SOLAR RADIATION DATA FORECAST AND INTERPOLATION ANALYSIS**FINAL REPORT****FOLDER I: #1****PART I. EXECUTIVE SUMMARY;****PART II. TECHNICAL ANALYSIS (TASKS I & II);****PART III. APPENDICES (TASKS I & II)****APRIL 1979**

by

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FOREWORD

This technical report presents work performed by Northrop Services, Inc., Huntsville, Alabama, while under contract (EG-77-C-02-4494) to the United States Department of Energy (DOE). The University of Alabama in Huntsville, Johnson Environmental and Energy Center (UAH/JEEC) was the subcontractor for Task III, which was to identify and analyze techniques for estimating solar radiation on inclined surfaces. The UAH/JEEC Project Manager was Mr. Gene Carter. The DOE Program Manager was Mr. Michael R. Riches, Division of Planning and Technology Transfer, Environmental Planning and Analysis Branch. Dr. Eldon Boes of Sandia Laboratories was the Technical Monitor.

A draft copy of this report was distributed to designated Government reviewers in January 1979 in accordance with contract instructions. This final report incorporates the constructive comments and suggestions of the reviewers.

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ABSTRACT

The widespread use of solar energy systems is a national goal which requires development of methods to describe the solar radiation received at the surface of the earth. Data were evaluated from the rehabilitated 52-station SOLMET solar radiation network. For economic reasons, it is important that solar radiation data measured at a station represent as broad an area within the contiguous United States as possible, and that techniques be established to transform radiation measurements taken on a horizontal surface to what would be seen by an inclined surface. During this study methods applicable to these problems have been developed. A Climatological Cell Statistics (CCS) Method was developed to obtain the statistics of up to 24 variables occurring in combination with each other using surface meteorological data and to relate these statistics to the solar radiation measurements. A method to evaluate the differences between two insolation data sets, called the Wedge Method, was developed to determine the representative area of a radiation measurement site. These methods were used to evaluate the capabilities of the NOAA Solar Radiation Model to interpolate between measurement sites. Twenty-four methods of calculating solar radiation on inclined surfaces were investigated. All algorithms were rewritten in a common convention and nomenclature and the measurements required for each method were categorized.

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PART I
EXECUTIVE SUMMARY

ES 1 BACKGROUND

The US Department of Energy (DOE) Division of Solar Energy addresses four technical options representing different types of insolation dependent energy sources (Photovoltaics, Solar Thermal Electric, Solar Heating and Cooling, and Agricultural and Process Heat). These technical options require general and specific insolation and support meteorological data for planning, design, and project evaluation. The existing, rehabilitated 52-station solar data sites (the SOLMET sites of Reference 1) and the new, improved, 38-station solar radiation network may or may not be sufficient to provide requisite data density. Because it is physically and economically impractical to monitor solar radiation everywhere, a well-designed network with stations representative of as broad an area as possible should be implemented. Tasks I and II of this study are directed toward determining the solar network density required to ensure nationwide coverage. Task I is to define representative areas for the existing and former solar radiation monitoring sites. Task II is to further this effort by assessing the abilities of models to interpolate between sites and thus extend the representative area of each site. Models to be considered will be the Machta-Cotton (National Oceanic and Atmospheric Administration (NOAA) Solar Radiation Model, Reference 2) and other usable satellite models.

The traditional solar radiation data are available only on a horizontal plane. Solar energy applications require data on inclined surfaces. Many models exist to calculate from the horizontal solar radiation data (or

1. *SOLMET VOLUME I - USER'S MANUAL TD-9724, Hourly Solar Radiation-Surface Meteorological Observations, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Asheville, North Carolina, December 1977.*
2. *Machta, L. and Cotton, G. F., "ARL Solar Radiation Model", Presented at Environmental Resource Assessments Branch Quarterly Contractors Program Review, Department of Energy, Washington, D.C., 22-24 February 1978.*

other meteorological data) the required inclined data. In Task III the models available to calculate inclined solar radiation are identified and evaluated. Comparisons between model results and real data may be used to establish the current ability to estimate the required inclined solar data. The results may be used to plan network instrumentation changes and/or model development.

ES 2 TASK I

ES 2.1 OBJECTIVES

The task objectives were to develop and apply a technique that defines the representative area around the site that can use site data for the rehabilitated 52-station solar data sites. The result of the application of the techniques shall include maps showing the area around each station for which the daily total of global solar radiation can be considered to be within 90, 80, 70, and 50 percent of the measured values at the respective stations. The contour lines with these percentage values are called representative area G-contours, where G has the value 90, 80, 70, or 50 percent. The G-contours enclose the area around the reference SOLMET site for which 70 percent, P, of the pair-wise total daily insolation values are within the value of G.

Specifically, representative area G-contours are to be determined for the Nashville, Tennessee SOLMET site for the months of January and June using data for the years 1953 through 1975. At the Albuquerque, New Mexico SOLMET site the representative area G-contours are to be defined for four months - January, April, June, and November - using data for the years 1953 through 1975.

ES 2.2 RESULTS

The existing SOLMET data base and Machta-Cotton Model plus the specially developed CCS and Wedge computer programs, discussed in detail in Part II of this folder, were used in generating the results for Tasks I and II. These results are based on the processing of data for over 50 SOLMET and NOAA Stations. The entire data base of over 222 stations can be processed and analyzed at reasonable cost using the methods developed in this study.

The representative area for a SOLMET Station for which the daily total of global solar radiation is within 90, 80, 70, and 50 percent of the values measured at the reference SOLMET Station has been defined in terms of the G-contours. The G-contours for the months of January and June around the Nashville and Albuquerque SOLMET Stations are shown in Figures ES-1 and ES-2. The M parameter refers to the number of years of data used in the analysis, while N refers to the solar time interval used (i.e., $N=1$ is defined as the solar time interval of one day).

Figure ES-1 shows the representative area G-contours for January around Nashville and Albuquerque based on the pair-wise comparisons of daily insolation totals between the reference station and each of the satellite stations. It is seen that the daily insolation values are much better correlated around Albuquerque than Nashville. The G-contours enclose the area around the reference SOLMET site for which $P = 70$ percent of the pair-wise daily insolation totals are within the value of G that is given. Thus, the $G = 80$ percent contour around Albuquerque represents the area where the 23 year (1953-1975) daily values of insolation in January have been found to be within $G = 80$ percent of the measured values at Albuquerque for $P = 70$ percent of the days.

Figure ES-2 shows the representative area G-contours for June around Nashville and Albuquerque. The daily correlation of solar radiation is still higher around Albuquerque when compared to Nashville. For $G = 80$ percent, the Albuquerque SOLMET Station represents a much larger surrounding area than is represented by the Nashville SOLMET site.

ES 2.3 CONCLUSIONS

The G-contours around each SOLMET site define a practical lower limit to the size of the area to be represented by the SOLMET site, based on this study. Further work may show that smaller representative area G-contours can be obtained by requiring the value of P to be larger than 70 percent or the pair-wise comparisons between stations based on hourly insolation values.

The representative area G-contours for a SOLMET site can be extended to encompass a larger area by two methods:

Figure ES-1. REPRESENTATIVE AREA G-CONTOURS IN JANUARY AROUND ALBUQUERQUE AND NASHVILLE FOR TOTAL DAILY INSOLATION ($M = 23$, $N = 1$)

- 1) The criteria of using daily insolation totals in the pair-wise comparisons between two stations could be relaxed to 2-day, 3-day, weekly, or even monthly totals. Some preliminary work has been done using 2-day, 5-day, 10-day, and 30-day totals. This method is discussed in Part II, Section 4 of this report.
- 2) Solar radiation models, such as the Machta-Cotton Model, may be validated at a SOLMET site. The coefficients of the model may then be applied wherever appropriate in the surrounding region..

Figure ES-2. REPRESENTATIVE AREA G-CONTOURS IN JUNE AROUND ALBUQUERQUE AND NASHVILLE FOR TOTAL DAILY INSOLATION (M = 23, N = 1)

ES 3 TASK II

ES 3.1 OBJECTIVES

The task objectives were to develop a technique to assess the ability of models to interpolate between the existing, rehabilitated 52-station solar data sites. The technique is to be applied to the NOAA solar radiation model at Nashville, Tennessee and at Lake Charles, Louisiana. A detailed discussion is to be given of the cloud structure around the Nashville site. The ability of the NOAA model to approximate this cloud structure through the opaque cloud cover variable in the regression model will be analyzed.

ES 3.2 RESULTS

Techniques were developed in this study to assess the ability of solar radiation models to interpolate between SOLMET sites. The Wedge Program (paragraph ES 5.2) has been used to provide a quantitative measure of the ability of the Machta-Cotton Model to determine the daily values of radiation at the reference SOLMET site and at satellite SOLMET sites using coefficients determined at the reference site. Methods developed to examine the detailed cloud structure information provided by the thousands of possible combinations of variables in the CCS method (ES 5.1) and to compare the characteristics obtained at a reference SOLMET site with those obtained at satellite stations are discussed in Appendix B.

The result of the Wedge Program is the wedge curve. The wedge curve presents the functional relationship of the daily insolation percentage difference, called W , and the percentage of days, called P , which are within a given value of W . The wedge curve example (Figure ES-3) is used to provide comparisons between reference site data and other locations, or any set of reference data and other data. For example, a data point at the intersection of $W = +25$ and $P = 90$ would indicate that the values of the comparative data are within $+25$ percent of the reference data 90 percent of the time. The perfect comparison curve is the horizontal line at $P = 100$. That is, the difference between the reference and comparative data is 0, 100 percent of the time.

The ability of the Machta-Cotton Model to interpolate between Nashville and the satellite SOLMET site at Lake Charles, LA. is shown in Figure ES-3. The results of the Wedge Analysis for June and January for daily insolation pair-wise comparisons for the period 1953-1975 are depicted. Curve 1 is a comparison between the measured insolation data at Lake Charles and the results of the Machta-Cotton Model applied at Lake Charles for the month of June, but using regression coefficients derived from the measured insolation data at Nashville. Curve 2 is the comparison between the daily measured insolation data at Nashville and the results of the Machta-Cotton Model applied at Nashville with regression coefficients derived from measured insolation data at Nashville. Curves 1 and 2 are separated by a difference of $W = +4\%$ at

Figure ES-3. WEDGE CURVE COMPARISONS AT NASHVILLE AND LAKE CHARLES

P = 70% of the days. Therefore, the errors at Lake Charles using Nashville regression coefficients (curve 1) are comparable to the errors at Nashville using Nashville coefficients (curve 2).

Curves 3 and 4 are similar to curves 1 and 2, respectively, but for the month of January. Curves 3 and 4 are separated by a difference of $W = \pm 10\%$ at $P = 70\%$ of the days. The June and January data show that it is possible to use the Machta-Cotton Model for interpolation as far away as the Lake Charles SOLMET site (a distance of 540 miles). Because the Machta-Cotton Model is used to determine the representative areas for Task I, it is of interest to evaluate the effect of using the Nashville coefficients to calculate the daily insolation at Lake Charles and to compare these calculations with the measured daily values at Nashville. Curve 5 of Figure ES-3 is such a comparison for June and curve 7 for January. Curve 6 is a comparison of the Nashville

measured daily totals with the Lake Charles measured daily totals for June and curve 8 is a similar curve for January. Curves 5 and 6 lie almost on top of each other and show that, when comparing Nashville measured daily totals with Lake Charles, almost identical results are obtained whether the Lake Charles data is from measurements or from calculations using regression coefficients determined at Nashville.

ES-3.3 - CONCLUSIONS

The comparison of curves 1 and 2 with 5 and 6 illustrate a very important result: In June the errors due to interpolation between Nashville and Lake Charles (curves 1 and 2) are much less than the decrease in correlation of the daily values of radiation between the two stations (curves 5 and 6). The same conclusion holds in January. The errors due to interpolation between the two stations in January (curves 7 and 8) are much less than the decrease in correlation of the daily values of radiation.

ES 4 TASK III

ES 4.1 OBJECTIVES

The task objectives were to identify and analyze the known techniques for estimating solar radiation on an inclined surface from existing solar radiation data and/or other meteorological data. Further, the task compares selected techniques to representative samples of real data at existing sites. A discussion and comparison of the techniques is given. The results also include a discussion of the accuracy for each technique.

ES 4.2 RESULTS

Twenty-four methods of calculating solar radiation on inclined surfaces were identified. Ten of these methods were selected for investigation. All algorithms were rewritten in a common convention and nomenclature and the measurements required for each method were categorized.

Seven months of horizontal global, direct or beam, diffuse, and tilted global solar radiation measurements were recorded at the Johnson Environmental and Energy Center. Available measurements from Arizona, Canada, and California also were used in the evaluation. Solar radiation was calculated for inclined

surfaces using the methods selected and compared with the measured values. Results indicate that errors for averaged data using any of the methods investigated are only slightly greater than those expected with actual measurements at tilt angles. Careful attention must be given to accuracy of recorded data to ensure satisfactory model results.

ES 4.3 CONCLUSIONS

A prime conclusion of this task is that accuracy of the measurements and use of the measurements may be as significant as any differences in the methods. Variations in calculating individual hourly radiation may be expected from the methods investigated but averaged values may be expected to be within 10 percent of measured tilted radiation.

ES 5 DATA BASE

The SOLMET data base available for this study included 25 years of hourly measurements of 63 variables recorded at each of 222 stations. This represents a voluminous data base of approximately 8 billion digits of information on 222 magnetic tape reels. The accomplishment of Tasks I and II in this study required the writing of major digital computer programs for use on the Univac 11/10 digital computer. These programs were subject to the severe constraints of efficiency and low cost in processing the large data base.

ES 5.1 THE CLIMATOLOGICAL CELL STATISTICS PROGRAM

To take full advantage of the extensive SOLMET data base, an empirical statistical approach, called the Climatological Cell Statistics (CCS) method, was developed to determine the simultaneous occurrence of up to 24 variables which exist on a SOLMET data tape for an entire station record. The CCS correlation can be used to understand the attenuation of solar radiation by the cloud variables. The ability of radiation models to interpolate between stations can be evaluated by combining the CCS method with the Machta-Cotton radiation model and with the Wedge Program discussed below. It is also possible to use the CCS method to calculate the solar radiation at NOAA Stations which have no solar radiation measurements.

ES 5.2 THE WEDGE PROGRAM

Task I required the development of a technique that defines the representative area around a SOLMET Station. The approach taken was to determine the daily values of radiation at NOAA and SOLMET Stations in the region surrounding the SOLMET Station (the reference site). The daily insolation values between pairs of stations (each pair consisting of the SOLMET reference site and one of the satellite stations) are then compared to determine the differences between the daily values for the same day. The daily values of the radiation are determined from hourly measurements (in the case of a SOLMET site) or from calculations (in the case of a NOAA site) using the CCS method or the Machta-Cotton Model (Reference 2).

There are approximately 85,000 daylight hours in the 25-year record at a station. The daily insolation data set at each station consists of approximately 10,000 daily values of insolation. The Wedge Program was developed to efficiently perform the comparisons of daily insolation values between pairs of stations and to determine the percent differences of daily insolation between the reference SOLMET Station and each of the surrounding satellite stations.

PART II TECHNICAL ANALYSIS

Section I

INTRODUCTION

The direct collection and utilization of radiant energy from the sun is an undertaking of great importance as the Nation seeks to extricate itself from an economy that is dependent primarily on petroleum and natural gas. Part II of this report is directed toward development of techniques to interpolate measured solar radiation data to representative areas around solar radiation measurement stations and to evaluate solar radiation models.

Section II discusses the technical foundation upon which the results of Tasks I and II reported in Sections IV and V are based. In Section 2.1 the sources of the meteorological and solar radiation data are briefly discussed, followed by a brief outline of the NOAA Solar Radiation Model in Section 2.2. Section 2.3 gives a detailed discussion of the multi-variable correlation technique, called the Climatological Cell Statistics (CCS) method. Then Section 2.4 presents a method of evaluating the differences between two insolation data sets, called the Wedge Method. In Section 2.5 the techniques to define the representative areas around SOLMET sites for Task I are presented. Section 2.6 presents the methods developed to evaluate solar radiation models for Task II.

Section III presents a discussion of the cost reduction associated with processing the SOLMET data base that was achieved in this study. Section IV and Section V present the results obtained in this study for Task I and Task II, respectively. The conclusions and recommendations are given in Section VI.

Some results obtained in this study that were considered too detailed for discussion in Part II are given as the appendices of Part III. Appendix A discusses the method of digitization of the variables from the SOLMET data base used in the CCS and Wedge methods. Appendix B presents methods for understanding and analyzing the cloud structure variables at a site, and the change in the cloud structure distribution between two stations. The effect of some combinations of cumulus and cirrus clouds on the attenuation of radiation are examined.

In Appendix C some of the Wedge Curves obtained in the analysis of data in the Nashville and Albuquerque area are presented. Finally, Appendix D evaluates the Nashville insolation data characteristics from several viewpoints: 1) The error due to interpolation for missing insolation data, 2) comparisons between standard year and engineering corrected data, and 3) comparisons involving the CCS method, Machta-Cotton Model, and standard year results.

Section II

DATA SOURCES AND METHODOLOGY

In this section the sources of the meteorological and solar radiation data upon which the study is based are briefly discussed. It is assumed that the reader is familiar with solar energy resource analysis and statistical models for calculation of the availability of solar radiation at the surface of the earth. A correlation technique for solar radiation and surface meteorological variables called the Climatological Cell Statistics Method, developed during this study, is discussed in detail. A method of evaluating differences (or errors) between two insolation data sets, called the Wedge Method, is discussed. Finally, the techniques to define representative areas around measurement sites and to evaluate solar radiation models are developed.

2.1 DATA SOURCES

The primary data source for this study is the SOLMET Hourly Solar Radiation-Surface Meteorological Observation Data Base discussed in Reference 1. This data base has a new common tape format that was designed to provide, in a single Fortran-compatible tape, quality controlled and serially complete hourly solar radiation and surface meteorological data that are available at the National Climatic Center (NCC) of the National Oceanic and Atmospheric Administration (NOAA). Throughout this report it will be assumed that the reader is already familiar with the contents of Reference 1. Only a brief description of the data base is given below.

In this study, a SOLMET Station refers to one of the 27 stations in the United States where solar radiation measurements were taken for approximately 24 years and where the data has undergone rehabilitation whenever necessary. Corrections to the measurements included known scale changes, station moves, and recorder and sensor calibration changes related to the pyranometer measurements. Included in this hourly data are surface meteorological observations

referred to as the TD-1440 Meteorological Observations. Figure 2-1 shows the location of the solar radiation data rehabilitation stations. Included also in the figure are the cities where daily solar radiation values will be available in the future. This study is based on the hourly solar radiation values given at the 27 stations so noted.

In this study, a NOAA Station refers to one of the 214 National Weather Service, Federal Aviation Administration, or military weather stations with solar insolation estimates from the Machta-Cotton Regression Model (See Reference 2) in tape field 108 and TD-1440 meteorological observations in the SOLMET format. Tapes for 196 stations have been received to date. Figure 2-2 shows the location of these stations.

In this report frequent reference will be made to the tape field number of the tape data field on the SOLMET tapes from which the values of the variables used in this study are obtained. Figure 2-3 gives the SOLMET format and identifies the tape field number with the element or variable name.

The reader should be aware that the numerical values for variables in this study have in many cases been redefined for convenience in computer processing. This redefinition applies only to this study and should not be construed as having any effect on the SOLMET format described in Reference 1. The digitization of the SOLMET variables used in this study is described in detail in Appendix A.

