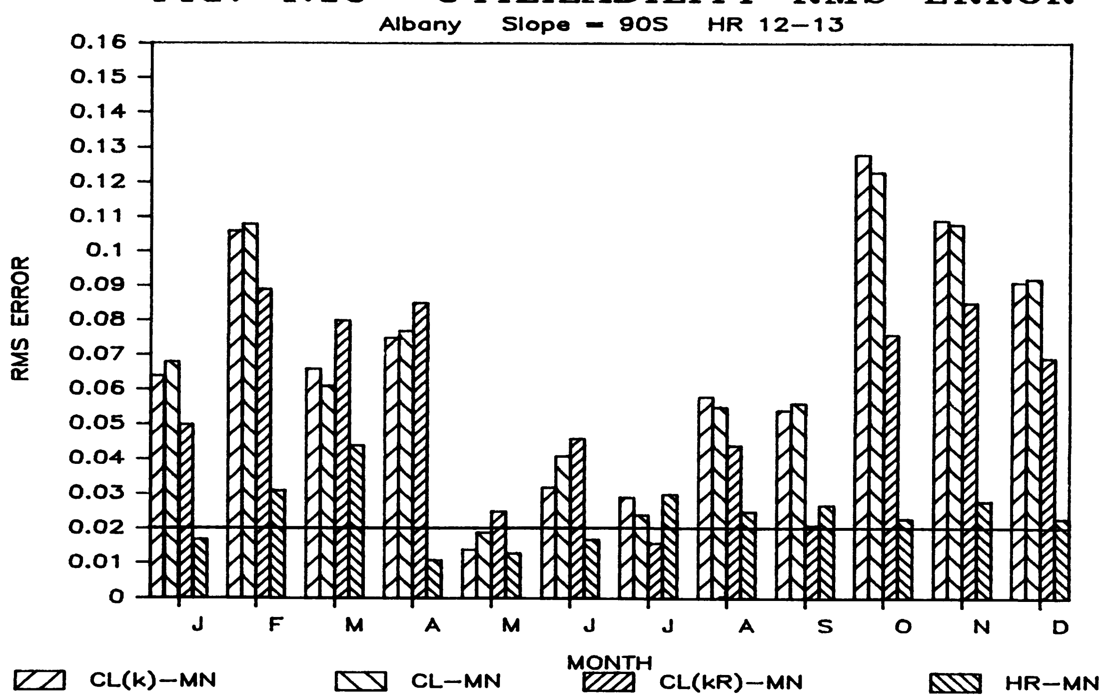



FIG. 4.10 UTILIZABILITY RMS ERROR



diffuse radiation underestimates the beam radiation component in the isotropic model, which adds a second source of error in the estimation of south-facing tilted surface radiation.

Figure 4.11 shows the minute data, CL(k), and CL(kR) utilizability values for December, where the CL(k)-MN RMS error is 0.145 and the CL(kR)-MN RMS error is 0.05. As expected for Clark's correlation using the isotropic model, CL(k) grossly underestimates the minute data values. At a 400 $W/m^2$ critical level, CL(k) shows a utilizability value that is 58% of the minute data value. Although this error results from comparing a long-term correlation to one month of data, an underestimation in utilizable energy by 42% would be a substantial error for a solar heating system during winter months.

For all critical levels, Clark's correlation using actual radiation ratios CL(kR), better estimates the minute data $\phi$ values than CL(k). At a 400 $W/m^2$ critical level, CL(kR) underestimates the minute data value by 16%. While a 16% error is still large, the underestimation of minute data $\phi$ by Clark's correlation is reduced by 26 percentage points, just by using the actual $\tilde{R}$. The 16% error is attributed to the minute data not corresponding to long-term hourly distributions, and to inherent correlation error in Clark's model.

For Albany - Fig. 4.10, the RMS error bars for CL(kR)-MN indicate the combined effect of Clark's correlation misrepresenting long-term hour distributions and the minute data base differing from long-term hour distributions, are substantial for most months. Since the minute data represents only a one year data base, the differences be-

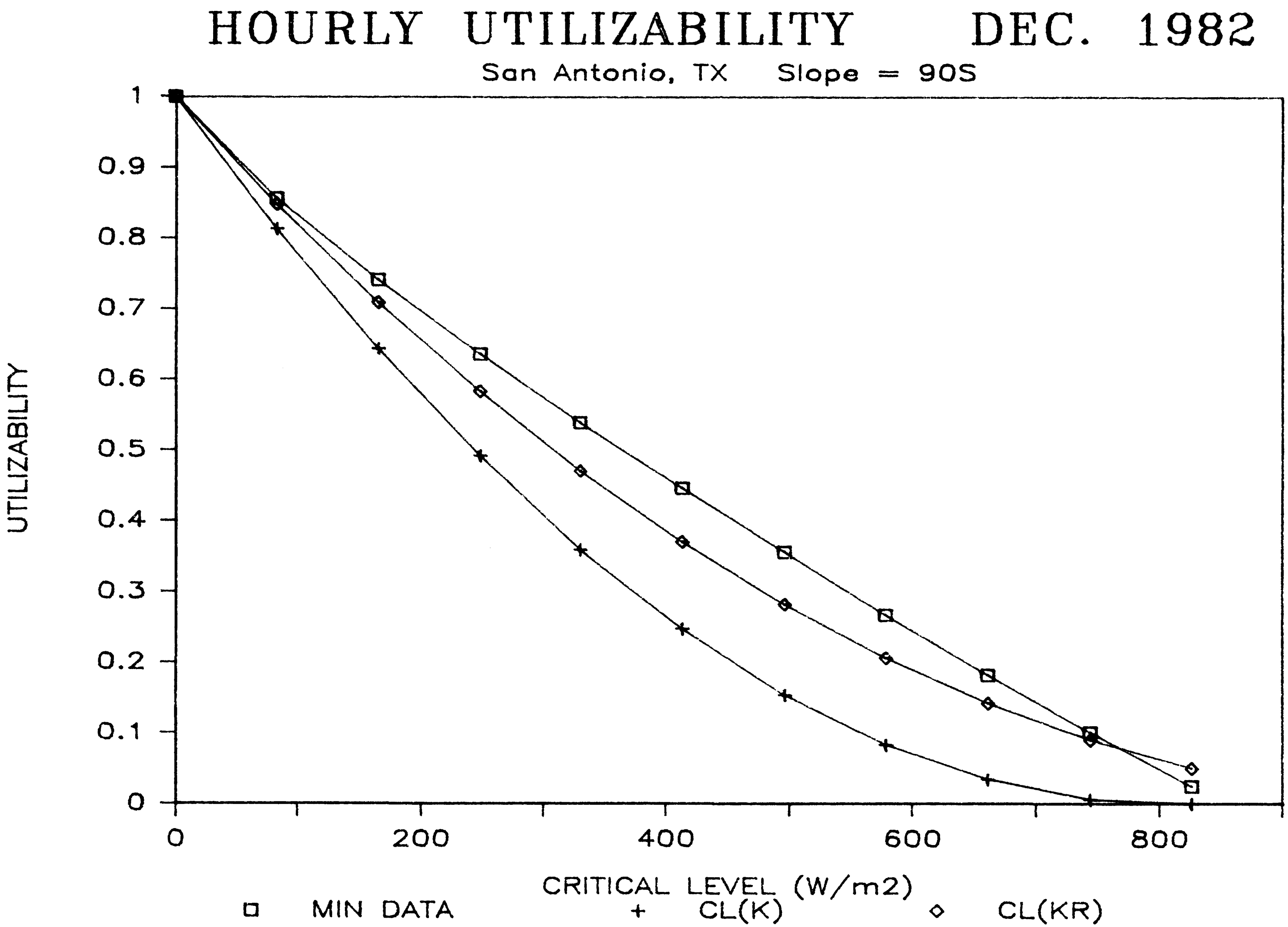



Figure 4.11: Monthly-Average Hourly Utilizability Values (Hour 12-13).

tween the minute data values and long-term hour distributions are suspected of causing the largest part of this error. As shown by the CL(k)-MN error bars, utilizability values calculated from Clark's correlation using the isotropic radiation model with Erbs' $\bar{H}_d/\bar{H}$ correlation are significant during winter months.

4.3.3 West-Facing Vertical Surfaces

Figures 4.12 and 4.13 show the $\phi$ RMS error for west-facing vertical surfaces in San Antonio and Albany, respectively. In San Antonio, the RMS errors are relatively small compared to the south-facing RMS errors. The worst RMS error is 0.045, which represents the difference between hour data and minute data utilizability. Because of the small and random changes in RMS error, no trends are found in the various utilizability calculation methods. In Albany, six months show substantial error in Clark's correlation using the isotropic radiation model. The worst cases show an RMS error around 0.17. However, as discussed in Chapter 3, some of the west-facing Albany data are questionable, which could cause these large differences in utilizability values between Clark's correlation and minute data.

4.3.4 North-Facing Vertical Surfaces

Figures 4.14 and 4.15 show the $\phi$ RMS error for north-facing vertical surfaces in San Antonio and Albany, respectively. For all 24 months studied, the difference in utilizability values between hour data and minute data are within the accepted 0.02 RMS error. The largest differences in minute data and hour data insolation

FIG. 4.12 UTILIZABILITY RMS ERROR

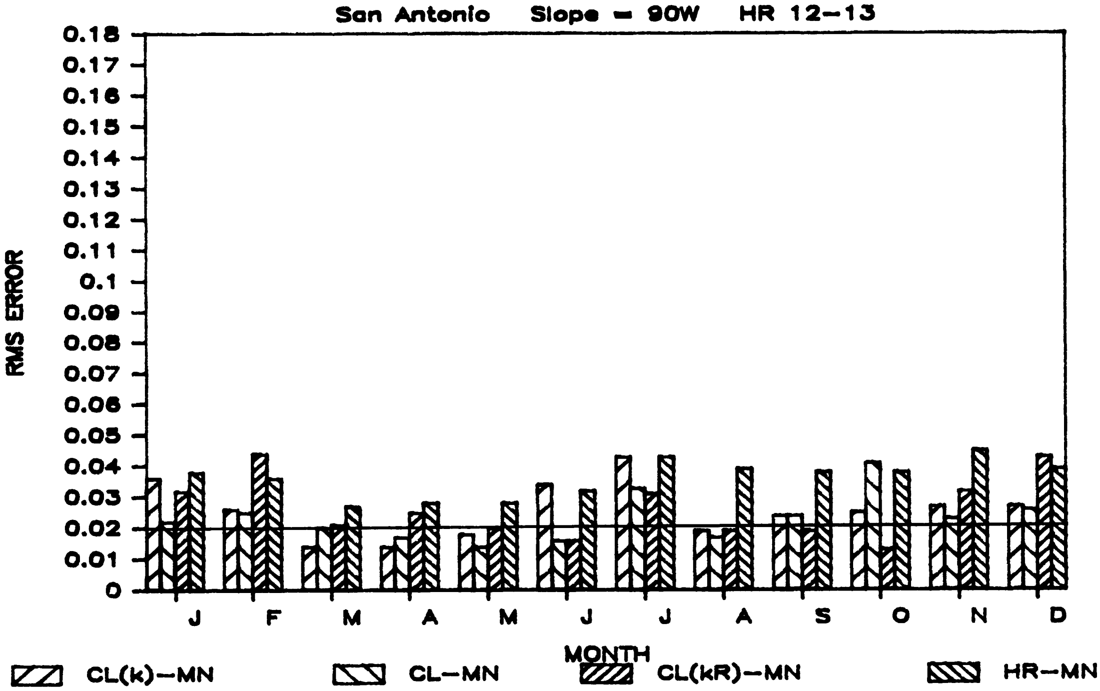



FIG. 4.13 UTILIZABILITY RMS ERROR

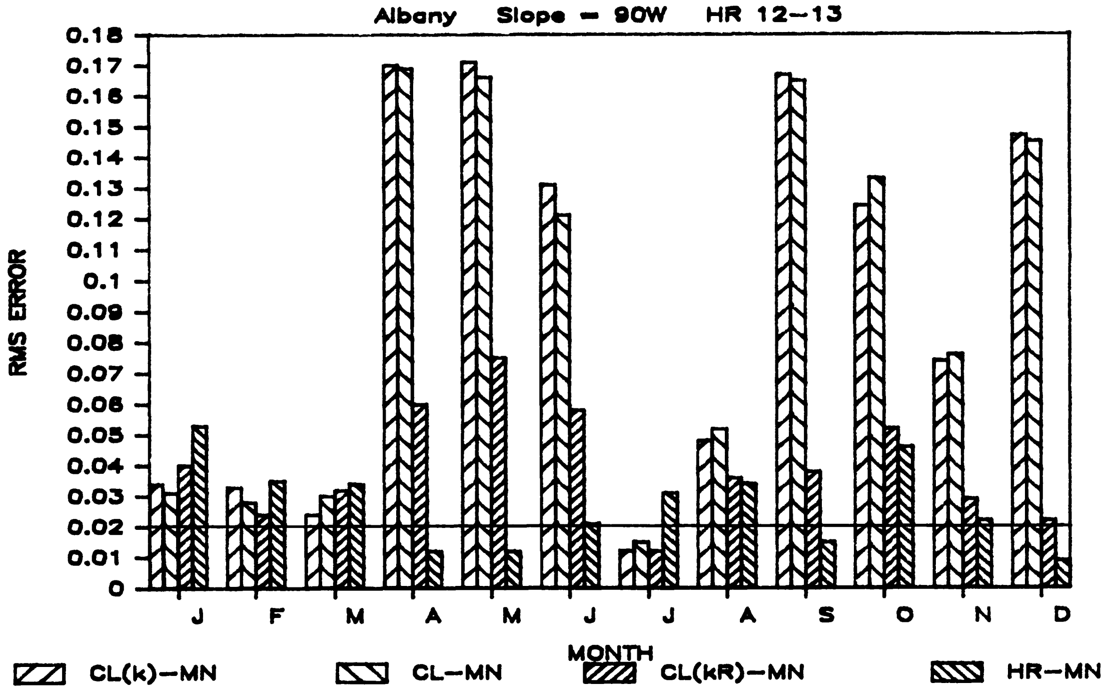


FIG. 4.14 UTILIZABILITY RMS ERROR

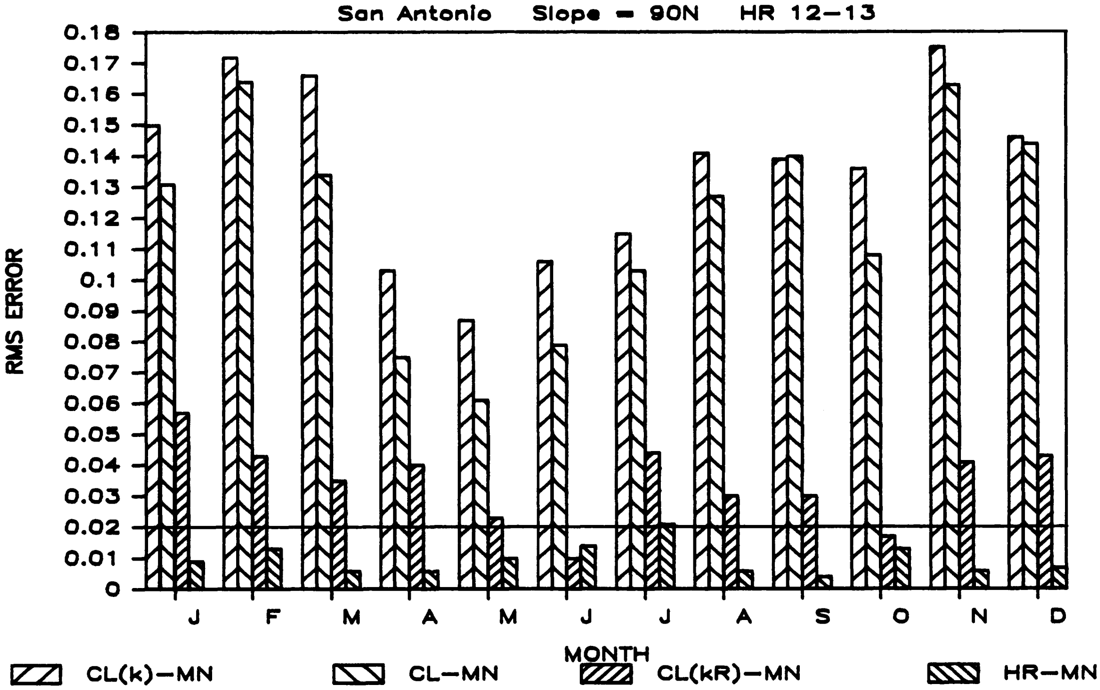
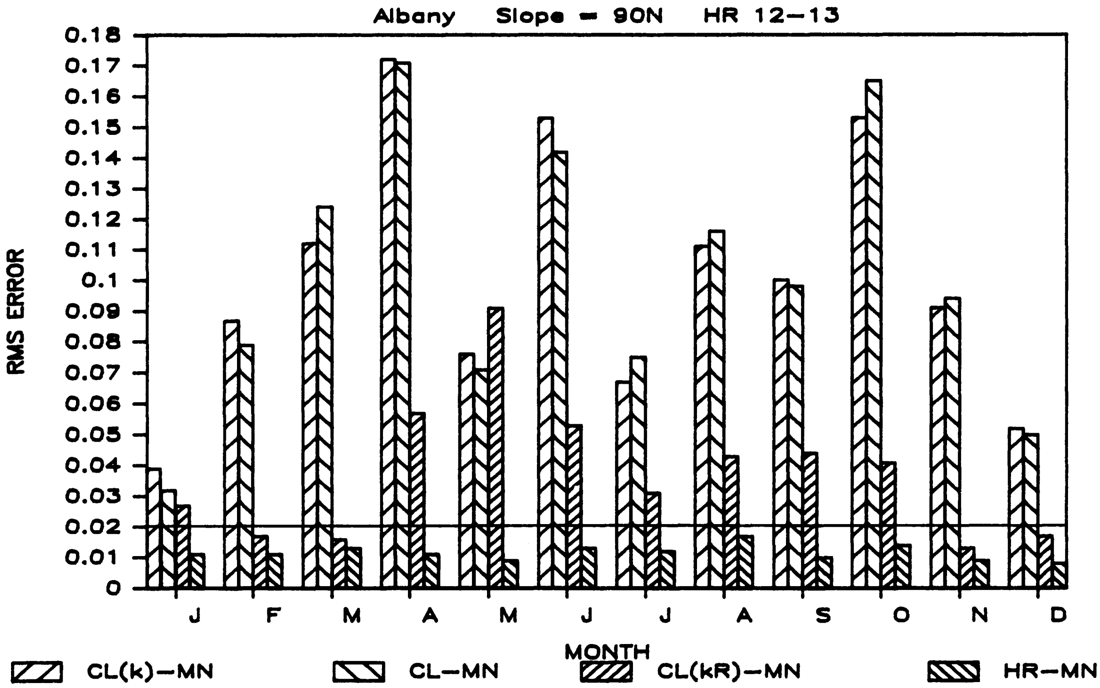



FIG. 4.15 UTILIZABILITY RMS ERROR



levels are thought to be caused from intermittent beam radiation. However, north-facing surfaces receive only diffuse and ground reflected radiation, except for possible early morning and late evening beam radiation during summer months. Therefore, the north-facing minute data and hour data insolation levels should be similar, as indicated by the low $\phi$ RMS errors.

The largest error associated with Clark's correlation is from the monthly-average hourly isotropic radiation model with Erbs' $\overline{H}_d/\overline{H}$ correlation. The worst cases show $\phi$ RMS errors exceeding 0.17. As shown in Chapter 2, the isotropic assumption noticeably overestimates the actual radiation on north-facing surfaces, which causes Clark's correlation to grossly overestimate the utilizable energy. A typical example is shown in Fig. 4.16 for April in Albany. Since north-facing surfaces receive low insolation levels, the critical levels are extremely low compared to south-facing surfaces. At a 70 W/m$^2$ critical level, CL(k) overestimates the minute data by 85%. Using the actual $\tilde{R}$ in Clark's correlation causes a 26% underestimation of the minute data value, as shown by CL(kR).

Another source of error in Clark's utilizability values are from the combined effects of Clark's correlation misrepresenting long-term data, and differences between this short-term minute data base and long-term hour insolation levels. The worst error for these effects is 0.09 in Albany during May. In this case, the $\phi$ RMS error increases by using actual $\tilde{R}$'s. For all other cases, using actual $\tilde{R}$'s in Clark's correlation decreases the $\phi$ RMS error.

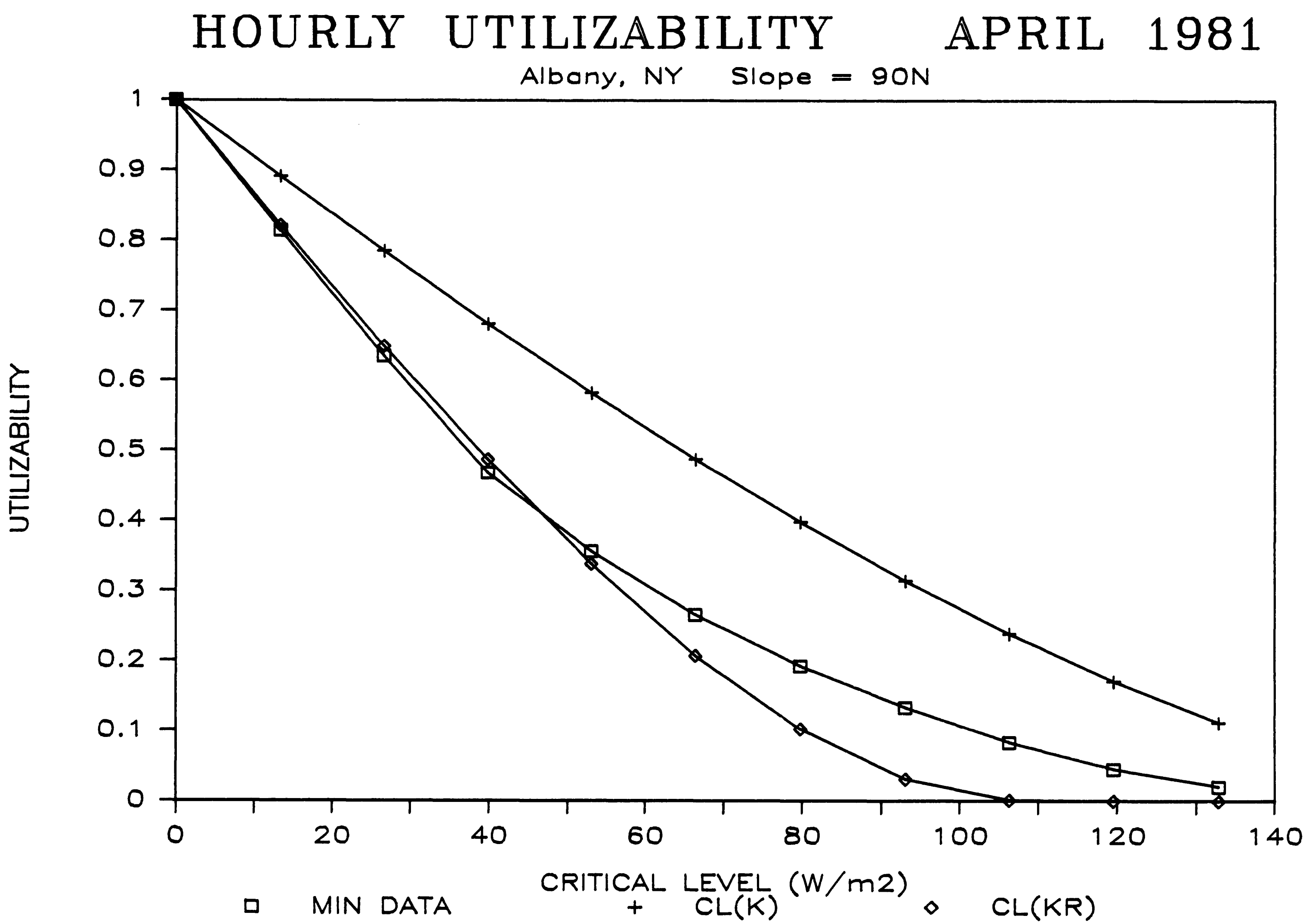



Figure 4.16: Monthly-Average Hourly Utilizability Values (Hour 12-13).

### 4.3.5 Summary of Monthly-Average Hourly Utilizability Comparisons

The comparison of utilizability values incorporates a short-term data base, and therefore conclusions concerning long-term effects can not be made. However, noteworthy indications have been found.

For south-facing surfaces during hour 12-13, half of the months studied show significant differences between minute data and hour data utilizabilities. This difference between minute data and hour data utilizability values is mostly attributed to variation in the beam component of radiation, caused by passing clouds. Although the long-term difference between minute and hour data are not known, a significant difference in utilizability is expected for some months with partly cloudy conditions (i.e., $\overline{K}_T \sim 0.5$). As discussed in Chapter 3, other unknown independent parameters may also affect insolation levels, besides $\overline{K}_T$. The effects of these parameters on utilizability is presently unknown. For north-facing surfaces, the differences between minute data and hour data $\phi$ values are negligible, due to the lack of a beam radiation component.

The largest error in Clark's correlation is from the monthly-average hourly isotropic radiation ratio model with Erbs' $\overline{H}_d/\overline{H}$ correlation. Substantial reduction in these utilizability correlation errors is usually made by using actual $\tilde{R}$'s calculated from the data. Although differences can usually be seen between Clark's correlation with actual $\overline{K}_T$'s and Clark's correlation with actual $\overline{K}_T$'s and the $r_t/r_d$ relation, this difference is typically small compared to the error from using the isotropic radiation model.

## 4.4 Monthly-Average Daily Utilizability

### 4.4.1 General Discussion

Monthly-average daily utilizability is useful for analysis of solar processes with constant critical levels for all hours during a month, or as a theoretical limit for a solar process. Clark's monthly-average hourly correlation can still be used to find the monthly-average daily value, by summing the numerator and denominator components of $\phi$, over all daylight hours. The ratio of these sums is the monthly-average daily utilizability, $\bar{\phi}$. For this study, the same five methods used to calculate $\phi$ were also used to calculate $\bar{\phi}$.

The $\bar{\Phi}$ RMS errors have been plotted on the same scales as the $\bar{\Phi}$ RMS errors, for the respective surface orientations. In general, the magnitude of the $\bar{\Phi}$ RMS error is smaller than the corresponding hourly values discussed in Section 4.3. Mid-day insolation levels are the largest values occurring within a day. Consequently, the potential differences between utilizable energy calculated by the five methods described is also large. In comparison, monthly-average daily utilizability calculations incorporate all daylight hours, and therefore minimize large deviations that were observed during mid-day hours. Even though the $\bar{\Phi}$ RMS error magnitudes are smaller, the trends shown by the $\bar{\Phi}$ RMS error analysis are still present.

Figures 4.17 through 4.24 show the $\bar{\phi}$ RMS errors for the same surface orientations discussed in Section 4.3 for both San Antonio and Albany. Figures 4.17 and 4.18 are for south-facing surfaces at slope equal to latitude, Figs. 4.19 and 4.20 are for south-facing

FIG 4.17 DAILY UTILIZABILITY RMS ERROR

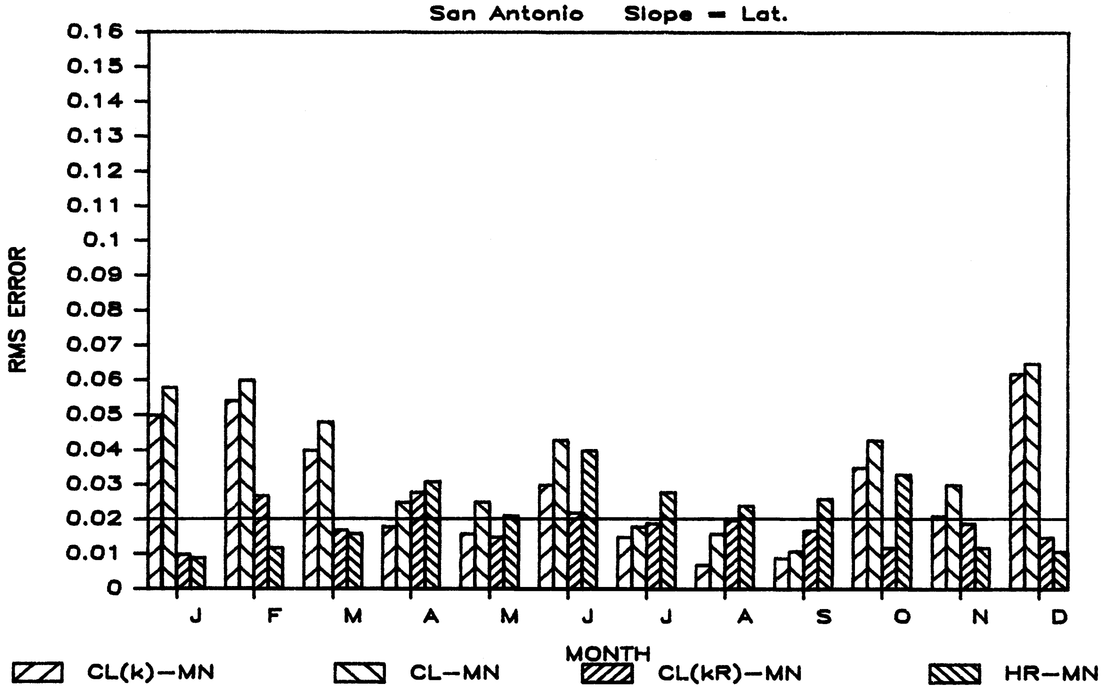



FIG 4.18 DAILY UTILIZABILITY RMS ERROR

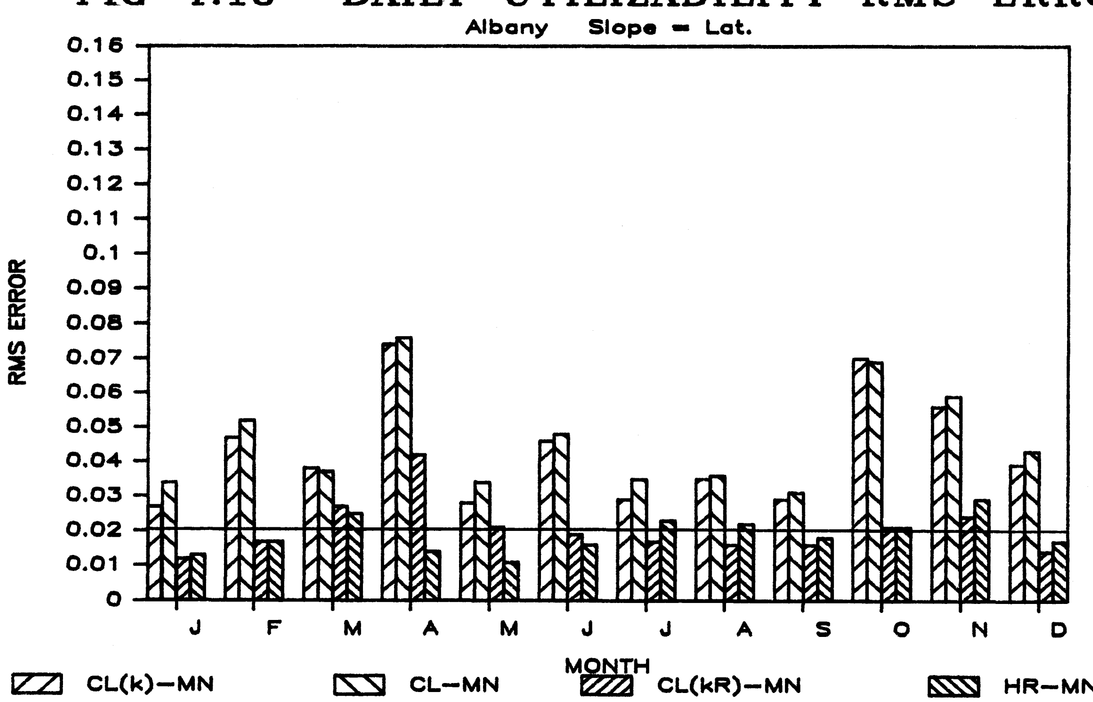


FIG 4.19 DAILY UTILIZABILITY RMS ERROR

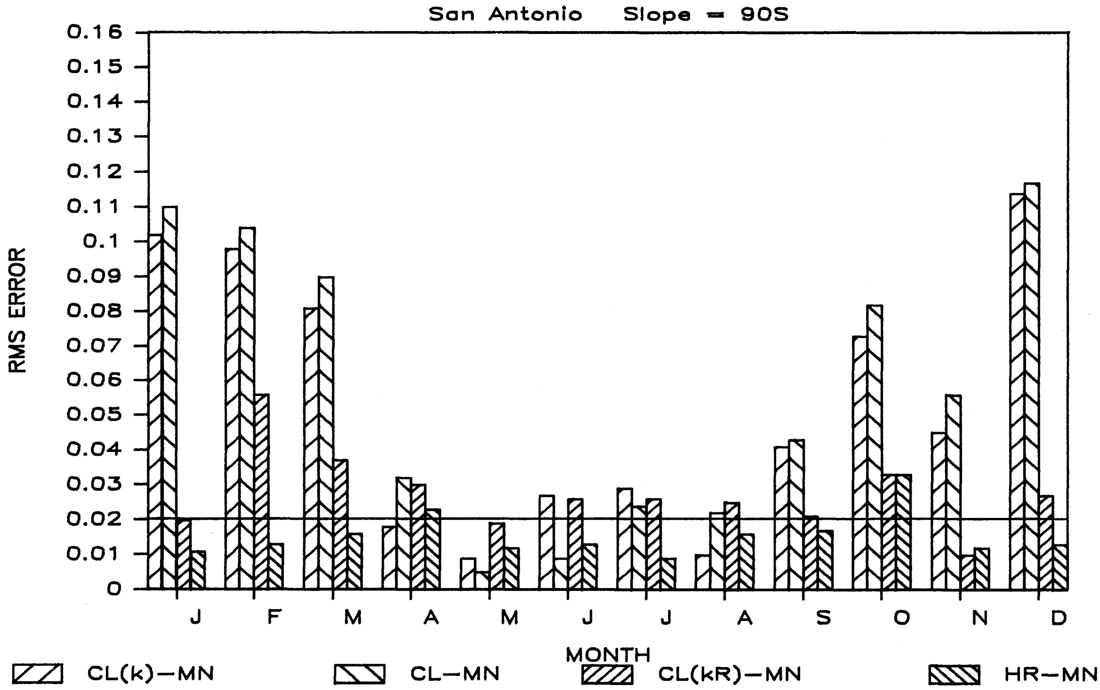



FIG 4.20 DAILY UTILIZABILITY RMS ERROR

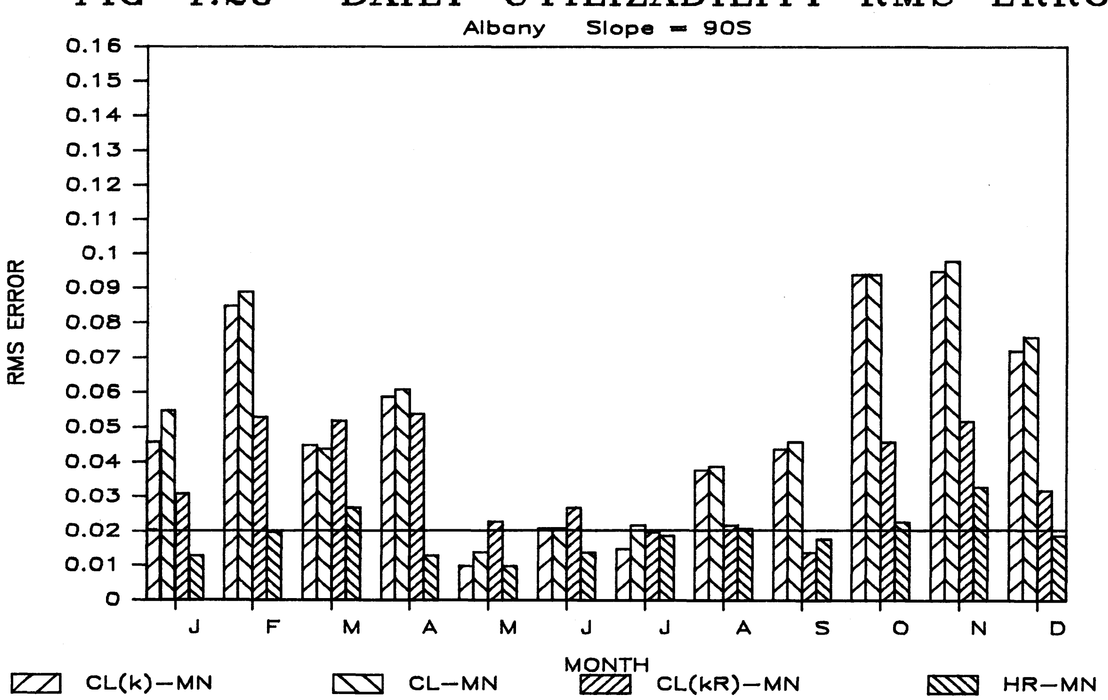


FIG 4.21 DAILY UTILIZABILITY RMS ERROR

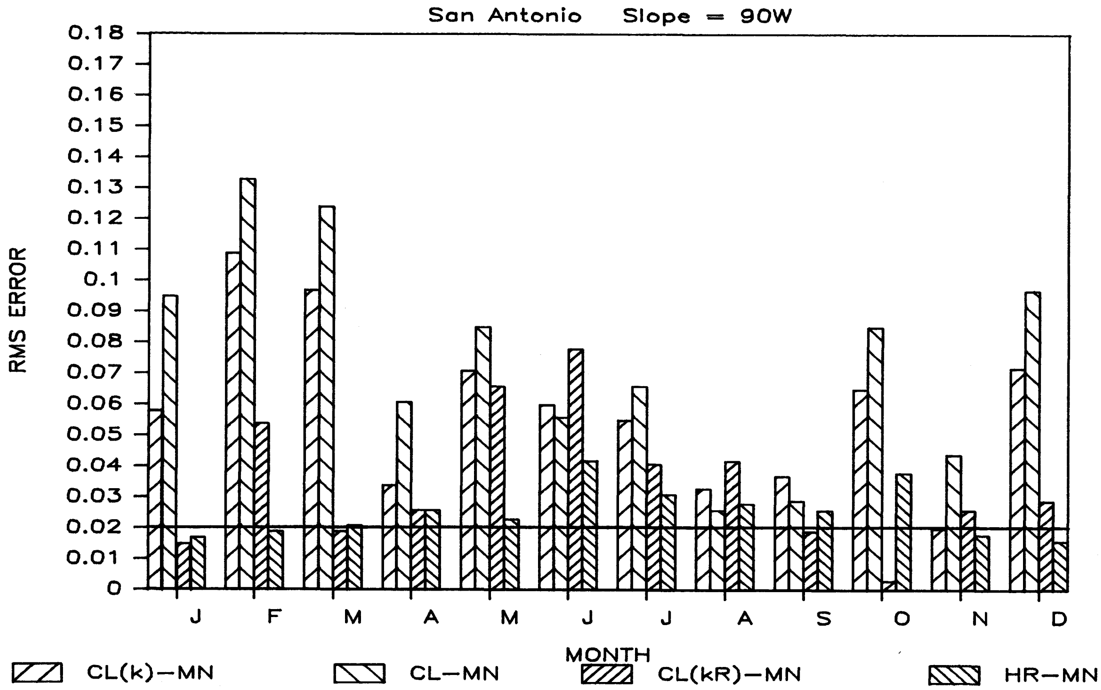



FIG 4.22 DAILY UTILIZABILITY RMS ERROR

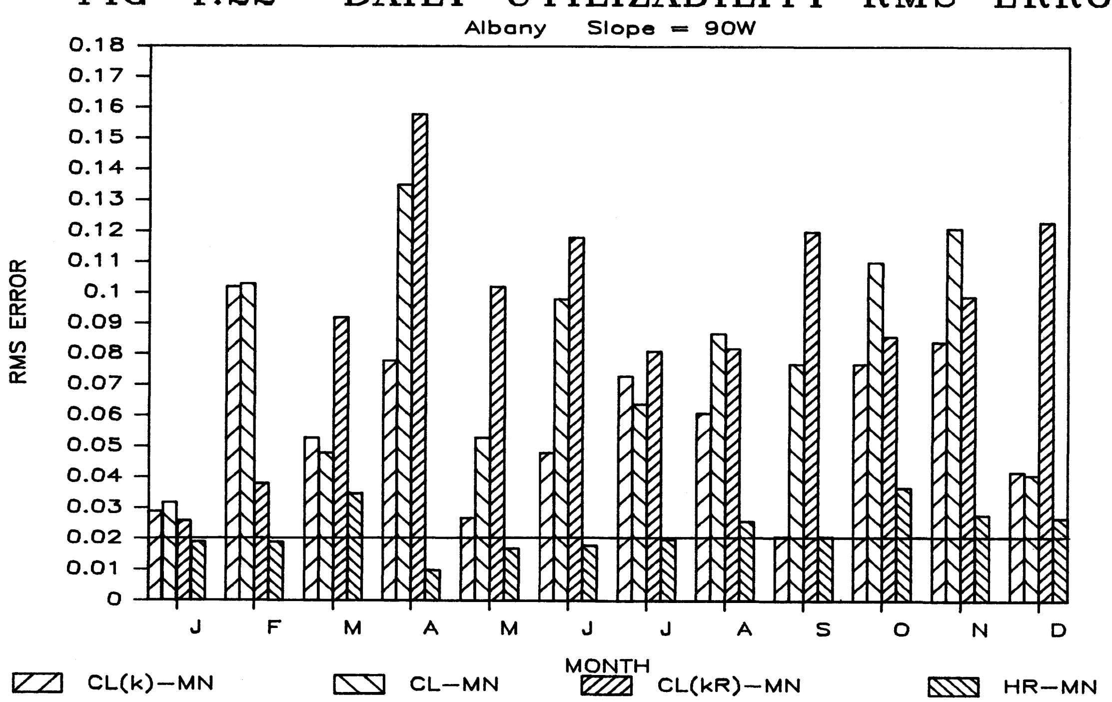


FIG 4.23 DAILY UTILIZABILITY RMS ERROR

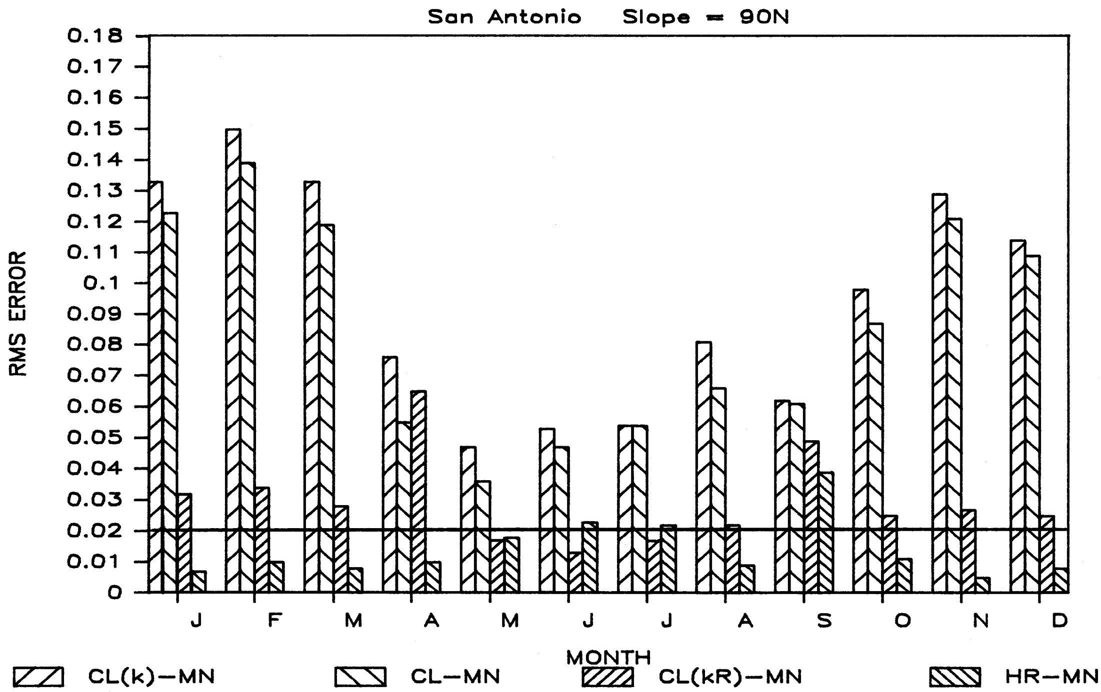
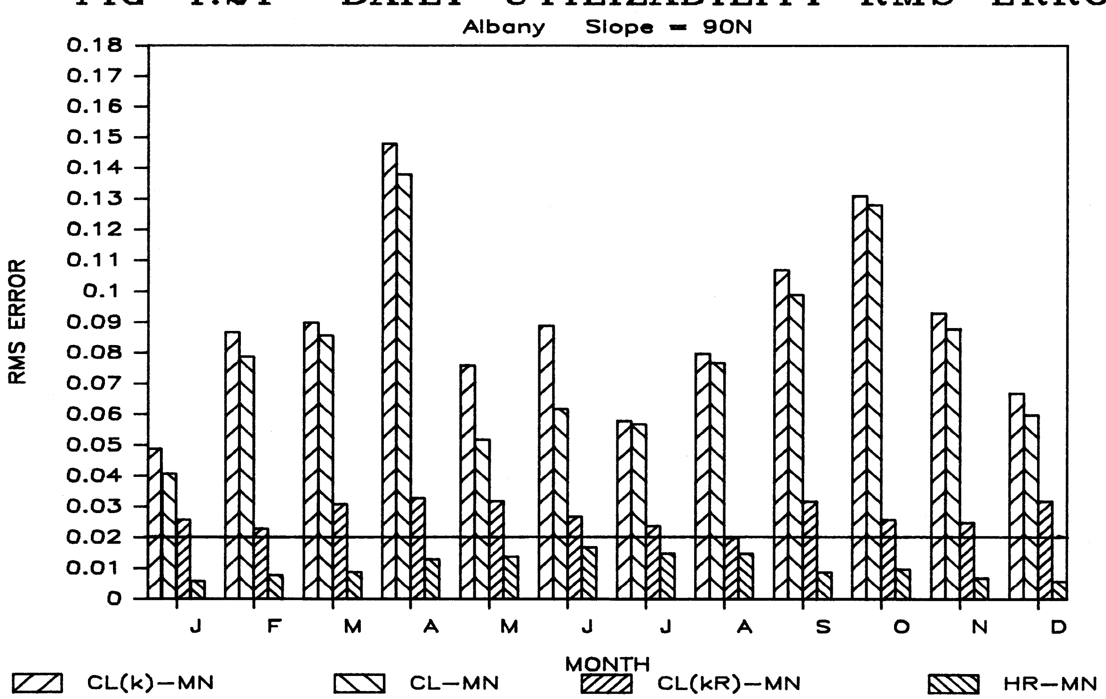



FIG 4.24 DAILY UTILIZABILITY RMS ERROR



vertical surfaces, 4.21 and 4.22 are for west-facing vertical surfaces, and 4.23 and 4.24 are for north-facing vertical surfaces.

Surfaces receiving large components of beam radiation show the largest difference between minute data and hour data utilizability. South-facing surfaces at slope equal to latitude, which potentially receive large amounts of beam radiation, show significant differences for approximately half of the months studied. South-facing vertical surfaces, which receive less beam radiation than surfaces at slope equal to latitude, only show significant differences in 4 of the 24 months studied. West-facing vertical surfaces may receive large amounts of beam radiation during afternoon hours. San Antonio frequently has afternoon clearings, and consequently 8 of the 12 months studied show significant differences between minute data and hour data utilizability values. Albany only shows 5 months with significant differences. North-facing surfaces may receive some beam radiation near sunrise and sunset during long summer days. Consequently, only June and July in San Antonio show minute data versus hour data $\phi$ RMS errors slightly exceeding 0.02. All other months studied show negligible differences.