Figure 2-1. SOLAR RADIATION DATA REHABILITATION STATIONS

Figure 2-2. REGRESSION MODELED SOLAR RADIATION DATA STATIONS

SOLMET TAPE FORMAT

(TAPE DECK 9724)

IDENTIFICATION											SOLAR RADIATION OBSERVATION										
TAPE DECK #	WBAN STN #	SOLAR TIME				LST TIME	STR KJ/m ²	RADIATION VALUES KJ/m ²											A	B	S U N S H I N E M I N
		YR	MO	DAY	HOUR			D I R E C T	D I F F U S E	N E T	T I L T E D	GLOBAL			OBS	ENG COR	STD YR COR				
9724	XXXXX	XX	XX	XX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	XXXXX	
FIELD NUMBER	001	002	003			004	101	102	103	104	105	106	107	108	109	110	111				

SURFACE METEOROLOGICAL OBSERVATION																					S N O W C O V E R	
O B S E R V E D T I M E	C E L I N G H T	SKY COND	VSBY km	WEATHER	PRESSURE		TEMP		WIND		CLOUDS											
					kPa	STA- TION	DRY BULB	DEW- PT.	D I R	S P E E D	LOWEST		SECOND		THIRD		FOURTH		O P A C I T Y			
											A M O U N T	A M O U N T	A M O U N T	A M O U N T	A M O U N T	A M O U N T	A M O U N T	A M O U N T				
XX	XXXX	XXXX	XXXX	XXXXXXXX	XXXXX	XXXXX	XXXX	XXXX	XX	XXXX	XX	XXXX	XX	XXXX	XX	XXXX	XX	XXXX	XX	XX		
01	201	202	203	204	205	206	207	208	209											210		

TAPE NUMBER	TAPE POSITIONS	ELEMENT
01	001 - 004	TAPE DECK NUMBER
02	005 - 009	WBAN STATION NUMBER
03	010 - 019	SOLAR TIME (YR, MO, DAY, HOUR, MINUTE)
04	020 - 023	LOCAL STANDARD TIME (HR AND MINUTE)
101	024 - 027	EXTRATERRESTRIAL RADIATION
102	028 - 032	DIRECT RADIATION
103	033 - 037	DIFFUSE RADIATION
104	038 - 042	NET RADIATION
105	043 - 047	GLOBAL RADIATION ON A TILTED SURFACE
106	048 - 052	GLOBAL RADIATION ON A HORIZONTAL SURFACE - OBSERVED DATA
107	053 - 057	GLOBAL RADIATION ON A HORIZONTAL SURFACE - ENGINEERING CORRECTED DATA
108	058 - 062	GLOBAL RADIATION ON A HORIZONTAL SURFACE - STANDARD YEAR CORRECTED DATA
109, 110	063 - 072	ADDITIONAL RADIATION MEASUREMENTS
111	073 - 074	MINUTES OF SUNSHINE
201	075 - 076	TIME OF COLLATERAL SURFACE OBSERVATION (LST)
202	077 - 080	CEILING HEIGHT (DEKAMETERS)
203	081 - 085	SKY CONDITION
204	086 - 089	VISIBILITY (HECTOMETERS)
205	090 - 097	WEATHER
206	098 - 107	PRESSURE (KILOPASCALS)
207	108 - 115	TEMPERATURE (DEGREES CELSIUS TO TENTHS)
208	116 - 122	WIND (SPEED IN METERS PER SECOND)
209	123 - 162	CLOUDS
210	163	SNOW COVER INDICATOR

Figure 2-3. SOLMET TAPE FORMAT (TAPE DECK 9724)

2.2 THE NOAA SOLAR RADIATION MODEL

Machta and Cotton at the NOAA Air Resources Laboratory (Reference 2) and Riches, Quinlan, Cotton, Flowers, and Machta (Reference 3) have developed a linear regression model for solar radiation based on the hourly insolation values in SOLMET tape field 108 and some of the TD-1440 Meteorological Observations. Among the variables considered were rain, opaque cloud cover, minutes of sunshine, and sky condition. In this study, the Machta-Cotton Model will refer more particularly to the correlation of the zenith angle, opaque cloud cover, and rain with the insolation as in Reference 2. These variables were used to calculate the hourly values of insolation in SOLMET tape data field 108 for the NOAA Stations. The clear sky regression equation and the correlation using opaque cloud cover and rain is discussed below.

The hourly total insolation (SRC) for clear skies on a horizontal surface at the SOLMET Stations has the form

$$SRC = A_0 + A_1 \cos ZA_c + A_2 \cos^2 ZA_c + A_3 \cos^3 ZA_c \quad (2-1)$$

where ZA_c is a continuous variable for the zenith angle of the sun at the midpoint of the solar hour.

The solar radiation (SR) in the presence of opaque cloudiness has been correlated as

$$SR = SRC [B_0 + B_1 OPQ + B_2 OPQ^2 + B_3 OPQ^3 + B_4 RA] \quad (2-2)$$

where OPQ is the tenths of opaque cloudiness as reported on the SOLMET tapes in tape field 209 and RA is a rain indicator which is zero for no precipitation and one when precipitation of some form is reported in tape field 205.

2.3 THE CLIMATOLOGICAL CELL STATISTICS METHOD

A technique called the Climatological Cell Statistics (CCS) method has been developed during this study to correlate the effects of the hourly TD 1440 Surface Meteorological Observations as reported on the SOLMET magnetic data tapes with the hourly values of the total global radiation as measured and

reported in the standard year corrected data field 108 of the same tape. A limited amount of correlation was performed using the engineering corrected data field 107 for comparison with the standard year field. Unless explicit reference is made to data field 107, it is to be understood that data field 108 was used.

Carter and Graves (References 4 and 5) determined the joint occurrence and persistence of weather phenomena for evaluating favorable and unfavorable weather conditions for space vehicle launch windows. Recently Thomas and Carnichaal (Reference 6) were successful in processing over 7 million measurements of climatic and other variables using a cell method to determine the simultaneous occurrence of combinations of variables for environmental testing of solar collector arrays. The CCS method is a cell method which is designed to correlate the joint occurrence of up to 24 variables for over one-half billion measurements.

From the CCS correlation the structure of the cloud variables that attenuate the hourly radiation can be understood. The ability of radiation models to interpolate between stations can be evaluated by combining the CCS method with the Wedge analysis discussed in Sections 2.4 and 2.6. It is also possible to use the CCS method to calculate the solar radiation at NOAA Stations which have no solar radiation measurements. A discussion of the basis of the CCS method is given below.

2.3.1 The CCS Cell Space

The CCS Cell Space is a hyperspace of 24 dimensions. The simultaneous occurrence of an event in this hyperspace is defined by a selection of these 24 variables from the 63 variables that may occur hourly on the SOLMET magnetic tape for a given station. It is assumed that these 24 variables are adequate to determine the climatic effects on the total horizontal radiation (insolation) for the station being analyzed over the 24-year record at the station.

The hourly values of insolation reported on the SOLMET tapes are integrated values over the solar hour. The TD 1440 Meteorological Observations represent both instrument measurements of some variables (such as dew point temperature) and subjective observations of others (such as the cloud variables)

by trained observers, all reported in Local Standard Time. The sample time of these TD 1440 data vary from times on the order of seconds to minutes. However, in the CCS method the assumption is made that the hourly reported values can be assumed to be constant over the entire solar hour of the radiation measurement.

The SOLMET vector, $\underline{Z}$, is the state vector for the 24-variable space. The hourly occurrence of an event defined by the SOLMET hourly data field defines a value for $\underline{Z}$, which positions a point in one of the cells of this hyperspace. Each of the axes of this hyperspace has been discretized into intervals which are the digitized values of the SOLMET variables or they may have undergone further digitization as in the case of insolation, which is discussed in Appendix A. The SOLMET vector $\underline{Z}$ is defined by

$$\underline{Z} = (\text{CC}, \text{SW}, \text{SN}, \text{ZN}, \text{RN}, \text{OPQ}, \text{A1}, \text{A2}, \text{T1}, \text{T2}, \text{H1}, \text{H2}, \text{A3}, \text{T3}, \text{H3}, \text{SS}, \text{VIS}, \text{DP}, \text{YR}, \text{MON}, \text{DAY}, \text{HR}, \text{EC}, \text{SY}) \quad (2-3)$$

where. CC is the clear/cloudy variable, taking on the value of zero when the total sky cover on SOLMET tape field 209 is zero, the value of one when the total sky cover is between one and 10 and the value of 9 when the data is missing.

SW is the summer/winter variable, taking on the value of zero for the months of April, May, June, July, and August, the value one for the months of January, February, March, September, October, November, and December, and the value of 9 when the data is missing.

SN is the snow cover variable, taking on the value of zero when the snow cover indicator on the SOLMET TAPE field 210 is zero, the value of one when there is more than a trace of snow on the ground, and 9 when the data is missing.

ZN is the zenith angle variable, taking on the value of zero when the zenith angle at the midpoint of the solar hour is between zero and 60 degrees, the value one when the zenith angle is between 60 and 80 degrees, and 9 when the data is missing. Zenith angles between 80 and 90 degrees are not explicitly considered and $\underline{Z}$ is zero for such data on the SOLMET tape: $\underline{Z}$ is also zero for all night-time data on the SOLMET tape.

- RN is the rain or precipitation variable. Its range is discussed in Appendix A.5.
- OPQ is the opaque cloud cover variable. Its range is discussed in Appendix A.1.
- A1, A2, and A3 are the variables for the amount of cloud cover in the lowest cloud layer, in the second layer, and in the third cloud layer, respectively. Their ranges are the same as the OPQ variable.
- T1, T2, and T3 are the variables for the type of cloud or obscuring phenomena in the lowest cloud layer, in the second layer, and in the third cloud layer, respectively. Their ranges are given in Appendix A.2.
- H1, H2, and H3 are the variables for height of the base of the cloud layer in the lowest cloud layer, in the second layer, and in the third cloud layer, respectively. Their ranges are discussed in Appendix A.6.
- SS is the variable for the minutes of sunshine recorded during the local standard hour most closely matching the solar hour. Its range of values is given in Appendix A.3.
- VIS is the horizontal visibility variable. Its range is given in Appendix A.7.
- DP is the dew point variable. Its range is reported in Appendix A.9.
- YR, MON, DAY, HR are the time variables for the year, month, day, and solar hour, respectively. Their ranges are given in Appendix A.4.
- EC and SY are the variables for global radiation on a horizontal surface. EC is the engineering corrected data variable and SY is the standard year corrected data variable. Their ranges are identical and are discussed in Appendix A.8.

2.3.2 Cascading of Variables in the CCS Cell Space

The 24-axes CCS cell space in which Z is defined would have at most a density of one point per cell. It is desired to find a statistical correlation between some of the meteorological variables and the solar radiation. The density of points per cell for a large number of cells must therefore be increased.

The process of changing the dimensionality of the cell space is called "cascading". Cascading symbolizes the set of complex computer operations whereby: (1) the dimensionality can be increased or decreased discrete intervals for each axis can be merged into larger intervals.

The 24-axes CCS cell space is cascaded down to a 15-axes space, where the dimensionality has been reduced by omitting the insolation variables EC and SY, the time variables YR, MON, DAY, and HR, and the variables SS, DP, and VIS. Since the number of points defined by $\underline{Z}$ is preserved in the cascading process, the density of points in some of the cells of the 15-axes space can be large. This has been found to be the case as discussed in Appendix B.

A vector of meteorological observations, $\underline{X}$, is defined by the following variables in the 15-axes space:

$$\underline{X} = (CC, SW, SN, ZN, RN, OPQ, A1, A2, T1, T2, H1, H2, A3, T3, H3) \quad (2-4)$$

For convenience, the cloud structure variable, $\underline{Y}$, is defined by

$$\underline{Y} = (A1, A2, T1, T2, H1, H2, A3, T3, H3) \quad (2-5)$$

so that the vector $\underline{X}$ can be rewritten

$$\underline{X} = (CC, SW, SN, ZN, RN, OPQ, \underline{Y}) \quad (2-6)$$

2.3.3 Calibration of $R(\underline{X})$ and Cloudy Sky Reference File

It is now desired to define a dependent variable, R , which is a function of all the variables in the 15 axes hyperspace defined above. The dependent variable R can be considered as an attenuation function for solar radiation in the presence of a cloudy sky. It is patterned after the Machta-Cotton ratio of cloudy sky radiation to clear sky radiation, SR/SRC , (see equations 2-1 and 2-2). The attenuation ratio is defined as

$$R = SY/SRC = R(\underline{X}) \quad (2-7)$$

A cloudy sky Reference File is constructed in the following way. Each point defined by a value of the vector $\underline{Z}$ in the 24-axes hyperspace has a particular value of SY . A value for solar radiation, for a clear sky SRC for the same value of the time variables MO, DAY, and HR, is calculated using the regression coefficients defined by equation 2-1 at the station being analyzed.

The ratio $R = SY/SRC$ is calculated. This process is repeated for all Z satisfying the condition that $CC = 1$. At this point all values of R have been defined in the 24-variable space. Now the cell space is cascaded from the 24-variable space down to the 15-variable space so that, in general, a distribution of values of R will be obtained in the 15-variable space for each X . For each distribution the mean

$$\mu = \mu(R(X)) \quad (2-8)$$

and the standard deviation

$$\sigma = \sigma(R(X)) \quad (2-9)$$

is calculated. The cloudy sky Reference File is composed of the meteorological states defining X , the mean for each $R(X)$, and the standard deviation for each $R(X)$.

It is to be emphasized that R is defined by actual measurements at the SOLMET Station site. In this way it is similar to other empirical statistical methods to predict solar radiation, which depend on the evaluation of unknown coefficients from data gathered at the station. The success of any such method depends on the accuracy of the measured data, the choice of variables, and the method of computation. Since the CCS method is designed to probe the underlying structure of variables not explicitly considered in models, it must be able to handle a large number of variables in a more direct manner. Hence, regression analysis is not an essential part of the technique to obtain R , although regression analysis could be applied to a limited part of the CCS hyperspace as the need arises. The CCS method is used to probe the underlying cloud structure in the Machta-Cotton Model. A discussion of this development is given in Appendix B.

2.3.4 Calculation of the Insolation at a NOAA Station Using the CCS Method and the Machta-Cotton Model

The CCS method and the Machta-Cotton Model are used to calculate the hourly values of insolation at a NOAA Station in the following way. A cloudy sky Reference File from a nearby SOLMET Station is chosen. The vector X is constructed from the values of the surface meteorological variables at the NOAA Station. Using this value of X , the Reference File is searched until an identical value of X from the SOLMET Station is obtained. The corresponding value of the mean $\mu(R(X))$ from the cloudy sky Reference File is chosen. If the

value of $\underline{X}$ defined at the NOAA Station does not exist in the Reference File of the SOLMET Station, equation 2-2 is used instead of $\mu(R(\underline{X}))$. If OPQ is missing, the insolation for this hour is obtained by a linear interpolation of the function formed by the ratio:

$$\frac{\text{solar radiation calculated at hours} \\ \text{where meteorological data is available}}{\text{extraterrestrial radiation}}$$

If the variable CC is zero at the NOAA Station (meaning that the sky is clear or that the total cloud cover is zero) the insolation at this hour is given by SRC alone.

2.3.5 Calculation of the Insolation at a NOAA Station Using the CCS Method with Cascaded Reference Files

The cascading of variables in the CCS cell space discussed in Section 2.3.2 can be applied to define a series of Cascaded Reference Files both for clear and cloudy skies at the SOLMET Station. These multiple files would replace the single cloudy sky Reference File used in the previous section to calculate the insolation. $\underline{X}^*$ would define a meteorological state vector with the number of variables depending on the particular Cascaded Reference File. The cascade up would define an $\underline{X}^*$ with a larger number of variables (perhaps adding SS, DP, and VIS) than was used in the present study. The cascade down would be a series of Reference Files with successively lesser numbers of variables and/or larger intervals per axis of the hyperspace. When $\underline{X}^*$ defined at the NOAA Station does not exist in a given Cascaded Reference File of the SOLMET Station, successive Cascaded Files are searched until a match is obtained. This calculational procedure would replace the use of equation 2-2 described in the section above. The computer program to calculate the insolation at a NOAA Station using the CCS method with Cascaded Reference Files has not been completely developed. In this report, the calculation of the insolation using the CCS method has been based on the single cloudy sky Reference File as outlined above in Section 2.3.4.

The relationship of the Machta-Cotton coefficients defined by equation 2-2 to the CCS calculational procedure of Section 2.3.4 above is explained from the point of view of Cascaded Reference Files in Appendix B-2.

2.4 THE WEDGE METHOD

For this study it is necessary to be able to evaluate certain characteristics of two insolation data sets that would exist serially for a given month over the period of years given on a SOLMET magnetic tape. The data sets might be from the same site, where one set is measured data and the other set is either calculated data from a solar radiation model or perhaps the measured data set to which certain corrections might have been applied. The two data sets might be each from different sites separated by distances of from 5 to 500 miles. The Wedge Method was developed to perform these data comparisons in a quantitative way.

From each of these two data sets can be constructed a histogram or frequency distribution of occurrence of insolation values over the station record for the month of interest. The joint distribution function would be constructed from the simultaneous values of radiation between the two sets of data. The definition of simultaneity used in this study is not the usual definition of two simultaneous events as measured by synchronized clocks. Simultaneity as defined in this study refers to two events which occur during the same solar time interval (as measured in solar time). If the solar time interval for two events (one value of insolation from each data set) is at the same solar hour and both data sets are from the same station, then the local standard time would be the same. However, if the two events occur at stations which are separated by a longitude difference, the local standard time may not be the same for the two events. The relationships between solar time and local standard time are explained in the book by Duffie and Beckman (Reference 7).

2.4.1 The Parameter N

Each of the two events discussed above may be each defined in the same or even different part of the same solar time interval. For the solar radiation, the value of the event is defined by integrating over the entire solar time interval. This is referred to as the summing period of the solar time interval, defined by the value of the parameter N. Thus, the total horizontal global radiation reported on the SOLMET magnetic tapes has a summing period of one solar hour or $N = 1/24$. And a joint two-variable distribution function

of the standard year data field 108 between two SOLMET Stations with the solar time interval being one hour could be constructed. If the solar time interval is one day, then the hourly values for each station are summed into daily values, for the same calendar day, and these daily values make up the joint distribution function. The solar time interval of one day is described by $N = 1$. If $N = 2$, hourly values for two adjacent days would be summed. If $N = 3$, hourly values for three consecutive days would be summed, etc.

2.4.2 The Parameter M

The parameter M specifies the number of years over which the two data sets are to be compared. In this study the years considered are $M = 23$ (1953-1975), 22 (1954-1975), 21 (1953-1973), 12 (1953-1964), 11 (1965-1975), and 1 (1953).

The month which contains the solar time interval must also be specified and in this study the months used are January, April, June, and November. Thus, the joint distribution function is characterized by three parameters: M, N, and month of the year. The parameter N may take on any value consistent with the choice of the month.

Several averages of insolation reported in the literature, such as daily, monthly, etc., can be discussed from a unified point of view using these parameters and can be plotted in the same graph as will be discussed in Section 2.4.6. Daily averages would be noted by $N = 1$. A monthly average would be described by $N = 30$ (or whatever the number of days in the month).

The mean daily solar radiation maps in the National Climatic Atlas (Reference 8) can be interpreted in terms of these parameters for two stations reporting radiation data. The joint distribution function between these two stations would consist of one point, assuming the value of M is the same for both of these stations. If M happened to have the value of 23 for the month of June and if there were no missing days of data at the two stations, then the joint distribution function would be characterized by: $M = 23$, $N = 690$, and June.

In this study the distribution function between two stations has been determined for $N = 1/24, 1, 2, 5, 10, 30$, and 690. However, most of the results have been obtained for $N = 1$. The computer programs to determine results for other values of N need further improvement in efficiency.

2.4.3 The Joint Distribution Function for $N = 1$, $M = 23$, and June

As an example, the joint distribution function of simultaneous daily totals of horizontal radiation between Nashville and Chattanooga, Tennessee for the month of June for the years 1953-1975 would consist of 30 joint daily points per month for 23 years or 690 points, provided there are no days where the data is missing for the entire day. The joint distribution function is constructed in the following way. The hourly values of solar insolation as recorded at the Nashville SOLMET Station in the standard year field 108 for a given day are summed into a daily value. For the same day the values of hourly radiation at Chattanooga are calculated from the CCS method and summed into daily totals. If the data for any hour is missing, a linear interpolation of the ratio of the calculated radiation to the extraterrestrial radiation defined at those hours where the calculated values exist for the same day is used. For example, on June 5, 1953 the daily total of horizontal radiation at Nashville was 25,141 kilojoules per square meter. In Chattanooga the CCS calculation result is 17,672 kilojoules per square meter for the same day. These two daily values form a single point in the two-dimensional joint distribution function of daily insolation values between Nashville and Chattanooga. This construction is repeated until all June daily totals for the 23 year period have been included in the joint distribution function.

Each point in the two-variable joint distribution comes from a particular day in June; i.e., June 5, 1953. As far as the distribution function is concerned each day is treated independently and once the function is created, any given point loses its date identity in the subsequent wedge analysis discussed below.

2.4.4 The Two-Dimensional Wedge

The two-dimensional wedge is introduced to intersect the two-variable joint distribution function at angles which are related to the percent departure of the first data set from the second data set. Using the Nashville and

Chattanooga example above, Figure 2-4a illustrates the coordinate system. The y represents the daily insolation axis for Nashville, x represents the daily insolation axis for Chattanooga. The z-axis represents the number of joint daily occurrences for given values of x and y. The plane formed by the dotted line $y = x$ and the z-axis would contain all the joint daily occurrences between Nashville and Chattanooga that would be equal to each other. The two-dimensional wedge formed by the 2 planes both containing the z-axis and the lines $y = \frac{10}{7}x$ and $y = \frac{10}{13}x$, respectively, would contain the points in the joint daily distribution function where the difference in the simultaneous daily values of insolation between Nashville and Chattanooga is within $\pm 30\%$. This is an example of the Wedge Percent variable W which is defined as

$$W = 100 \left[\frac{A-B}{A} \right] \quad (2-10)$$

where A is the value of the global horizontal radiation at the given simultaneous solar time interval for the first data set

and B is the radiation value at the same time interval for the second data set.

In the example the summing time interval is one day ($N = 1$) using the definition of simultaneity defined above.

The Wedge angle is the acute angle formed by the two intersecting planes defined by $W(+)$ and $W(-)$ where $W(+)$ is equal in magnitude to the absolute value of $W(-)$. P is defined as the percentage of joint distribution points:

$$P = 100 \left[\frac{C}{D} \right] \quad (2-11)$$

where C is the number of joint distribution points at the given value of N and wedge angle

and D is the total number of joint distribution points for the given values of N and M.

In Figure 2-4b the Wedge Curve is the locus of points defined by pairs of values of P and W as defined above for the two sets of data at given values of M, N, and month of the year.

Figure 2-4a. WEDGE COORDINATE SYSTEM

Figure 2-4b. WEDGE CURVE

2.4.5 Types of Comparisons Using Wedge Approach

It is clear from the above discussion that there are many types of data that may be compared in the Wedge Analysis. The list below summarizes 17 types of comparisons that were considered for this study. Only Type B curves listed below cannot be calculated because of the lack of a long-term set of accurate reference pyranometer data. Data for the Type E comparisons is available but the actual wedge curves were not constructed. All other types have been determined in this study for some stations for at least one month.

A. SOLMET Station (standard year field 108) compared with NOAA Station (standard year field 108 from Machta-Cotton Model).

B. SOLMET Station (data set from accurate reference pyranometer) compared with same SOLMET Station (standard year field 108). (Hypothetical)

C. SOLMET Station (standard year field 108) compared with same SOLMET Station (standard year field 108), where the hourly data field is artificially forced to be missing two out of every three hours so as to simulate conditions at a NOAA Station where the TD 1440 Meteorological Observations are only reported every third hour from 1965 through 1975. In these cases at the NOAA Station, insolation calculations would be based on a model which would be in turn based on some of the variables reported in the TD 1440 Meteorological Observations. For those hours where the Meteorological Observations are missing, the insolation at those hours would have to be calculated by an interpolation over other hours where the insolation has been calculated from the meteorological data.

D. SOLMET Station (standard year field 108) compared with CCS calculations at the same SOLMET Station using the Reference File derived from measured data in the standard year field 108 at the same SOLMET Station.

E. SOLMET Station (engineering corrected field 107) compared with CCS calculations at the same SOLMET Station using the Reference File derived from measured data in the engineering corrected field 107 at the same SOLMET Station.

F. SOLMET Station (CCS calculations) compared with the same SOLMET Station (Machta-Cotton Model).

G. SOLMET Station (standard year field 108) compared with the Machta-Cotton Model at the same SOLMET Station using regression coefficients derived from data at the same SOLMET Station.

- H. SOLMET Station (standard year field 108) compared with a NOAA Station using CCS calculations based on the Reference File from the same SOLMET Station.
- I. NOAA Station (standard year field 108 from Machta-Cotton Model) compared with another NOAA Station (standard year field 108 from Machta-Cotton Model).
- J. NOAA Station (CCS calculations) compared with another NOAA Station (CCS calculations).
- K. SOLMET Station (standard year field 108) compared with the same SOLMET Station (engineering corrected field 107).
- L. NOAA Station (CCS calculations) compared with the same NOAA Station (standard year field 108 from Machta-Cotton Model).
- Q. SOLMET Station (standard year field 108) compared with a neighboring SOLMET Station (standard year field 108).
- R. SOLMET Station (standard year field 108) compared with CCS calculations at the same SOLMET Station using Reference File derived from measured data in the standard year field at another SOLMET Station.
- S. SOLMET Station (standard year field 108) compared with the Machta-Cotton Model at the same SOLMET Station using regression coefficients derived from measured data at another SOLMET Station.
- T. SOLMET Station (standard year field 108) compared with CCS calculations at another SOLMET Station using Reference File derived from measured data in the standard year field at the first SOLMET Station.
- U. SOLMET Station (standard year field 108) compared with the Machta-Cotton Model at another SOLMET Station using regression coefficients derived from measured data at the first SOLMET Station.

2.4.6 Constructed Examples

Using the joint distribution function between two data sets and the two-dimensional wedge it is possible to construct wedge curves as described in Section 2.4.4. Certain characteristics of the wedge curves and the language to be used in discussing the wedge analysis results in Section 4 and 5 are introduced below, using hypothetical curves.

The Type B curve shown in Figure 2-5 represents, hypothetically, the comparison between a data set from an accurate reference pyranometer (such a data set is not available at any SOLMET station) and a field instrument at the same

Figure 2-5. HYPOTHETICAL WEDGE CURVES

Figure 2-6. HYPOTHETICAL CUSP CURVE

2-20

SOLMET Station for a given month, $M = 23$, and $N = 1$. The rise rate would be the steepest of the curves shown. In the figure, 70% of the daily values from the field instrument would be within a wedge percent $W^* = \pm 3\%$ of the values measured by the reference pyranometer. W^* would be a function of the insol-climatic conditions, the field instrument characteristics, and the maintenance schedule at the station.

An often quoted accuracy criterion for global insolation measurements in a well maintained network such as the new NOAA/NWS 38 station network is ± 5 percent. It would be very interesting to generate Type B wedge curves from such a network. Such curves would give better understanding of the error in the overall measurement process.

The Type C curve shows the error due to interpolation for missing hourly insolation data in order to get daily values ($N = 1$). In the figure, 70% of the daily values interpolated two out of every three solar hours are within a wedge percent $W_3 = \pm 5\%$ of the daily values obtained from measurements every hour.

The Type I_t curve is a "transplanted" wedge curve. It is a wedge curve between two NOAA stations at a minimum distance apart (say $R^* = 65$ miles) in the same insol-climatic region as the SOLMET station. This distance R^* is used as an approximation to the radius of closest approach to the SOLMET station with wedge percent W_0 . A true R^* must be established by actual insolation measurement near the SOLMET station.

The closest NOAA station (say 125 miles) to the SOLMET station is described by a Type A_1 curve. Two other Type A curves are shown as A_2 and A_3 . These are for NOAA stations progressively further away from the SOLMET Station. It has been found in the study that these Type A (and also Type D) curves (when compared to each other) each rise less steeply (bend over) with increasing distance from the SOLMET Station. Thus, for $P = 70\%$ of the daily values the A_1 curve gives $W = \pm 24\%$, the A_2 gives $W = \pm 29\%$ and the furthest location away from the SOLMET Station has the curve A_3 which gives $W = \pm 36\%$. Curve A_3 does not reach $P = 100\%$ of the percent joint daily insolation points even at W equal to $\pm 95\%$. This is an observed characteristic of the Wedge Curves as the satellite stations are located further away from the SOLMET Station.

2.4.4 Cusp Curves

The Cusp Curve between two sets of data is illustrated in Figure 2-6. The Cusp Curve is simply the two branches of the Wedge Curve for the two sets of data where the x-axis goes from -100% to 0 to 100% and the y-axis is exactly the same as in the Wedge Curves. By comparing the two branches it is possible to determine whether the two data sets possess a joint distribution function which have approximately the same number of points for the plus wedge angle and the minus wedge angle, or whether the points are predominantly on the plus or the minus wedge angle side.

For example, assume that Figure 2-6 represents the Cusp for $N = 1$ and $M = 23$ for the month of June between 2 sets of data, one set at Nashville and the other set at Birmingham. From the figure it is clear that for each wedge angle there are more points on the positive side. From the definition of the wedge percent in equation 2-10:

$$W = 100 \times \frac{\text{INSOLATION}(\text{NASHVILLE}, N=1) - \text{INSOLATION}(\text{BIRMINGHAM}, N=1)}{\text{INSOLATION}(\text{NASHVILLE}, N=1)}$$

it is clear that $W = +100\%$ includes all joint distribution points for the Nashville data set with values greater than the Birmingham data set but $W = -100\%$ does not include all joint distribution points for the Nashville data set with values less than the Birmingham data set. In the figure there are another 10% of the points that are in the region for wedge percentages less than $W = -100\%$ which are not shown.

It is to be emphasized that in wedge or cusp curve comparisons between two stations the above definition of the wedge percent, W , is strictly adhered to. The first of the two stations mentioned in the comparison always goes first in the numerator and in the denominator.

2.5 DEVELOPMENT OF TECHNIQUE TO DEFINE REPRESENTATIVE AREAS

A major objective of this study is to develop a technique to define the representative area for the SOLMET Stations. This objective has been successfully accomplished through the use of the Machta-Cotton Model, the CCS method, and the Wedge analysis discussed above. Using these methods it is possible to determine the area around a SOLMET Station for which the daily total of global solar radiation is within 90, 80, 70, and 50 percent of the values measured at the SOLMET Station. These representative areas can be determined separately for each month of the year. Progress in determining the representative areas for the Nashville and Albuquerque SOLMET Stations is reported in Section 4. The discussion below provides the details of the technique that was developed.

2.5.1 Calculation of Daily Totals of Insolation

The first step in the determination of the representative areas for a given month around a SOLMET Station is to calculate the daily total of global solar radiation at the SOLMET Station (to be referred to as the reference station), at satellite NOAA Stations around the reference station, and at several of the satellite SOLMET Stations which are nearest the reference station for the entire station record existing on the magnetic data tapes (normally the station record is for 21 to 25 years for a given month). For the SOLMET Stations these daily totals are based on measured data and are determined by summing the hourly values of insolation recorded in the standard year corrected data field 108. For the NOAA satellite stations the daily totals are based on: (1) the results of the Machta-Cotton Model which are available hourly on the NOAA Station data tapes in the standard year corrected data field 108, and/or (2) the results of the CCS method which is based on the hourly surface meteorological data reported on the NOAA Station tapes. Whenever the variables used for the calculation of hourly values of radiation are missing from the data tapes (for example, the TD-1440 Meteorological Observations are reported hourly from 1952-1964 and once every three hours from 1965-1975), a linear interpolation is used of the ratio of the calculated radiation to the extraterrestrial radiation defined at those hours where the calculated values exist for the same day.

2.5.2 Use of the Wedge Analysis

The joint distribution function of daily totals of solar radiation for a given month is created between the reference station and each of the satellite stations, including NOAA Stations and neighboring SOLMET Stations. For each pair of stations the Wedge curves are determined as described in Section 2.4. The resulting Wedge curves are then based on daily totals of radiation and are described by the parameter $N = 1$. For each Wedge curve, the value of the wedge percent, W , defined in terms of $\pm$ percentage of the reference station daily insolation is determined at $P = 70\%$ of the joint daily insolation points by interpolation of each wedge curve. These values of W are then placed on a map at the location of the satellite station. From these values a spatial interpolation is performed to determine the locus of points around the reference station for which the values of W are $\pm 10\%$, $\pm 20\%$, $\pm 30\%$, and $\pm 50\%$. For $W = \pm 10\%$, the daily total of global solar radiation would be within $G = 90$ percent of the measured values at the reference SOLMET Station. For $W = \pm 20\%$, the daily total of radiation would be within $G = 80$ percent of the measured values at the reference station, etc.

2.6 DEVELOPMENT OF TECHNIQUE TO EVALUATE SOLAR RADIATION MODELS

A major objective of this study is to develop a technique to assess the ability of solar radiation models to interpolate between SOLMET Station sites. This objective has been successfully accomplished through the use of the CCS and Wedge methodology discussed above. Progress on the evaluation of the NOAA Machta-Cotton Model is given in Section 5. The discussion below provides details of the technique that was developed.

2.6.1 Application of Wedge Methodology at the SOLMET Site

The ability of a solar radiation model to interpolate between SOLMET sites can be evaluated using the following criteria based on the Wedge Methodology:

- (1) How well do the parameters of the model and their coefficients estimate the radiation at the site itself? The Wedge Curves discussed in Section 2.4 can be used to evaluate the errors produced by the model by choosing one set of data for a given month to be the actual measurements in the standard year corrected field

108 at the SOLMET site and the other set to be the data calculated from the model. Crucial to this comparison is a decision on what the minimum summing solar time interval (the value of N) should be, so as to facilitate comparisons with other models and to provide a bridge to calculated comparisons at satellite sites. It was decided that the choice of $N = 1$ (daily values of insolation) would be suitable as the minimum summing period.

- (2) How well do the model parameters desired at the reference SOLMET site estimate the radiation at adjacent SOLMET sites? The Wedge Curves would be used to evaluate the error involved. The first set of data would be actual measurements in the standard year corrected field 108 from the adjacent SOLMET site and the other set would be data calculated from the model using coefficients derived at the reference SOLMET site and values of the parameters as they occur hourly at the adjacent SOLMET site. The error involved based on the reference site can be evaluated by comparing wedge curves based on measurements from the reference site and measurements from the adjacent SOLMET site with measurements from the reference site and model calculations from the adjacent SOLMET site.
- (3) How do the Wedge Curve characteristics change with increasing distance of the NOAA Stations from the reference site? The Wedge Curves involved here would be those determined between the reference site and each NOAA station site as well as those determined between pairs of NOAA sites. The Wedge Curves between pairs of NOAA sites would indicate whether there are unusual gradients (such as those due to mountains or large bodies of water) existing between the two sites.

2.6.2 Application of CCS Method at the SOLMET Site

As discussed in Section 2.3.3, the solar radiation models considered in this study and the CCS method are empirical statistical methods which depend on actual measurements at a solar radiation measurement station in order to calculate insolation. If the insolation is desired at a site for which no solar radiation measurements exist, the calculations that are made depend, in the case of solar radiation models, on the regression coefficients determined at a nearby SOLMET Station and, for the CCS method, on the cloudy

sky Reference File determined at a nearby SOLMET Station. Since the CCS method explicitly considers a large number of variables, results from the method can be compared with results from solar radiation models. It will be recalled from Section 2.3.4 that, at the present state of development, the CCS method uses the results of the Machta-Cotton Model when the $\underline{X}$ (meteorological state) at the satellite station does not match any $\underline{X}$ from the cloudy sky Reference File. This must be taken into account in the evaluation by considering the number of times that equation 2-2 is used in the CCS calculation at the satellite station.

The CCS method is used to calculate the hourly values of radiation at the satellite station and the results are summed into daily totals to generate Wedge Curves based on measurements at the reference station and the CCS daily totals. These Wedge Curves are then compared to those generated using the solar radiation model. When the wedge percent difference, W , at $P = 70\%$ of the joint daily insolation points between these two methods is large (greater than a few percent), there are two factors that could be causing this difference:

- a. The change in frequency of occurrence of the variables at the satellite station, compared to the reference station, is large enough to influence the calculation of daily values of insolation.
- b. The model coefficients, if they could be determined at the satellite station, would produce values of the radiation attenuation function that would vary by more than a few percent from values obtained with coefficients determined at the reference station.

The techniques and criteria developed in this section do not attempt to describe the structure behind the model variables using the CCS method when the wedge percent differences, W , are large. There are from 5000 to over 20,000 values of $\underline{X}$ in the cloudy sky Reference File for both summer and winter conditions at each SOLMET Station, and the detailed understanding of how these values of $\underline{X}$ interact to give the solar radiation model variables and their coefficients involve complex procedures which have not been efficiently coded into computer programs. Progress on these detailed comparisons are given in Appendix B.

The fourth and last criteria developed in this section assumes that:

- (4) When the wedge percent differences are small (less than a few percent)

between the radiation model and the CCS method, the radiation model is calculating the daily values ($N = 1$) of radiation with acceptable error as defined by the Wedge Curves. The wedge percent difference is taken at $P = 70\%$ of the joint daily insolation points for the wedge curves calculated by both methods.

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Section III

COMPUTER PROGRAM DEVELOPMENT

In this section the digital computer programs are discussed that were developed during the study to determine the representative areas around SOLMET Stations for which data from that site can be used with specified confidence levels and to evaluate solar radiation models. A major achievement of this study is the reduction of costs associated with the processing of the extensive data base by factors of ten or more. This cost reduction and a short description of the computer programs that were written to perform the study are described.

3.1 DATA BASE PROCESSING AND COST REDUCTION

The data base available for the study includes hourly values of solar radiation and surface meteorological observations at over 225 stations in the United States for periods of record up to twenty-five years. Section 2.1 and Appendix A discuss the data sources. Figures 2-1 and 2-2 are maps showing the location of these stations. The data that have been received for these stations and other stations not shown on the maps are listed below:

- A total of 26 SOLMET data tapes were received from the National Climatic Center in Asheville, North Carolina. The stations include all of the stations reporting hourly solar radiation data shown in Figure 2-1 with the exception of Stephenville, Texas.
- Data tapes for 196 NOAA Stations have been received from the Air Resources Laboratory of NOAA located in Silver Spring, Maryland. Nearly all of these stations are shown in Figure 2-2.
- Data tapes for eight Tennessee Valley Authority (TVA) stations with solar radiation and weather data in the TVA area were received. However, during this study it was found that large gaps and uncertainties exist in the TVA data. Consequently, the TVA data was not used to generate the results shown in Sections 4 and 5.

For the SOLMET and NOAA Stations listed above there are 163 digits of information recorded each hour for the entire station record. This would represent a voluminous data base of approximately eight billion digits of information on 222 magnetic tape reels. In order to process such a large amount of data, low cost and efficiency is required in two areas:

- (1) The magnetic tape data conversion routines
- (2) The input/output routines

Very significant progress was made in both areas during the study. Based on the processing of data from the entire station record of over 50 stations it can be confidently stated that the entire data base could be processed at a reasonable cost. The discussion below summarizes what was accomplished in these two areas.