The largest error in Clark's correlation results from using the isotropic radiation model with Erbs' diffuse fraction, as is seen by comparing the CL(k)-MN error bars to the CL(kR)-MN error bars. Based on the findings of Chapter 2, including a circumsolar diffuse radiation component in the radiation ratio model should usually improve the accuracy of utilizability calculated from Clark's correlation.

Improved methods for calculating $\overline{H}_d/\overline{H}$ and the resulting monthly-average hourly diffuse fraction also need to be made, as indicated in Section 2.6.1. Bad data is suspected of causing the large CL(kR)-MN errors shown in Fig. 4.22, for west-facing vertical surfaces in Albany.

Using $r_t/r_d$ to calculate $\overline{k}_T$ from $\overline{K}_T$ in Clark's correlation does cause a noticeable difference in utilizability values. As discussed in Section 4.3, the $r_t/r_d$ relation assumes symmetrical insolation levels during the day. While both San Antonio and Albany show asymmetrical insolation levels, as reflected by the difference between CL-MN and CL(k)-MN error bars, the error associated with the symmetrical assumption is small compared to the error resulting from using the isotropic $\tilde{R}$.

#### 4.4.2 Summary of Monthly-Average Daily Utilizability Comparisons

The trends found in the $\phi$ analysis, Section 4.3, are also found in the $\overline{\phi}$ analysis. Minute data versus hour data $\overline{\phi}$'s are frequently significantly different for those surfaces that receive large components of beam radiation during the day. Surfaces with little or no beam radiation usually show negligible differences between minute data and hour data $\overline{\phi}$'s. The largest error in Clark's correlation is from the monthly-average hourly isotropic radiation ratio model with Erbs' $\overline{H}_d/\overline{H}$ correlation. The error associated with the symmetrical insolation assumption for calculating $\overline{k}_T$ is small compared to the error resulting from using the isotropic radiation model and estimated diffuse fraction.

## 4.5 Conclusion

Comparisons of monthly-average hourly utilizability and monthly-average daily utilizability calculated from minute data, hour data, and three versions of Clark's correlation, were made. The comparisons incorporate a two year data base, and therefore conclusions concerning long-term effects can not be made. However, the following indications were found.

The largest difference between minute data and hour data values result mostly from intermittent beam radiation. Therefore, surfaces with large amounts of normal incident beam radiation (e.g., south-facing surfaces at slope equal to latitude) will show the largest differences between minute data and hour data utilizability values. In comparison, surfaces with little or no beam radiation will show small differences between minute data and hour data utilizability values.

The comparison of short-term minute data utilizability values to Clark's long-term hourly correlation values show significant differences in some months and orientations. Based on the comparison of clearness frequency distributions in Chapter 3, a long-term difference between minute data and Clark's correlation is expected for surfaces receiving large amounts of normal incident beam radiation.

The monthly-average hourly isotropic radiation ratio model using Erbs diffuse fraction correlation is usually the largest source of error in Clark's utilizability correlation. For south-facing surfaces, the largest errors occur during winter months, where underestimations are sometimes substantial. The worst case is a 42% underestimation of the minute data utilizability. In comparison, Clark's correlation using actual $\tilde{R}$'s underestimates the minute data utilizability by 16% for the same conditions. This 16% error results from: the data base not corresponding to long-term distributions, inherent correlation errors, and modeling discrepancies between a minute-by-minute data base and an hourly data base. Using actual $\tilde{R}$'s in Clark's correlation usually reduces the error in estimating utilizability. Therefore, improvements as large as 30% are predicted for long-term estimations for south-facing surfaces, with the use of improved $\tilde{R}$ models and a utilizability correlation based on minute data.

# RECOMMENDATIONS

This study reevaluates isotropic radiation ratio models; clearness frequency distributions; and utilizability values calculated from minute data, hour data, and Clark's [3] correlation. Mathematical model results are compared to a two year data base, which was collected by Trinity University and State University of New York at Albany as part of the Solar Energy and Meteorological Research and Training Site Program. Based on the findings in this present study, the following topics should be investigated.

RMS errors as large as 0.32 were found between Erbs' hourly diffuse fraction correlation and data values. Garrison [7] found the diffuse fraction to be related to five independent parameters: global solar irradiance; solar elevation; surface albedo; atmospheric precipitable water; and atmospheric turbidity. However, most of these parameters are not generally available. A "clear sky" parameter, which is dependent on air mass, surface altitude, and climate, is an alternative approach. Existing clear sky correlations are described by Erbs [5]. An evaluation should be made concerning the significance of the Garrison parameters, versus the significance of the clear sky parameter, versus improving existing correlations based only on the clearness index.

The average variance between Erbs' [5] monthly-average daily diffuse fraction correlation and data monthly-average daily diffuse fractions values is 6%. For the 24 months studied, the largest variance is 14%. However, the accuracy of monthly-average hourly diffuse fractions, $\bar{I}_d/\bar{I}$, calculated from $\bar{H}_d/\bar{H}$ were not investigated. Diffuse fractions are important parameters in radiation ratio models. The evaluation of utilizability values calculated by Clark's correlation show the monthly-average hourly radiation ratio, $\tilde{R}$, to be the largest source of error. It is not known if the major cause of this error in $\tilde{R}$ is from poor estimates of $\bar{I}_d/\bar{I}$, error from the isotropic diffuse radiation assumption, or both.

Hay's [8] hourly anisotropic correction factor for the isotropic radiation ratio model typically improved estimation of radiation levels on tilted surfaces. The correction factor can be defined by the hourly diffuse fraction and the hourly clearness index. Because of this simple relation, Hay's correction factor is probably valid on a monthly-average bases when used with monthly-average hourly diffuse fractions and clearness indexes. However, the accuracy of Hay's anisotropic correction factor on a monthly-average hourly basis needs to be investigated. A simple monthly-average anisotropic correction factor could be useful for calculating monthly-average hourly tilted surface radiation, as required for Clark's correlation.

Minute data clearness frequency distributions for an hourly period within a month show considerably more variability in insolation levels then the presently used long-term hourly distributions. These minute clearness frequency distributions sometimes coincide and sometimes differ from hour data clearness frequency distributions calculated from the same data base. This observation, indicates a possible dependence of tilted solar radiation on more parameters than just the monthly-average hourly clearness index. An investigation needs to be made on the significance of long-term minute clearness frequency distributions, along with the possibility of more than one independent parameter defining both the minute and hourly distributions.

Utilizability RMS errors equal to 0.02 or less, represent a pair of approximately identical utilizability values. For surfaces receiving large amounts of beam radiation, the utilizability RMS error between minute and hour data exceeded this 0.02 value for half of the 24 months studied. Depending on the results from future investigations of the previously discussed minute clearness frequency distributions, the possibility of basing utilizability correlations on minute data should be studied. Judging from this present investigation, long-term utilizable energy estimations for south-facing surfaces could be improved up to 30%, through a correlation based on minute data and using an improved model to calculate tilted surface radiation.

# APPENDIX: COMPUTER PROGRAM LISTINGS

# APPENDIX A

```
C   PROGRAM TO MAKE AN HOURLY DATA TAPE FROM A MINUTE-BY-MINUTE SOLAR DATA
C   TAPE, BY SUMMATION OF THE MINUTE VALUES.  OUTPUT IS IN TRUE SOLAR TIME.
C   INPUT (MINUTE TAPE) IS IN LOCAL STANDARD TIME.  DATA WITH '99' AND '13'
C   FLAGS ARE REJECTED.  AVERAGE VALUES ARE USED IN THEIR PLACE.
C       THIS VERSION IS WRITTEN SPECIFICALLY FOR THE TRINITY TAPES.
C       (*** SOLAR TIME LAGS LOCAL STANDARD TIME ***)
C       MAXIMUM NUMBER OF INSTRUMENTS = 20.
C       MAXIMUM NUMBER OF RADIATION READING INSTRUMENTS = 15.
C   NOMENCLATURE:  I = # OF WANTED INSTRUMENTS;
C                  M = # OF INSTRUMENTS TO SKIP;
C                  N = # OF DAYS IN MONTH.
C   TRACK1 IS A RUNNING TOTAL OF THE HOURS WITH 15 OR LESS GOOD DATA POINTS.
C   TRACK2 IS A RUNNING TOTAL OF THE HOURS WITH ALL OF THE DATA POINTS.
C   TRACK3 IS A RUNNING TOTAL OF THE HOURS WITH ALL BAD DATA POINTS.
C
      DEFINE FILE 11(ANSI, FB, 567, 6237, 0)
      DEFINE FILE 12(ANSI, FB, 243, 6075, 0)
C
      CHARACTER*2 FLAG
      CHARACTER*4 AINST, AIN(15)
      CHARACTER*6 HRMN, HRM(15)
      CHARACTER*10 RTCODE
      INTEGER YR, DAY, HOUR, TRACK1(15), TRACK2(15), TRACK3(15)
      INTEGER EXP(15), EX, SUM1, SUM2(15), SUM(24,15)
      INTEGER COUNT, COUNT1, COUNT2(15), SOLART
      DIMENSION NFLAG(24,15)
      COMMON /COM1/MDATA(60),FLAG(60)
      DATA SUM,TRACK1,TRACK2,TRACK3/360*0,15*0,15*0,15*0/
      PI = 3.1415927
      IHOUR = 0
C
      WRITE(*,10)
      WRITE(*,15)
      WRITE(*,16)
 10   FORMAT('0','**** SEMRTS:  TRINITY UNIVERSITY ****')
 15   FORMAT(' ','PROGRAM CHECK FOR HOURLY SUMMATION OF MINUTE DATA,',
     &' WITH REVISED FLAGS AND UPDATED EXPONENTS')
 16   FORMAT(' ','OUTPUT TO TAPE IS IN TRUE SOLAR TIME')
      READ(*,20) I,M,N
 20   FORMAT(I2,I2,I2)
      WRITE(*,25) I,M,N
 25   FORMAT('0','DESIRED INSTRUMENTS = ',I2,'  INSTRUMENTS TO SKIP = ',
     &  I2,'  DAYS IN MONTH = ',I2)
 50   FORMAT(1X)
 100  FORMAT(A10,A4,I2,I2,A6,I3,60(I7,A2))
 110  FORMAT(A10,A4,J2,J2,A6,I3.2,60(I7,J2))
C
C   ********************************
```

```
C   *** START OF TAPE PROCESSING ***
C   ******************************
      DO 1000 DAY = 1,N
         DO 500 HOUR = 1,24
            IHOUR = IHOUR + 1
            DO 200 INST = 1,I
            READ(11,100) RTCODE,AINST,YR,MONTH,HRMN,EX,(MDATA(MIN),
     &           FLAG(MIN), MIN = 1,60)
               IF(HOUR .EQ. 1) THEN
                  IF(DAY .EQ. 1) THEN
                     AIN(INST) = AINST
                     IF(INST .EQ. 1) CALL DAYCAL(MONTH,YDAY)
                  END IF
                  EXP(INST) = EX
                  HRM(INST) = HRMN
C   CALCULATE THE CONVERSION FROM STANDARD TIME TO TRUE SOLAR TIME
C   4 * (STAND. MER. - LONGTITUDE) = -34 MINUTES (TRINITY UNIVERSITY)
                  IF (INST .EQ. 1) THEN
                     YDAY = YDAY + 1.0
                     B = 2.*PI*(YDAY-81.0)/364.0
C   MINUTES SOLAR TIME LAGS STANDARD TIME (EMIN WILL BE NEGATIVE)
                     EMIN = 9.87*SIN(2.*B)-7.53*COS(B)-1.5*SIN(B)-34.
                     INDEX2 = -IFIX(EMIN)
                     INDEX1 = INDEX2 - 1
                     WRITE(*,111) YDAY, INDEX2, INDEX1
 111                 FORMAT(' ','YDAY = ',F5.1,'   INDEX2 = ',I3,
     &                      'INDEX1 = ',I3)
                  END IF
                  CALL SUMSUB(SUM2(INST),COUNT2(INST),AINST,HRMN,
     &                  INDEX2,60)
                  GO TO 200
               ELSE
                  IF(AINST .NE. AIN(INST)) THEN
                     WRITE(*,1005) AIN(INST),AINST,HRMN
                     GO TO 2000
                  END IF
                  IF(EX .NE. EXP(INST)) THEN
                     WRITE(*,1010) AINST,EX,EXP(INST),HRMN
                     GO TO 2000
                  END IF
                  CALL SUMSUB(SUM1,COUNT1,AINST,HRMN,1,INDEX1)
               END IF
C   *** DO FOR ALL HOURS ***
               SOLART = HOUR - 1
               COUNT = COUNT1 + COUNT2(INST)
               SUM(SOLART,INST) = SUM1 + SUM2(INST)
               CALL CHECK(AINST,HRMN,COUNT,SUM(SOLART,INST),
     &              TRACK1(INST),TRACK2(INST),TRACK3(INST))
               NFLAG(SOLART,INST) = COUNT
               CALL SUMSUB(SUM2(INST),COUNT2(INST),AINST,HRMN,
     &                 INDEX2,60)
```

```
              IF(HOUR .EQ. 24) THEN
                 SUM(HOUR,INST) = SUM2(INST)
                 COUNT = COUNT2(INST)
                 CALL CHECK(AINST,HRMN,COUNT,SUM(HOUR,INST),
     &                TRACK1(INST),TRACK2(INST),TRACK3(INST))
                 NFLAG(HOUR,INST) = COUNT
              END IF
C   *** REPEAT FOR NEXT INSTRUMENT ***
 200        CONTINUE
C
C   *** SKIP OVER UNWANTED INSTRUMENTS ***
          DO 300 ISKIP = 1,M
 300        READ(11,50)
C
C   *** REPEAT FOR NEXT HOUR ***
 500      CONTINUE
C
C   *** OUTPUT ***
C   FORMAT: 1 RECORD = 1 DAY'S (24 HOURS) WORTH OF DATA FOR 1 INSTRUMENT.
          DO 600 INST = 1,I
            EXP(INST) = EXP(INST) + 2
            WRITE(*,1020)  RTCODE,AIN(INST),YR,MONTH,HRM(INST),
     &                               EXP(INST)
            WRITE(*,1040) (SUM(HOUR,INST),NFLAG(HOUR,INST),HOUR=1,12)
            WRITE(*,1040) (SUM(HOUR,INST),NFLAG(HOUR,INST),HOUR=13,24)
C           WRITE(12,110) RTCODE,AIN(INST),YR,MONTH,HRM(INST),
C    &        EXP(INST),(SUM(HOUR,INST),NFLAG(HOUR,INST), HOUR=1,24)
 600      CONTINUE
C
C   *** REPEAT FOR FOLLOWING DAY ***
 1000 CONTINUE
C
 1005 FORMAT('0','MISMATCH IN INSTRUMENTS:  OLD = ',A4,'  NEW = ',A4,
     &  '  DAY,HR,MN = ',A6)
 1010 FORMAT('0','MISMATCH IN EXPONENTS:  INST = ',A4,
     &  '  NEW EXP = ',I3.2,'  OLD EXP = ',I3.2,' DAY,HR,MN = ',A6)
 1020     FORMAT(' ',A10,A4,J2,J2,A6,I3.2)
 1040     FORMAT(' ',12(I7,I2))
C
C   ******************************
C   *** CHECK IF AT END OF TAPE ***
C   ******************************
       DO 1060 INST = 1,10
          READ(11,100,END=1070) RTCODE,AINST,YR,MONTH,HRMN,EX,
     &        (MDATA(MIN),FLAG(MIN), MIN = 1,60)
          WRITE(*,*) 'NEXT RECORD IN FILE:'
          WRITE(*,1020) RTCODE,AINST,YR,MONTH,HRMN,EX
 1060 CONTINUE
 1070 CONTINUE
C
C  *****************************
```

```
C  *** FINAL MONTHLY OUTPUT  ***
C  ****************************
      WRITE(*,1100)
 1100 FORMAT('0','NUMBER OF HOURS WITH ALL BAD DATA POINTS',
     &  '   (60 BAD MINUTE VALUES)')
      WRITE(*,1125)
 1125 FORMAT(' ','INST  HORI  20S  30S  40S  90N  90E  90S  90W',
     &   '  NIP DIFF  UV   PIR O530 R630 R690')
      WRITE(*,1150) (TRACK3(INST),INST=1,I)
 1150 FORMAT(' ','HOURS',15(I5))
      WRITE(*,1200)
 1200 FORMAT('0','NUMBER OF HOURS WITH 15 OR LESS GOOD DATA POINTS')
      WRITE(*,1125)
      WRITE(*,1150) (TRACK1(INST),INST=1,I)
      WRITE(*,1400)
 1400 FORMAT('0','NUMBER OF HOURS WITH ALL GOOD DATA POINTS')
      WRITE(*,1125)
      WRITE(*,1150) (TRACK2(INST),INST=1,I)
      WRITE(*,1500) IHOUR
 1500 FORMAT('0','TOTAL NUMBER OF HOURS IN MONTH = ',I4)
      IDAY = IHOUR/24
      WRITE(*,1510) IDAY
 1510 FORMAT(' ','TOTAL NUMBER OF DAYS IN MONTH = ',I3)
C   END OF MONTH (END OF FILE)
C     ENDFILE 12
C
 2000 WRITE(*,*)
      STOP
      END


      SUBROUTINE CHECK(AINST,HRMN,COUNT,SUM,TRACK1,TRACK2,TRACK3)
C   SUBROUTINE TO MODIFY THE SUMMATION OF MINUTE DATA, ACCORDING TO THE NUMBER
C   OF BAD DATA POINTS.
C
      CHARACTER*4 AINST
      CHARACTER*6 HRMN
      INTEGER COUNT, SUM, TRACK1, TRACK2, TRACK3
C
      IF (COUNT .EQ. 0) THEN
         SUM = 999999
         TRACK3 = TRACK3 + 1
         TRACK1 = TRACK1 + 1
      ELSE IF (COUNT .LT. 15) THEN
         SUM = (SUM*60)/(COUNT*100)
         TRACK1 = TRACK1 + 1
      ELSE IF (COUNT .LT. 60) THEN
         SUM = (SUM*60)/(COUNT*100)
      ELSE IF (COUNT .EQ. 60) THEN
         SUM = SUM/100
```

```
         TRACK2 = TRACK2 + 1
      ELSE
         WRITE(*,200) COUNT, AINST, HRMN
 200     FORMAT('0','ERROR IN COUNT:  COUNT = ',I3,'  INST = ',A4,
     &  '  DAY,HR,MN = ',A6)
      END IF
C
      RETURN
      END


      SUBROUTINE SUMSUB(SUM,COUNT,AINST,HRMN,I1,I2)
      INTEGER COUNT,SUM
      CHARACTER*2 FLAG
      CHARACTER*4 AINST
      CHARACTER*6 HRMN
      COMMON /COM1/MDATA(60),FLAG(60)
      COUNT = 0
      SUM = 0
C
      DO 400 MIN = I1,I2
            IF(FLAG(MIN).EQ.'11' .OR. FLAG(MIN).EQ.'12') THEN
               COUNT = COUNT + 1
               SUM = SUM + MDATA(MIN)
            ELSE IF(FLAG(MIN).EQ.'99' .OR. FLAG(MIN).EQ.'13') THEN
               GO TO 400
            ELSE
               WRITE(*,600) FLAG(MIN),AINST,HRMN
               COUNT = COUNT + 1
               SUM = SUM + MDATA(MIN)
            END IF
 400  CONTINUE
 600  FORMAT('0','UNRECOGNIZED FLAG (',A2,'):  INST = ',A4,
     &    '  DAY,HR,MN = ',A6)
C
      RETURN
      END


      SUBROUTINE DAYCAL(MONTH,DAY)
      IF (MONTH .EQ. 1) THEN
            WRITE(*,*) 'JANUARY'
            DAY = 0.0
         ELSE IF (MONTH .EQ. 2) THEN
            WRITE(*,*) 'FEBRUARY'
            DAY = 31.0
         ELSE IF (MONTH .EQ. 3) THEN
            WRITE(*,*) 'MARCH'
            WRITE(*,*) '*** NOTE:  NO DIFFUSE DATA ***'
            DAY = 59.0
         ELSE IF (MONTH .EQ. 4) THEN
```

```
          WRITE(*,*) 'APRIL'
          DAY = 90.0
       ELSE IF (MONTH .EQ. 5) THEN
          WRITE(*,*) 'MAY'
          DAY = 120.0
       ELSE IF (MONTH .EQ. 6) THEN
          WRITE(*,*) 'JUNE'
          DAY = 151.0
       ELSE IF (MONTH .EQ. 7) THEN
          WRITE(*,*) 'JULY'
          DAY = 181.0
       ELSE IF (MONTH .EQ. 8) THEN
          WRITE(*,*) 'AUGUST'
          DAY = 212.0
       ELSE IF (MONTH .EQ. 9) THEN
          WRITE(*,*) 'SEPTEMBER'
          DAY = 243.0
       ELSE IF (MONTH .EQ. 10) THEN
          WRITE(*,*) 'OCTOBER'
          DAY = 273.0
       ELSE IF (MONTH .EQ. 11) THEN
          WRITE(*,*) 'NOVEMBER'
          DAY = 304.0
       ELSE IF (MONTH .EQ. 12) THEN
          WRITE(*,*) 'DECEMBER'
          DAY = 334.0
       ELSE
          WRITE(*,50) MONTH
 50       FORMAT('0','PROGRAM ERROR:  MONTH = ',I3)
    END IF
C
    RETURN
    END
```