1. THE MAGNETIC TAPE DATA CONVERSION ROUTINES. Several methods of converting the EBCDIC character representation of the SOLMET format to the ASCII character representation or to FIELDATA which are compatible with the Univac 1100 series computers have been investigated. A COBOL routine was written which was quite efficient compared to FORTRAN library subroutines for conversion. Data conversion cost problems have been essentially eliminated with the development of an assembly language code written especially for the Univac 1100 system, which converts the 24-year record of one SOLMET Station into Univac binary values for not much more than the cost of the reel of tape.
2. THE INPUT/OUTPUT ROUTINES. The converted data can now be accessed in a random manner on magnetic disk, mass-storage units. The hourly data can be brought into core memory in one-hour blocks for the entire 24-year record for less than the cost of the reel of tape.

3.2 COMPUTER PROGRAMS DEVELOPED

Four large computer programs were developed for Tasks I and II, along with numerous supporting subroutines to perform such functions as interpolation or calculating the sunrise hour. The CCS Program and output has already been discussed in several sections of this report (Executive Summary, Section 2.3, and Appendix B). The Wedge Program is discussed in the Executive Summary, Section 2.4, and examples of the output are given in Appendix C in the form of the Wedge Curves. The remaining two programs are discussed below: THE SINGLE VARIABLE STATISTICS PROGRAM. This program determines the frequency of occurrence of 40 variables in the SOLMET data tapes for specified variable intervals, solar hours, and months over the entire station record. The results of this program were used to determine cell size in the CCS Program. THE PERCENT MEAN SERIES PROGRAM. This program evaluates the Percent Mean Series discussed in Appendix B.1 and examples of the output are given in Appendix B.3.

Section IV

DETERMINATION OF REPRESENTATIVE AREAS AROUND SOLMET STATIONS

During this study, a technique to determine the area around a SOLMET Station for which the daily total of global solar radiation is within 50, 70, 80, and 90 percent of the values measured at the station was developed. Section 2.5 discussed in detail the method that was developed. This section presents the results of the analysis for the months of January and June around the Nashville and Albuquerque SOLMET Stations and for the months of April and November around Albuquerque. Maps showing the contours defining the representative areas around each station for each month are presented. The notation used below for the Wedge and Cusp Curves is defined in detail in Section 2.4.

4.1 DETERMINATION OF THE REPRESENTATIVE AREAS AROUND THE NASHVILLE AND ALBUQUERQUE SOLMET STATIONS

In Section 2.4.6 and Figure 2-5 it was pointed out using hypothetical wedge curves that, as the distances between the SOLMET reference station and the satellite stations increase, the curves rise less steeply. This rise rate also depends on the geographical properties separating the satellite station and the SOLMET Station. The Wedge Curves then are quantitative measures over climatic time periods of what is well known qualitatively on a day-to-day basis: That the weather becomes less correlated as the distance from the place of reference increases and that this has some effect on the amount of radiation received.

These characteristics of the Wedge Curves have been found to exist between the Nashville and Albuquerque SOLMET Stations and their respective satellite stations in this study. These curves also show markedly different behavior as the climatic zone and/or the month of the year is changed. Types A, H, and Q Wedge Curves were determined for daily values of insolation ($N = 1$) for satellite stations around Nashville and Albuquerque listed in Tables 4-1 and 4-2, respectively. The types of Wedge Curves are defined in Section 2.4.5.

TABLE 4-1. SATELLITE STATIONS ANALYZED AROUND NASHVILLE

STATIONS	CCS	MACHTA
GREENSBORO, N.C.		X
EVANSVILLE, IND.	X	X
CHATTANOOGA, TENN.	X	X
ASHEVILLE, N.C.	X	X
RALEIGH, N.C.	X	X
MEMPHIS, TENN.	X	
LITTLE ROCK, ARK.	X	
JACKSON, MISS.	X	
BIRMINGHAM, ALA.	X	
MONTGOMERY, ALA.	X	
AUGUSTA, GA.	X	
LEXINGTON, KY.	X	X
ROANOKE, VA.	X	X
KNOXVILLE, TENN.		X
CHARLOTTE, N.C.		X
GREENVILLE, S.C.		X
LOUISVILLE, KY.		X
INDIANAPOLIS, IND.		X
SPRINGFIELD, MO.		X
CHARLESTON, W. VA.		X
COLUMBIA, S.C.		X
BATON ROUGH, LA.	X	

TABLE 4-2. SATELLITE STATIONS ANALYZED AROUND ALBUQUERQUE

STATIONS	CCS	MACHTA
GRAND JUNCTION, COLO.	X	X
PUEBLO, COLO.	X	X
TRUTH OR CONSEQUENCES, N.M.		X
EAGLE, COLO.		X
PRESCOTT, ARIZ.		X
TUSCON, ARIZ.		X
FARMINGTON, N.M.		X
CLAYTON, N.M.		X
TUCUMCARI, N.M.		X
MIDLAND, TX.		X
LUBBOCK, TX.		X
WINSLOW, ARIZ.	X	X
CEDAR CITY, UT.		X
BRYCE CANYON,		X
COLORADO SPRINGS, CO.		X

4.1.1 Wedge and Cusp Curves for Satellite Stations Around Nashville and Albuquerque

Appendix C presents a large selection of curves from the Wedge Analysis used in determining the representative areas.

4.1.2 Criteria for Representative Areas

The criteria used to determine the representative areas are based on the techniques developed in Section 2.5. For each satellite station listed in Tables 4-1 and 4-2 wedge curves are determined, some of which are shown in Appendix C. For each curve, the value of the wedge percent, W , is determined at $P = 70\%$ by interpolation. Tables 4-1 and 4-2 show that for some of the satellite stations both the CCS and Machta-Cotton methods were used to calculate wedge curves, so as to compare the two methods on a daily basis ($N = 1$). It was found that the results using the Machta-Cotton Model (Type A) agreed with the CCS calculation (Type B) to within a few wedge percent at $P = 70\%$, except for Roanoke and Raleigh in January. In comparing Figures C-3b and C-2c in Appendix C it can be seen that the two methods differ by about $\pm 10\%$ in wedge percent at $P = 70\%$ for January at Roanoke. In Figures C-3b and C-2b the wedge percent difference is $\pm 13\%$ for January at Raleigh. Although the differences in these wedge percentages are relative large, the actual values of W involved are around $W = \pm 70\%$ and are beyond the range of W needed for this study. Consequently, the reasons for these differences have not been analyzed. As an approximation, the average of the value of W by both methods was used at Roanoke and Raleigh in January to determine the contour line corresponding to $W = \pm 75\%$.

Although not shown in Appendix C, calculations using both CCS and Machta-Cotton at Evansville, Chattanooga, Asheville, and Lexington for January and June are within two percent in W for $P = 70\%$ using Nashville as the reference station. Calculations using both methods at Winslow, Pueblo, and Grand Junction for January and June are also within two percent based on Albuquerque as the reference station.

The reader is reminded that in Section 2.6.2 the CCS method, at the present state of development, uses the results of equation 2-2 when the vectors $\underline{X}$ do not match between the SOLMET Station and the satellite station. The number of times that this occurs varies from month to month and station to station.

For example, in Evansville, Indiana this situation occurs 750 times out of 2558 cloudy sky hourly occurrences in January. In June it occurs 1508 times out of 4641 cloudy sky hourly occurrences. Appendix B.2 provides a discussion of how equation 2-2 can be viewed as an approximation to the Cascaded Reference Files introduced in Section 2.3.5.

4.1.3 Comparisons Between Pairs of NOAA Stations

In Section 2.4.6 a Type I_c curve, called a "transplanted" wedge curve, was discussed. It was defined as the wedge curve between two NOAA Stations at a minimum distance apart in the same insol-climatic region as the SOLMET Station. Such wedge curves between pairs of NOAA Stations are useful for extrapolating to obtain representative area contours in terms of W when the contour lines would lie between the reference station and the nearest satellite stations. This situation occurred around Nashville in June for the $W = \pm 20\%$ contour. Additional results on these characteristics between pairs of NOAA stations are presented in Section V.

4.1.4 Representative Area Contours around Albuquerque and Nashville

Using the results above from the Wedge Curves at $P = 70\%$ of the joint distribution points, the locus of points can be determined around each reference station for which the wedge percentages are $W = \pm 10\%$, $\pm 20\%$, $\pm 30\%$, $\pm 35\%$, $\pm 40\%$, $\pm 50\%$, $\pm 75\%$ and $\pm 100\%$. Contractually, it is required to show the area around each reference station for which the daily total of global solar radiation can be considered to be within $G = 90, 80, 70$, and 50 percent of the measured values at the respective SOLMET Station. For $W = \pm 10\%$, the daily total of global solar radiation would be within $G = 90$ percent of the measured values at the reference SOLMET Station. For $W = \pm 20\%$, the daily total of global solar radiation would be within $G = 80\%$ of the measured values at the reference station. For $W = \pm 30\%$, $G = 70\%$. For $W = 50\%$, $G = 50\%$, etc. For a given reference station, it is not always practical to determine all the G -contour values given above. Therefore for some months at a given reference station, values of the G -contours = 65% , 60% , and 25% have also been determined.

Figure 4-1 shows the representative area G -contours for January around Albuquerque and Nashville for daily totals of insolation ($N = 1$). There is a dramatic difference in the daily correlation of solar radiation around the two

Figure 4-1. REPRESENTATIVE AREA G-CONTOURS IN JANUARY AROUND ALBUQUERQUE AND NASHVILLE FOR TOTAL DAILY INSOLATION ($M = 23$, $N = 1$)

SOLMET sites. Figure 4-2 shows the representative area G-contours for June around Albuquerque and Nashville for daily totals of radiation ($N=1$). Again, the daily values of radiation around the Albuquerque site are much better correlated than around Nashville. Figures 4-3 and 4-4 show the G-contours for Albuquerque in April and November, respectively.

4.2 WEDGE ANALYSIS AT NASHVILLE SATELLITE STATIONS FOR VALUES OF N OTHER THAN ONE

The study results above have characterized the representative areas in terms of $N = 1$ Wedge Curves. In Section 2.4 the parameter N for values other than one was discussed. It would be possible to determine the representative areas based on values of N greater than one, although this was not done in the present study. As the value of N increased (for the same value of $P = 70\%$) the G-contour lines would shift away from the reference station and the contours would tend to become more circular in shape.

Figures 4-5 through 4-7 show Wedge Curves for January at Chattanooga, Tennessee, Evansville, Indiana, and Knoxville, Tennessee, respectively, with $M = 23$ and $N = 1, 2, 5, 10$, and 30 . An important characteristic of these curves is that as the value of N increases, the curves become more steep (rise at a faster rate). It is important to note that as N increases, the number of points in the joint distribution function decreases. For $N = 30$, the number of points in the joint distribution function would be 23. January 31 has been omitted in the analysis.

Figures 4-8 through 4-10 show Wedge Curves for June at Chattanooga, Evansville, and Knoxville, respectively, with $M = 23$ and $N = 1/24, 1, 2, 5, 10$, and 30 .

Figure 4-11 is a graph of W versus N at $P = 70\%$ for Chattanooga, Evansville and Knoxville in January and June. An important feature of these curves is the decrease in the absolute value of W as N increases. In the future, representative areas based on values of N greater than one may be useful for the sizing of solar storage systems.

Figure 4-2. REPRESENTATIVE AREA G-CONTOURS IN JUNE AROUND ALBUQUERQUE AND NASHVILLE FOR TOTAL DAILY INSOLATION ($M = 23$, $N = 1$)

Figure 4-4. REPRESENTATIVE AREA G-CONTOURS, IN NOVEMBER AROUND ALBUQUERQUE FOR TOTAL DAILY INSOLATION ($M = 23$, $N = 1$)

Figure 4-5. CHARACTERISTIC WEDGE FUNCTION FOR REFERENCE STATION COMPARED WITH CHATTANOOGA

Figure 4-6. CHARACTERISTIC WEDGE FUNCTION FOR REFERENCE STATION COMPARED WITH EVANSVILLE

Figure 4-7. CHARACTERISTIC WEDGE FUNCTION FOR REFERENCE STATION COMPARED WITH KNOXVILLE

Figure 4-8. CHARACTERISTIC WEDGE FUNCTION FOR REFERENCE STATION COMPARED WITH CHATTANOOGA

Figure 4-9. CHARACTERISTIC WEDGE FUNCTION FOR REFERENCE STATION COMPARED WITH EVANSVILLE

Figure 4-10. CHARACTERISTIC WEDGE FUNCTION FOR REFERENCE STATION COMPARED WITH KNOXVILLE

Figure 4-11. N VARIATION AT P = 70%

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Section V

EVALUATION OF SOLAR RADIATION MODELS FOR INTERPOLATION BETWEEN STATIONS

During this study, a technique to assess the ability of solar radiation models to interpolate between SOLMET Station sites was developed. Section 2.6 discussed in detail the method that was developed by using the Wedge and CCS Methodology. Four criteria were formulated to test the ability of the Machta-Cotton Model to interpolate between the Nashville and the Lake Charles SOLMET Stations for the months of January and June. The notation used below for the Wedge Analysis is defined in Section 2.4.

5.1 EVALUATION OF MODEL PERFORMANCE AT THE NASHVILLE SOLMET SITE

The ability of the Machta-Cotton Model to interpolate between SOLMET sites depends first of all on how well the variables of the model and their coefficients estimate the solar radiation at the reference site itself. The performance of the Machta-Cotton Model at Nashville is discussed in detail in Appendix D. The following discussion summarizes the results of the Appendix pertinent to this section:

1. When the model is applied at the site at which the coefficients are determined there will be errors in the prediction of radiation on an hourly basis. This error is unavoidable and is inherent in the empirical statistical approach used in the radiation model. For example, even when the skies are clear for a given solar hour (total cloud cover equal to zero and no trace of cloud types reported in the first two cloud layers), the standard deviation of the ratio SR/SRC from equation 2-7 was 0.044 for 1604 hourly time intervals in April, May, June, July, and August for the years 1953-1975. The mean was 0.986.

On a daily basis the errors due to the model are less. It was decided in this study to evaluate the model errors on a daily basis using the Wedge Curves for $N = 1$.

2. When the meteorological data is missing at some solar hours (such as during the period 1965-1975 when the meteorological data was missing two out of every three solar hours) this introduces error into the daily calculation that can be quantitatively determined. From Figure D-9 in Appendix D, the effect of omitting the meteorological data twice every three hours for $M = 23$ introduces error. The effect of interpolation introduces an error expressed as $W = +5\%$ for June and $W = +10\%$ for January, both for $P = 70\%$. In June, for $W = +15\%$, P is 93% (or $0.93 \times 690 = 642$ days) and P decreases to 84% (or $0.84 \times 713 = 599$ days) in January. In January there were 113 days (or $113/713 = 0.16$) where the range of W was from $+15\%$ to $+70\%$. In June there were 48 days (or $48/690 = 0.07$) where the range of W was from $+15\%$ to $+40\%$. These results show the dramatic effect on the daily insolation calculations when the only error involved in the calculation is due to the interpolation for missing hourly values of radiation.

5.2 THE BEHAVIOR OF SR/SRC AT SATELLITE SOLMET SITES

The Machta-Cotton Model provides values of the B_1 coefficients in equation 2-2 for the solar radiation in the presence of opaque cloudiness. The ratio SR/SRC has been evaluated for each value of OPQ for the case of no precipitation by Cotton (Reference 9) for all the SOLMET sites of Figure 2-1. Table 5-1 shows the ratio for the Nashville SOLMET Station and for several of the satellite SOLMET sites. It can be seen from the table that from $OPQ = 0$ to $OPQ = 8$, the largest percent deviation of the ratio from the Nashville value is $+4.6\%$. The deviations at $OPQ = 9$ and 10 are somewhat larger in absolute value. The percent deviation from Nashville, PD, is:

$$PD = \frac{\frac{SR}{SRC} (NASHVILLE, OPQ) - \frac{SR}{SRC} (SATELLITE STATION, OPQ)}{\frac{SR}{SRC} (NASHVILLE, OPQ)} \times 100 \quad (5-1)$$

The table shows that the Lake Charles SR/SRC ratio and those for Cape Hatteras and Appalachicola show the largest percent deviations from Nashville. Columbia, Missouri shows the smallest percent deviations.

Table 5-1. OPAQUE CLOUDINESS ATTENUATION RATIOS AT SELECTED SOLMET STATIONS

MILES FROM NASHVILLE		544	451	432	623	551	506	335	749	621		
OPQ	NASHVILLE	LAKE CHARLES	APALACHICOLA	CHARLESTON	CAPE HATTERAS	WASHINGTON DC	MADISON	COLUMBIA	DODGE CITY	FORT WORTH	PD _{MAX}	PD _{MIN}
	SR/SRC	SR/SRC PD	SR/SRC PD	SR/SRC PD	SR/SRC PD	SR/SRC PD	SR/SRC PD	SR/SRC PD	SR/SRC PD	SR/SRC PD		
0	1.010	1.000 1.	1.000 1.	1.000 1.	1.000 1.	1.000 1.	.999 1.1	1.000 1.	1.000 1.	1.000 1.	+1.1	1
1	.964	.968 - .4	.966 - .2	.972 - .8	.975 -1.1	.961 .3	.965 - .1	.957 .7	.972 - .8	.967 - .3	+ .7	-1.1
2	.936	.950 -1.5	.941 - .5	.952 -1.7	.958 -2.4	.933 .3	.942 - .6	.932 .4	.954 -1.9	.943 - .7	.4	-1.9
3	.917	.938 -2.3	.921 - .4	.934 -1.9	.943 -2.8	.912 .5	.924 - .8	.916 .1	.938 -2.3	.923 - .7	.5	-2.8
4	.900	.925 -2.8	.900 0	.913 -1.4	.924 -2.7	.889 1.2	.904 - .4	.902 - .2	.919 -2.1	.899 .1	1.2	-2.8
5	.876	.903 -3.1	.873 .3	.882 - .7	.895 -2.2	.859 1.9	.874 .2	.880 - .5	.891 -1.7	.866 1.1	1.9	-3.1
6	.837	.865 -3.3	.836 .1	.835 .2	.852 -1.8	.816 2.5	.830 .8	.843 - .7	.846 -1.1	.819 2.2	2.5	-3.3
7	.774	.803 -3.7	.783 -1.2	.767 .9	.787 -1.7	.752 2.8	.762 1.6	.780 - .8	.778 - .5	.752 2.8	2.8	-3.7
8	.679	.710 -4.6	.709 -4.4	.670 1.3	.696 -2.5	.662 2.5	.665 2.1	.684 - .7	.680 - .1	.659 2.9	2.9	-4.6
9	.544	.578 -6.3	.609 -11.9	.539 .9	.573 -5.3	.539 .9	.532 2.2	.545 - .2	.547 - .6	.533 2.0	2.2	-11.9
10	.360	.401 -11.4	.478 -32.8	.367 -1.9	.412 -14.4	.376 -4.4	.356 1.1	.356 1.1	.372 -3.3	.370 -2.8	1.1	-32.8
PD _{MAX}		+1	+1	+1.3	+1	+2.8	+2.2	+1.1	+1.	+2.9		
PD _{MIN}		-11.4	-32.8	-1.9	-14.4	-4.4	- .8	- .8	-3.3	-2.8		

Although not shown, the evaluation of equation 2-1 for clear sky solar radiation at the same SOLMET sites for the month of June show about +4% deviation from Nashville for the same zenith angles.

Thus, it appears from the above results that the Nashville regression coefficients may be used for interpolation around Nashville, even as far away in a given direction as the next satellite SOLMET Station in Table 5-1, provided there are no unusual gradients, such as the presence of mountains. The amount of error involved in using Nashville coefficients to calculate the radiation at the satellite SOLMET sites can be quantitatively evaluated using the Wedge Analysis for $N = 1$. The next section performs this evaluation for Lake Charles in the months of January and June.

5.3 EVALUATION OF MODEL PERFORMANCE AT LAKE CHARLES AND NASHVILLE

In order to assess the ability of the Machta-Cotton Model to interpolate between Nashville and the satellite SOLMET site at Lake Charles, the clear sky coefficients A_1 from equation 2-1 and the opaque cloudiness coefficients B_1 from equation 2-2, both sets being evaluated at Nashville, were used in conjunction with the TD-1440 Surface Meteorological Observations on the Lake Charles and Nashville SOLMET magnetic tapes to calculate the solar radiation at Lake Charles and Nashville for June and January. Wedge Curves for $N = 1$ and $M = 11, 12$, and 23 were generated. Some of the results of the analysis are shown in Figure 5-1. The curves are numbered from 1 to 8 and are explained below for $N = 1$ and $M = 23$ (Section 2.4.5 provides definitions for the types of Wedge Curves):

1. This curve is a Type S Wedge Curve for June. It is the Lake Charles standard year field compared with the Machta-Cotton Model using the regression coefficients derived from the standard year measured data at Nashville. Lake Charles TD-1440 data is used in the Model calculations.
2. This curve is a Type G Wedge Curve for June. It is the Nashville standard year field compared with model calculations at Nashville using regression coefficients derived from Nashville standard year data.
3. This curve is a Type S Wedge Curve for January, similar to Curve 1.
4. This curve is a Type G Wedge Curve for January, similar to Curve 2.

FIGURE 5-1. WEDGE CURVE COMPARISONS AT NASHVILLE AND LAKE CHARLES.

5. This curve is a Type U Wedge Curve for June. It is the Nashville standard year field compared with the Machta-Cotton Model calculations at Lake Charles using regression coefficients derived from measured data at Nashville. Lake Charles TD-1440 data is used in the Model calculations at Lake Charles.
6. This curve is a Type Q Wedge Curve for June. It is the Nashville standard year data compared with the Lake Charles standard year data. This wedge curve compares measured data with measured data.
7. This curve is a Type U Wedge Curve for January, similar to Curve 5.
8. This curve is a Type Q Wedge Curve for January, similar to Curve 6.

Curves 1 and 2 are separated by a difference in wedge percent of $\pm 4\%$ at $P = 70\%$ of the joint daily distribution points. This means that the errors at Lake Charles from using Nashville regression coefficients are comparable to the daily wedge percent errors at Nashville using Nashville coefficients. Curves 5 and 6 almost lie on top of each other and show that when comparing Nashville with Lake Charles in a Type Q analysis, almost identical results are obtained if the second data set is calculated from regression coefficients derived from the first data set. The comparison of Curves 1 and 2 with 5 and 6 bring out a very important result: In June the errors due to interpolation between Nashville and Lake Charles (Curves 1 and 2) are much less than the decrease in correlation of the daily values of radiation between the two cities (Curves 5 and 6).

Curves 3 and 4 are separated by a difference in wedge percent of $\pm 10\%$ at $P = 70\%$ of the joint daily distribution points for January. This difference in January is larger in absolute value than in June. Curves 7 and 8 follow each other within a wedge difference of $\pm 5\%$ out to $W = +80\%$. Again in January the errors due to interpolation between Nashville and Lake Charles (Curves 3 and 4) are much less than the decrease in correlation of the daily values of radiation between the two cities (Curves 7 and 8).

5.4 WEDGE CURVE CHARACTERISTICS

The behavior of the Wedge Curves are given in Appendix C for daily (N=1) standard year measurements at SOLMET reference sites compared with the CCS method (Type H), the Machta-Cotton Model (Type A), and satellite SOLMET stations (Type Q). These results when combined with the results of Section IV for the representative areas show, as the distance from the reference station increases, that there is a gradual increase in the absolute value of W, the Wedge percent variable.

Greater detail on the variability of daily values of insolation within the SOLMET reference station insolation climatic region is obtained by determining W at P = 70% for pairs of NOAA Stations using Type I or J Wedge Curves, in addition to the Types A, H, and Q. Within the Nashville region, 23 stations have been analyzed as listed in Table 4-1. There would be 253 possible station-pairs, some of which have been analyzed using the Wedge Program. Table 5-2 lists the station-pairs which are plotted in Figures 5-2 and 5-3 as W (for P = 70%) versus distance between pairs of stations for January and June, respectively. For a given distance apart, the plots show the variability in daily values of insolation around the Nashville region. Figures 5-4 and 5-5 show the daily variability around the Albuquerque region for nine station-pairs. From Figure 5-4 the large variability in daily insolation between Eagle and Colorado Springs and between Grand Junction and Pueblo compared to the other station-pairs is seen for January. From Figure 5-5 it is seen that this variability has diminished considerably for June.

5.5 WEDGE PERCENT DIFFERENCES BETWEEN THE MACHTA-COTTON MODEL AND THE CCS METHOD

For the stations analyzed using both the Machta-Cotton Model and the CCS method shown in Tables 4-1 and 4-2, it was found that the wedge percent differences between both methods were within a few percent. A detailed discussion of these results is given in Section 4.1.2.

Table 5-2. STATION PAIRS FOR FIGURE 5-2 AND 5-3

NASHVILLE
1 CHATTANOOGA
	2 AUGUSTA
	3 CHARLESTON, S.C.
	4 BIRMINGHAM
1 MONTGOMERY
	2 JACKSON
	3 KNOXVILLE
1 LAKE CHARLES
	2 APPALACHICOLA
	3 COLUMBIA, MO.
	4 MADISON
	5 CAPE HATTERAS
	6 DODGE CITY
	7 WASHINGTON
	8 FORT WORTH
1 MONTGOMERY/BIRMINGHAM
	2 RALEIGH/GREENSBORO
	3 ROANOKE/GREENSBORO
	4 LEXINGTON/LOUISVILLE
	5 EVANSVILLE/LOUISVILLE
1 MEMPHIS/LITTLE ROCK
	2 COLUMBIA, S.C./CHARLOTTE, N.C.
	3 GREENVILLE/COLUMBIA, S.C.
	4 JACKSON/MONTGOMERY
	5 CHARLOTTE, N.C./GREENVILLE
1 JACKSON/BIRMINGHAM
	2 LITTLE ROCK/RALEIGH
	3 MEMPHIS/RALEIGH
	4 CHATTANOOGA/ASHEVILLE
	5 CHATTANOOGA/EVANSVILLE
1 ASHEVILLE/KNOXVILLE
	2 LEXINGTON/AUGUSTA
	3 LEXINGTON/ROANOKE
	4 ROANOKE/AUGUSTA
	5 RALEIGH/ROANOKE
1 CHATTANOOGA/KNOXVILLE
	2 ASHEVILLE/KNOXVILLE
	3 EVANSVILLE/LEXINGTON
	4 INDIANAPOLIS/SPRINGFIELD
	5 INDIANAPOLIS/CHARLESTON, W. VA.

Figure 5-2. WEDGE PERCENT VERSUS DISTANCE BETWEEN PAIRS OF STATIONS AT P 70% FOR JANUARY

FIGURE 5-3. WEDGE PERCENT VERSUS DISTANCE BETWEEN PAIRS OF STATIONS AT P=70% FOR JUNE.

Figure 5-4. WEDGE PERCENT VERSUS DISTANCE BETWEEN INDICATED PAIRS OF CITIES AT P = 70% FOR JANUARY

Figure 5-5. WEDGE PERCENT VERSUS DISTANCE BETWEEN INDICATED PAIRS OF CITIES
AT P = 70% FOR JUNE

Section VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

All requirements of the Scope of Work, as amended, were fulfilled during this study. The computer programs and associated sub-routines developed to aid in the analyses are capable of considerably reducing the costs associated with processing the large volume of data available from the SOLMET tapes. Application of the techniques developed to define the representative area around a SOLMET Station and to evaluate solar radiation models lead to the following conclusions:

1. Areas around a SOLMET Station can be characterized into "representative areas" using data from other sources.
2. Confidence limits on the utility of single-site data can be established on the representative areas.
3. The size of the representative areas around the SOLMET Stations will vary depending on the nature of the local geography and season of the year.
4. The Machta-Cotton Model for insolation attenuation is quite good, generally within ± 5 percent except for the highest values of OPQ (OPQ = 9,10). This conclusion is based on data from only five SOLMET Stations for summer months of the year.
5. Techniques for determining the effects of the SOLMET data variables on daily insolation values have been developed (the CCS Program).
6. Techniques have been developed for time-wise comparisons of two solar radiation data sets to determine the percentage of variation between the data sets.

6.2 RECOMMENDATIONS

The analytical techniques used in this study allowed for a large number of variables to be used in the Climatological Cell Statistics (CCS) program. The logical next step is to review the present results to select the significant variables and then to group the variables and their ranges to reduce the cell space. These steps would make the computer programs even more efficient. Once this is done, the techniques developed in Tasks I and II can be used to:

1. Develop contour curves of representative areas around additional SOLMET Station for selected months of the year.
2. Further evaluate the application of the Machta-Cotton Model to the additional site(s).
3. Provide data for improvement of the Model if the high OPQ values still show high variability.
4. Further define network density requirements and extend the representative area of each radiation measurement site.

Section VII

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PART III APPENDICES

Appendix A

DATA SOURCES AND DIGITIZATION OF VARIABLES

This appendix discusses in detail the digitization of variables from the SOLMET Hourly Solar Radiation-Surface Meteorological Observation Data Base discussed briefly in Section 2.1 and more fully in Reference 1. It is to be emphasized that the redefinition of values for the variables discussed below is for convenience in computer processing and does not change in any way the SOLMET format. The magnetic tape data fields referred to below are shown in Figure 2-3. The reader is expected to already be familiar with the contents of Reference 1.

A.1 CLOUD LAYER AMOUNT

In the SOLMET Manual tape field 209 the amount of celestial dome in tenths covered by clouds or obscuring phenomena has the values 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10. Missing data is coded with the value 99. These values are retained in the present study. The SOLMET variable for the amount of opaque sky cover means the amount of clouds or obscuration through which the sky or higher cloud layers cannot be seen. It has the same range as above.

A.2 TYPE OF CLOUD OR OBSCURING PHENOMENA

In the SOLMET manual tape field 209 the generic cloud type or obscuring phenomena has the code:

- 0 = None
- 1 = Fog
- 2 = Stratus
- 3 = Stratocumulus
- 4 = Cumulus
- 5 = Cumulonimbus
- 6 = Altostratus
- 7 = Altocumulus

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1. *SOLMET VOLUME I - USER'S MANUAL TD-9784, Hourly Solar Radiation-Surface Meteorological Observations, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Asheville, North Carolina, December 1977.*

- 8 = Cirrus
- 9 = Cirrostratus
- 10 = Stratus Fractus
- 11 = Cumulus Fractus
- 12 = Cumulonimbus Mamma
- 13 = Nimbostratus
- 14 = Altocumulus Castellanus
- 15 = Cirrocumulus
- 16 = Obscuring phenomena other than fog
- 99 = Missing Data

This code is retained in the present study for cloud type.

A.3 MINUTES OF SUNSHINE

In the SOLMET Manual tape field 111 the range of the variable minutes of sunshine is given in minutes from 0 to 60 with 99 indicating missing data. These values are retained in the present study.

A.4 TIME VARIABLES

In the SOLMET Manual tape field 3 the following variables are listed.

SOLAR TIME

YEAR	00 - 99	Year of observation, 00 - 99 = 1900 - 1999
MONTH	01 - 12	Month of observation, 01 - 12 = Jan. - Dec.
DAY	01 - 31	Day of month
HOURL	0001 - 2400	End of the hour of observation in solar time (hours and minutes)

These ranges have been retained in the present study with the exception of the solar hour variable, which has been truncated to hours only.

A.5 THE PRECIPITATION VARIABLE RN

Some of the weather variables in the SOLMET data field 205 are combined into a single precipitation variable RN for the study. Table A-1 shows the range of values of RN and how it relates to the original SOLMET variable range and name. This variable is also referred to as the rain variable.

Table A-1. MERGING OF SOLMET WEATHER VARIABLES INTO A PRECIPITATION VARIABLE RN.

DIGITIZED VALUES OF RN. RN is the precipitation variable used in the present study.			
	SOLMET CODE	SOLMET DEFINITION AND DESCRIPTION	SOLMET VARIABLE NAME
0	0	None	OCCURRENCE OF RAIN, RAIN SHOWERS OR FREEZING RAIN
1	1	light rain	
2	2	moderate rain	
3	3	heavy rain	
4	4	light rain shower	
5	5	moderate rain shower	
6	6	heavy rain shower	
7	7	light freezing rain	
8	8	moderate or heavy freezing rain	
99	9	missing data	
11	0	none	OCCURRENCE OF DRIZZLE, FREEZING DRIZZLE
12	1	light drizzle	
13	2	moderate drizzle	
14	3	heavy drizzle	
15	4	light freezing drizzle	
16	5	moderate freezing drizzle	
	6	heavy freezing drizzle	
	9	missing data	
21	0	none	OCCURRENCE OF SNOW, SNOW PELLETS OR ICE CRYSTALS
22	1	light snow	
23	2	moderate snow	
24	3	heavy snow	
25	4	light snow pellets	
26	5	moderate snow pellets	
	6	heavy snow pellets	
IF=7,8	7	light ice crystals	
set=8	8	moderate ice crystals	
	9	missing data	
31	0	none	OCCURRENCE OF SNOW SHOWERS AND SNOW GRAINS
32	1	light snow showers	
33	2	moderate snow showers	
	3	heavy snow showers	
IF=4,5,6	4	light snow grains	
set=5	5	moderate snow grains	
	6	heavy snow grains	
	9	missing data	
41	0	none	OCCURRENCE OF SLEET (ICE PELLETS), SLEET SHOWERS OR HAIL
42	1	light sleet	
43	2	moderate sleet	
	3	heavy sleet	
IF=4,5,6	4	light hail	
7,8 set=5	5	moderate hail	
	6	heavy hail	
	7	light small hail	
	8	moderate or heavy small hail	
	9	missing data	

A.6 HEIGHT OF BASE OF CLOUD LAYER

In the SOLMET Manual tape field 209, the height of the base of the cloud layer has been redefined for this study with the range 0 to 9 as follows:

0	0 meters	- 999 meters
1	1000	- 1999 meters
2	2000	- 2999
3	3000	- 3999
4	4000	- 4999
5	5000	- 5999
6	6000	- 6999
7	UNLIMITED, CLEAR	
8	UNKNOWN HEIGHT	
9	MISSING DATA	

A.7 HORIZONTAL VISIBILITY

In the SOLMET Manual tape field 204 the horizontal visibility has been redefined for this study with the range 0,1,2,80 with 99 as missing data.

0	0 - 1.9 km
1	2 - 3.9 km
2	4 - 5.9 km
3	6 - 7.9 km
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80	160 - 160.9 km
99	MISSING DATA

A.8 INSOLATION

In the SOLMET Manual tape fields 107 and 108 the global radiation on a horizontal surface has been redefined for this study with range 0,1,2,98 with 99 as missing data.

0 0 - 49 kJ/m²

1 50 - 99

2 100 - 149

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80 4000 - 4049

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97 4850 - 4899

98 4900 - 4957

99 MISSING DATA

A.9 DEW POINT

In the SOLMET Manual tape field 207 the dew point has been redefined for this study with range 0,1,2,86 with 99 as missing data.

0 -70°C to -68.4°C

1 -68.5 to -66.9

2 -67 to -65.4

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47 0.5 to 1.9

48 2 to 3.4

49 3.5 to 4.9

50 5 to 6.4

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85 57.5 to 58.9

86 59 to 60

99 MISSING DATA

APPENDIX B

ANALYSIS OF $R(\underline{X})$ IN THE CLOUDY SKY REFERENCE FILE

Techniques to assess the ability of solar radiation models to interpolate between SOLMET Stations using the CCS and Wedge methodology were discussed in Section 2.6. When the wedge curves for a site calculated by CCS and the radiation model show large differences in wedge percent W (W is defined in Section 2.4.1), the techniques of Section 2.6 stop short of analyzing the detailed cloud structure information contained in the cloudy sky Reference File at the site because of the great complexity involved in understanding the interplay of the thousands of combinations of possible values of $\underline{X}$. This Appendix develops the methods to examine the detailed cloud structure information provided by the CCS method in order to understand the attenuation of radiation by cloud type, amount, and height at a site. Some combinations of cumulus and cirrus clouds are examined for their effect on the attenuation of radiation at some values of OPQ.

B.1 THE PERCENT MEAN SERIES

In the CCS method the meteorological observations vector $\underline{X}$ (defined in Section 2.3.2) includes the OPQ variable plus the amount, type, and height of clouds in the first three layers reported on the SOLMET data tapes. By holding OPQ constant it is possible to examine the distribution of the cloud structure variable $\underline{Y}$ and its effect on the mean and standard deviation of the dependent variable R , defined in Section 2.3.3. The degree of similarity in the solar radiation between two sites depends on the similarity of the $\underline{Y}$ distribution between the two sites, holding all other variables constant, and for a given $\underline{Y}$ on the mean and standard deviation of R .

To investigate the underlying cloud structure with each value of OPQ in the Machta-Cotton Model for the summer cloudy sky Reference File, no rain, and zenith angles less than 60° , the R ratio is defined by

$$R = R(CC=1, SW=0, SN=0, ZN=0, RN=0, OPQ, \underline{Y}) \quad (B-1)$$

For this special case the notation can be shortened

$$R(1,0,0,0,0,1,j) \equiv R_{1,j,l}(ST) \quad (B-2)$$

where i refers to the particular value of OPQ

j refers to the particular value of the cloud structure vector $\underline{Y}$

l is the subscript for all values of R for the given values of i and j

and

ST denotes the SOLMET Station at which R is determined.

The mean value of this ratio for a given OPQ is given by

$$\mu_i(ST) = \frac{1}{K_i(ST)} \sum_{j=1}^{K_i(ST)} \sum_l R_{1,j,l}(ST) \quad (B-3)$$

where $K_i(ST)$ is the number of terms of R at the site for the i^{th} value of OPQ.

The inner sum can be replaced by

$$n_{1,j}(ST) \mu'_{1,j}(ST) = \sum_l R_{1,j,l}(ST) \quad (B-4)$$

The mean for the i^{th} value of OPQ becomes

$$\mu_i(ST) = \frac{1}{K_i(ST)} \sum_{j=1}^{K_i(ST)} n_{1,j}(ST) \mu'_{1,j}(ST) \quad (B-5)$$

This series is the Mean Series at the given site.

Converting to the percentage of the mean

$$100\% = 100 \sum_{j=1}^{K_i(ST)} \frac{n_{1,j}(ST)}{K_i(ST)} \frac{\mu'_{1,j}(ST)}{\mu_i(ST)} \quad (B-6)$$

This series is called the Percent Mean Series at the given site for the summer cloudy sky Reference File, $ZN = 0$, and $RN = 0$. Each term can be evaluated for a given SOLMET Station once the cloudy sky Reference File has been determined. Each term contributes a certain percentage to the mean value and, of course, the series converges to 100 percent.