# APPENDIX B

```
C   PROGRAM TO MAKE AN HOURLY DATA TAPE FROM A MINUTE-BY-MINUTE SOLAR DATA
C   TAPE, BY SUMMATION OF THE MINUTE VALUES.  OUTPUT IS IN TRUE SOLAR TIME.
C   INPUT (MINUTE TAPE) IS IN LOCAL STANDARD TIME.  DATA WITH '99' AND '13'
C   FLAGS ARE REJECTED.  AVERAGE VALUES ARE USED IN THEIR PLACE.
C   TEMPERATURES (AMBIENT & DEWPOINT) ARE AVERAGED OVER THE HOUR.
C       THIS VERSION IS WRITTEN SPECIFICALLY FOR THE ALBANY SEMRTS TAPES.
C       MAXIMUM NUMBER OF INSTRUMENTS = 28.
C       NUMBER OF DESIRED INSTRUMENTS = 15.
C       COUNT OF DESIRED INSTRUMENTS = I.
C   TRACK1 IS A RUNNING TOTAL OF THE HOURS WITH 15 OR LESS GOOD DATA POINTS.
C   TRACK2 IS A RUNNING TOTAL OF THE HOURS WITH ALL OF THE DATA POINTS.
C   TRACK3 IS A RUNNING TOTAL OF THE HOURS WITH ALL BAD DATA POINTS.
C
      DEFINE FILE 11(ANSI, FB, 567, 6237, 0)
      DEFINE FILE 12(ANSI, FB, 243, 6075, 0)
C
      CHARACTER*2 FLAG
      CHARACTER*4 AINST, AIN(28), SOURCE(15)
      CHARACTER*6 HRMN, HRM(28,31)
      CHARACTER*10 RTCODE
      INTEGER YR, DAY, HOUR, TRACK1, TRACK2, TRACK3
      INTEGER EXP(15,31), EX, SUM
      DIMENSION EMIN(31)
      COMMON /COM1/MDATA(24,60),FLAG(24,60)
      COMMON /COM2/SUM(15,31,24),NFLAG(15,31,24)
      COMMON /COM3/TRACK1(15),TRACK2(15),TRACK3(15)
      DATA TRACK1,TRACK2,TRACK3/15*0,15*0,15*0/
      DATA AIN/'1000','1001','1460','1560','1660','1920','1940','1960',
     &  '1980','2010','2011','2012','2013','3000','3001','3002','5000',
     &  '6000','6001','7000','7001','7002','9150','9200','9210','9300',
     &  '9320','9400'/
C
      I = 0
      PI = 3.141593
C   10 DIGIT STATION NUMBER, RESOLUTION & TIME CODE (ALBANY, N.Y.)
C   TRUE SOLAR TIME (TST) AVERAGED VALUE.
      RTCODE = '3054727660'
C
      WRITE(*,10)
      WRITE(*,15)
      WRITE(*,16)
 10   FORMAT('0','**** SEMRTS:  ALBANY, NEW YORK ****')
 15   FORMAT(' ','PROGRAM CHECK FOR HOURLY SUMMATION OF MINUTE DATA,',
     &' WITH REVISED FLAGS AND UPDATED EXPONENTS')
 16   FORMAT(' ','OUTPUT TO TAPE IS IN TRUE SOLAR TIME')
C
C   READ IN DAYS IN MONTH
      READ(*,20,ERR=35) N
```

```
 20   FORMAT(I2)
      WRITE(*,22) N
 22   FORMAT('0','DAYS IN MONTH = ',I2)
      GO TO 45
 35      WRITE(*,40)
 40      FORMAT('0','INPUT ERROR FOR DAYS IN MONTH')
         STOP
 45   CONTINUE
 50   FORMAT(1X)
 100  FORMAT(10X,A4,I2,I2,A6,I3,60(I7,A2))
 110  FORMAT(A10,A4,J2,J2,A6,I3.2,60(I7,J2))
C
C    ********************************
C    *** START OF TAPE PROCESSING ***
C    ********************************
C    NOTE:  HOUR COUNTER IS ENDING HOUR OF HOUR INTERVAL (STANDARD TIME)
C                    (I.E. HOUR 1-2:  HOUR COUNTER = 2)
C      HOUR IN TAPE RECORD HEADER IS STARTING HOUR (STANDARD TIME)
C      HOUR IN OUTPUT TAPE RECORD HEADER WILL BE STARTING HOUR (SOLAR TIME)
      DO 1000 INST = 1,28
C    SKIP UNWANTED INSTRUMENTS
         IF (INST .EQ. 2  .OR.  INST .EQ. 11) GO TO 140
         IF (INST .EQ. 12  .OR.  INST .EQ. 13) GO TO 140
         IF (INST .EQ. 15  .OR.  INST .EQ. 18) GO TO 140
         IF (INST .EQ. 20  .OR.  INST .EQ. 21) GO TO 140
         IF (INST .EQ. 22  .OR.  INST .EQ. 23) GO TO 140
         IF (INST .EQ. 24  .OR.  INST .EQ. 25) GO TO 140
         IF (INST .EQ. 28) GO TO 140
         GO TO 170
C
 140        DO 160 DAY = 1,N
               DO 150 HOUR = 1,24
 150              READ(11,50,END=1200)
 160        CONTINUE
            GO TO 1000
C
C    DESIRED INSTRUMENTS
 170     I = I + 1
         DO 900 DAY = 1,N
C    READ IN A DAY'S WORTH OF DATA FOR GIVEN INSTRUMENT
            DO 300 HOUR = 1,24
               READ(11,100,END=1200) AINST,YR,MONTH,HRMN,EX,
     &             (MDATA(HOUR,MIN),FLAG(HOUR,MIN), MIN = 1,60)
               IF(AINST .NE. AIN(INST)) THEN
                  WRITE(*,1005) AIN(INST),AINST,HRMN
                  STOP
               END IF
               IF(HOUR .EQ. 1) THEN
                  HRM(I,DAY) = HRMN
                  EXP(I,DAY) = EX
                  IF (DAY .EQ. 1) THEN
```

```
                  SOURCE(I) = AINST
                  IF (INST .EQ. 1) CALL DAYCAL(MONTH,YDAY)
                END IF
             ELSE
                IF (EXP(I,DAY) .NE. EX) THEN
                   WRITE(*,1010) AINST,EX,EXP(I,DAY),HRMN
                   STOP
                END IF
             END IF
 300       CONTINUE
C
C   CONVERSION FROM STANDARD TIME TO TRUE SOLAR TIME
C   4 * (STAND. MER. - LONGITUDE) = 4.7 MINUTES (ALBANY, N.Y.)
           IF (INST .EQ. 1) THEN
              YDAY = YDAY + 1.0
              B = 2.*PI*(YDAY - 81.0)/364.0
              EMIN(DAY) = 9.87*SIN(2.*B) - 7.53*COS(B) -
     &                     1.5*SIN(B) + 4.7
           END IF
C
           IF (EMIN(DAY) .GT. -2.0  .AND.  EMIN(DAY) .LT. 2.0) THEN
C   SOLAR TIME EQUALS STANDARD TIME
              IF(INST .EQ. 1  .AND.  DAY .EQ. 1)
     &            WRITE(*,*) 'SOLAR TIME EQUALS STANDARD TIME'
              CALL EQUAL(I,DAY,AINST)
           ELSE IF (EMIN(DAY) .LE. -2.0) THEN
C   SOLAR TIME LAGS STANDARD TIME
              IF(INST .EQ. 1  .AND.  DAY .EQ. 1)
     &            WRITE(*,*) 'SOLAR TIME LAGS STANDARD TIME'
              CALL LAG(EMIN(DAY),I,DAY,AINST)
           ELSE
C   SOLAR TIME LEADS STANDARD TIME
              IF(INST .EQ. 1  .AND.  DAY .EQ. 1)
     &            WRITE(*,*) 'SOLAR TIME LEADS STANDARD TIME'
              CALL LEAD(EMIN(DAY),I,DAY,AINST)
           END IF
C
 900     CONTINUE
1000  CONTINUE
1005  FORMAT('0','MISMATCH IN INSTRUMENTS:  OLD = ',A4,'  NEW = ',A4,
     &  '  DAY,HR,MN = ',A6)
1010  FORMAT('0','MISMATCH IN EXPONENTS:  INST = ',A4,
     &  '  NEW EXP = ',I3.2,'  OLD EXP = ',I3.2,' DAY,HR,MN = ',A6)
C
C   ******************************
C   *** CHECK IF AT END OF TAPE ***
C   ******************************
1025  FORMAT(10X,A4,4X,A6)
1030  FORMAT(' ','NEXT RECORD IN FILE:  INST = ',A4,'  DAY/HR/MN = ',
     &           A6)
1050  FORMAT('0','PREDICTED END OF MONTH')
```

```
      WRITE(*,1050)
      DO 1060 INST = 1,10
         READ(11,1025,END=1070) AINST,HRMN
1060     WRITE(*,1030) AINST,HRMN
      STOP
1070  WRITE(*,*) 'END OF FILE DETECTED'
      GO TO 1250
C
C   PREMATURE END OF FILE
1200     WRITE(*,1205)
1205     FORMAT('0','*** END OF FILE PREMATURELY FOUND ***')
         WRITE(*,1210) DAY,INST,HOUR
1210     FORMAT(' ','DAY = ',I2,'   INST = ',I2,'   HOUR = ',I2)
         STOP
1250  CONTINUE
C
C   **************
C   *** OUTPUT ***
C   **************
C   FORMAT: 1 RECORD = 1 DAY'S (24 HOURS) WORTH OF DATA FOR 1 INSTRUMENT.
C   OUTPUT ONLY DESIRED INSTRUMENTS
1300  FORMAT('0',A10,A4,J2,J2,A6,I3.2)
1310  FORMAT(' ',12(I7,I2))
      DO 1600 DAY = 1,N
         DO 1500 INST = 1,I
C   UPDATE EXPONENT ON RADIATION INSTRUMENTS.
            IF (SOURCE(INST) .NE. '9300'  .AND.
     &          SOURCE(INST) .NE. '9320') THEN
               EXP(INST,DAY) = EXP(INST,DAY) + 2
            END IF
C           WRITE(*,1300)  RTCODE,SOURCE(INST),YR,MONTH,HRM(INST,DAY),
C    &                                EXP(INST,DAY)
C           WRITE(*,1310) (SUM(INST,DAY,HOUR),NFLAG(INST,DAY,HOUR),
C    &                        HOUR=1,12)
C           WRITE(*,1310) (SUM(INST,DAY,HOUR),NFLAG(INST,DAY,HOUR),
C    &                        HOUR=13,24)
            WRITE(12,110) RTCODE,SOURCE(INST),YR,MONTH,HRM(INST,DAY),
     &         EXP(INST,DAY),(SUM(INST,DAY,HOUR),NFLAG(INST,DAY,HOUR),
     &         HOUR=1,24)
1500     CONTINUE
1600  CONTINUE
C
C  *****************************
C  *** FINAL MONTHLY OUTPUT  ***
C  *****************************
      WRITE(*,1650)
1650  FORMAT('0','NUMBER OF HOURS WITH ALL BAD DATA POINTS',
     & '   (60 BAD MINUTE VALUES)')
      WRITE(*,1655)
1655  FORMAT(' ','INST  HORI  33S  43S  53S  90N  90E  90S  90W',
     &  '  NIP DIFF DCAL  UV   IR  TAMB TDEW')
```

```
      WRITE(*,1660) (TRACK3(INST),INST=1,I)
1660  FORMAT(' ','HOURS',15(I5))
      WRITE(*,1670)
1670  FORMAT('0','NUMBER OF HOURS WITH 15 OR LESS GOOD DATA POINTS')
      WRITE(*,1655)
      WRITE(*,1660) (TRACK1(INST),INST=1,I)
      WRITE(*,1680)
1680  FORMAT('0','NUMBER OF HOURS WITH ALL GOOD DATA POINTS')
      WRITE(*,1655)
      WRITE(*,1660) (TRACK2(INST),INST=1,I)
      IHOUR = N * 24
      WRITE(*,1690) IHOUR
1690  FORMAT('0','TOTAL NUMBER OF HOURS IN MONTH = ',I4)
C   END OF MONTH (END OF FILE)
      ENDFILE 12
C
 2000 WRITE(*,*)
      WRITE(*,*)
      STOP
      END


      SUBROUTINE CHECK(AINST,DAY,HOUR,COUNT,SUM,I)
C   SUBROUTINE TO MODIFY THE SUMMATION OF MINUTE DATA, ACCORDING TO THE NUMBER
C   OF BAD DATA POINTS.
C
      CHARACTER*4 AINST
      INTEGER COUNT,SUM,TRACK1,TRACK2,TRACK3,DAY,HOUR
      COMMON /COM3/TRACK1(15),TRACK2(15),TRACK3(15)
C
      IF (COUNT .EQ. 0) THEN
         SUM = 999999
         TRACK3(I) = TRACK3(I) + 1
         TRACK1(I) = TRACK1(I) + 1
      ELSE IF (COUNT .LT. 15) THEN
         TRACK1(I) = TRACK1(I) + 1
         IF(AINST .EQ. '9300'  .OR.  AINST .EQ. '9320') GO TO 300
         SUM = (SUM*60)/(COUNT*100)
      ELSE IF (COUNT .LT. 60) THEN
         IF(AINST .EQ. '9300'  .OR.  AINST .EQ. '9320') GO TO 300
         SUM = (SUM*60)/(COUNT*100)
      ELSE IF (COUNT .EQ. 60) THEN
         TRACK2(I) = TRACK2(I) + 1
         IF(AINST .EQ. '9300'  .OR.  AINST .EQ. '9320') GO TO 300
         SUM = SUM/100
      ELSE
         WRITE(*,200) COUNT,AINST,DAY,HOUR
 200     FORMAT('0','ERROR IN COUNT:  COUNT = ',I3,'  INST = ',A4,
     &  '  DAY/HR = ',I2,'/',I2)
      END IF
```

```
      RETURN
C
C   AMBIENT OR DEWPOINT TEMPERATURE.  TAKE AVERAGE VALUE.
 300  SUM = SUM/COUNT
      RETURN
      END


      SUBROUTINE SUMSUB(SUM,COUNT,AINST,DAY,I1,I2,HOUR)
      INTEGER COUNT,SUM,DAY,HOUR
      CHARACTER*2 FLAG
      CHARACTER*4 AINST
      COMMON /COM1/MDATA(24,60),FLAG(24,60)
      COUNT = 0
      SUM = 0
C
      DO 400 MIN = I1,I2
      IF(FLAG(HOUR,MIN).EQ.'11' .OR. FLAG(HOUR,MIN).EQ.'12') THEN
         COUNT = COUNT + 1
         SUM = SUM + MDATA(HOUR,MIN)
      ELSE IF(FLAG(HOUR,MIN).EQ.'99' .OR. FLAG(HOUR,MIN).EQ.'13') THEN
         GO TO 400
      ELSE
         WRITE(*,600) FLAG(HOUR,MIN),AINST,DAY,HOUR,MIN
         COUNT = COUNT + 1
         SUM = SUM + MDATA(HOUR,MIN)
      END IF
 400  CONTINUE
 600  FORMAT('0','UNRECOGNIZED FLAG (',A2,'):  INST = ',A4,
     &   '  DAY/HR/MIN = 'I2,'/',I2,'/',I2)
C
      RETURN
      END


      SUBROUTINE DAYCAL(MONTH,DAY)
      IF (MONTH .EQ. 1) THEN
            WRITE(*,*) 'JANUARY'
            DAY = 0.0
         ELSE IF (MONTH .EQ. 2) THEN
            WRITE(*,*) 'FEBRUARY'
            DAY = 31.0
         ELSE IF (MONTH .EQ. 3) THEN
            WRITE(*,*) 'MARCH'
            DAY = 59.0
         ELSE IF (MONTH .EQ. 4) THEN
            WRITE(*,*) 'APRIL'
            DAY = 90.0
         ELSE IF (MONTH .EQ. 5) THEN
            WRITE(*,*) 'MAY'
            DAY = 120.0
```

```
         ELSE IF (MONTH .EQ. 6) THEN
            WRITE(*,*) 'JUNE'
            DAY = 151.0
         ELSE IF (MONTH .EQ. 7) THEN
            WRITE(*,*) 'JULY'
            DAY = 181.0
         ELSE IF (MONTH .EQ. 8) THEN
            WRITE(*,*) 'AUGUST'
            DAY = 212.0
         ELSE IF (MONTH .EQ. 9) THEN
            WRITE(*,*) 'SEPTEMBER'
            DAY = 243.0
         ELSE IF (MONTH .EQ. 10) THEN
            WRITE(*,*) 'OCTOBER'
            DAY = 273.0
         ELSE IF (MONTH .EQ. 11) THEN
            WRITE(*,*) 'NOVEMBER'
            DAY = 304.0
         ELSE IF (MONTH .EQ. 12) THEN
            WRITE(*,*) 'DECEMBER'
            DAY = 334.0
         ELSE
            WRITE(*,50) MONTH
 50         FORMAT('0','PROGRAM ERROR:  MONTH = ',I3)
      END IF
C
      RETURN
      END



      SUBROUTINE LAG(EMIN,I,DAY,AINST)
C   SOLAR TIME LAGS STANDARD TIME
      INTEGER DAY,HOUR,COUNT,COUNT1,COUNT2,SUM1,SUM2,SUM,SOLART
      CHARACTER*4 AINST
      COMMON /COM2/SUM(15,31,24),NFLAG(15,31,24)
C
      INDEX2 = -IFIX(EMIN)
      INDEX1 = INDEX2 - 1
      HOUR = 1
      CALL SUMSUB(SUM2,COUNT2,AINST,DAY,INDEX2,60,HOUR)
      DO 100 HOUR = 2,24
         SOLART = HOUR - 1
         CALL SUMSUB(SUM1,COUNT1,AINST,DAY,1,INDEX1,HOUR)
         COUNT = COUNT1 + COUNT2
         SUM(I,DAY,SOLART) = SUM1 + SUM2
         CALL CHECK(AINST,DAY,HOUR,COUNT,SUM(I,DAY,SOLART),I)
         NFLAG(I,DAY,SOLART) = COUNT
         CALL SUMSUB(SUM2,COUNT2,AINST,DAY,INDEX2,60,HOUR)
 100  CONTINUE
C
```

```
      SOLART = 24
      SUM(I,DAY,SOLART) = SUM2
      COUNT = COUNT2
      CALL CHECK(AINST,DAY,HOUR,COUNT,SUM(I,DAY,SOLART),I)
      NFLAG(I,DAY,SOLART) = COUNT
C
      RETURN
      END


      SUBROUTINE LEAD(EMIN,I,DAY,AINST)
C   SOLAR TIME LEADS STANDARD TIME
      INTEGER DAY,HOUR,COUNT,COUNT1,COUNT2,SUM1,SUM2,SUM
      CHARACTER*4 AINST
      COMMON /COM2/SUM(15,31,24),NFLAG(15,31,24)
C
      INDEX2 = IFIX(EMIN)
      INDEX1 = INDEX2 - 1
      SUM2 = 0.0
      COUNT2 = 0
C
      DO 100 HOUR = 1,24
         CALL SUMSUB(SUM1,COUNT1,AINST,DAY,1,INDEX1,HOUR)
         SUM(I,DAY,HOUR) = SUM1 + SUM2
         COUNT = COUNT1 + COUNT2
         CALL CHECK(AINST,DAY,HOUR,COUNT,SUM(I,DAY,HOUR),I)
         NFLAG(I,DAY,HOUR) = COUNT
         CALL SUMSUB(SUM2,COUNT2,AINST,DAY,INDEX2,60,HOUR)
 100  CONTINUE
C
      RETURN
      END


      SUBROUTINE EQUAL(I,DAY,AINST)
C   SOLAR TIME EQUALS STANDARD TIME
      INTEGER DAY,HOUR,COUNT,SUM1,SUM
      CHARACTER*4 AINST
      COMMON /COM2/SUM(15,31,24),NFLAG(15,31,24)
C
      DO 100 HOUR = 1,24
         CALL SUMSUB(SUM1,COUNT,AINST,DAY,1,60,HOUR)
         CALL CHECK(AINST,DAY,HOUR,COUNT,SUM1,I)
         SUM(I,DAY,HOUR) = SUM1
         NFLAG(I,DAY,HOUR) = COUNT
 100  CONTINUE
C
      RETURN
      END
```