Let $ST = NA$ for the Nashville SOLMET Station; $ST = LC$ for the Lake Charles, Louisiana SOLMET Station and $ST = JA$ for the Jackson, Mississippi NOAA Station. The Mean Series for Lake Charles,

CC = 1 and SW = SN = ZN = RN = 0 is

$$\mu_i(LC) = \frac{1}{K_i(LC)} \sum_{j=1}^{K_i(LC)} n_{i,j}(LC) \mu'_{i,j}(LC) \quad (B-7)$$

The Series for Nashville is

$$\mu_i(NA) = \frac{1}{K_i(NA)} \sum_{j=1}^{K_i(NA)} n_{i,j}(NA) \mu'_{i,j}(NA) \quad (B-8)$$

It is possible to define $\mu_i(LC)$ in terms of $\mu_i(NA)$

$$\mu_i(LC) = k_i(LC, LC/NA) \mu_i(NA) \quad (B-9)$$

so that the Mean Series for Lake Charles in terms of k_i is

$$k_i(LC, LC/NA) = \frac{\sum_{j=1}^{K_i(LC)} \frac{n_{i,j}(LC)}{K_i(LC)} \frac{\mu'_{i,j}(LC)}{\mu_i(NA)}}{\sum_{j=1}^{K_i(LC)} \frac{n_{i,j}(LC)}{K_i(LC)}} \quad (B-10)$$

where the ratio LC/NA stands for $\mu'_{i,j}(LC)/\mu_i(NA)$. To determine the degree of similarity in the cloud structure between Lake Charles and Nashville let

$$\mu'_{i,j}(LC) \approx \mu'_{i,j}(NA) \quad (B-11)$$

so that $k_i(LC, NA/NA)$ is evaluated

$$k_i(LC, NA/NA) = \frac{\sum_{j=1}^{K_i(LC)} \frac{n_{i,j}(LC)}{K_i(LC)} \frac{\mu'_{i,j}(NA)}{\mu_i(NA)}}{\sum_{j=1}^{K_i(LC)} \frac{n_{i,j}(LC)}{K_i(LC)}} \quad (B-12)$$

The Mean Series for Jackson is

$$\mu_i(JA) = \frac{1}{K_i(JA)} \sum_{j=1}^{K_i(JA)} n_{i,j}(JA) \mu'_{i,j}(JA) \quad (B-13)$$

Unfortunately Jackson is a NOAA Station and there are no solar radiation measurements at that site so that $\mu'_{i,j}(JA)$ is unknown. However, to determine whether the frequency of occurrence of the cloud structure variables is similar to Nashville, let

$$\mu'_{1,j}(JA) = \mu'_{1,j}(NA) \quad (B-14)$$

so that $k_1(JA, NA/NA)$ is evaluated

$$k_1(JA, NA/NA) = \sum_{i=1}^{K_1(JA)} \frac{\eta_{1,j}(JA)}{K_1(JA)} \frac{\mu'_{1,j}(NA)}{\mu_1(NA)} \quad (B-15)$$

To determine if the frequency of occurrence of $\underline{Y}$ at Jackson is similar to Lake Charles let

$$\mu'_{1,j}(JA) = \mu'_{1,j}(LC) \quad (B-16)$$

so that $k_1(JA, LC/LC)$ is evaluated

$$k_1(JA, LC/LC) = \sum_{i=1}^{K_1(JA)} \frac{\eta_{1,j}(JA)}{K_1(JA)} \frac{\mu'_{1,j}(LC)}{\mu_1(LC)} \quad (B-17)$$

The intersite coefficients k_1 are an approximate measure of the degree of similarity in the cloud structure between two sites. Equations B-12, B-15, and B-17 determine the influence of the frequency of occurrence of the cloud structure variables $\underline{Y}$ on the OPQ variable in the Machta-Cotton Model. The k_1 defined by these three equations have not been evaluated, pending the development of the Cascading Cloudy Sky Reference Files discussed in Section 2.3.5. The k_1 defined by equation B-10 can be evaluated without summing the series by direct use of equation B-9. The results are given below in Section B.2.1.

At the SOLMET site itself, the Percent Mean Series as defined by equation B-6 can be determined term-by-term. There would be a separate series for each value of OPQ in the Machta-Cotton Model for both the rain and no-rain conditions. A few of these series have been evaluated for some of the Nashville satellite SOLMET sites for the no-rain condition in Section B.3.

B.2 CASCADING OF VARIABLES IN THE REFERENCE FILE

The process of cascading variables in the CCS cell space was discussed in Section 2.3.2. In that section the 24-variable cell space in which Z was defined was cascaded down to a 15-variable space where X was defined by equation 2-6. It is possible to continue this process and eliminate the cloud structure variables. This would be a cascade (down) to a 6-variable space and μ becomes:

$$\mu = \mu(CC, SW, SN, ZN, RN, OPQ) \quad (B-18)$$

In Section 2.3.5 a discussion was given of Cascaded Reference Files that could be developed in the future for the calculation of solar radiation to be used when the 15-variable X for a given solar hour at a NOAA satellite station did not match any X from the reference file determined at the SOLMET station. The manipulations involved in developing equation B-18 are examples of how the Cascaded Reference Files would be constructed. In the sense of Section 2.3.5 the last Cascaded (down) Reference File, where the 15-variable Reference File has been reduced to 3 variables, would have the mean given by

$$\mu(R(X)) = \mu(CC, RN, OPQ) \quad (B-19)$$

where the only surviving variables are those in the Machta-Cotton Model.

Tables B-1 and B-2 give some results of the Cascading process described in equations B-18 and B-19 for values of μ from the summer and winter cloudy sky Reference Files for the no-snow-cover ($SN=0$) and no-rain ($RN=0$) conditions for Nashville, Lake Charles, Cape Hatteras, Albuquerque, and Phoenix. Also given are the attenuation ratios SR/SRC from the Machta-Cotton Model for opaque cloudiness using equation 2-2. The results of the cascading process from equation B-18 are defined by:

$$\mu_1 = \mu(CC=1, SW=0, SN=0, ZN=0, RN=0, OPQ) \quad (B-20)$$

from the summer cloudy sky Reference File mean, zenith angles less than 60° ;

$$\mu_2 = \mu(CC=1, SW=0, SN=0, ZN=1, RN=0, OPQ) \quad (B-21)$$

from the summer file mean, zenith angles greater than 60° ;

Table B-1. COMPARISON OF MEANS BETWEEN SOLMET STATIONS

OPQ	μ_1	μ_2	μ_3	μ_4	CCS _{μ}	SR/SRC	PD
NASHVILLE, TENN.							
0	.983	.988	1.003	.984	.989	1.010	-2.1%
1	.969	.958	.990	.980	.975	.964	1.1
2	.946	.926	.962	.943	.947	.936	1.2
3	.914	.878	.927	.911	.912	.917	-.5
4	.882	.841	.886	.860	.876	.900	-2.7
5	.849	.795	.849	.799	.838	.876	-4.5
6	.805	.718	.816	.783	.796	.837	-5.2
7	.754	.684	.755	.716	.741	.774	-4.5
8	.686	.638	.696	.648	.678	.679	-.2
9	.582	.512	.584	.539	.568	.544	4.2
10	.380	.346	.314	.284	.328	.360	-9.8
LAKE CHARLES, LA							
0	.996	1.015	.997	.985	.997	1.000	-.3
1	.975	.985	.989	.985	.984	.968	1.6
2	.964	.971	.969	.956	.966	.950	1.7
3	.937	.953	.952	.918	.941	.938	+ .3
4	.925	.932	.915	.871	.917	.925	-.9
5	.900	.888	.890	.850	.891	.903	-1.3
6	.860	.826	.835	.798	.845	.865	-2.4
7	.795	.787	.787	.782	.785	.803	-2.3
8	.714	.696	.709	.650	.703	.710	-1.0
9	.602	.588	.609	.566	.597	.578	3.2
10	.413	.389	.379	.340	.379	.401	-5.8
CAPE HATTERAS, NC							
0	.985	1.000	1.008	1.014	.998	1.000	-0.2
1	.979	.979	1.001	.998	.988	.975	1.3
2	.966	.960	.981	.966	.969	.958	1.1
3	.944	.918	.956	.931	.942	.943	-0.1
4	.917	.902	.923	.905	.915	.924	-1.0
5	.875	.854	.880	.842	.869	.895	-3.
6	.825	.805	.835	.778	.818	.852	-4.2
7	.779	.748	.781	.736	.768	.787	-2.5
8	.710	.645	.702	.653	.690	.696	-0.9
9	.621	.573	.611	.563	.601	.573	4.7
10	.424	.375	.379	.337	.383	.412	-7.6

Table B-2. COMPARISON OF MEANS BETWEEN SOLMET STATIONS

OPQ	μ_1	μ_2	μ_3	μ_4	CCS μ	SR/SRC	PD
ALBUQUERQUE, NEW MEXICO							
0	1.002	1.004	.993	.982	.997	1.000	-.3
1	.994	.990	.986	.971	.987	.987	0
2	.971	.957	.971	.947	.965	.968	-.3
3	.933	.906	.938	.894	.926	.940	-1.5
4	.888	.865	.900	.849	.884	.903	-2.1
5	.857	.811	.848	.809	.838	.856	-2.1
6	.797	.763	.787	.750	.781	.798	-2.2
7	.729	.687	.721	.666	.709	.727	-2.5
8	.665	.605	.643	.569	.629	.642	-2.1
9	.560	.520	.536	.463	.527	.543	-3.
10	.427	.382	.432	.354	.408	.428	-4.9
PHOENIX, ARIZONA							
0	1.005	1.009	.992	.990	.999	1.000	-.1
1	.989	.987	.978	.970	.981	.977	.4
2	.968	.959	.965	.950	.963	.958	.5
3	.942	.924	.933	.918	.932	.938	-.6
4	.907	.881	.906	.862	.896	.913	-1.9
5	.870	.842	.871	.835	.861	.879	-2.1
6	.822	.781	.825	.805	.814	.832	-2.2
7	.754	.743	.764	.744	.754	.769	-2.
8	.708	.683	.707	.673	.698	.685	1.9
9	.588	.532	.572	.526	.561	.576	-2.7
10	.417	.392	.432	.415	.412	.438	-6.3

$$\mu_3 = \mu(CC=1, SW=1, SN=0, ZN=1, RN=0, OPQ) \quad (B-22)$$

from the winter file mean, zenith angles less than 60°;
and

$$\mu_4 = \mu(CC=1, SW=1, SN=0, ZN=1, RN=0, OPQ) \quad (B-23)$$

from the winter file mean, zenith angles greater than 60°. These subscripts for μ are defined to present the data in the tables and are not to be confused with the $\mu_i(ST)$ of equation B-3.

The result of the cascading process from equation B-19 gives

$$CCS_\mu = \mu(CC=1, RN=0, OPQ) \quad (B-24)$$

where CCS_μ is the mean value of R for all combinations of 12 of the 15 variables in $\underline{X}$ for the summer and winter cloudy sky Reference Files for a given value of OPQ (which is the 13th variable). The last two variables held constant are CC (set to CC=1 for cloudy skies) and RN (set to RN=0 for no-rain). The percentage difference between CCS_μ and SR/SRC is defined as

$$PD = \frac{CCS_\mu - SR/SRC}{CCS_\mu} \times 100 \quad (B-25)$$

The reader is reminded that in the digitization process used in this study, the numbers in CCS_μ represent the beginning point of the class interval so that .005 should be added to CCS_μ in order to convert to the midpoint of the interval for comparison with SR/SRC. However, this would only be a one-half percent correction and was not applied to the tabulated results.

In comparing CCS_μ with SR/SRC for the SOLMET Stations in Tables B-1 and B-2 in the PD column it can be seen that from OPQ=0 to OPQ=9 the differences are from +4.7% to -5.2%. At OPQ=10 the differences are from -4.9% to -9.8%. Thus the use of the Machta-Cotton coefficients defined in equation 2-2 for the CCS method when $\underline{X}$ at a satellite site does not match $\underline{X}$ at the SOLMET Reference Station is, in the sense of this Appendix, a close approximation to the last

Cascaded (down) Reference File defined by equation B-19. The differences involved in using SR/SRC as opposed to CCS_u could be quantitatively evaluated using the Wedge Analysis. The differences in terms of W for N=1 should be small but due to lack of time this comparison was not made.

B.2.1 Evaluation of Intersite Coefficients

The intersite coefficients $k_1(LC, LC/NA)$ can be evaluated using Table B-1. The results for the no-rain condition are $k_1'(LC, LC/NA) = .99(OPQ=0)$, 1.004 (OPQ=1), 1.015(OPQ=2), 1.023(OPQ=3), 1.028(OPQ=4), 1.031(OPQ=5), 1.033(OPQ=6), 1.037(OPQ=7), 1.046(OPQ=8), 1.063(OPQ=9), 1.114(OPQ=10). These results show that k_1 does not change much between Nashville and Lake Charles, with the larger differences occurring at the larger values of OPQ. Table 5-1 of Section 5-2 gives the same results in terms of PD defined by equation 5-1.

B.3 EVALUATION OF THE PERCENT MEAN SERIES AT SOLMET SITES

The Percent Mean Series can be used to determine how well the coefficients of the Mach-Cotton Model for no rain approximates the cloud structure at each value of OPQ. Equation B-6 has been evaluated at the Nashville, Lake Charles, Cape Hatteras, Albuquerque, and Phoenix SOLMET Stations for the summer cloudy sky Reference File; ZN = 0 and RN = 0. Each term of the Percent Mean Series

$$y = \frac{\eta_{1,j}(ST)}{K_1(ST)} \frac{\mu_{1,j}'(ST)}{\mu_1(ST)} \times 100 \quad (B-18)$$

with the same value of

$$x = \frac{\mu_1(ST) - \mu_{1,j}'(ST)}{\mu_1(ST)} \times 100 \quad (B-19)$$

truncated to a whole percent has been separately summed so that the ordinate shows the sum of all y terms for a given truncated value of x.

Figures B-1 through B-11 show the resulting distributions of y(x) for Nashville for all values of OPQ. Figures B-12 through B-14 show y(x) for Lake Charles at OPQ = 2, 5 and 10. Figures B-15 through B-17 show y(x) for Cape Hatteras at OPQ = 2, 5, and 10. Figures B-18 through B-20 show y(x) for Phoenix and B-21 through B-23 for Albuquerque. All values of x greater than 50% and less than -50% are plotted at x = $\pm 51\%$, respectively.

Figure B-1. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0)$, $OPQ=0,\underline{Y}$

Figure B-2. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0)$, $OPQ=1,\underline{Y}$

Figure B-3. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0)$, $OPQ=2,\underline{Y}$

Figure B-4. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0)$, $OPQ=3,\underline{Y}$

Figure B-5. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0, OPQ=4,Y)$

Figure B-6. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0, OPQ=5,Y)$

Figure B-7. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0, OPQ=6,Y)$

Figure B-8. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0, OPQ=7,Y)$

Figure B-9. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0, OPQ=8,Y)$

Figure B-10. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0, OPQ=9,Y)$

Figure B-11. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR NASHVILLE, $\underline{X} = (1,0,0,0,0, OPQ=10,Y)$

Figure B-12. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR LAKE CHARLES, $\underline{X} = (1,0,0,0,0, OPQ=2,Y)$

Figure B-13. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR LAKE CHARLES, $\underline{X} = (1,0,0,0,0, OPQ=5,Y)$

Figure B-14. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR LAKE CHARLES, $\underline{X} = (1,0,0,0,0, OPQ=10,Y)$

Figure B-15. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR CAPE HATTERAS, $\underline{X} = (1,0,0,0,0, OPQ=2,Y)$

Figure B-16. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR CAPE HATTERAS, $\underline{X} = (1,0,0,0,0, OPQ=5,Y)$

Figure 8-17. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR CAPE HATTERAS, $\underline{X} = (1,0,0,0,0, OPQ=10, Y)$

Figure 8-18. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR PHOENIX, $\underline{X} = (1,0,0,0,0, OPQ=2, Y)$

Figure 8-19. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR PHOENIX, $\underline{X} = (1,0,0,0,0, OPQ=5, Y)$

Figure 8-20. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR PHOENIX, $\underline{X} = (1,0,0,0,0, OPQ=10, Y)$

Figure B-21. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR ALBUQUERQUE, $\underline{X} = (1,0,0,0,0,OPQ=2,Y)$

Figure B-22. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR ALBUQUERQUE, $\underline{X} = (1,0,0,0,0,OPQ=5,Y)$

Figure B-23. CONTRIBUTION OF $R(Y)$ TO THE PERCENT MEAN SERIES AT THE GIVEN VALUE OF OPQ FOR ALBUQUERQUE, $\underline{X} = (1,0,0,0,0,OPQ=10,Y)$

B.4 $R(\underline{X})$ AND $\underline{Y}$ AT SOLMET STATIONS

The CCS analysis has been performed for the Nashville, Lake Charles, Cape Hatteras, Charleston, Albuquerque, Phoenix, Fort Worth, and Dodge City SOLMET Stations. Tables B-3, B-4, and B-5 give selected results for the summer cloudy sky Reference Files (CC=1), no snow cover (SN=0), no rain (RN=0), zenith angles less than 60° (ZN=0), and OPQ = 2, 5, and 10. The first main column headed by 'Y-VECTOR' provides the values for the cloud structure variables defined in Appendix A. Under each SOLMET Station main column heading, the 'KCELL' column gives the number of occurrences of a given value of $\underline{Y}$, the 'MEAN' column gives the percentage of clear sky radiation (which is equation 2-8 for the mean value $\nu(R(\underline{X}))$ multiplied by 100), the '(1)' column is defined by equation B-26, and the '(2)' is defined by equation B-27. Under the 'MEAN' column for Nashville and Lake Charles the 'S' in front of the value denotes use of the standard year corrected data field 108 and the 'E' denotes use of the engineering corrected data field 107. An unlettered value is understood to be 'S'. For Cape Hatteras, Albuquerque, and Phoenix all values under the 'MEAN' column were determined by the standard year field. For Charleston, Fort Worth, and Dodge City all values under the 'MEAN' column were determined by the engineering corrected field.

The values of 'MEAN' and 'KCELL' from cumulus clouds in the five summer months at the eight SOLMET Stations due to $\underline{Y} = (2,0,4,0,1,7,0,0,7)$ can be inter-compared for OPQ = 2 in Table B-3. At Nashville this value of $\underline{Y}$ is a major term in the Percent Mean Series with '(1)' equal to 25.55%. This effect is also shown in Figure B-3 at $x = 1\%$.

The values of 'MEAN' and 'KCELL' from cirrus clouds in the five summer months at the eight SOLMET Stations due to $\underline{Y} = (2,0,8,0,6,7,0,0,7)$ can be inter-compared for OPQ = 2 in Table B-3. At Nashville this value of $\underline{Y}$ contributes 1.42% to the Percent Mean Series. It is to be noted that for this $\underline{Y}$ value, '(2)' equals -4.49%, which means there is less attenuation of radiation from cirrus clouds compared to the mean value at OPQ = 2. This effect is also seen in Figure B-3 at $x = -4\%$.

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B-17

2. SECTION										MOUNTAIN				LONG TUNNEL				CAMP HATTINGS				CAMP EBBON		ALBANY				PHOTO				PICTURE		CAMP GALT	
NO	1	2	3	4	5	6	7	8	9	NO	1	2	3	NO	1	2	3	NO	1	2	NO	1	2	NO	1	2	3	NO	1	2	NO	1	2		
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3		
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		
5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5		
6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6		
7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7		
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8		
9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9		
10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10		
 																																

Table B-4. CLIMATOLOGICAL CELL STATISTICS (CCS) FOR NASHVILLE AND NEIGHBORING SOLMET STATIONS, $\underline{X} = (1,0,0,0,0,0,0,5,Y)$

FACILITY DATA										SALE DATES										DOSE INFORMATION										JUGS/DOSES										PAGES										COST DATA										UNIT COSTS										TOTAL COST									
SP	AP	17	18	19	20	21	22	23	24	DATE	17	18	19	20	21	22	23	24	25	DOSE	17	18	19	20	21	22	23	24	25	JUGS	17	18	19	20	21	22	23	24	25	PAGE	17	18	19	20	21	22	23	24	25	COST	17	18	19	20	21	22	23	24	25	UNIT	17	18	19	20	21	22	23	24	25	TOTAL	17	18	19	20	21	22	23	24	25
1	1	1	1	1	1	1	1	1	1	17	18	19	20	21	22	23	24	25	26	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table B-5. CLIMATOLOGICAL CELL STATISTICS (CCS) FOR NASHVILLE AND NEIGHBORING SOLMET STATIONS,
X = (1,0,0,0,0,0PO=10,Y)

[illegible]

APPENDIX C

WEDGE AND CUSP CURVES FOR NASHVILLE AND ALBUQUERQUE

This Appendix provides selected Wedge and Cusp Curves that were obtained when the representative areas for Albuquerque and Nashville presented in Section 4 were obtained. Careful study of these curves will show that the Wedge Curves for a given value of P increase in absolute values of W as the distance from the reference station increases. The curves are also functions of geographical location of reference station, direction of satellite station from reference station, and month of the year.

Figure C-1. WEDGE FUNCTIONS FOR NASHVILLE COMPARED WITH NEIGHBORING STATIONS. (For January, unless otherwise noted, these curves are Type Q wedge comparisons for $M = 23$ and $N = 1$.)

Figure C-2. WEDGE FUNCTIONS FOR NASHVILLE COMPARED WITH NEIGHBORING STATIONS. (For January, unless otherwise noted, these curves are Type H wedge comparisons for $M = 23$ and $N = 1$.)

Figure C-4. WEDGE FUNCTIONS FOR NASHVILLE COMPARED WITH NEIGHBORING STATIONS. (For June, unless otherwise noted, these curves are Type Q wedge comparisons for $M = 23$ and $N = 1$. Figure (d) is Type H.)

Figure C-6. WEDGE FUNCTIONS FOR ALBUQUERQUE COMPARED WITH NEIGHBORING STATIONS. (For January, unless otherwise noted, these curves are Type Q wedge comparisons for $M = 23$ and $N = 1$.)

Figure C-8. WEDGE FUNCTIONS FOR ALBUQUERQUE COMPARED WITH NEIGHBORING STATIONS. (Figure (a) for January and Figure (b) for June, unless otherwise noted these curves are Type A wedge comparisons for $M = 23$ and $N = 1$.)

Figure C-9. WEDGE FUNCTIONS FOR ALBUQUERQUE COMPARED WITH NEIGHBORING STATIONS. (For June, unless otherwise noted, these curves are Type A wedge comparisons for $M = 23$ and $N = 1$.)

(a) $M = \text{WEDGE PERCENT IN } \frac{1}{2}$ PERCENTAGE REFERENCE STATION INSOLATION

(b) $M = \text{WEDGE PERCENT IN } \frac{1}{2}$ PERCENTAGE REFERENCE STATION INSOLATION

(c) $M = \text{WEDGE PERCENT IN } \frac{1}{2}$ PERCENTAGE REFERENCE STATION INSOLATION

(d) $M = \text{WEDGE PERCENT IN } \frac{1}{2}$ PERCENTAGE REFERENCE STATION INSOLATION

Figure C-10. WEDGE FUNCTIONS FOR ALBUQUERQUE COMPARED WITH NEIGHBORING STATIONS. (For June, unless otherwise noted, these curves are Type Q wedge comparisons for $M = 23$ and $N = 1$.)

(a) WEDGE AND SPECTRUM CURVES FOR ALBUQUERQUE

(b) WEDGE AND SPECTRUM CURVES FOR ALBUQUERQUE

(c) WEDGE AND SPECTRUM CURVES FOR ALBUQUERQUE

Figure C-11. CUSP CURVES FOR ALBUQUERQUE COMPARED WITH NEIGHBORING STATIONS. (For January, unless otherwise noted, these curves are related to Type A wedge curves for $M = 23$ and $N = 1$.)

Figure C-12. CUSP CURVES FOR ALBUQUERQUE COMPARED WITH NEIGHBORING STATIONS. (For June, these curves are related to Line A wedge curves for $N = 23$ and $N = 1$.)

Figure C-13. CUSP CURVES FOR NASHVILLE COMPARED WITH NEIGHBORING STATIONS. (For January, unless otherwise noted, these curves are related to Type A wedge curves for $M = 23$ and $N = 1$.)

Figure C-14. CUSP CURVES FOR NASHVILLE COMPARED WITH NEIGHBORING STATIONS. (For June, unless otherwise noted, these curves are related to Type A wedge curves for $M = 23$ and $N = 1$.)

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APPENDIX D

DETAILED CHARACTERISTICS OF NASHVILLE INSOLATION DATA

This appendix presents analyses and intercomparisons of Nashville radiation data sets from the engineering corrected data field 107, the standard year corrected data field 108, the CCS method, and the Machta-Cotton Model, and evaluates the increase in error when insolation data for a given hour is missing and interpolation routines must be used. The notation used has been defined in Section 2.

D.1 DISTRIBUTION OF DAILY VALUES OF INSOLATION FOR JANUARY AND JUNE

Before comparing the engineering corrected and standard year data fields at Nashville which exist on the SOLMET magnetic tapes, it is of interest to present the frequency distribution (or histogram) of the daily values of insolation. Figures D-1 and D-2 show the daily distributions based on the standard year and the engineering corrected fields, respectively, for the month of January during the period 1953-1975 ($N = 23$). The y-axis is labeled as the log (base 10) of the number of occurrences of that value of insolation over the 23-year period, so that a value of 1.8 on the y-axis means that a given daily value of insolation occurred 63 times. The maximum daily value of insolation for the engineering corrected field is 1000 kilojoules per square meter higher than the standard year field maximum value. Figures D-3 and D-4 show the daily distributions based on the standard year and the engineering corrected fields, respectively, for the month of June during the period $M = 23$. The maximum daily value of insolation for the engineering corrected field is 3000 kilojoules per square meter higher than the standard year field maximum value. These differences are due to the corrections that were applied to the (Ref. 1) hourly values of the engineering corrected fields to obtain the standard year field.

1. Machta, L., "Final Report on the Air Resources Laboratory Solar Radiation Model", Presented at ERAB/ERDA Quarterly Contractor Review For Insolation and Wind, Boulder, Colorado, August 15-17, 1977.

Figure D-1. NASHVILLE DAILY INSOLATION DISTRIBUTION BASED ON STANDARD YEAR CORRECTED FIELD 108, MONTH OF JANUARY, $N = 1$, $M = 23$

Figure D-2. NASHVILLE DAILY INSOLATION DISTRIBUTION BASED ON ENGINEERING CORRECTED FIELD 107, MONTH OF JANUARY, $N = 1$, $M = 23$

Figure D-3. NASHVILLE DAILY INSOLATION DISTRIBUTION BASED ON STANDARD YEAR CORRECTED FIELD 108, MONTH OF JUNE, $N = 1$, $M = 23$

Figure D-4. NASHVILLE DAILY INSOLATION DISTRIBUTION BASED ON ENGINEERING CORRECTED FIELD 107, MONTH OF JUNE, $N = 1$, $M = 23$

D.2 COMPARISONS BETWEEN STANDARD YEAR AND ENGINEERING CORRECTED FIELDS

The Wedge Program can be used to evaluate the magnitude of the correction in the standard year data field by comparing the standard year daily values with the engineering corrected daily values. By choosing the year intervals to be 1953-1964 ($M = 12$), 1965-1975 ($M = 11$), and 1953-1975 ($M = 23$) it is possible to evaluate the effect on the standard year correction when the surface meteorological data is reported only once every three hours, as is the case for $M = 11$. Figures D-5 and D-6 are Type K Wedge Curves for the Nashville SOLMET Station for the months of January and June, respectively. Type K Wedge Curves have been defined in Section 2.4.5 as the comparison between two data sets at the same SOLMET Station, the first set being the standard year field and the second being the engineering corrected field. It is clear from the figures that the corrections made to the engineering corrected data to arrive at the standard year data are larger in absolute value for the $M = 11$ period when the meteorological data is reported every third hour than the $M = 12$ period when the meteorological data is reported hourly.

Referring to Figure D-5 for January it can be seen that at $P = 70\%$ (P was defined in Section 2.4 as the percent of joint distribution points contained in the given wedge percent W), $W = \pm 9\%$ for $M = 12$ and W increases to 12% for $M = 11$. For $M = 12$, (340 total days during this period) $P = 100\%$ of the joint daily values are contained within the wedge percent $W = \pm 15\%$. For $M = 11$, P drops off to 87% for the same value of W . There are 43 days ($43 = .13 \times 336$ total days) in which the value of W exceeds $\pm 15\%$ for $M = 11$. For the $M = 12$ period there should have been $31 \times 12 = 372$ total days available for comparison in the wedge analysis, instead of the 340 given above. The reason for the decrease is that there were days when the engineering corrected data field was missing for every solar hour. When an entire day is missing from either of the two data sets, this day is not used in the joint distribution function. The same explanation holds for the $M = 11$ period. For the entire 23-year period ($M = 23$) the average daily total insolation based on the standard year field was 6580 kilojoules per square meter and for the engineering corrected field 6950, a difference of 5.6%. Using the wedge notation for the 23-year period $N = 676$, $W = \pm 5.6\%$, and $P = 100\%$. The wedge curve would degenerate to only this one point at the given value of P and W .

Figure D-5. (NASHVILLE FOR JANUARY, CURVES ARE TYPE K WEDGE CURVES FOR $N = 1$.)

Figure D-6. (NASHVILLE FOR JUNE, CURVES ARE TYPE K WEDGE CURVES FOR $N = 1$.)

Figure D-7. (NASHVILLE FOR JUNE, CURVE IS RELATED TO TYPE K WEDGE CURVES FOR $M = 23$ AND $N = 1$.)

Figure D-8. (NASHVILLE FOR JANUARY, CURVE IS RELATED TO TYPE K WEDGE CURVES FOR $M = 23$ AND $N = 1$.)

Referring to Figure D-6 for June it can be seen that at $P = 70\%$, the corresponding value of $W = +7\%$ for $M = 12$ and increases to $W = +11\%$ for $M = 11$. At $W = +15\%$, $P = 94\%$ (or 339 out of 360 days) for $M = 12$, and P drops to 82% for $M = 11$ (or 261 out of 315 days). For the entire 23 year period the average daily total insolation based on the standard year field was 22,300 kilojoules per square meter and for the engineering corrected field 23,000, a difference of 3%. Using the wedge notation for the 23-year period $N = 675$, $W = +3\%$ and $P = 100\%$.

Figure D-7 is the Cusp Curve associated with the Type K Wedge Curve from Figure D-6 for $M = 23$. The Cusp Curve shows that 31% of the joint distribution points lie on the right branch of the curve which means that for these points the standard year corrected daily values were higher than the engineering corrected daily values for the same day. The left branch shows that approximately 68% of the points gave daily values based on the engineering corrected field that were higher than those based on the standard year corrected field. For this figure the two branches do not add up to 100% because the program output data is printed out in 1% increments and the plot itself is only accurate to 2% along the P axis. Figure D-8 is the Cusp Curve for $M = 23$ associated with the Type K Wedge Curve from Figure D-5. It can be seen that approximately 93% of the daily values of horizontal insolation based on the engineering corrected field are higher than those based on the standard year corrected field. It is possible that these differences arise in part from the change in frequency of reporting of the TD 1440 Meteorological Observations from once every hour to once every three hours or from changes in the meteorological conditions. However, other SOLMET Stations must be analyzed before a definitive statement can be made.

D.3 THE INCREASE IN ERROR FOR DAILY INSOLATION CALCULATIONS WHEN METEOROLOGICAL DATA IS MISSING

It is of interest to evaluate the increase in error as a result of using meteorological data every three hours as opposed to using data every hour. This was done by taking the measured data in the standard year field at Nashville and artificially omitting the data two out of every three solar hours, thereby simulating what would occur if a model which depended on

meteorological data had been used to calculate the insolation values hourly. In this situation, interpolation for the solar insolation at the hours that the meteorological data was missing would be necessary. The method of interpolation is discussed in Section 2.3.4. The results of this calculation using the Wedge Program are shown in Figure D-9 as Type C, $M = 23$ for the months of January and June at Nashville.

If the daily insolation values (which included some hourly values of insolation that were interpolated) agreed exactly with the standard year data field (where each hour of measured insolation is retained), the wedge curves would rise vertically at $W = 0$ to $P = 100\%$. However, this is not the case. Interpolation introduced errors as can be seen by inspection of the wedge curves for January and June. In June, for $P = 70\%$, $W = +5\%$ and in January W increases to $+10\%$. In June, for $W = +15\%$, P is 93% (or $.93 \times 690 = 642$ days) and P decreases to 84% (or $.84 \times 713 = 599$ days) in January. The short vertical lines on each curve show the small differences between $M = 11$ and 12 , there being only a P difference of 2% at a given value of W between $+8\%$ and $+70\%$. In January $P = 100\%$ is not reached until $W = +70\%$. There were 113 days (or $113/713 = .16$) where the range of W was from $+15\%$ to $+70\%$. In June $P = 100\%$ is reached at $W = +40\%$. There were 48 days (or $48/690 = .07$) where the range of W was from $+15\%$ to $+40\%$. For the entire 23-year period in January the average daily total insolation based on the standard year field was 6580 kilojoules per square meter and that due to interpolation two out of three hours was 6700 , representing an error of 1.8% . In June the error was 1% (the daily average using interpolation being 22060 kilojoules per square meter). Figure D-10 shows the cusp curves for January and June. From the figure it can be seen that in January the joint distribution points are more densely populated on the negative wedge axis, but the opposite is true in June.

It is clear from these comparisons that the errors due to interpolation when hourly values of insolation are missing can be sizable and for a few

Figure D-9. NASHVILLE FOR TYPE C WEDGE CURVES $N = 1$

Figure D-10. NASHVILLE CUSP CURVES RELATED TO TYPE C WEDGE CURVES FOR $M = 23$ AND $N = 1$.

Figure D-11. (NASHVILLE FOR JANUARY, CURVES ARE TYPE D WEDGE CURVES FOR $N = 1$.)

Figure D-12. (NASHVILLE FOR JANUARY, CURVE IS RELATED TO TYPE D WEDGE CURVES FOR $M = 23$ AND $N = 1$.)

of the days the errors involved can be quite large. However, averaged over the 23 year record it was seen above that the error in daily totals was only 1.8% in January and 1% in June.

D.4 COMPARISONS BETWEEN STANDARD YEAR FIELD AND CCS CALCULATIONS

Figure D-13 shows the comparison between the measured standard year data field and the results of the CCS calculation for $N = 1$ in the month of June. At $P = 70\%$ the error is $W = +7\%$ for $M = 23$. The effect of missing meteorological data is clearly seen in that the difference in W is 2% between $M = 12$ and $M = 11$, both for $P = 70\%$. At $W = +15\%$; $P = 97\%$ for $M = 12$, $P = 91\%$ for $M = 23$, and $P = 85\%$ for $M = 11$. There is a 12% decrease in P from $M = 12$ to $M = 11$, which is a large effect due primarily to the meteorological data being given only once every three hours. Appendix D.8 above showed that differences in the surface meteorological observations between $M = 11$ and $M = 12$ only gives a P difference of 2% from the standard year field. It is to be noted that the error due to the use of the CCS method for $M = 12$ is quite similar to the error in the standard year field when the meteorological data is missing two out of three hours as given in the Type C wedge curve in Figure D-9 for June. The associated cusp curve is shown in Figure D-14. It can be seen that 62% of the daily values based on the standard year corrected data are larger than those based on the CCS method for the same day. The 23-year average daily total insolation was 22000 kilojoules per square meter based on the CCS calculation which gives a difference of 1.2% when compared to the standard year average daily total of 22300.

Figure D-11 is the comparison for the month of January. The errors using the CCS calculation are appreciably larger in January than in June. At $P = 70\%$, the value of W is $+14\%$ for $M = 12$, $+18\%$ for $M = 23$ and $+21\%$ for $M = 11$. At $W = +15\%$, P is 72% for $M = 12$, 66% for $M = 23$, and 60% for $M = 11$. There is again a 12% decrease in P from $M = 12$ to $M = 11$. It is to be noted that the error due to the use of the CCS method for $M = 12$ is much greater than the error in the standard year field when the meteorological data is missing two out of three hours as given in Figure D-9 for January. This is to be contrasted with June where the errors were comparable. The associated cusp curve is shown in Figure D-12. It can be seen that 53% of the

Figure D-13. (NASHVILLE FOR JUNE, CURVES ARE TYPE D WEDGE CURVES FOR $N = 1$.)

Figure D-14. (NASHVILLE FOR JUNE, CURVE IS RELATED TO TYPE D WEDGE CURVES FOR $M = 23$ AND $N = 1$.)

Figure D-15. (NASHVILLE FOR JUNE, CURVES ARE TYPE G WEDGE CURVES, FOR $N = 1$.)

Figure D-16. (NASHVILLE FOR JUNE, CURVE IS RELATED TO TYPE G WEDGE CURVES FOR $M = 23$ AND $N = 1$.)

daily values based on the standard year corrected data are larger than those based on the CCS method for the same day. The 23-year average daily total insolation was 6500 kilojoules per square meter based on the CCS calculation which gives a difference of 1.8% when compared to the standard year daily total of 6600.

D.5 COMPARISONS BETWEEN THE STANDARD YEAR FIELD AND THE MACHTA-COTTON MODEL

Figure D-15 shows the Type G Wedge Curves for comparisons between the measured data in the standard year data field at Nashville and the results of the Machta-Cotton Model for June. Figure D-16 shows the associated cusp curve.

D.6 COMPARISON BETWEEN CCS CALCULATIONS AND THE MACHTA-COTTON MODEL

Figure D-17 shows the Type F Wedge Curves for comparisons of daily calculated values of insolation between the CCS calculation and the Machta-Cotton Model for June. Figure D-18 shows the associated cusp curve.

D.7 STABILITY OF WEDGE CURVES

It is of interest to investigate the amount of data that is necessary to stabilize the Wedge Curves. A definitive statement on this problem can not be formulated until more experience is gained by the systematic variation of the parameter M for a large number of stations and months for the types of Wedge curves listed in Section 2.4.5. The discussion below reports on the study of Type C Wedge Curves at Nashville.

The stability of the Wedge Curves for January and June for the year 1953 ($M = 1$), 1965-1975 ($M = 11$), 1953-1964 ($M = 12$), and 1953-1975 ($M = 23$) was investigated for the Type C Wedge Curves discussed in Appendix D.3. These results seem to indicate that one year ($M = 1$) of data for a given month is not sufficient to stabilize the Wedge Curves. In Figure D-19, curves 2 and 3 are envelopes of Wedge Curves for $M = 11, 12$, and 23 for June and January, respectively. The results for $M = 23$ have already been shown in Figure D-9. Curves 1 and 4 are for $M = 1$ for the months of June and January, respectively. The greater variability for $M = 1$ as compared to $M = 11, 12$, or 23 is easily seen.

Figure D-17. (NASHVILLE FOR JUNE, CURVES ARE TYPE F WEDGE CURVES FOR $N = 1$.)

Figure D-18. (NASHVILLE FOR JUNE, CURVE IS RELATED TO TYPE F WEDGE CURVES FOR $N = 23$ AND $N = 1$.)

Figure D-19. NASHVILLE TYPE C WEDGE CURVES $N = 1$ AND $N = 11$

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SOLAR RADIATION DATA FORECAST AND INTERPOLATION ANALYSIS

FINAL REPORT

FOLDER II

TASK III

**EVALUATION OF METHODS OF CALCULATING SOLAR RADIATION ON
AN INCLINED SURFACE**

**PERFORMED BY
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
JOHNSON ENVIRONMENTAL & ENERGY CENTER**

**Under Subcontract 714-11125 to
Northrop Services, Inc.**

Prepared for:

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ARGONNE, ILLINOIS 60439**

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NORTHROP SERVICES, INC.

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EVALUATION OF METHODS OF CALCULATING
SOLAR RADIATION ON AN INCLINED SURFACE
FINAL REPORT

OCTOBER 1978

PREPARED FOR
U.S. DEPARTMENT OF ENERGY
ASSISTANT SECRETARY FOR ENERGY TECHNOLOGY
DIVISION OF SOLAR TECHNOLOGY
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ABSTRACT

Twenty-four methods of calculating solar radiation on inclined surfaces were investigated. All algorithms were re-written in a common convention and nomenclature and the measurements required for each method were categorized. The Liu & Jordan (L&J) and Temps & Coulson (T&C) methods for hourly values offered significantly different approaches in that the T&C method used an anisotropic approximation and all others assumed isotropic sky conditions similar to the L&J method. The Kondratyev & Manolova (K&M) procedure was applied to determine daily values. Also, the Becker & Boyd (B&B) procedure was used to calculate daily values which was an entirely different approach than other methods.