APPENDIX C

```
C  THIS PROGRAM CALCULATES THE MONTHLY AVERAGED RADIATION RATIO
C  FOR EACH GLOBAL RADIATION INSTRUMENT FROM REAL DATA.  HOURLY HORIZONTAL
C  AND NIP VALUES ARE THEN USED TO NUMBERICALLY INTEGRATE THE MONTHLY AVERAGED
C  RADIATION RATIOS, USING THE:  1) ISOTROPIC MODEL; 2) HAY MODEL.
C  ERBS MONTHLY-AVERAGED DIFFUSE RATIO IS ALSO USED TO CALCULATE THE RADIATION
C  RATIO, USING THE MONTHLY-AVERAGED CLEARNESS INDEX AS CALCULATED FROM THE
C  HORIZONTAL DATA.
      DEFINE FILE 11(ANSI, FB, 243, 6075, 0)
C   DHOUR = TOTAL NUMBER OF DAYLIGHT HOURS IN MONTH
C   TIME = TOTAL NUMBER OF HOURS IN MONTH WITH GOOD DATA (EACH INST)
C   NDAY = TOTAL NUMBER OF DAYS FOR GIVEN TIME PERIOD AND INSTRUMENT
C              WITH GOOD DATA     (NDAY(HOUR,INST))
C   DKTB = MONTHLY AVERAGED DAILY CLEARNESS INDEX
C   IBAR(HOUR) = MONTHLY AVERAGED HOURLY RADIATION ON HOR. SURFACE
C   RC=PI/180=0.01745, RLAT=LATITUDE, GSC=SOLAR CONSTANT (KW/M2)
C   N = # OF DAYS IN THE MONTH, DAY= DAY OF YEAR
C   AVRAD(INST) = MONTHLY AVERAGED RADIATION FOR ALL HOURS FOR GIVEN
C                    INSTRUMENT
      INTEGER  EXP, HOUR, INST(9), HDATA, FLAG
      REAL IBAR, AVRAD(9), NDAY, NDAY2, NDAY3, AZ(8), B(8)
      CHARACTER*4 CFLAG
      CHARACTER*5 AINST(9)
      DIMENSION HKTB(21),RBAR(8),ERBHKT(21),RBAR2(8),RBAR3(8)
      COMMON /COM1/HDATA(24,9),FLAG(24,9),EXP(9)
      COMMON /COM2/SETR(21),SUMI(21,9),SUMH(9),NDAY(21,9),TIME(9),
     &  W2W1(21),HRBAR2(21,8),SUMH2(8),NDAY2(21,8),TIME2(8),
     &  HRBAR3(21,8),SUMH3(8),NDAY3(21,8),TIME3(8)
      COMMON /COM3/PI,GSC,RC,TANLAT,SINLAT,COSLAT,COSB(8),SINB(8),
     &  COSAZ(8),SINAZ(8),COS1(8),COS2(8)
      COMMON /COM4/HRBAR(21,8),RBERB(21,8),IBAR(21)
C
      DATA PI, RC, GSC / 3.141593, 0.01745, 1.353/
      DATA SUMH,SETR,SUMI,HKTB/9*0.0,21*0.0,189*0.0,21*0.0/
      DATA NDAY,TIME,W2W1/189*0,9*0,21*0.0/
      DATA NDAY2,TIME2,NDAY3,TIME3/168*0.0,8*0.0,168*0.0,8*0.0/
      DATA AZ/4*0.0,180.0,-90.0,0.0,90.0/
C   TRINITY DATA
      DATA AINST,RLAT,RHO/'HORIZ','20S','30S','40S','90N','90E',
     &   '90S','90W','NIP',29.53,0.05/
      DATA B/0.0,20.0,30.0,40.0,4*90.0/
C
      WRITE(*,20) RLAT
 20   FORMAT('0','TRINITY SEMRT:  HOURLY DATA',20X,'LATITUDE = ',F5.2)
      RLAT = RLAT*RC
      TANLAT = TAN(RLAT)
      SINLAT = SIN(RLAT)
      COSLAT = COS(RLAT)
      IEQUIP = 9
```

```
      DO 50 I = 1,8
         B(I) = B(I)*RC
         AZ(I) = AZ(I)*RC
         COSB(I) = COS(B(I))
         SINB(I) = SIN(B(I))
         COSAZ(I) = COS(AZ(I))
         SINAZ(I) = SIN(AZ(I))
         COS1(I) = (1. + COSB(I))/2.
 50      COS2(I) = RHO*(1. - COSB(I))/2.
      SUMHO = 0.0
      DHOUR = 0.0
C
C   **************************
C   ***** REAL DATA PART *****
C   **************************
C   PROCESS DATA
 90   FORMAT(1X)
 100  FORMAT(10X,I4,2X,I2,I2,4X,I3,24(I7,I2))
      DO 1500 JDAY = 1,32
         DO 1000 I = 1,IEQUIP
            READ(11,100,END=1800) IN,MONTH,IDAY,EXP(I), (HDATA(HOUR,I),
     &                    FLAG(HOUR,I), HOUR=1,24)
C
            IF (JDAY .EQ. 1) THEN
               INST(I) = IN
               IF (I .EQ. 1) THEN
                  CALL DAYCAL(MONTH,IDAY,DAY,N,ISKIP)
                  IF (N .EQ. 0) STOP
               END IF
            ELSE
               IF (IN .NE. INST(I)) THEN
                  WRITE(*,1510) INST(I), IN
                  WRITE(*,*) 'ERROR OCCURED ON DAY:  ',JDAY
                  STOP
               END IF
            END IF
 1000    CONTINUE
C
         DO 1200 I = 10,ISKIP
 1200       READ(11,90)
         DAY = DAY + 1.0
         CALL EXTR(DAY,CFLAG)
         IF (CFLAG .EQ. 'STOP') STOP
 1500 CONTINUE
 1510 FORMAT('0','MISMATCH IN INSTRUMENTS:  OLD = ',I4,'   NEW = ',I4)
      WRITE(*,*) '**** END OF FILE NOT FOUND ****'
      GO TO 2000
C
C   END OF TAPE FOUND
 1800 LDAY = JDAY - 1
      IF (N .NE. LDAY) WRITE(*,1815)
```

```
 1815 FORMAT('0','*** IMPROPER MATCH IN NUMBER OF DAYS IN MONTH ***')
 2000 CONTINUE
C
C    **********************************
C    ***  KTBAR, RBAR CALCULATIONS  ***
C    **********************************
      DKTB = SUMH(1)*DHOUR/(SUMHO*TIME(1))
      DO 2030 HOUR = 5,20
         IBAR(HOUR) = SUMI(HOUR,1)/NDAY(HOUR,1)
         HKTB(HOUR) = IBAR(HOUR)*W2W1(HOUR)/SETR(HOUR)
 2030 CONTINUE
      AVRAD(1) = SUMH(1)/TIME(1)
      DO 2080 I = 2,8
         AVRAD(I) = SUMH(I)/TIME(I)
         RBAR(I) = AVRAD(I)/AVRAD(1)
         RBAR2(I) = SUMH2(I)/(AVRAD(1)*TIME2(I))
         RBAR3(I) = SUMH3(I)/(AVRAD(1)*TIME3(I))
         DO 2060 HOUR = 5,20
            HRBAR(HOUR,I) = SUMI(HOUR,I)/(IBAR(HOUR)*NDAY(HOUR,I))
            HRBAR2(HOUR,I) = HRBAR2(HOUR,I)/(IBAR(HOUR)*NDAY2(HOUR,I))
 2060       HRBAR3(HOUR,I) = HRBAR3(HOUR,I)/(IBAR(HOUR)*NDAY3(HOUR,I))
 2080 CONTINUE
      GO TO 4000
C
C    *********************
C    ***  DATA OUTPUT  ***
C    *********************
 2085 WRITE(*,2090)
 2090 FORMAT('0','THE FOLLOWING NUMBERS WHERE GENERATED FROM REAL DATA')
      WRITE(*,2100)  DKTB
 2100 FORMAT(' ','MONTHLY AVERAGED DAILY CLEARNESS INDEX = ',F5.3)
      WRITE(*,*) 'DHOUR = ',DHOUR,'   TIME(1) = ',TIME(1)
      WRITE(*,2275)
 2275 FORMAT('0','KTBARS & RBARS FOR LISTED INSTRUMENTS AND TIMES')
      WRITE(*,2300)
 2300 FORMAT(' ','TIME  05-06 06-07 07-08 08-09 09-10 10-11 11-12 ',
     & '12-13 13-14 14-15 15-16 16-17 17-18 18-19  DAILY')
      WRITE(*,2400)  (HKTB(HOUR),HOUR=6,19), DKTB
 2400 FORMAT(' ','KTBAR',14(2X,F4.2),3X,F4.2)
      DO 2600 I = 2,8
         WRITE(*,2500) AINST(I),(HRBAR(HOUR,I),HOUR=6,19),RBAR(I)
 2500    FORMAT(' ',A5,14(2X,F4.2),3X,F4.2)
 2600 CONTINUE
C
C    ****************************
C    ***** CORRELATION PART *****
C    ****************************
 2800 CALL RBCORR(DKTB,AINST,ERBHKT,MONTH)
C     GO TO 4000
C
C    **************************
```

```
C    *** CORRELATION OUTPUT ***
C    **************************
      WRITE(*,3300)
 3300 FORMAT('0','THE FOLLOWING NUMBERS WHERE GENERATED FROM',
     &     ' CORRELATIONS.')
      WRITE(*,*) 'THE INPUT WAS MONTHLY AVERAGED DAILY CLEARNESS INDEX',
     &     ' AS FOUND FROM THE REAL DATA'
      WRITE(*,2275)
      WRITE(*,3320)
 3320 FORMAT(' ','TIME  05-06 06-07 07-08 08-09 09-10 10-11 11-12 ',
     & '12-13 13-14 14-15 15-16 16-17 17-18 18-19')
      WRITE(*,3340)  (ERBHKT(HOUR),HOUR=6,19)
 3340 FORMAT(' ','KTBAR',14(2X,F4.2))
      DO 3350 I = 2,8
 3350    WRITE(*,3360) AINST(I),(RBERB(HOUR,I),HOUR=6,19)
 3360 FORMAT(' ',A5,14(1X,F5.2))
C
C   DAILY RBAR OUTPUT
 4000 WRITE(*,4100)
 4100 FORMAT('0','MONTHLY-AVERAGED DAILY RBARS')
      WRITE(*,4120)
 4120 FORMAT(' ','INST',3X,'DATA',2X,'ISO',3X,'HAY')
      DO 4150 I = 2,8
 4150    WRITE(*,4160) AINST(I),RBAR(I),RBAR2(I),RBAR3(I)
 4160 FORMAT(' ',A5,3(F6.2))
C
 6000 STOP
      END


      SUBROUTINE DAYCAL(MONTH, IDAY, DAY, N, ISKIP)
      ISKIP = 15
      IF (IDAY .NE. 1) THEN
         WRITE(*,10) MONTH, IDAY
 10      FORMAT('0','INITIAL DAY OF MONTH ',I2,' IS NOT DAY 1.',
     &   '  DAY = ',I2)
         N = 0
         RETURN
      END IF
      IF (MONTH .EQ. 1) THEN
            DAY = 0.0
            N = 31
            WRITE(*,*) 'JAN'
         ELSE IF (MONTH .EQ. 2) THEN
            DAY = 31.0
            N = 28
            WRITE(*,*) 'FEB'
         ELSE IF (MONTH .EQ. 3) THEN
            DAY = 59.0
            N = 31
            ISKIP = 14
```

```
            WRITE(*,*) 'MARCH'
         ELSE IF (MONTH .EQ. 4) THEN
            DAY = 90.0
            N = 30
            WRITE(*,*) 'APRIL'
         ELSE IF (MONTH .EQ. 5) THEN
            DAY = 120.0
            N = 31
            WRITE(*,*) 'MAY'
         ELSE IF (MONTH .EQ. 6) THEN
            DAY = 151.0
            N = 30
            WRITE(*,*) 'JUNE'
         ELSE IF (MONTH .EQ. 7) THEN
            DAY = 181.0
            N = 31
            WRITE(*,*) 'JULY'
         ELSE IF (MONTH .EQ. 8) THEN
            DAY = 212.0
            N = 31
            WRITE(*,*) 'AUG'
         ELSE IF (MONTH .EQ. 9) THEN
            DAY = 243.0
            N = 30
            WRITE(*,*) 'SEPT'
         ELSE IF (MONTH .EQ. 10) THEN
            DAY = 273.0
            N = 31
            WRITE(*,*) 'OCT'
         ELSE IF (MONTH .EQ. 11) THEN
            DAY = 304.0
            N = 30
            WRITE(*,*) 'NOV'
         ELSE IF (MONTH .EQ. 12) THEN
            DAY = 334.0
            N = 31
            WRITE(*,*) 'DEC'
         ELSE
            WRITE(*,50) MONTH
 50         FORMAT('0','PROGRAM ERROR:  (NONEXISTENT MONTH)',
     &      '  MONTH = ',I3)
            N = 0
      END IF
C
100   RETURN
      END


      SUBROUTINE EXTR(DAY,CFLAG)
C   SUBROUTINE TO CALCULATE EXTRATERRESTRIAL RADIATION, AND TO ADD UP
```

```
C   THE RADIATION IN A GIVEN HOUR.
      CHARACTER*4 CFLAG
      INTEGER HOUR,EXP,HDATA,FLAG
      REAL RDATA(9),THETA(9),NDAY,NDAY2,NDAY3
      COMMON /COM1/HDATA(24,9),FLAG(24,9),EXP(9)
      COMMON /COM2/SETR(21),SUMI(21,9),SUMH(9),NDAY(21,9),TIME(9),
     &  W2W1(21),HRBAR2(21,8),SUMH2(8),NDAY2(21,8),TIME2(8),
     &  HRBAR3(21,8),SUMH3(8),NDAY3(21,8),TIME3(8)
      COMMON /COM3/PI,GSC,RC,TANLAT,SINLAT,COSLAT,COSB(8),SINB(8),
     &  COSAZ(8),SINAZ(8),COS1(8),COS2(8)
      CFLAG = 'GO'
C
C   DECLINATION IN RADIANS
      DEC = 23.45*RC*SIN(2*PI*(284. + DAY)/365.0)
      COSDEC = COS(DEC)
      SINDEC = SIN(DEC)
C   SUNSET HOUR ANGLE IN RADIANS
      WS = ACOS(-TANLAT * TAN(DEC))
      DHOUR = DHOUR + 2.*WS/0.2618
C   DAILY EXTRATERRESTRIAL RADIATION ON HORIZ. SURFACE (KJ/M2)
      HO = 27500.0*GSC*(1.0+0.033*COS(2.*PI*DAY/365.)) *
     &      (COSLAT*COSDEC*SIN(WS) + WS*SINLAT*SINDEC)
      SUMHO = SUMHO + HO
C
C   DO FOR POSSIBLE DAYLIGHT HOURS 4 TO 20
      DO 200 HOUR = 5,20
         W2 = FLOAT(HOUR)
         W1 = W2 - 1.0
C   CONVERSION TO HOUR ANGLES IN +/-  RADIANS
         W2 = (W2-12.0) * 0.2618
         W1 = (W1-12.0) * 0.2618
C   CHECK WITH SUNSET HOUR ANGLE
         IF (W2 .LT. -WS) GO TO 200
         IF (W1 .GT. WS) GO TO 200
C   IF GETTING DARK
         IF (W2 .GE. WS) W2 = WS
C   IF GETTING LIGHT
         IF (W1 .LE. -WS) W1 = -WS
         W = (W1 + W2)/2.
C
C    HOURLY EXTRATERRESTRIAL RADIATION (KJ/M2)
         ETRR = 13750.*GSC*(1.0+0.033*COS(2.*PI*DAY/365.))
         ETRL = COSLAT*COS(DEC)*(SIN(W2)-SIN(W1)) +
     &            (W2-W1)*SINLAT*SIN(DEC)
         ETR = ETRR * ETRL
         SETR(HOUR) = SETR(HOUR) + ETR
         W2W1(HOUR) = W2W1(HOUR) + (W2 - W1)/0.2618
         THEZ = COSDEC*COSLAT*COS(W) + SINDEC*SINLAT
         IF (THEZ .LT. 1.0E-06) THEZ = 0.0
         DO 100 I = 1,9
            RDATA(I) = 0.0
```

```
            IF (FLAG(HOUR,I) .EQ. 0) GO TO 200
            IF (HDATA(HOUR,I) .LE. 0) GO TO 200
            RDATA(I) = (FLOAT(HDATA(HOUR,I))) * 10.**EXP(I)
            TIME(I) = TIME(I) + 1.
            NDAY(HOUR,I) = NDAY(HOUR,I) + 1.
            SUMI(HOUR,I) = SUMI(HOUR,I) + RDATA(I)
            SUMH(I) = SUMH(I) + RDATA(I)
            P = SINDEC*(SINLAT*COSB(I) - COSLAT*SINB(I)*COSAZ(I))
            Q = COSDEC*COS(W)*(COSLAT*COSB(I) + SINLAT*SINB(I)*COSAZ(I))
            S = COSDEC*SINB(I)*SINAZ(I)*SIN(W)
            THETA(I) = P + Q + S
            IF (THETA(I) .LT. 1.0E-04) THETA(I) = 0.0
 100     CONTINUE
C
C   CALCULATE NUMERATORS FOR RBARS
         IF( RDATA(1) .EQ. 0.0  .OR.  RDATA(9) .EQ. 0.0) GO TO 200
         RTHEZ = RDATA(9)*THEZ
         DO 150 I = 2,8
C   ISOTROPIC MODEL (HRBAR2)
            RISO = (RDATA(1)-RTHEZ)*COS1(I) + RDATA(9)*THETA(I) +
     &             RDATA(1)*COS2(I)
            IF (RISO .LT. 0.0) THEN
               WRITE(*,*) 'ERROR:  RISO = ',RISO
               WRITE(*,*) 'I = ',I,'  HOUR = ',HOUR
               CFLAG = 'STOP'
            END IF
            HRBAR2(HOUR,I) = HRBAR2(HOUR,I) + RISO
            SUMH2(I) = SUMH2(I) + RISO
            NDAY2(HOUR,I) = NDAY2(HOUR,I) + 1.
            TIME2(I) = TIME2(I) + 1.
C   HAY MODEL (HRBAR3)
            HAY = ((RDATA(1)-RTHEZ)*COS1(I) + RDATA(9)*THETA(I))*
     &            (1.-RTHEZ/ETR) + RDATA(1)*COS2(I)
            IF (HAY .LT. 0.0) THEN
               WRITE(*,*) 'ERROR:  HAY = ',HAY
               WRITE(*,*) 'I = ',I,'  HOUR = ',HOUR
               CFLAG = 'STOP'
            END IF
            HRBAR3(HOUR,I) = HRBAR3(HOUR,I) + HAY
            SUMH3(I) = SUMH3(I) + HAY
            NDAY3(HOUR,I) = NDAY3(HOUR,I) + 1.
            TIME3(I) = TIME3(I) + 1.
 150     CONTINUE
 200  CONTINUE
C
      RETURN
      END


      SUBROUTINE RBCORR(DKTB,AINST,HKTB,MONTH)
C   THIS SUBROUTINE CALCULATES RBARS FROM CORRELATIONS.
```

```
C   RBERB = DIFFUSE + BEAM + GROUND REFLECTANCE  (RBAR WITH ERBS CORR. INPUT)
C   NOTE:  RANGE OF ERBS NONSEASONAL HD/H CORRELATION IS FOR 0.3 < KT < 0.8
C     B(INST) = SLOPE,  AZ(INST) = AZIMUITH ANGLE
C   AVDAY(MONTH) = AVE. DAY FOR MONTH IN YEAR
      CHARACTER*5 AINST(9)
      INTEGER HOUR
      REAL IDI, IBAR
      DIMENSION  AVDEC(12), HKTB(21), AVDAY(12)
      COMMON /COM3/PI,GSC,RC,TANLAT,SINLAT,COSLAT,COSB(8),SINB(8),
     &  COSAZ(8),SINAZ(8),COS1(8),COS2(8)
      COMMON /COM4/HRBAR(21,8),RBERB(21,8),IBAR(21)
      DATA AVDEC/-20.9,-13.0,-2.4,9.4,18.8,23.1,21.2,13.5,2.2,-9.6,
     &    -18.9,-23.0/
      DATA AVDAY/17.,47.,75.,105.,135.,162.,198.,228.,258.,288.,
     &    318.,344./
      DATA RBERB/168*0.0/
      RHO = 0.05
C
      WRITE(*,100)
 100  FORMAT('0','TRINITY SERMRT:  ERBS RBAR CORRELATION')
      WRITE(*,110) RHO
 110  FORMAT(' ','GROUND REFLECTANCE = ',F4.2)
C
C   *** CALCULATE CONSTANTS ***
      DECL = AVDEC(MONTH) * RC
C  (SUNSET HOUR ANGLE IN DEGREES)
      WS = ACOS(-TANLAT*TAN(DECL))/RC
      INST = 8
      COSDEC = COS(DECL)
      SINDEC = SIN(DECL)
      GON = GSC*(1.+0.033*COS(2.*PI*AVDAY(MONTH)/365.))
C   CONSTANTS FOR RT (EQ. 2.13.1)
      RTA = 0.409 + 0.5016*SIN((WS-60)*RC)
      RTB = 0.6609 - 0.4767*SIN((WS-60)*RC)
C   CONVERT SUNSET HOUR ANGLE BACK TO RADIANS
      WS = WS * RC
C   HD/H:  FROM ERBS NONSEASONAL CORRELATION (EQ. 4.23)
      HDH = 1.317 + (-3.023 + (3.373 - 1.760*DKTB)*DKTB) * DKTB
      IF (HDH .GT. 1.0) THEN
         HDH = 1.0
         WRITE(*,*) 'HDH > 1.0'
      END IF
C   FROM ERBS RBAR PROGRAM:
      IF (DKTB .GT. 0.8) HDH = 0.156
C
      DO 2000 HOUR=6,19
C   CHECK IF ALL OF HOUR IS DARK
         WBEG = (FLOAT(HOUR) - 1.0 - 12.0) * 0.2618
         WEND = (FLOAT(HOUR) - 12.0) * 0.2618
         IF (WBEG .GE. WS) GO TO 2000
         IF (WEND .LE. -WS) GO TO 2000
```

```
C   USE MIDDLE OF HOUR FOR ACTUAL CALCULATION (IN RADIANS)
         W = (FLOAT(HOUR) - 0.5 - 12.0) * 0.2618
         IF (W .LT. -WS) THEN
            IF ((WEND+WS) .LT. 0.01) GO TO 2000
            IF ((WEND+WS) .LT. 0.05) THEN
               W = WEND
            ELSE
               W = (-WS + WEND)/2.
            END IF
         END IF
         IF (W .GT. WS) THEN
            IF ((WS-WBEG) .LT. 0.01) GO TO 2000
            IF ((WS-WBEG) .LT. 0.05) THEN
               W = WBEG
            ELSE
               W = (WS + WBEG)/2.
            END IF
         END IF
      RDRT = 1/(RTA + RTB*COS(W))
      HKTB(HOUR) = DKTB/RDRT
C   ID/I = (RD/RT)(HD/H)
      IDI = HDH*RDRT
      IF (IDI .LE. 0.0) THEN
         WRITE(*,*) 'HOUR = ',HOUR,'   IDI = ',IDI
         IDI = 0.0
      END IF
      IF (IDI .GE. 1.0) THEN
         WRITE(*,*) 'HOUR = ',HOUR,'   IDI = ',IDI
         IDI = 1.0
      END IF
      THEZ = COSDEC*COSLAT*COS(W) + SINDEC*SINLAT
      IF (THEZ .LT. 1.0E-06) THEN
C   BEAM COMPONENT, RB(HOUR,I) = 0.0
         THEZ = 0.0
         DO 300 I = 2,INST
 300        RBERB(HOUR,I) = IDI*COS1(I) + COS2(I)
         GO TO 2000
      END IF
C
      DO 1000 I = 2,INST
         P = SINDEC*(SINLAT*COSB(I) - COSLAT*SINB(I)*COSAZ(I))
         Q = COSDEC*COS(W)*(COSLAT*COSB(I) + SINLAT*SINB(I)*COSAZ(I))
         S = COSDEC*SINB(I)*SINAZ(I)*SIN(W)
         THETA = P + Q + S
         IF (THETA .LT. 1.0E-04) THETA = 0.0
         RB = THETA/THEZ
         RBERB(HOUR,I) = IDI*COS1(I) + (1-IDI)*RB + COS2(I)
         IF (RBERB(HOUR,I) .LT. 0.0) THEN
            RBERB(HOUR,I) = 0.0
            WRITE(*,2100) AINST(I),HOUR
            WRITE(*,*) 'IDI = ',IDI,'   COS2(I) = ',COS2(I)
```

```
          END IF
 1000 CONTINUE
C
 2000 CONTINUE
 2100 FORMAT('0','RBAR WAS < 0  FOR INST ',A5,', HOUR ',I2)
C
      WS = WS/0.2618
      WRITE(*,*) 'WS (HOURS AFTER NOON) = ',WS
      RETURN
      END
```

APPENDIX D

```
C   THIS PROGRAM CALCULATES THE FREQUENCY DISTRIBUTION OF HOURLY & DAILY
C   CLEARNESS INDEXES FOR A GIVEN MONTH.
C   COMPLETE HOURS ONLY FOR DAILY CLEARNESS INDEX.
C   N = NUMBER OF GOOD DATA POINTS
C
      DEFINE FILE 11(ANSI, FB, 243, 6075, 0)
C
      INTEGER DESHR(6),HOUR,TDAY,EXP,HDATA(24),FLAG(24),N(6),IHOUR(6)
      REAL KT(6,31),KTPLOT(6,31),FRAC(6,31),DKT(31),DKPLOT(31),
     &   DFRAC(31),SUMRAD(6),SUMEXT(6),HKTB(6),DUMKT(31)
      COMMON /COM1/EX1,EX2(6),EX3(6),PI2,DECL,TANLAT,COSLAT,SINLAT,HEX
C   DESIRED ENDING HOURS
      DATA DESHR/10,11,12,13,14,15/
      DATA KTPLOT,SUMRAD,SUMEXT,N/186*0.0,6*0.0,6*0.0,6*0.0/
      DATA SUMH,SUMHO,SUMDH,SUMDL/0.0,0.0,0.0,0.0/
C   LATITUDE FOR TRINITY UNIVERSITY
      RLAT = 29.53
C   LATITUDE FOR ALBANY N.Y.
C     RLAT = 42.70
      CALL CONST(DESHR,RLAT)
C
C   *******************************************************
C   *** READ IN DATA & CALCULATE KT'S.  DO FOR EACH DAY. ***
C   *******************************************************
C   DAY = DAY IN YEAR, TDAY = DAY ON TAPE, MDAY = DAY OF MONTH
C   NDAY = DAYS IN MONTH
      WRITE(*,50)
C 50   FORMAT('0','ALBANY, NY')
 50   FORMAT('0','TRINITY UNIVERSITY')
      DO 200 MDAY = 1,32
C   READ IN GLOBAL HORIZONTAL RADIATION
         READ(11,250,END=290) INST,MO,TDAY,EXP,(HDATA(HOUR),
     &          FLAG(HOUR), HOUR = 1,24)
         IF (MDAY .EQ. 1) THEN
            INCHK = INST
            CALL DAYCAL(MO,TDAY,DAY,ISKIP,NDAY)
         ELSE
            DAY = DAY + 1.0
            IF (INST .NE. INCHK) THEN
               WRITE(*,260) MDAY, INST
               STOP
            END IF
         END IF
C
         H = 0.0
         DHOURS = 0.0
C   DECLINATION (IN RADIANS), SUNSET HOUR ANGLE (IN RADIANS)
         DEC = DECL*SIN(PI2*(284.0 + DAY))
```

```
         WS = ACOS(-TANLAT * TAN(DEC))
C   DAY LENGTH IN HOURS
         DAYLGT = 2.*WS/0.2618
         SUMDL = SUMDL + DAYLGT
C   CHECK FLAG TO SEE IF DESIRED DATA IS GOOD
         DO 100 HOUR = 5,20
               W2 = (FLOAT(HOUR) - 12.0) * 0.2618
               W1 = (FLOAT(HOUR) - 1.0 - 12.0) * 0.2618
C   SKIP EARLY MORNING & LATE EVENING PART HOURS
               IF (W1 .LT. -WS) GO TO 100
               IF (W2 .GT. WS) GO TO 100
            IF (FLAG(HOUR) .NE. 0  .AND.  HDATA(HOUR) .GT. 0) THEN
               DHOURS = DHOURS + 1.0
               SUMDH = SUMDH  + 1.0
               RAD = (FLOAT(HDATA(HOUR))) * 10.0**EXP
               H = H + RAD
               SUMH = SUMH + RAD
C   CHECK IF HOUR IS DESIRED HOUR
               DO 75 I = 1,6
               IF (HOUR .EQ. DESHR(I)) THEN
                  N(I) = N(I) + 1
                  SUMRAD(I) = SUMRAD(I) + RAD
                  EXTR = EX1*(1.0 + 0.033*COS(PI2*DAY)) *
     &                  (EX2(I)*COS(DEC) + EX3(I)*SIN(DEC))
                  SUMEXT(I) = SUMEXT(I) + EXTR
                  N1 = N(I)
                  KT(I,N1) = RAD/EXTR
                  GO TO 100
               END IF
 75            CONTINUE
            END IF
 100     CONTINUE
C
         HEXTR = HEX*(1.+0.033*COS(PI2*DAY))*(COSLAT*COS(DEC)*SIN(WS) +
     &            WS*SINLAT*SIN(DEC))
         SUMHO = SUMHO + HEXTR
         DKT(MDAY) = H*DAYLGT/(DHOURS*HEXTR)
C
C   SKIP OVER UNWANTED INSTRUMENTS
         DO 190 JUMP = 2,ISKIP
 190        READ(11,255)
C
C   REPEAT FOR FOLLOWING DAY
 200  CONTINUE
C
 250  FORMAT(10X,I4,2X,I2,I2,4X,I3,24(I7,I2))
 255  FORMAT(1X)
 260  FORMAT('0','READING TAPE IN WRONG SPOT:  DAY = ',I2,
     &     '  INST = ',I4)
      WRITE(*,*) 'END OF FILE NOT FOUND'
      STOP
```

```
C   CHECK IF LAST DAY
 290     LDAY = MDAY - 1
         IF (LDAY .NE. NDAY) WRITE(*,295) LDAY,NDAY
 295     FORMAT(' ','ERROR:  LAST DAY = ',I2,'  DAYS IN MONTH = ',I2)
C
C   **********************************************
C   *** CALCULATE KT & CUMULATIVE FREQUENCIES ***
C   **********************************************
C   DO FOR HOUR KT
      DO 400 I = 1,6
         J = N(I)
         DO 350 M = 1,J
 350        DUMKT(M) = KT(I,M)
         CALL FREQ(DUMKT,J,KTPLOT,FRAC)
         DO 375 M = 1,J
 375        KT(I,M) = DUMKT(M)
         N(I) = J
C   MONTHLY AVERAGED HOURLY CLEARNESS INDEX
         HKTB(I) = SUMRAD(I)/SUMEXT(I)
         IHOUR(I) = DESHR(I) - 1
 400  CONTINUE
C
C   DO FOR DAILY KT
      CALL FREQ(DKT,LDAY,DKPLOT,DFRAC)
C   MONTHLY AVERAGED DAILY CLEARNESS INDEX
      DKTB = SUMH*SUMDL/(SUMHO*SUMDH)
C
C   ********************
C   *** FINAL OUTPUT ***
C   ********************
      WRITE(*,1020) (IHOUR(I),DESHR(I), I = 1,6)
 1020 FORMAT('0','HOUR: ',6(6X,I2,'-',I2))
      WRITE(*,1025) (HKTB(I), I = 1,6)
 1025 FORMAT(' ','KTBAR:',4X,6(F5.3,11X))
      WRITE(*,1030)
 1030 FORMAT(' ',6(7X,'KT',6X,'FRAC'))
      DO 1050 M = 1,31
 1050    WRITE(*,1100) (KTPLOT(I,M),FRAC(I,M), I = 1,6)
 1100 FORMAT(' ',6X,6(6X,F5.3,4X,F5.2))
C   DAILY OUTPUT
      WRITE(*,2000) DKTB
 2000 FORMAT('0','MONTHLY AVERAGED DAILY CLEARNESS INDEX = ',F5.3)
      WRITE(*,1030)
      DO 2100 M = 1,LDAY
 2100    WRITE(*,1100) DKPLOT(M), DFRAC(M)
C
      WRITE(*,*)
      STOP
      END
```

```
      SUBROUTINE CONST(DESHR, RLAT)
C   SUBROUTINE TO CALCULATE CONSTANTS FOR THE DECLINATION FUNCTION AND THE
C   EXTRATERRESTRIAL RADIATION FUNCTION.
      INTEGER DESHR(6)
      COMMON /COM1/EX1,EX2(6),EX3(6),PI2,DECL,TANLAT,COSLAT,SINLAT,HEX
C   RC=PI/180=0.01745, RLAT=LATITUDE, GSC = SOLAR CONSTANT (KW/M2)
      DATA PI,RC,GSC/3.141593,0.01745,1.353/
      RLAT = RLAT * RC
      TANLAT = TAN(RLAT)
      COSLAT = COS(RLAT)
      SINLAT = SIN(RLAT)
C   DECLINATION CONSTANTS
      DECL = 23.45*RC
C   EXTRATERRESTRIAL RADIATION CONSTANTS
      PI2 = 2. * PI/365.
      EX1 = 13750. * GSC
      HEX = 27500.0 * GSC
C
      DO 200 I = 1,6
C   HOUR ANGLES IN +/- RADIANS
         W2 = (FLOAT(DESHR(I)) - 12.0)*0.2618
         W1 = (FLOAT(DESHR(I)) - 13.0)*0.2618
         EX2(I) = COS(RLAT)*(SIN(W2) - SIN(W1))
         EX3(I) = (W2 - W1)*SIN(RLAT)
 200  CONTINUE
C
      RETURN
      END


      SUBROUTINE DAYCAL(MONTH, IDAY, DAY,ISKIP,N)
C   SUBROUTINE TO DETERMINE MONTH OF YEAR, AND INITIAL DAY IN YEAR
      ISKIP = 15
      IF (IDAY .NE. 1) THEN
         WRITE(*,10) MONTH, IDAY
 10      FORMAT('0','INITIAL DAY OF MONTH ',I2,' IS NOT DAY 1.',
     &   '  DAY = ',I2)
         GO TO 60
      END IF
      IF (MONTH .EQ. 1) THEN
            DAY = FLOAT(IDAY)
            N = 31
            WRITE(*,*) 'JAN'
         ELSE IF (MONTH .EQ. 2) THEN
            DAY = FLOAT(31 + IDAY)
C           N = 29
            N = 28
            WRITE(*,*) 'FEB'
         ELSE IF (MONTH .EQ. 3) THEN
            ISKIP = 14
            DAY = FLOAT(59 + IDAY)
```

```
            N = 31
            WRITE(*,*) 'MARCH'
         ELSE IF (MONTH .EQ. 4) THEN
            DAY = FLOAT(90 + IDAY)
            N = 30
            WRITE(*,*) 'APRIL'
         ELSE IF (MONTH .EQ. 5) THEN
            DAY = FLOAT(120 + IDAY)
            N = 31
            WRITE(*,*) 'MAY'
         ELSE IF (MONTH .EQ. 6) THEN
            DAY = FLOAT(151 + IDAY)
            N = 30
            WRITE(*,*) 'JUNE'
         ELSE IF (MONTH .EQ. 7) THEN
            DAY = FLOAT(181 + IDAY)
            N = 31
            WRITE(*,*) 'JULY'
         ELSE IF (MONTH .EQ. 8) THEN
            DAY = FLOAT(212 + IDAY)
            N = 31
            WRITE(*,*) 'AUG'
         ELSE IF (MONTH .EQ. 9) THEN
            DAY = FLOAT(243 + IDAY)
            N = 30
            WRITE(*,*) 'SEPT'
         ELSE IF (MONTH .EQ. 10) THEN
            DAY = FLOAT(273 + IDAY)
            N = 31
            WRITE(*,*) 'OCT'
         ELSE IF (MONTH .EQ. 11) THEN
            DAY = FLOAT(304 + IDAY)
            N = 30
            WRITE(*,*) 'NOV'
         ELSE IF (MONTH .EQ. 12) THEN
            DAY = FLOAT(334 + IDAY)
            N = 31
            WRITE(*,*) 'DEC'
         ELSE
            WRITE(*,50) MONTH
 50         FORMAT('0','PROGRAM ERROR:  (NONEXISTENT MONTH)',
     &      '  MONTH = ',I3)
            N = 0
      END IF
C
 60   RETURN
      END


      SUBROUTINE FREQ(KT,J,KTPLOT,FRAC)
```

```
C   SUBROUTINE TO FIND THE FREQUENCY DISTRIBUTION OF A SET OF DATA
      REAL KT(31),KTPLOT(31),FRAC(31)
C
C   ROUND OFF KT VALUES TO 3 DECIMAL PLACES
      DO 400 M = 1,J
         ITEMP = IFIX((KT(M) + 0.0005)*1000)
 400     KT(M) = FLOAT(ITEMP)/1000.0
C   SORT KT IN INCREASING ORDER
      CALL SELECT (KT,J)
C   ACTUAL FREQUENCY CALCULATION
      J1 = 0
      DEN = FLOAT(J-1)
      DO 500 I = 1,J
         IF (I .LT. J) THEN
            IF (KT(I) .LT. KT(I+1)) THEN
               J1 = J1 + 1
               FRAC(J1) = FLOAT(I-1)/DEN
               KTPLOT(J1) = KT(I)
            END IF
         ELSE
            J1 = J1 + 1
            FRAC(J1) = 1.0
            KTPLOT(J1) = KT(J)
         END IF
 500  CONTINUE
      J = J1
      RETURN
      END


      SUBROUTINE SELECT(DATA,N)
C   THIS SUBROUTINE SORTS REAL NUMBERS BY THE SELECTION SORTING METHOD.
C   NUMBERS ARE ORDERED IN INCREASING VALUE.
C
      INTEGER PRESNT, SMALL, SEARCH
      DIMENSION DATA(N)
C
      J = N - 1
      DO 1000 PRESNT = 1,J
         SMALL = PRESNT
         K = PRESNT + 1
         DO 500 SEARCH = K,N
            IF (DATA(SEARCH) .LT. DATA(SMALL))  SMALL = SEARCH
 500     CONTINUE
         IF (SMALL .NE. PRESNT) THEN
            TEMP = DATA(PRESNT)
            DATA(PRESNT) = DATA(SMALL)
            DATA(SMALL) = TEMP
         END IF
 1000 CONTINUE
C
```

```
RETURN
END
```

# APPENDIX E

```
C   PROGRAM TO CALCULATE THE MINUTE CLEARNESS FREQUENCY DISTRIBUTION.
C   OUTPUT IS IN TRUE SOLAR TIME.
C   DATA WITH '99' AND '13' FLAGS ARE REJECTED.
C   THIS VERSION IS WRITTEN SPECIFICALLY FOR THE ALBANY SEMRTS TAPES.
C
      DEFINE FILE 11(ANSI, FB, 567, 6237, 0)
C
      CHARACTER*2 FLAG
      CHARACTER*6 HRMN
      INTEGER DAY, HOUR, EX
      REAL KT,KTBIN(51),EMIN(31)
      COMMON /COM1/MDATA(14,60),FLAG(14,60),KT(1860),FRAC(51)
      COMMON /COM2/PI2,EX1,EX2,EX3,COSDEC,SINDEC,SUMRAD,SUMEXT
C   RC = PI/180 =0.01745, RLAT = LATITUDE
      DATA PI,RC,GSC/3.141593,0.01745,1.353/
C   ALBANY DATA:  LATITUDE   &   4*(STAND. MER. - LONG)
      DATA RLAT,ECON/42.70,4.7/
C   TRINITY DATA:  LATITUDE   &   4*(STAND. MER. - LONG)
C     DATA RLAT,ECON/29.53,-34.0/
      RLAT = RLAT*RC
      SINLAT = SIN(RLAT)
      COSLAT = COS(RLAT)
C   NUMBER OF CLEARNESS INDEXES FROM MINUTE DATA
      K = 0
      SUMRAD = 0.0
      SUMEXT = 0.0
C   HOUR ANGLES IN RADIANS (W2 = HOUR 13, W1 = HOUR 12)
      W2 = 0.2618
      W1 = 0.0
C   EXTRATERRESTRIAL CONSTANTS
      DECL = 23.45*RC
      PI2 = 2.*PI/365.
      EX1 = 229.2*GSC
      EX2 = COSLAT*(SIN(W2) - SIN(W1))
      EX3 = (W2 - W1)*SINLAT
C
      WRITE(*,10)
 10   FORMAT('0','**** SEMRTS:  ALBANY NEW YORK ****')
C 10   FORMAT('0','**** SEMTRS:  TRINITY UNIVERSITY ****')
C
C   READ IN DAYS IN MONTH
      READ(*,20,ERR=35) N
 20   FORMAT(I2)
      WRITE(*,22) N
 22   FORMAT(' ','DAYS IN MONTH = ',I2)
      GO TO 45
 35      WRITE(*,40)
 40      FORMAT('0','INPUT ERROR FOR DAYS IN MONTH')
```

```
        STOP
 45   CONTINUE
 50   FORMAT(1X)
 100  FORMAT(10X,A4,2X,I2,A6,I3,60(I7,A2))
C
C   ********************************
C   *** START OF TAPE PROCESSING ***
C   ********************************
C   NOTE:  HOUR COUNTER IS ENDING HOUR OF HOUR INTERVAL (STANDARD TIME)
C                   (I.E. HOUR 1-2:  HOUR COUNTER = 2)
C     HOUR IN TAPE RECORD HEADER IS STARTING HOUR (STANDARD TIME)
      DO 1000 DAY = 1,N
         DO 200 HOUR = 1,11
 200        READ(11,50)
C   READ IN A DAY'S WORTH OF DATA FOR GIVEN INSTRUMENT
         DO 300 HOUR = 12,14
            READ(11,100) INST,MONTH,HRMN,EX,
     &          (MDATA(HOUR,MIN),FLAG(HOUR,MIN), MIN = 1,60)
            IF(HOUR .EQ. 4) THEN
               IN = INST
               IF (DAY .EQ. 1) CALL DAYCAL(MONTH,YDAY,ISKIP)
            ELSE
               IF (IN .NE. INST) THEN
                 WRITE(*,1005) IN,INST,HRMN
                 STOP
               END IF
            END IF
 300     CONTINUE
C
C   CONVERSION FROM STANDARD TIME TO TRUE SOLAR TIME
         YDAY = YDAY + 1.0
         DEC = DECL*SIN(PI2*(284. + YDAY))
         COSDEC = COS(DEC)
         SINDEC = SIN(DEC)
         B = 2.*PI*(YDAY - 81.0)/364.0
         EMIN(DAY) = 9.87*SIN(2.*B) - 7.53*COS(B) - 1.5*SIN(B) + ECON
C
         IF (EMIN(DAY) .GT. -2.0  .AND.  EMIN(DAY) .LT. 2.0) THEN
C   SOLAR TIME EQUALS STANDARD TIME
            CALL PHISUB(13,1,60,EX,YDAY,K)
         ELSE IF (EMIN(DAY) .LE. -2.0) THEN
C   SOLAR TIME LAGS STANDARD TIME
            INDEX2 = -IFIX(EMIN(DAY))
            INDEX1 = INDEX2 - 1
            CALL PHISUB(13,INDEX2,60,EX,YDAY,K)
            CALL PHISUB(14,1,INDEX1,EX,YDAY,K)
         ELSE
C   SOLAR TIME LEADS STANDARD TIME
            INDEX2 = IFIX(EMIN(DAY))
            INDEX1 = INDEX2 - 1
            CALL PHISUB(12,INDEX2,60,EX,YDAY,K)
```

```
           CALL PHISUB(13,1,INDEX1,EX,YDAY,K)
        END IF
C
        DO 950 HOUR = 15,24
 950       READ(11,50)
C
C   FOR TRINITY MINUTE TAPES, SKIP OTHER INSTRUMENTS
C       DO 970 I = 2,ISKIP
C          DO 960 HOUR = 1,24
C960          READ(11,50)
 970    CONTINUE
C
C   REPEAT FOR NEXT DAY
1000  CONTINUE
1005  FORMAT('0','MISMATCH IN INSTRUMENTS:  OLD = ',I4,'  NEW = ',I4,
     &  '  DAY,HR,MN = ',A6)
C
C   PUT CLEARNESS INDEXES INTO BINS FOR PLOTTING
      CALL BIN(K)
C
C   **************
C   *** OUTPUT ***
C   **************
      HKT = SUMRAD/SUMEXT
      WRITE(*,2010) HKT
 2010 FORMAT(' ','M.A. HOURLY INDEX (HOUR: 12-13) = ',F5.3)
      WRITE(*,2020)
 2020 FORMAT(' ','  KT',5X,'FRACTION')
      DO 2100 J = 1,50
         KTBIN(J) = FLOAT(J)*0.02 - 0.01
 2100    WRITE(*,2120) KTBIN(J),FRAC(J)
 2120 FORMAT(' ',F5.3,4X,F5.2)
C
      WRITE(*,*)
      STOP
      END



      SUBROUTINE PHISUB(HOUR,I1,I2,EX,DAY,K)
C   SUBROUTINE TO CALCULATE CLEARNESS INDEX
      REAL KT
      INTEGER HOUR,EX
      CHARACTER*2 FLAG
      COMMON /COM1/MDATA(14,60),FLAG(14,60),KT(1860),FRAC(51)
      COMMON /COM2/PI2,EX1,EX2,EX3,COSDEC,SINDEC,SUMRAD,SUMEXT
C
      DO 400 MIN = I1,I2
      IF(MDATA(HOUR,MIN) .LE. 0) GO TO 400
      IF(FLAG(HOUR,MIN).EQ.'99' .OR. FLAG(HOUR,MIN).EQ.'13') GO TO 400
      IF(FLAG(HOUR,MIN).EQ.'11' .OR. FLAG(HOUR,MIN).EQ.'12') THEN
```

```
          RDATA = (FLOAT(MDATA(HOUR,MIN))) * 10.0**EX
          K = K + 1
          EXTR = EX1*(1.0 + 0.033*COS(PI2*DAY)) *
     &           (EX2*COSDEC + EX3*SINDEC)
          KT(K) = RDATA/EXTR
          SUMRAD = SUMRAD + RDATA
          SUMEXT = SUMEXT + EXTR
       ELSE
          WRITE(*,600) FLAG(HOUR,MIN),HOUR,MIN
       END IF
 400   CONTINUE
 600   FORMAT('0','UNRECOGNIZED FLAG (',A2,'):  HR/MIN = ',I2,'/',I2)
C
       RETURN
       END


       SUBROUTINE DAYCAL(MONTH,DAY,ISKIP)
C    SUBROUTINE TO CALCULATE THE MONTH & CRITICAL LEVELS FOR INSTRUMENTS
       CHARACTER*2 FLAG
       ISKIP = 15
C
       IF (MONTH .EQ. 1) THEN
             WRITE(*,*) 'JANUARY'
             DAY = 0.0
          ELSE IF (MONTH .EQ. 2) THEN
             WRITE(*,*) 'FEBRUARY'
             DAY = 31.0
          ELSE IF (MONTH .EQ. 3) THEN
             WRITE(*,*) 'MARCH'
             DAY = 59.0
C            ISKIP = 14
          ELSE IF (MONTH .EQ. 4) THEN
             WRITE(*,*) 'APRIL'
             DAY = 90.0
          ELSE IF (MONTH .EQ. 5) THEN
             WRITE(*,*) 'MAY'
             DAY = 120.0
          ELSE IF (MONTH .EQ. 6) THEN
             WRITE(*,*) 'JUNE'
             DAY = 151.0
          ELSE IF (MONTH .EQ. 7) THEN
             WRITE(*,*) 'JULY'
             DAY = 181.0
          ELSE IF (MONTH .EQ. 8) THEN
             WRITE(*,*) 'AUGUST'
             DAY = 212.0
          ELSE IF (MONTH .EQ. 9) THEN
             WRITE(*,*) 'SEPTEMBER'
             DAY = 243.0
          ELSE IF (MONTH .EQ. 10) THEN
```

```
            WRITE(*,*) 'OCTOBER'
            DAY = 273.0
         ELSE IF (MONTH .EQ. 11) THEN
            WRITE(*,*) 'NOVEMBER'
            DAY = 304.0
         ELSE IF (MONTH .EQ. 12) THEN
            WRITE(*,*) 'DECEMBER'
            DAY = 334.0
         ELSE
            WRITE(*,50) MONTH
 50         FORMAT('0','PROGRAM ERROR:  MONTH = ',I3)
      END IF
C
      RETURN
      END


      SUBROUTINE BIN(K)
C   SUBROUTINE TO PUT THE CLEARNESS INDEXES INTO BINS, AND TO CALCULATE THE
C   APPROPRIATE CUMULATIVE FREQUENCY.
      REAL KT, CHECK(51)
      COMMON /COM1/MDATA(14,60),FLAG(14,60),KT(1860),FRAC(51)
      TFRAC = 0.0
C
C   SET BIN BOUNDARIES  (0.0 TO 1.0 IN 0.02 INCREMENTS)
      DO 100 J = 1,51
 100     CHECK(J) = FLOAT(J - 1)*0.02
C
C   FIND BIN FOR EACH CLEARNESS INDEX
      DO 500 I = 1,K
         DO 400 J = 1,50
            J1 = J + 1
            IF (KT(I) .GE. CHECK(J)  .AND.  KT(I) .LT. CHECK(J)) THEN
               DO 300 J2 = J,50
                  FRAC(J2) = FRAC(J2) + 1.0
 300              TFRAC = TFRAC + 1.0
            END IF
 400     CONTINUE
 500  CONTINUE
C
C   CALCULATE THE ACTUAL CUMULATIVE FRACTION FOR EACH BIN
      DO 600 J = 1,50
 600     FRAC(J) = FRAC(J)/TFRAC
C
      RETURN
      END
```

APPENDIX F

```
C    PROGRAM TO CALCULATE HOURLY AND DAILY UTILIZABILITY FROM EITHER SAN
C    ANTONIO OR ALBANY HOUR DATA.
       DEFINE FILE 11(ANSI, FB, 243, 6075, 0)
C
C    TIME = TOTAL NUMBER OF HOURS IN MONTH WITH GOOD DATA (EACH INST)
C    NDAY = TOTAL NUMBER OF DAYS FOR GIVEN TIME PERIOD AND INSTRUMENT
C             WITH GOOD DATA (NDAY(TIME,INST))
C    N = # OF DAYS IN THE MONTH, DAY= DAY OF YEAR
C    IC = I-CRITICAL  (KJ/M2-HR)
C    HPHI(HOUR,INST,IC) = HOURLY UTILIZABILITY
C    DPHI(INST,IC) = DAILY UTILIZABILITY
C    ARAD(HOUR,INST) = MONTHLY AVERAGED HOURLY RADIATION (KN/M2)
C    SLOPE(HOUR,INST) = INITIAL SLOPE OF UTILIZABILITY CURVE (DPHI/DXC)
C    RC=PI/180=0.01745, RLAT=LATITUDE, GSC=SOLAR CONSTANT (KW/M2)
C
       REAL IC, NDAY
       INTEGER HDATA(24,15), EXP(15), HOUR, FLAG(24,15)
       CHARACTER*5 AINST(15)
       DIMENSION INST(15),HKTB(21),HRBAR(21,15),RBAR(15),NDAY(21,15),
      &   ARAD(20,15),SLOPE(20,15),SETR(21),SUMI(21,15),SUMH(15)
       COMMON /COM1/ HPHI(21,8,11), DPHI(8,11), IC(8,11)
       COMMON /COM2/PI,RLAT,GSC,RC,TIME(15),TANLAT,SINLAT,COSLAT
C
       DATA PI,RC,GSC,HRBAR / 3.141593,0.01745,1.353,315*0.0/
       DATA SUMH,SETR,SUMI,HKTB / 15*0.0,21*0.0,315*0.0,21*0.0/
       DATA HPHI,DPHI,NDAY,TIME/1848*0.0,88*0.0,315*0.0,15*0.0/
C    TRINITY DATA
       DATA AINST,RLAT/'HORIZ','20S','30S','40S','90N','90E','90S',
      &  '90W','NIP','DIFF','UV-EP','PIR','OG530','RG630','RG690',29.53/
C    ALBANY DATA
C      DATA AINST,RLAT/'HORIZ','33S','43S','53S','90N','90E','90S',
C     &  '90W','NIP','DIF-D','DIF-C','UV','IR','AMB','DEW',42.70/
C
       WRITE(*,5) RLAT
 5     FORMAT('0','TRINITY SEMRT:  HOURLY DATA',20X,'LATITUDE = ',F5.2)
C 5     FORMAT('0','ALBANY NY:  HOURLY SEMRT DATA',15X,'LATITUDE = ',F5.2)
       RLAT = RLAT*RC
       TANLAT = TAN(RLAT)
       SINLAT = SIN(RLAT)
       COSLAT = COS(RLAT)
       IEQUIP = 8
       I2 = IEQUIP + 1
       SUMHO = 0.0
 10    FORMAT(1X)
 100   FORMAT(10X,I4,2X,I2,I2,4X,I3,24(I7,I2))
 110   FORMAT('0','MISMATCH IN INST:  OLD = ',I4,'   NEW = ',I4)
C
C    ***********************************
```

```
C   *** READ IN THE DATA FOR THE DAY ***
C   **********************************
      DO 2000 JDAY = 1,32
         DO 1000 I = 1,IEQUIP
            READ(11,100,END=2002) IN,MO,IDAY,EXP(I),(HDATA(HOUR,I),
     &            FLAG(HOUR,I),HOUR=1,24)
            IF (JDAY .EQ. 1) THEN
               INST(I) = IN
               IF (I .EQ. 1) THEN
                  CALL DAYCAL(MONTH,IDAY,DAY,N,ISKIP)
                  IF (N .EQ. 0) STOP
               END IF
            END IF
            IF (IN .NE. INST(I)) THEN
               WRITE(*,*) 'JDAY = ',JDAY
               WRITE(*,110) INST(I),IN
               STOP
            END IF
            IF (I .EQ. 1) THEN
               DAY = DAY + 1.0
               DEC = 23.45*RC*SIN(2*PI*(284. + DAY)/365.0)
               WS = ACOS(-TANLAT*TAN(DEC))
            END IF
 1000    CONTINUE
C
C   SKIP UNWANTED INSTRUMENTS
         DO 1050 I = I2,ISKIP
 1050       READ(11,10)
C
C   *** CALCULATIONS ***
         DO 1900 HOUR = 5,20
C   CALCULATE HOUR ANGLES (IN RADIANS)
            W2 = (FLOAT(HOUR)-12.0)*0.2618
            W1 = (FLOAT(HOUR)-13.0)*0.2618
C   CHECK IF BEFORE SUNRISE OR AFTER SUNSET
            IF (W2 .LT. -WS) GO TO 1900
            IF (W1 .GT. WS) GO TO 1900
C   CHECK FOR PARTIAL HOUR
            IF (W1 .LT. -WS) W1 = -WS
            IF (W2 .GT. WS) W2 = WS
C   CHECK FOR VALID DATA
            DO 1500 I = 1,IEQUIP
               IF (FLAG(HOUR,I) .EQ. 0) GO TO 1900
               IF (HDATA(HOUR,I) .LE. 0) GO TO 1900
               RDATA = (FLOAT(HDATA(HOUR,I))) * 10.**EXP(I)
               IF (I .EQ. 1) THEN
C   HOURLY EXTRATERRESTRIAL RADIATION (KJ/M2)
                  ETRR = 13750.*GSC*(1.0+0.033*COS(2.*PI*DAY/365.))
                  ETRL = COSLAT*COS(DEC)*(SIN(W2)-SIN(W1)) +
     &                   (W2-W1)*SINLAT*SIN(DEC)
                  ETR = ETRR * ETRL
```

```
                  SETR(HOUR) = SETR(HOUR) + ETR
                  SUMHO = SUMHO + ETR
               END IF
               SUMI(HOUR,I) = SUMI(HOUR,I) + RDATA
               NDAY(HOUR,I) = NDAY(HOUR,I) + 1.
               SUMH(I) = SUMH(I) + RDATA
               TIME(I) = TIME(I) + 1.
               DO 1400 J = 1,11
                  IF (RDATA .GT. IC(I,J)) THEN
                     HPHI(HOUR,I,J) = HPHI(HOUR,I,J) + RDATA - IC(I,J)
                     DPHI(I,J) = DPHI(I,J) + RDATA - IC(I,J)
                  END IF
 1400          CONTINUE
C   REPEAT FOR NEXT INSTRUMENT
 1500       CONTINUE
C   REPEAT FOR NEXT HOUR
 1900    CONTINUE
C   REPEAT FOR NEXT DAY
 2000 CONTINUE
      WRITE(*,*) 'END OF FILE NOT FOUND'
      STOP
C
C   *** END OF TAPE ***
 2002 LAST = JDAY - 1
      IF (LAST .NE. N) THEN
         WRITE(*,*) 'ERROR IN NUMBER OF DAYS'
         WRITE(*,2005) N,LAST
         STOP
      END IF
 2005 FORMAT(' ','DAYS IN MONTH = ',I2,'   LAST DAY READ = ',I2)
C
C   *******************************************
C   ***  KTBAR, RBAR & PHIBAR CALCULATIONS  ***
C   *******************************************
 2010 DKTB = SUMH(1)/SUMHO
      DO 2015 J = 1,11
 2015   DPHI(1,J) = DPHI(1,J)/SUMH(1)
      DO 2030 HOUR = 5,20
         HKTB(HOUR) = SUMI(HOUR,1)/SETR(HOUR)
         IF (HKTB(HOUR) .GT. 1.0) HKTB(HOUR) = 1.0
         ARAD(HOUR,1) = SUMI(HOUR,1)/NDAY(HOUR,1)
         DO 2020 J = 1,11
 2020      HPHI(HOUR,1,J) = HPHI(HOUR,1,J)/SUMI(HOUR,1)
         SLOPE(HOUR,1) = -(HPHI(HOUR,1,1)-HPHI(HOUR,1,2))*
     &      ARAD(HOUR,1)/IC(1,2)
 2030 CONTINUE
      DO 2080 I = 2,IEQUIP
         RBAR(I) = SUMH(I)*TIME(1)/(SUMH(1)*TIME(I))
         DO 2040 J = 1,11
 2040    DPHI(I,J) = DPHI(I,J)/SUMH(I)
         DO 2060 HOUR = 5,20
```

```
            HRBAR(HOUR,I) = SUMI(HOUR,I)*NDAY(HOUR,1)/
     &       (SUMI(HOUR,1)*NDAY(HOUR,I))
            ARAD(HOUR,I) = SUMI(HOUR,I)/NDAY(HOUR,I)
            DO 2050 J = 1,11
 2050          HPHI(HOUR,I,J) = HPHI(HOUR,I,J)/SUMI(HOUR,I)
            SLOPE(HOUR,I) = -(HPHI(HOUR,I,1)-HPHI(HOUR,I,2))*
     &         ARAD(HOUR,I)/IC(I,2)
 2060    CONTINUE
 2080 CONTINUE
C   CONVERT IC(I,J) FROM KJ/M2-HR TO W/M2 FOR OUTPUT
      DO 2095 I = 1,IEQUIP
         DO 2090 J = 1,11
 2090       IC(I,J) = IC(I,J)/3.6
 2095 CONTINUE
      GO TO 4000
C
C   ************************************************
C   ***  OUTPUT TYPE A:  RBAR, DAILY & HOURLY PHI ***
C   ************************************************
 2100 WRITE(*,2150) SUMH(1), SUMHO, DKTB
 2150 FORMAT('0','SUMH(1) = ',F10.1,' SUMHO = ',F10.1,' DKTB = ',F5.3)
      WRITE(*,2275)
 2275 FORMAT('0','KTBARS & RBARS FOR LISTED INSTRUMENTS AND TIMES')
 2280 WRITE(*,2300)
C 2300 FORMAT(' ','TIME  04-05 05-06 06-07 07-08 08-09 09-10 10-11 ',
C     & '11-12 12-13 13-14 14-15 15-16 16-17 17-18 18-19 19-20')
 2300 FORMAT(' ','TIME  05-06 06-07 07-08 08-09 09-10 10-11 11-12 ',
     & '12-13 13-14 14-15 15-16 16-17 17-18 18-19  DAILY')
      WRITE(*,2400)  (HKTB(HOUR),HOUR=6,19), DKTB
 2400 FORMAT(' ','KTBAR',14(2X,F4.2),3X,F4.2)
      DO 2500 I = 2,IEQUIP
C2500    WRITE(*,2600) AINST(I),(HRBAR(HOUR,I),HOUR=6,19),RBAR(I)
 2500    WRITE(*,2600) AINST(I),(HRBAR(HOUR,I),HOUR=5,20)
C2600 FORMAT(' ',A5,14(2X,F4.2),3X,F4.2)
 2600 FORMAT(' ',A5,16(1X,F5.2))
 2610 DO 2700 I = 1,IEQUIP
      WRITE(*,2800) AINST(I)
      WRITE(*,2300)
      DO 2650 J = 1,11
 2650    WRITE(*,2900) IC(I,J),(HPHI(HOUR,I,J),HOUR=6,19),DPHI(I,J)
      WRITE(*,2910) (SLOPE(HOUR,I), HOUR=6,19)
 2700 CONTINUE
 2800 FORMAT('0','UTILIZABILITY FOR LISTED CRITICAL LEVEL (W/M2)',
     &  ' AND TIME',15X,'INSTRUMENT ',A5)
 2900    FORMAT(' ',F5.1,14(2X,F4.2),3X,F4.2)
 2910 FORMAT(' ','SLOPE',14(F6.2))
      WRITE(*,*)
      STOP
C
C   ******************************************
C   ***** OUTPUT TYPE B:  DAILY PHI ONLY *****
```

```
C    ******************************************
 4000 WRITE(*,*) 'DAILY UTILIZABILITY'
      WRITE(*,4010) AINST(1),AINST(3),AINST(7),AINST(5),AINST(8)
 4010 FORMAT(' ','IC1(W/M2)',5(3X,A5))
      DO 4050  J = 1,11
 4050    WRITE(*,4060) IC(1,J),DPHI(1,J),DPHI(3,J),DPHI(7,J),DPHI(5,J),
     &        DPHI(8,J)
 4060 FORMAT(' ',F7.1,2X,5(2X,F6.3))
      WRITE(*,*)
      STOP
C
C    *******************************************
C    ***** OUTPUT TYPE C:  HOURLY PHI ONLY *****
C    *******************************************
 5000 HOUR = 13
      LHOUR = HOUR - 1
      WRITE(*,5010) LHOUR,HOUR
 5010 FORMAT(' ','HOURLY UTILIZABILITY:  HOUR ',I2,'-',I2)
      WRITE(*,4010) AINST(1),AINST(3),AINST(7),AINST(5),AINST(8)
      DO 5050 J =1,11
 5050    WRITE(*,4060) IC(1,J),HPHI(HOUR,1,J),HPHI(HOUR,3,J),
     &      HPHI(HOUR,7,J),HPHI(HOUR,5,J),HPHI(HOUR,8,J)
      WRITE(*,*)
      STOP
C
      END


      SUBROUTINE DAYCAL(MONTH, IDAY, DAY, N, ISKIP)
C    SUBROUTINE TO CALCULATE MONTH & CRITICAL LEVELS FOR INSTRUMENTS.
      REAL IC,KMAX,DECL(12),B(8),AZ(8),DKT(12)
      COMMON /COM1/ HPHI(21,8,11), DPHI(8,11), IC(8,11)
      COMMON /COM2/PI,RLAT,GSC,RC,TIME(15),TANLAT,SINLAT,COSLAT
      DATA DECL/-20.9,-13.0,-2.4,9.4,18.8,23.1,21.2,13.5,2.2,-9.6,
     &    -18.9,-23.0/
      DATA AZ/4*0.0,180.0,-90.0,0.0,90.0/
C    TRINITY DATA
      DATA B/0.0,20.0,30.0,40.0,4*90.0/
      DATA DKT,CONST/0.463,0.406,0.390,0.376,0.488,0.475,0.557,0.540,
     &     0.577,0.452,0.533,0.443,0.8/
C    ALBANY DATA
C     DATA B/0.0,33.0,43.0,53.0,4*90.0/
C     DATA DKT,CONST/0.461,0.353,0.423,0.428,0.546,0.487,0.459,0.453,
C    &    0.517,0.408,0.372,0.406,0.7/
C
      ISKIP = 15
      IF (IDAY .NE. 1) THEN
         WRITE(*,10) MONTH, IDAY
 10      FORMAT('0','INITIAL DAY OF MONTH ',I2,' IS NOT DAY 1.',
     &   '  DAY = ',I2)
         N = 0
```

```
         RETURN
      END IF
      IF (MONTH .EQ. 1) THEN
            DAY = 0.0
            N = 31
            WRITE(*,*) 'JAN'
         ELSE IF (MONTH .EQ. 2) THEN
            DAY = 31.0
            N = 28
C   ALBANY DATA INCLUDES LEAP YEAR
C           N = 29
            WRITE(*,*) 'FEB'
         ELSE IF (MONTH .EQ. 3) THEN
            DAY = 59.0
            N = 31
C   TRINITY DATA LACKED DIFFUSE DATA FOR MARCH
            ISKIP = 14
            WRITE(*,*) 'MARCH'
         ELSE IF (MONTH .EQ. 4) THEN
            DAY = 90.0
            N = 30
            WRITE(*,*) 'APRIL'
         ELSE IF (MONTH .EQ. 5) THEN
            DAY = 120.0
            N = 31
            WRITE(*,*) 'MAY'
         ELSE IF (MONTH .EQ. 6) THEN
            DAY = 151.0
            N = 30
            WRITE(*,*) 'JUNE'
         ELSE IF (MONTH .EQ. 7) THEN
            DAY = 181.0
            N = 31
            WRITE(*,*) 'JULY'
         ELSE IF (MONTH .EQ. 8) THEN
            DAY = 212.0
            N = 31
            WRITE(*,*) 'AUG'
         ELSE IF (MONTH .EQ. 9) THEN
            DAY = 243.0
            N = 30
            WRITE(*,*) 'SEPT'
         ELSE IF (MONTH .EQ. 10) THEN
            DAY = 273.0
            N = 31
            WRITE(*,*) 'OCT'
         ELSE IF (MONTH .EQ. 11) THEN
            DAY = 304.0
            N = 30
            WRITE(*,*) 'NOV'
         ELSE IF (MONTH .EQ. 12) THEN
```

```
            DAY = 334.0
            N = 31
            WRITE(*,*) 'DEC'
         ELSE
            WRITE(*,50) MONTH
 50         FORMAT('0','PROGRAM ERROR:  MONTH = ',I3)
            N = 0
            RETURN
      END IF
C
C   CRITICAL LEVELS (CALCULATE NOON IRRADIATION TO FIND)
      SINDEC = SIN(RC*DECL(MONTH))
      COSDEC = COS(RC*DECL(MONTH))
      KMAX = 0.208 + DKT(MONTH)*(2.77 + DKT(MONTH)*(-4.75 + 2.92*
     &   DKT(MONTH)))
      DO 200 I = 1,8
         COSB = COS(B(I)*RC)
         SINB = SIN(B(I)*RC)
         COSAZ = COS(AZ(I)*RC)
         THETA = SINDEC*(SINLAT*COSB - COSLAT*SINB*COSAZ) +
     &           COSDEC*(COSLAT*COSB + SINLAT*SINB*COSAZ)
C   CHECK IF SUN IS BEHIND SURFACE AT NOON
         IF (THETA .LT. 0.3) THEN
            IF (I .EQ. 6  .OR.  I .EQ. 8) THEN
C   EAST & WEST SURFACES
               THETA = CONST*DKT(MONTH)
            ELSE IF(I .EQ. 5) THEN
C   NORTH SURFACE
               THETA = 0.3*DKT(MONTH)
            ELSE
C   SOUTH SURFACE, SUN HIGH ABOVE TILT
               THETA = 0.3
            END IF
         END IF
         RMAX = 495.0*THETA*KMAX
         DO 100 J = 1,11
 100        IC(I,J) = FLOAT(J - 1)*RMAX
 200  CONTINUE
C
      RETURN
      END
```

APPENDIX G

```
C    PROGRAM TO CALCULATE DAILY AND HOURLY UTILIZABILITY FROM MINUTE DATA.
C    OUTPUT IS IN TRUE SOLAR TIME.
C    LATITUDE IS FOR TRINITY UNIVERSITY.
C         IC = I-CRITICAL (KJ/M2-MIN)
C         HPHI(HOUR,INST,IC) = HOURLY UTILIZABILITY
C         DPHI(INST,IC) = DAILY UTILIZABILITY
C         SUMI(HOUR,INST) = HOURLY RADIATION TOTAL
C         SUMH(INST) = DAILY RADIATION TOTAL
C         IEQUIP = # OF WANTED INSTRUMENTS
C         ISKIP = # OF INSTRUMENTS TO SKIP
C         N = DAYS IN MONTH
C
      DEFINE FILE 11(ANSI, FB, 567, 6237, 0)
      REAL IC
      INTEGER  EX, HOUR, FLAG, SOLART, HRMN
      CHARACTER*5 AINST(15)
      DIMENSION IN(15)
      COMMON /COM1/ HPHI(21,8,11), DPHI(8,11)
      COMMON /COM2/ SUMI(21,15),SUMH(15),IC(8,11),RC,RLAT,PI
      COMMON /COM3/ MDATA(60), FLAG(60)
C    RC=PI/180=0.01745, RLAT=LATITUDE
      DATA RC, RLAT, PI / 0.01745, 29.53, 3.1415927/
      DATA SUMH, SUMI / 15*0.0, 315*0.0 /
      DATA HPHI,DPHI / 1848*0.0, 88*0.0 /
      DATA AINST/'HORIZ',' 20S ',' 30S ',' 40S ',' 90N ',
     & ' 90E ',' 90S ',' 90W ',' NIP ',' DIFF','UV-EP',
     & ' PIR ','OG530','RG630','RG690'/
C
      READ(*,25) IEQUIP,ISKIP,N
 25   FORMAT(I2,I2,I2)
      IBEGIN = 6
      ISTART = IBEGIN - 1
      ISTOP = 21
      ITOTAL = IEQUIP + ISKIP
      IJUMP1 = ITOTAL * 4
      IJUMP2 = ITOTAL * 3
C
      WRITE(*,50) RLAT
 50   FORMAT('0','TRINITY SEMRT:  MINUTE DATA',20X,'LATITUDE = ',F5.2)
      WRITE(*,*) 'OUTPUT IS IN TRUE SOLAR TIME'
      WRITE(*,60) IEQUIP, ISKIP, N
 60   FORMAT(' ','DESIRED INSTRUMENTS = ',I2,'  INSTRUMENTS TO SKIP = ',
     &   I2,'  DAYS IN MONTH = ',I2)
      RLAT = RLAT*RC
 75   FORMAT(1X)
 100  FORMAT(10X,I4,2X,I2,I6,I3,60(I7,I2))
 120  FORMAT('0','MISMATCH IN INSTRUMENTS:  OLD = ',I4,
     &  '  NEW = ',I4)
```

```
 150  FORMAT('0','DAY = ',I2)
C
C   ********************************
C   *** START OF TAPE PROCESSING ***
C   ********************************
      DO 1700 JDAY = 1,N
C   *** SKIP PRE-DAWN HOURS, ALL INSTRUMENTS ***
         DO 200 J = 1,IJUMP1
 200        READ(11,75)
C   *** HOURS 5 THROUGH 21, ALL DESIRED INSTRUMENTS ***
         DO 1500 HOUR = ISTART,ISTOP
            DO 1300 I = 1,IEQUIP
            READ(11,100) INST,MO,HRMN,EX,(MDATA(MIN),
     &                FLAG(MIN),MIN=1,60)
               IF(HOUR .EQ. ISTART) THEN
                  IF(JDAY .EQ. 1) THEN
                    IN(I) = INST
                    IF(I .EQ. 1) THEN
                       CALL DAYCAL(MO,INDEX1,INDEX2)
                       IF (MO .EQ. 0) STOP
                    END IF
                  END IF
               ELSE
                  IF(INST .NE. IN(I)) THEN
                     WRITE(*,120) IN(I), INST
                     STOP
                  END IF
                  SOLART = HOUR - 1
C   SUM SECTION1 FOR SOLAR HOUR SOLART
                  CALL PHI(I,SOLART,AINST(I),1,INDEX1,HRMN,EX)
               END IF
C   SUM SECTION2 FOR FOLLOWING SOLAR HOUR
               CALL PHI(I,HOUR,AINST(I),INDEX2,60,HRMN,EX)
C
C   *** REPEAT FOR NEXT INSTRUMENT ***
 1300       CONTINUE
C
C   SKIP UNWANTED INSTRUMENTS
            DO 1400 J = 1,ISKIP
 1400          READ(11,75)
C   *** REPEAT FOR NEXT HOUR ***
 1500    CONTINUE
C
C   ***  SKIP NIGHT HOURS, ALL INSTRUMENTS ***
         DO 1600 J = 1,IJUMP2
 1600       READ(11,75)
C   *** REPEAT FOR NEXT DAY ***
 1700 CONTINUE
C
C   ********************************
C   *** CHECK IF AT END OF TAPE ***
```

```
C    ******************************
      DO 1740 I = 1,5
         READ(11,100,END=1780) INST,MO,HRMN,EX,(MDATA(MIN),FLAG(MIN),
     &              MIN = 1,60)
         WRITE(*,*) 'NEXT RECORD IN FILE:'
         WRITE(*,*) 'INST = ',INST,'   DAY/HR/MN = ',HRMN
 1740 CONTINUE
      GO TO 1790
 1780 WRITE(*,*) ' END OF FILE DETECTED'
 1790 CONTINUE
C
C    ****************************
C    ***  PHIBAR CALCULATIONS  ***
C    ****************************
      DO 2000 I = 1,IEQUIP
         DO 1900 J = 1,11
            DPHI(I,J) = DPHI(I,J)/SUMH(I)
            DO 1800 HOUR = IBEGIN,ISTOP
 1800          HPHI(HOUR,I,J) = HPHI(HOUR,I,J)/SUMI(HOUR,I)
 1900    CONTINUE
 2000 CONTINUE
C   CONVERT IC(I,J) BACK TO W/M2 FOR OUTPUT
      DO 2055 I = 1,IEQUIP
         DO 2050 J = 1,11
 2050       IC(I,J) = IC(I,J) * 16.66667
 2055 CONTINUE
      GO TO 4000
C
C    *******************************************
C    ***  OUTPUT TYPE A:  DAILY & HOURLY PHI ***
C    *******************************************
 2100 DO 2300 I = 1,IEQUIP
         WRITE(*,2400) AINST(I)
         WRITE(*,2500)
         DO 2200 J = 1,11
 2200       WRITE(*,2800) IC(I,J),(HPHI(HOUR,I,J),HOUR=6,19),
     &      DPHI(I,J)
 2300 CONTINUE
 2400 FORMAT('0','UTILIZABILITY FOR LISTED CRITICAL LEVEL (W/M2)',
     &  ' AND TIME',15X,'INSTRUMENT ',A5)
 2500 FORMAT(' ','ICRT  05-06 06-07 07-08 08-09 09-10 10-11 11-12',
     & '12-13 13-14 14-15 15-16 16-17 17-18 18-19  DAILY')
 2800 FORMAT(' ',F5.1,14(2X,F4.2),3X,F4.2)
      WRITE(*,*)
      STOP
C
C    **************************************
C    *** OUTPUT TYPE B:  DAILY PHI ONLY ***
C    **************************************
 4000 WRITE(*,*) 'DAILY UTILIZABILITY'
      WRITE(*,4010) AINST(1),AINST(3),AINST(7),AINST(5),AINST(8)
```

```
 4010 FORMAT(' ','IC1(W/M2)',5(3X,A5))
      DO 4050  J = 1,11
 4050    WRITE(*,4060) IC(1,J),DPHI(1,J),DPHI(3,J),DPHI(7,J),DPHI(5,J),
     &      DPHI(8,J)
 4060 FORMAT(' ',F7.1,2X,5(2X,F6.3))
      WRITE(*,*)
C     STOP
C
C   ****************************************
C   *** OUTPUT TYPE C:  HOURLY PHI ONLY ***
C   ****************************************
 5000 HOUR = 13
      LHOUR = HOUR - 1
      WRITE(*,5010) LHOUR,HOUR
 5010 FORMAT(' ','HOURLY UTILIZABILITY:  HOUR ',I2,'-',I2)
      WRITE(*,4010) AINST(1),AINST(3),AINST(7),AINST(5),AINST(8)
      DO 5050 J = 1,11
 5050    WRITE(*,4060) IC(1,J),HPHI(HOUR,1,J),HPHI(HOUR,3,J),
     &      HPHI(HOUR,7,J),HPHI(HOUR,5,J),HPHI(HOUR,8,J)
      WRITE(*,*)
      STOP
C
      END


      SUBROUTINE DAYCAL(MONTH, INDEX1,INDEX2)
C   SUBROUTINE TO CALCULATE THE MONTH, EQUATION OF TIME INDEXES, &
C   CRITICAL LEVELS FOR EACH INSTRUMENT.
      REAL IC,KMAX,DECL(12),BE(8),AZ(8),DKT(12)
      COMMON /COM2/SUMI(21,15),SUMH(15),IC(8,11),RC,RLAT,PI
      DATA DECL/-20.9,-13.0,-2.4,9.4,18.8,23.1,21.2,13.5,2.2,-9.6,
     &     -18.9,-23.0/
      DATA BE/0.0,20.0,30.0,40.0,4*90.0/
      DATA AZ/4*0.0,180.0,-90.0,0.0,90.0/
      DATA DKT/0.463,0.406,0.390,0.376,0.488,0.475,0.557,0.540,
     &         0.577,0.452,0.533,0.443/
C
      IF (MONTH .EQ. 1) THEN
            WRITE(*,*) 'JAN'
            DAY = 1.0
         ELSE IF (MONTH .EQ. 2) THEN
            WRITE(*,*) 'FEB'
            DAY = 32.0
         ELSE IF (MONTH .EQ. 3) THEN
            WRITE(*,*) 'MARCH'
            DAY = 60.0
         ELSE IF (MONTH .EQ. 4) THEN
            WRITE(*,*) 'APRIL'
            DAY = 91.0
         ELSE IF (MONTH .EQ. 5) THEN
            WRITE(*,*) 'MAY'
```

```
            DAY = 121.0
         ELSE IF (MONTH .EQ. 6) THEN
            WRITE(*,*) 'JUNE'
            DAY = 152.0
         ELSE IF (MONTH .EQ. 7) THEN
            WRITE(*,*) 'JULY'
            DAY = 182.0
         ELSE IF (MONTH .EQ. 8) THEN
            WRITE(*,*) 'AUG'
            DAY = 213.0
         ELSE IF (MONTH .EQ. 9) THEN
            WRITE(*,*) 'SEPT'
            DAY = 244.0
         ELSE IF (MONTH .EQ. 10) THEN
            WRITE(*,*) 'OCT'
            DAY = 274.0
         ELSE IF (MONTH .EQ. 11) THEN
            WRITE(*,*) 'NOV'
            DAY = 305.0
         ELSE IF (MONTH .EQ. 12) THEN
            WRITE(*,*) 'DEC'
            DAY = 335.0
         ELSE
            WRITE(*,50) MONTH
 50         FORMAT('0','PROGRAM ERROR:  (NONEXISTENT MONTH)',
     &      '  MONTH = ',I3)
            MONTH = 0
            RETURN
      END IF
C
C   CALCULATE THE CONVERSION FROM STANDARD TIME TO TRUE SOLAR TIME
C   4 * (STAND. MER. - LONGITUDE) = -34 MINUTES  (TRINITY UNIVERSITY)
      B = 2.*PI*(DAY-81.0)/364.0
C   MINUTES SOLAR TIME LAGS STANDARD TIME  (EMIN WILL BE NEGATIVE)
      EMIN = 9.87*SIN(2*B) - 7.53*COS(B) - 1.5*SIN(B) - 34.0
C   INDEXES TO CONTROL THE PHASE SHIFT FROM LOCAL TO SOLAR TIME
      INDEX2 = -IFIX(EMIN)
      INDEX1 = INDEX2 - 1
      WRITE(*,55) INDEX1, INDEX2
 55   FORMAT('0','INDEXES TO SHIFT FROM LOCAL TO SOLAR TIME:  I1 = ',
     & I2,'   I2 = ',I2)
C
C   CALCULATE CRITICAL LEVELS (FIND NOON IRRADIATION)
      SINDEC = SIN(RC*DECL(MONTH))
      COSDEC = COS(RC*DECL(MONTH))
      SINLAT = SIN(RLAT)
      COSLAT = COS(RLAT)
      KMAX = 0.208 + DKT(MONTH)*(2.77 + DKT(MONTH)*(-4.75 + 2.92*
     &     DKT(MONTH)))
      DO 200 I = 1,8
         COSB = COS(RC*BE(I))
```

```
          SINB = SIN(RC*BE(I))
          COSAZ = COS(RC*AZ(I))
          THETA = SINDEC*(SINLAT*COSB - COSLAT*SINB*COSAZ) +
     &            COSDEC*(COSLAT*COSB + SINLAT*SINB*COSAZ)
C    CHECK IF SUN IS BEHIND SURFACE AT NOON
          IF (THETA .LT. 0.3) THEN
             IF (I .EQ. 6  .OR.  I .EQ. 8) THEN
C    EAST & WEST SURFACES
                THETA = 0.8*DKT(MONTH)
             ELSE IF(I .EQ. 5) THEN
C    NORTH SURFACE
                THETA = 0.3*DKT(MONTH)
             ELSE
C    SOUTH SURFACE, SUN HIGH ABOVE TILT
                THETA = 0.3
             END IF
          END IF
          RMAX = 8.25*THETA*KMAX
          DO 100 J = 1,11
 100         IC(I,J) = FLOAT(J - 1)*RMAX
 200   CONTINUE
C
       RETURN
       END



       SUBROUTINE PHI(IN,HOUR,AINST,I1,I2,HRMN,EX)
C    SUBROUTINE TO CALCULATE THE UTILIZABILITY NUMERATOR
C    IN = INSTRUMENT INDEX NUMBER, AINST = INSTRUMENT LABEL
       REAL IC
       INTEGER FLAG,HOUR,EX,HRMN
       CHARACTER*5 AINST
       COMMON /COM1/HPHI(21,8,11), DPHI(8,11)
       COMMON /COM2/ SUMI(21,15),SUMH(15),IC(8,11),RC,RLAT,PI
       COMMON /COM3/ MDATA(60), FLAG(60)
       DO 500 MIN = I1,I2
       IF(MDATA(MIN) .LE. 0) GO TO 500
       IF(FLAG(MIN).EQ.99 .OR. FLAG(MIN).EQ.13) GO TO 500
       IF(FLAG(MIN).EQ.11 .OR. FLAG(MIN).EQ.12) THEN
          RDATA = (FLOAT(MDATA(MIN))) * 10.**EX
          SUMI(HOUR,IN) = SUMI(HOUR,IN) + RDATA
          SUMH(IN) = SUMH(IN) + RDATA
          DO 100 J = 1,11
             IF ( RDATA .GT. IC(IN,J)) THEN
                HPHI(HOUR,IN,J) = HPHI(HOUR,IN,J) + RDATA - IC(IN,J)
                DPHI(IN,J) = DPHI(IN,J) + RDATA - IC(IN,J)
             END IF
 100      CONTINUE
       ELSE
          WRITE(*,600) AINST,HRMN,FLAG(MIN)
```

```
      END IF
500   CONTINUE
600   FORMAT('0','UNRECOGNIZED FLAG:  INST ',A5,'  DAY/HR/MN ',I6,
     &     '  FLAG = ',I2)
      RETURN
      END
```

APPENDIX H

```
C  THIS PROGRAM CALCULATES THE DAILY UTILIZABILITY USING CLARK'S HOURLY
C  CORRELATION.  OUTPUT ALSO INCLUDES HOURLY UTILIZABILITY FOR HOUR 12-13.
C  THIS VERSION USES EITHER MONTHLY-AVERAGE DAILY KT'S OR READS IN
C  MONTHLY-AVERAGE HOURLY KT'S FROM LFN 16.
C  WRITTEN BY ALAN SCHULER, SEPT. 1985, FOR THE HARRIS COMPUTER.
C
C   DKTB = MONTHLY-AVERAGE DAILY CLEARNESS INDEX FROM REAL DATA.
C   HKTB(HOUR) = MONTHLY-AVERAGE HOURLY CLEARNESS INDEXES.
C   RC=PI/180=0.01745, RLAT=LATITUDE, GSC=SOLAR CONSTANT (KW/M2)
C   RBERB = DIFFUSE + BEAM + GROUND REFLECTANCE  (RBAR WITH ERBS CORR. INPUT)
C   NOTE:  RANGE OF ERBS NONSEASONAL HD/H CORRELATION IS FOR 0.3 < KT < 0.8
C   B(INST) = SLOPE,  AZ(INST) = AZIMUITH ANGLE
C   AVDAY(MONTH) = AVE. DAY FOR MONTH IN YEAR
C
      INTEGER HOUR
      REAL IC, IMAX, IDI, DKTB(12)
      CHARACTER*5 AINST(8),AMONTH(12),AMO
      CHARACTER*7 LOCTN
      DIMENSION B(8),AVDEC(12),AZ(8),COS1(8),COS2(8),AVDAY(12)
      COMMON /COM3/PI,GSC,RC,TANLAT,SINLAT,COSLAT,COSDEC,SINDEC,
     &        COSAZ(8),SINAZ(8),COSB(8),SINB(8)
      COMMON /COM4/HKTB(21),RBERB(21,8),IC(8,11),DPHI(8,11),DEN(8),
     &        HPHI(8,11),HDEN(8)
C
      DATA AZ/4*0.0,180.,-90.,0.0,90./
      DATA AVDEC/-20.9,-13.0,-2.4,9.4,18.8,23.1,21.2,13.5,2.2,-9.6,
     &    -18.9,-23.0/
      DATA AVDAY/17.,47.,75.,105.,135.,162.,198.,228.,258.,288.,
     &    318.,344./
      DATA AMONTH/'JAN','FEB','MARCH','APRIL','MAY','JUNE',
     &    'JULY','AUG','SEPT','OCT','NOV','DEC'/
      DATA PI, RC, GSC / 3.141593, 0.01745, 1.353/
      DATA HKTB/21*0.0/
C
C   *** TRINITY UNIVERSITY DATA SECTION ***
C     DATA AINST,RLAT/'HORIZ',' 20S ',' 30S ',' 40S ',' 90N ',' 90E ',
C    &   ' 90S ',' 90W ',29.53/
C     DATA DKTB,RHO,CONST/0.498,0.445,0.402,0.405,0.507,0.479,0.570,
C    &   0.579,0.603,0.482,0.593,0.472,0.05,0.8/
C     DATA B/0.0,20.,30.,40.,4*90./
C
C   *** ALBANY, N.Y. DATA SECTION ***
      DATA AINST,RLAT/'HORIZ',' 33S ',' 43S ',' 53S ',' 90N ',' 90E ',
     &   ' 90S ',' 90W ',42.7/
      DATA DKTB,RHO,CONST/0.499,0.382,0.443,0.432,0.561,0.489,0.489,
     &   0.450,0.533,0.435,0.387,0.418,0.0,0.7/
      DATA B/0.0,33.,43.,53.,4*90./
C
```

```
      RLAT = RLAT*RC
      TANLAT = TAN(RLAT)
      SINLAT = SIN(RLAT)
      COSLAT = COS(RLAT)
      INST = 8
C   *** CALCULATE CONSTANTS FOR GIVEN INSTRUMENT ***
      DO 50 I = 1,INST
         AZ(I) = AZ(I) * RC
         COSAZ(I) = COS(AZ(I))
         SINAZ(I) = SIN(AZ(I))
         B(I) = B(I) * RC
         COSB(I) = COS(B(I))
         SINB(I) = SIN(B(I))
         COS1(I) = (1. + COSB(I))/2.
 50      COS2(I) = RHO*(1. - COSB(I))/2.
C100  FORMAT('TRINITY SEMRT:  CLARKS METHOD')
 100  FORMAT('ALBANY SEMRT:  CLARKS METHOD')
 110  FORMAT(' ',A5)
 120  FORMAT(A5)
 125  FORMAT('DAILY UTILIZABILITY')
 126  FORMAT('HOURLY UTILIZABILITY')
C130  FORMAT('TRINITY SEMRT:  CLARKS HOURLY (12-13) UTILIZABILITY')
 130  FORMAT('ALBANY SEMRT:  CLARKS HOURLY (12-13) UTILIZABILITY')
 131  FORMAT(A7)
 133  FORMAT(' ','MISMATCH IN MONTHS:  FILE = ',A5)
 135  FORMAT(16(F4.2))
C
C   READ IN HOURLY KT'S
      READ(16,131) LOCTN
C     IF (LOCTN .NE. 'TRINITY') THEN
      IF (LOCTN .NE. 'ALBANY') THEN
         WRITE(3,*) 'MISMATCH IN KT LOCATIONS'
         STOP
      END IF
C
      DO 5000 MONTH = 1,12
         WRITE(12,100)
         WRITE(3,110) AMONTH(MONTH)
         WRITE(12,120) AMONTH(MONTH)
         WRITE(12,125)
C   READ IN HOURLY KT'S
         READ(16,120) AMO
         IF (AMO .NE. AMONTH(MONTH)) THEN
            WRITE(3,133) AMO
            STOP
         END IF
         READ(16,135) (HKTB(HOUR),HOUR = 5,20)
C
         DECL = AVDEC(MONTH) * RC
         COSDEC = COS(DECL)
         SINDEC = SIN(DECL)
```

```
C  (SUNSET HOUR ANGLE IN DEGREES)
       WS = ACOS(-TANLAT*TAN(DECL))/RC
C   EXTRATERRESTRIAL (KJ/M2-HR)
       GON = 13750.*GSC*(1.+0.033*COS(2.*PI*AVDAY(MONTH)/365.))
C   CONSTANTS FOR RT (EQ. 2.13.1)
       RTA = 0.409 + 0.5016*SIN((WS-60)*RC)
       RTB = 0.6609 - 0.4767*SIN((WS-60)*RC)
C   CONVERT SUNSET HOUR ANGLE BACK TO RADIANS
       WS = WS * RC
C   HD/H:  FROM ERBS NONSEASONAL CORRELATION (EQ. 4.23)
       HDH = (-3.023 + (3.373 - 1.760*DKTB(MONTH))*DKTB(MONTH))*
     &         DKTB(MONTH) + 1.317
       IF (HDH .GT. 1.0) THEN
          HDH = 1.0
          WRITE(3,*) 'HDH > 1.0'
       END IF
C   FROM ERBS RBAR PROGRAM:
       IF (DKTB(MONTH) .GT. 0.8) HDH = 0.156
C
C   RESET VALUES AT THE START OF EACH MONTH
       DO 200 I = 1,INST
          DO 150 J = 1,11
             HPHI(I,J) = 0.0
 150         DPHI(I,J) = 0.0
          HDEN(I) = 0.0
          DEN(I) = 0.0
 200      CALL ICRIT(I,MONTH,AINST,CONST)
C
    DO 2000 HOUR=5,20
       DO 300 I = 1,INST
 300      RBERB(HOUR,I) = 0.0
C   HOUR ANGLES IN RADIANS
       W1 = (FLOAT(HOUR) - 1.0 - 12.0) * 0.2618
       W2 = (FLOAT(HOUR) - 12.0) * 0.2618
C   CHECK IF ALL OF HOUR IS DARK
       IF (W1 .GE. WS) GO TO 2000
       IF (W2 .LE. -WS) GO TO 2000
C   CHECK IF PART OF HOUR IS DARK
       IF (W1 .LT. -WS) W1 = -WS
       IF (W2 .GT. WS) W2 = WS
C   USE MIDDLE OF HOUR FOR ZENITH ANGLE, AND RDRT CALCULATIONS (IN RADIANS)
       W = (W1 + W2)/2.
       RDRT = 1./(RTA + RTB*COS(W))
C      HKTB(HOUR) = DKTB(MONTH)/RDRT
C   ID/I = (RD/RT)(HD/H)
       IDI = HDH*RDRT
       IF (IDI .LE. 0.0) THEN
          WRITE(3,*) 'HOUR = ',HOUR,'   IDI = ',IDI
          IDI = 0.0
       END IF
       IF (IDI .GE. 1.0) THEN
```

```
            WRITE(3,*) 'HOUR = ',HOUR,'   IDI = ',IDI
            IDI = 1.0
         END IF
         THEZ = COSDEC*COSLAT*COS(W) + SINDEC*SINLAT
         IF (THEZ .LT. 1.0E-06) THEN
C    BEAM COMPONENT, RB(HOUR,I) = 0.0
         THEZ = 0.0
         DO 500 I = 2,INST
 500        RBERB(HOUR,I) = IDI*COS1(I) + COS2(I)
         GO TO 1500
      END IF
C
      DO 1000 I = 1,INST
         P = SINDEC*(SINLAT*COSB(I) - COSLAT*SINB(I)*COSAZ(I))
         Q = COSDEC*COS(W)*(COSLAT*COSB(I) + SINLAT*SINB(I)*COSAZ(I))
         S = COSDEC*SINB(I)*SINAZ(I)*SIN(W)
         THETA = P + Q + S
         IF (THETA .LT. 1.0E-04) THETA = 0.0
         RB = THETA/THEZ
         RBERB(HOUR,I) = IDI*COS1(I) + (1-IDI)*RB + COS2(I)
         IF (RBERB(HOUR,I) .LT. 0.0) THEN
            RBERB(HOUR,I) = 0.0
            WRITE(3,2100) AINST(I),HOUR
            WRITE(3,*) 'IDI = ',IDI,'   COS2(I) = ',COS2(I)
         END IF
 1000 CONTINUE
C
 1500 CALL PHICAL(GON,W2,W1,HOUR,INST)
C
 2000 CONTINUE
 2100 FORMAT('0','RBAR WAS < 0  FOR INST ',A5,', HOUR ',I2)
C
C    *** UTILIZABILITY ***
      DO 2500 I = 1,INST
         DO 2400 J = 1,11
            HPHI(I,J) = HPHI(I,J)/HDEN(I)
 2400       DPHI(I,J) = DPHI(I,J)/DEN(I)
 2500 CONTINUE
      GO TO 4000
C
C    *** RBAR OUTPUT ***
      WRITE(3,3320)
 3320 FORMAT(' ','TIME  05-06 06-07 07-08 08-09 09-10 10-11 11-12 ',
     & '12-13 13-14 14-15 15-16 16-17 17-18 18-19')
      WRITE(3,3340)  (HKTB(HOUR),HOUR=6,19)
 3340 FORMAT(' ','KTBAR',14(2X,F4.2))
      DO 3350 I = 2,8
 3350    WRITE(3,3360) AINST(I),(RBERB(HOUR,I),HOUR=6,19)
 3360 FORMAT(' ',A5,14(1X,F5.2))
C
C    *** CRITICAL LEVEL OUTPUT ***
```

```
 3500 WRITE(3,3540)
 3540 FORMAT(' ','CRITICAL LEVELS (W/M2)')
      WRITE(3,3550) AINST(1),AINST(3),AINST(7),AINST(5),AINST(8)
 3550 FORMAT(' ',5(2X,A5))
      DO 3600 J = 1,11
         IC(1,J) = IC(1,J)/3.6
         IC(3,J) = IC(3,J)/3.6
         IC(7,J) = IC(7,J)/3.6
         IC(5,J) = IC(5,J)/3.6
         IC(8,J) = IC(8,J)/3.6
 3600    WRITE(3,3700) IC(1,J),IC(3,J),IC(7,J),IC(5,J),IC(8,J)
 3700 FORMAT(' ',5(F7.1))
C
C   *** DAILY PHI OUTPUT ***
 4000 WRITE(12,4010) AINST(1),AINST(2),AINST(7),AINST(4),AINST(6)
 4010 FORMAT('IC1(W/M2)',5(3X,A5))
C   DO FOR ALL CRITICAL LEVELS, SURFACES 1,2,7,4,6
      DO 4050 J = 1,11
         IC(1,J) = IC(1,J)/3.6
 4050    WRITE(12,4060) IC(1,J),DPHI(1,J),DPHI(2,J),DPHI(7,J),
     &          DPHI(4,J),DPHI(6,J)
 4060 FORMAT(F7.1,2X,5(2X,F6.3))
C
C   *** HOURLY PHI OUTPUT, HOUR 12-13 ***
      WRITE(14,130)
      WRITE(14,120) AMONTH(MONTH)
      WRITE(14,126)
      WRITE(14,4010) AINST(1),AINST(2),AINST(7),AINST(4),AINST(6)
      DO 4080 J = 1,11
         WRITE(14,4060) IC(1,J),HPHI(1,J),HPHI(2,J),HPHI(7,J),
     &          HPHI(4,J),HPHI(6,J)
 4080    IC(1,J) = IC(1,J)*3.6
C
C   REPEAT FOR NEXT MONTH
 5000 CONTINUE
C
 6000 STOP
      END


      SUBROUTINE PHICAL(GON,W2,W1,HOUR,INST)
C   SUBROUTINE TO CALCULATE THE DAILY UTILIZABILITY
C   IHOR = IRRADIATION ON HORIZONTAL SURFACE (KJ/M2-HR)
C   IT = TILTED IRRADIATION (KJ/M2-HR)
      INTEGER HOUR
      REAL IC,IT,IHOR
      COMMON /COM3/PI,GSC,RC,TANLAT,SINLAT,COSLAT,COSDEC,SINDEC,
     &        COSAZ(8),SINAZ(8),COSB(8),SINB(8)
      COMMON /COM4/HKTB(21),RBERB(21,8),IC(8,11),DPHI(8,11),DEN(8),
     &        HPHI(8,11),HDEN(8)
C
```

```
      IF (HKTB(HOUR) .LE. 0.0001)  RETURN
      IHOR = GON*(COSLAT*COSDEC*(SIN(W2)-SIN(W1)) +
     &     (W2-W1)*SINLAT*SINDEC)*HKTB(HOUR)
      IF (IHOR .LT. 0.0) THEN
         WRITE(3,*) 'ERROR:  IHOR = ',IHOR
         IHOR = 0.0
      END IF
C
      DO 1000 I = 1,INST
         IT = IHOR*RBERB(HOUR,I)
         IF (IT .LT. 0.0) THEN
            WRITE(3,*) 'ERROR:  IT = ',IT
            IT = 0.0
         END IF
         DEN(I) = DEN(I) + IT
         XM = 1.85 + 0.169*RBERB(HOUR,I)/(HKTB(HOUR)*HKTB(HOUR)) -
     &        0.0696*COSB(I)/(HKTB(HOUR)*HKTB(HOUR)) -
     &        0.981*HKTB(HOUR)/(COSDEC*COSDEC)
         XM = AMAX1(XM,1.)
         DO 500 J = 1,11
            IF (IT. EQ. 0.0) THEN
               PHID = 0.0
               GO TO 500
            ELSE
               XC = IC(I,J)/IT
            END IF
            IF (XC .GE. XM) THEN
               PHID = 0.0
            ELSE IF(XM .EQ. 2.0) THEN
               SPHI = 1. - XC/XM
               PHID = SPHI*SPHI
            ELSE
               A = (XM - 1.0)/(2.0 - XM)
               DISCR = A*A + (1.+2.*A)*(XM-XC)*(XM-XC)/(XM*XM)
               DISCR = AMAX1(DISCR,0.0)
               PHID = ABS(ABS(A) - SQRT(DISCR))
            END IF
            DPHI(I,J) = DPHI(I,J) + PHID*IT
            IF (HOUR .EQ. 13) THEN
               HPHI(I,J) = HPHI(I,J) + PHID*IT
               IF (J .EQ. 1) HDEN(I) = HDEN(I) + IT
            END IF
 500     CONTINUE
 1000 CONTINUE
C
      RETURN
      END


      SUBROUTINE ICRIT(I,MONTH,AINST,CONST)
C   SUBROUTINE TO CALCULATE CRITICAL LEVELS FOR EACH INSTRUMENT.
```

```
C   USE FRACTION OF MAXIMUM NOON TIME VALUES (W=0.0) FOR LARGEST CRITICAL
C   LEVEL.
      REAL IC,KMAX,KTB(12)
      CHARACTER*5 AINST(8)
      COMMON /COM3/PI,GSC,RC,TANLAT,SINLAT,COSLAT,COSDEC,SINDEC,
     &   COSAZ(8),SINAZ(8),COSB(8),SINB(8)
      COMMON /COM4/HKTB(21),RBERB(21,8),IC(8,11),DPHI(8,11),DEN(8),
     &       HPHI(8,11),HDEN(8)
C
C   TRINITY DKTB'S FOR CRITICAL LEVEL CALCULATIONS (OLD VALUES)
C     DATA KTB/0.463,0.406,0.390,0.376,0.488,0.475,0.557,0.540,0.577,
C    &    0.452,0.533,0.443/
C   ALBANY DKTB'S FOR CRITICAL LEVEL CALCULATIONS (OLD VALUES)
      DATA KTB/0.461,0.353,0.423,0.428,0.546,0.487,0.459,0.453,0.517,
     &    0.408,0.372,0.406/
C
      DKTB = KTB(MONTH)
      THETA = SINDEC*(SINLAT*COSB(I) - COSLAT*SINB(I)*COSAZ(I))
     &        + COSDEC*(COSLAT*COSB(I) + SINLAT*SINB(I)*COSAZ(I))
      KMAX = 0.208 + DKTB*(2.77 + DKTB*(-4.75 + 2.92*DKTB))
C   CHECK IF SUN IS BEHIND SURFACE AT NOON
      IF (THETA .LT. 0.3) THEN
         IF(I .EQ. 6  .OR.  I .EQ. 8) THEN
C   EAST & WEST SURFACES
            THETA = CONST*DKTB
         ELSE IF(I .EQ. 5) THEN
C   NORTH SURFACE
            THETA = 0.3*DKTB
         ELSE
C   SOUTH SURFACE, SUN HIGH ABOVE TILT
            THETA =  0.3
         END IF
      END IF
      RMAX = 495.0*THETA*KMAX
      DO 100 J = 1,11
 100     IC(I,J) = FLOAT(J - 1)*RMAX
C
      RETURN
      END
```

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## CLOSING THOUGHTS

And so ends my thesis,
There's no where else to look.
You may read it again,
If you're really hooked.

I do hope you learned
Something interesting today.
For God's world is exciting,
In a most wonderful way.

-- Alan Schuler
January, 1986