Seven months of solar radiation measurements of horizontal global (G_H), direct or beam (B_N , with a normal incident pyrheliometer, NIP), diffuse (D_H , with a pyranometer under a shadowband), and tilted global (G_T) were recorded at the Johnson Environmental and Energy Center and available measurements from Arizona, Canada and California were used in the evaluation.

Solar radiation was calculated for inclined surfaces using the methods selected and compared with the measured values. Results are shown in the tables.

Conclusions are drawn as a result of the comparisons. A prime conclusion is that the measurements and use of the measurements may be as significant as any differences in the methods. Wide variations in calculating individual hourly radiation may be expected but averaged values may be expected to be within 10% of measured tilted radiation. A second important conclusion is that when the amount of hourly diffuse radiation is more than half of the global radiation the Liu & Jordan method yields results closer to the measured tilted radiation than other methods.

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INTRODUCTION

Twenty-four different methods for computing solar radiation on inclined surfaces have been identified [References 1-24]. While there are basic differences, such as some methods that use instantaneous, or hourly values which require a value for the solar angle and other methods that estimate total daily solar radiation, there are many procedures which are similar or identical. The various methods have been grouped according to their procedures and results, and primary methods have been evaluated with tilted measurements.

Some of the methods listed in the references have been set aside for the purpose of this project because they require special measurements which are not available or the methods were limited in their scope. The remaining methods have been grouped for similarity in Table I.

The table gives short titles assigned from the references cited for the methods which yield hourly, daily or monthly solar radiation values on inclined or vertical surfaces. (Hereafter references to inclined or tilted surfaces will imply that vertical surfaces are included.)

It should be emphasized here that this project is not to develop new methods for calculating solar radiation on inclined surfaces but to evaluate existing methods.

TABLE I METHODS CLASSIFICATION

INSTANTANEOUS AND HOURLY	DAILY	MONTHLY MEAN	OTHERS
ASHRAE	BECKER & BOYD	PAGE	LÖF & WEISS
BASHETT	FULLWOOD	RANKINS & WILSON	
EI & I	KONDRATYEV & MANOLOVA		
GARNIER & OHMURA	PAGE		
KONDRATYEV	RANKINS & WILSON		
KREITH			
LIU & JORDON			
LOUDON			
TEMPS & COULSON			
THRELKELD & JORDON			

STANDARD CONVENTION

Because each author used his own angular convention and nomenclature it was necessary to adopt a common convention and rewrite each method for comparison. The convention and nomenclature adopted is shown in Appendix A.

The methods using hourly data were then organized in Table II to show the information required for each method and the results produced. Identical and similar methods were grouped and the most promising selected from each group. Table III shows the methods using daily data and are also applicable to monthly values. Of course, hourly data will also yield daily values and daily values will yield monthly values.

The equations for the methods in the adopted convention are given in Appendix B.

TABLE II INSTANTANEOUS OR HOURLY DATA REQUIREMENT

METHOD	θ INCLINATION ANGLE	α SUN ZENITH ANGLE	ϕ SUN AZIMUTH ANGLE	β SUN ALTITUDE ANGLE	γ HOUR ANGLE	δ SURFACE AZIMUTH ANGLE	ϵ SUN DECLINATION	ϕ LATITUDE	θ_H DIRECT HORIZONTAL	θ_N DIRECT NORMAL	θ_H DIFFUSE HORIZONTAL	θ_N DIFFUSE NORMAL	θ_H GLOBAL HORIZONTAL	θ_N GLOBAL REFLECTIVITY	REMARKS
	θ - ANGLE OF INCIDENCE														
ASHRAE TABLES	X			X			X					X			TWO SETS OF TILT MEASUREMENTS READ
BASNETT	90		X	X	X	X	X		X	X		X	0.1		REQUIRES SOLAR CONSTANT
EL & I	X						X					X			
GARNIER & DHMURA	X			X	X	X	X		X	X		X	X		
KONDRATYEV	X	X	X	X		X	X		X						
KREITH	X	X	X	X	X	X	X		X						AN ISOTROPIC APPROXIMATION
LIU & JORDON	X			X	X	X	X	X		X		X	X		
LOUDON	X		X	X	X	X	X			X		X	X		
TEMPS & COULSON	X	X	X	X	X	X	X		X	X			X		
THRELKELD & JORDON	X		X	X					X						

TABLE III DAILY DATA REQUIREMENT

METHOD	INCINATION ANGLE	SUN ZENITH ANGLE	SUN AZIMUTH ANGLE	SUN ALTITUDE ANGLE	HOUR ANGLE	SURFACE AZIMUTH ANGLE	SUN DECLINATION	LATITUDE	DIRECT - HORIZONTAL	DIRECT - NORMAL	DIFFUSE - HORIZONTAL	DIFFUSE - NORMAL	GLOBAL HORIZONTAL	GLOBAL GROSS REFLECTIVITY	REMARKS
	θ - ANGLE OF INCIDENCE								B_H	B_N	D_H	D_N	G_H	P	
BECKER & BOYD	X												X		REQUIRES VALUES FOR THREE DIFFERENT COEFFICIENTS
FULLWOOD	90°			X	X	X	X	X			X		X		
KONDRATYEV & MANOLOVA	X				X	X	X	X	X		X		X	X	
PAGE	X				X	X	X	X	X		X		X	X	
RANKINS & WILSON	X							X					X		
															REQUIRES SOLAR CONSTANT

GENERAL PROCEDURES FOR CALCULATIONS

The global radiation on a horizontal surface consists of direct and diffuse radiation and is measured with a pyranometer on a horizontal surface, Figure 1. The diffuse radiation is measured with a shadowband over a pyranometer, Figure 2. The direct radiation is measured with a Normal

Figure 1 - Pyranometer, measures global radiation

Figure 2 - Pyranometer with shadowband,
measures diffuse radiation

Incidence Pyrheliometer (NIP) tracking the sun, Figure 3. Both the direct and diffuse measurements require adjustments before they can be combined to compare with the global measurements. When these differences are resolved one may calculate what would be expected on a tilted surface. The calculations are then compared with the measurements recorded on an inclined surface. The measurement procedures are those used for the global measurement on a horizontal surface except the instrument is tilted, Figure 4. The various components of radiation are depicted in Figure 5.

Figure 3 - Normal Incidence Pyrheliometer (NIP)
with sun tracking mount, measures direct normal
solar radiation plus some circumsolar radiation

Figure 4 - Comparison of Inclined and Horizontal Receivers

θ = Incident Angle: the angle between the direction of the sun and the perpendicular to the surface illuminated.

Figure 5 - Components of solar radiation

All hourly tilt calculations must relate to solar time. The usual equation to convert local time to solar time is:

$$TST = LST + E + 4(L_{st} - L_{loc})$$

where TST = True Solar Time

LST = Local Standard Time

E = Equation of time in minutes from Figure 6.

L_{st} = Standard time meridian, for the continental U.S., time zones are 75° (Eastern), 90° (Central), 105° (Mountain) and 120° (Pacific)

L_{loc} = Longitude at the recording location, (note that the sun takes 4 minutes to traverse 1° of longitude)

Figure 6 - The equation of time, E, in minutes, as a function of time of year

A simple procedure is to find the time half way between sunrise and sunset and that is the time of solar noon. Each solar hour is then off-set that difference from local noon.

Example for San Diego on the 27th of June where SS is time of sunset and SR is time of sunrise in PST:

$$\frac{12 + SS - SR}{2} + SR = \frac{12 + SS + SR}{2} = \frac{12 + 7:03 + 4:39}{2} = 11:51$$

Solar noon (12:00 TST) occurs at 11:51 PST. Solar time, ω , is used in the equations.

The special considerations which are treated in the equations to calculate radiation on inclined surfaces are:

1. For diffuse radiation:

- a. Deduct the sky radiation loss from tilting--geometry;
- b. Add the radiation reflected from the surface into the collector--the albedo.

2. For direct radiation:

- a. Reduce the direct radiation for the area of the surface of the collector exposed--geometry;
- b. Reduce the direct radiation for the loss through the atmosphere. Path length, scattering and/or absorption by precipitable water, turbidity, dust, ozone, dry air molecules, cloudy, etc.

3. For circumsolar-diffuse radiation:

The circumsolar-diffuse is measured in the $5\frac{1}{2}$ degrees apperture of the NIP. There are no good methods of treating this situation. In all cases the circumsolar-diffuse is included with the direct. There are experimental techniques but no operational method of measuring circumsolar-diffuse radiation.

4. For measurement procedures:

- a. The shadowband measurements must be corrected to allow for the diffuse radiation blocked by the band. New procedures may use a sun tracking disk to shade only the pyranometer;
- b. The NIP tracking the sun must be reliable and adjusted frequently;
- c. The adjusted measurements of direct and diffuse must be resolved to equal the global radiation. With 3 instruments, each with a possible error of 2%, the combined error could be considered as the square root of the sum of the errors squared or 3.5%, i.e.:

$$\sqrt{(.02)^2 + (.02)^2 + (.02)^2} \approx 3.5\%$$

- d. Measurements of the atmospheric effects introduce an error which is difficult to evaluate.

5. For treatment of the isotropic (homogeneous qualities of the sky radiation) and anisotropic (effects of clouds and other transient variables):

The anisotropic conditions are most apparent with rapidly varying atmospheric conditions. The Liu and Jordan method addresses the isotropic case primarily and is basically a cosine approximation. The Temps and Coulson method adds the anisotropic approximation. Therefore, these two are the best method to compare in calculations of hourly data.

CALCULATIONS AND COMPARISONS

Only south-facing surfaces are considered for this study, although it can be extended to include other orientations. Most of the methods consider an isotropic approximation for diffuse and reflected solar radiation components. The Temps and Coulson method adds a term for anisotropic conditions.

It is apparent from an examination of Appendix B that when a common nomenclature and convention are used for the various methods, only the Liu and Jordan method and Temps and Coulson method will provide a significant difference in results in hourly data. Appendix B shows the similarities and limitations of each of the significant methods. Explanations are included which make it apparent that calculations with those methods would not offer any addition to the methods chosen.

Therefore, the Liu and Jordan (L&J) and Temps and Coulson (T&C) methods are used in calculations of hourly data and Becker and Boyd (B&B) and Kondratyev and Manolova (K&M) are used for daily data. The K&M method will give identical results as the Page method.

Liu and Jordan have authored many papers concerning solar energy applications and we have found that some who are familiar with other special works of Liu and Jordan relate that work to the procedure discussed here, which may or may not be appropriate. It is important that the reader realize what part of Liu and Jordan's work is being investigated [Ref. 12].

DATA SOURCES, ANALYSIS AND APPLICATIONS

The data used for comparison of the various methods require special attention because it was determined that the methods used in recording the data were equally important as the method used in calculating a tilted value. Then, to validate the calculation, the results are compared with a measured value at a tilted angle.

Data from several sources are used in the evaluations. All the data that was intended to be used did not become available in time for the comparisons but it is believed that sufficient data from different locations were used so that results provide valid comparisons. It is believed that additional data will substantiate the findings.

1. The primary data used to test the measurements and calculation procedures are seven months of data collected at the Johnson Environmental and Energy Center (JEEC) specifically for this project. The data were collected from January through July 1978. There were three days of about one inch of snow when we learned that no correction was required for the shadowband on either clear or cloudy days with snow on the ground. The global measurement was in close agreement with the pyranometer under the shadowband. It was apparent that the reflections on each pyranometer were yielding similar measurements from the sky and from the shadowband.

Either the beam radiation (Normal Incident Pyrheliometer, NIP) or the diffuse (shadowband corrected) may be used in the calculations. A program was written to compare and resolve any differences in these measurements before calculations were made so that using either the diffuse or beam measurement would provide similar results for the tilt calculation. Generally, $(G_H - D_H) / \sin \alpha$ was used in the calculations except for small elevation angles when the B_N measured value gave better results.

2. Five months of hourly data recorded at the Laboratory of Climatology at Arizona State University were also suitable for calculations and comparisons with measured data at 45° tilt. Shadowband and Normal Incident measurements were recorded but since the shadowband measurements were uncorrected, we increased the shadowband measurement by 10%, which appeared reasonable in considering the NIP measurement.

3. One clear and one cloudy day with carefully controlled hourly measurements including 30°, 60°, and 90° tilt measurements recorded at the Meteorological Research Station (MRS), Toronto, Canada were used.

For hourly calculations, the solar angle at the midpoint of the hour was used. Several tests were made in selecting this solar angle.

Five-minute data were available and tests were made calculating five-minute values and combining them for an hourly value. Results did not show any significant advantage in resorting to this detail.

Tests were made using the solar angle at the start of the hour and the end of the hour as well as at the midpoint. Of course one calculation or the other would show better agreement with the measured value but there was no consistency. It was reasoned that on clear days more energy would be collected during the portion of the hour toward solar noon and perhaps the time for selecting the solar angle should be biased toward solar noon. Tests were made but the procedure was not pursued because it would require establishing a rate of collection, would have been a modification to the methods being evaluated and was beyond the scope of the present study.

Considerable latitude and judgement is required in selecting a value for the albedo or ground reflectance (p). It is noted that the study in Reference 26 eliminated ground reflectance from the measurements and calculations. The ground reflectance is discussed in several references [7, 11, 19] and is dependent upon moisture, the sun angle, as well as the vegetation and type of soil. Table IV, from Reference 12, was used for this study. In most cases a value of p of .20 was used. The term for reflectivity does not provide a large contribution and is a small percent when radiation levels are average or above average.

TABLE IV Reflectivity of the Various
Types of Surfaces

Surface	Reflectivity, %
Desert	24-28
Fields, various types	3-25
Forest, green	3-10
Grass, various conditions	14-37
Ground, bare	7-20
Mold, black	8-14
Sand, dry	18
Sand, wet	9
Snow or ice	46-86

Selecting the correct albedo is not critical. If ρ is selected too low the tilted measurement (G_T) will be higher than with the lower albedo. Also, if ground reflectance is higher than selected, the shadowband will reflect more ground reflected radiation onto the pyranometer under the shadowband than expected (note the diffuse measurements with snow on the ground described earlier). This will result in a diffuse (D_H) higher than expected and will compensate to some degree for ρ being selected too low.

Several methods of presenting the results of calculations and comparisons with tilted measurements were investigated. Because the sun declination angles are significantly different for the same hour in different months it was decided to group the data by months. So that calculations would not be needed for each hour of each day, it was decided to find the hourly average solar radiation measured horizontal (G_H), tilted (G_T), direct (B_N) and diffuse (shadowband corrected, D_H) for each month.

The averaged data was then used to calculate tilted values ($\overline{G_{TC}}$) for the month and compared with the average tilted measurement ($\overline{G_{TM}}$).

$$\Delta\% = \frac{\overline{G_{TC}} - \overline{G_{TM}}}{\overline{G_{TM}}} \times 100 \quad (1)$$

The L&J and T&C methods were used to show the percent difference from the averaged hourly data. This percent difference is the difference from the means and not the mean percent difference. Because percentages are large when the sun is low in the sky, i.e., the first two hours after sunrise and before sunset while the solar radiation values are low, the percent differences cannot be averaged for a daily percent difference. Therefore, the K&M procedure was followed by retaining the values of the hourly calculated data and finding daily values of the difference in calculated and measured tilted data.

While the K&M method refers only to isotropic approximation (L&J), the same procedure was used with the anisotropic approximation (T&C). These daily differences are converted to percent and referred to as K&M₁ and K&M₂, respectively.

$$K\&M_1 \Delta\% = \frac{\overline{\Sigma G_{TC}} - \overline{\Sigma G_{TM}}}{\overline{\Sigma G_{TM}}} \times 100 ; \overline{G_{TC}} \text{ from L\&J method} \quad (2)$$

$$K\&M_2 \Delta\% = \frac{\overline{\Sigma G_{TC}} - \overline{\Sigma G_{TM}}}{\overline{\Sigma G_{TM}}} \times 100 ; \overline{G_{TC}} \text{ from T\&C method} \quad (3)$$

With the data combined in this manner, direct comparison of the methods is possible without the need for other statistical parameters.

The B&B method was also used to calculate a daily total. The results, therefore, show two methods of calculating hourly tilt values and three methods of calculating daily tilt values compared with tilted measurements.

For further analysis, the UAH data were divided into cloudy, partly cloudy and clear days for each month. Arbitrary sky cover amounts, sunrise to sunset, were used to separate the days. Overcast and 0.9 was considered cloudy, 0.4 to 0.8 inclusive as partly cloudy and ≤ 0.3 as clear. It was hoped that this division may help in evaluating the isotropic and anisotropic method. The results of the calculations did not show any consistent pattern, except that the $\Delta\%$ appears large for cloudy days. Of course, this is due to the fact that radiation values are low and small absolute differences will show large percent differences, see Tables V a through V j.

The data from the Laboratory of Climatology, Tempe, Arizona, were used for the results shown in Table VI. February 1978 results are not shown because of obvious errors in the tilt angle measurements on several days, thus re-emphasizing that the careful collection of data is probably the most important single item for calculating solar radiation on inclined surfaces.

Data for two days from the Meteorological Research Station (MRS) at Toronto, Ontario, Canada, were available for 30°, 60° and 90° tilt measurements. The comparisons of calculated and measured values are shown in Tables VII a & b. May 26, 1977, represents a clear day and June 12, 1977, represents a cloudy day. One year of similar data has been recorded by MRS and is expected to become available to us. It is planned to treat this data in the same manner as was used for the JEEC data to compare the methods of calculating solar radiation on inclined surfaces.

Table VIII is presented from a recent report with a modification of the L&J method as it was compared to the L&J method by the author [Ref. 25]. Also attention is invited to a recent report comparing the L&J method and T&C method and resulting modification to the T&C method which more closely fit the data used [Ref. 26].

SAMPLE CALCULATIONS

So the reader may understand the data and calculations the following examples are shown.

Example 1 - January 1978 data combined from 7 cloudy days, 6 partly cloudy days and 7 clear days provided the following data in Wh/m²

SOLAR TIME	CLOUDY				PARTLY CLOUDY				CLEAR				ALL DAYS			
	B _N	G _H	D _H	G _{TM}	B _N	G _H	D _H	G _{TM}	B _N	G _H	D _H	G _{TM}	B _N	G _H	D _H	G _{TM}
7:55- 8:55	6	44	44	36	115	126	90	146	416	204	85	330	179	125	73	171
11:55-12:55	4	84	84	61	158	243	165	310	727	543	154	957	297	290	135	443
DAILY TOTAL	48	601	597	470	1205	1615	1130	2104	5406	3711	983	5978	2252	1837	903	2851

For 15 January at $s = 34.7^\circ$, $\theta = 22^\circ$, $z = 56^\circ$, $\alpha = 34^\circ$, $\delta = -21.27^\circ$, and $\omega = -6.25$ at 12:25 solar time.

LIU & JORDAN

$$G_{TC} = (G_H - D_H) \frac{\cos \theta}{\sin \alpha} + D_H \cos^2 \frac{s}{2} + \rho G_H \sin^2 \frac{s}{2}$$

Considering all days and $\rho = 0.2$; from 11:55 to 12:55 solar time

$$\begin{aligned}
 G_{TC} &= (290 - 135) \frac{\cos 22}{\sin 34} + 135 \cos^2 \frac{34.7}{2} + 0.2 (290) \sin^2 \frac{34.7}{2} \\
 &= 385.15 \\
 \Delta\% &= \frac{G_{TC} - G_{TM}}{G_{TM}} \times 100 \\
 &= \frac{385.15 - 443}{443} \times 100 \\
 &= -13.06
 \end{aligned}$$

TEMPS & COULSON

$$G_{TC} = B_N \cos \theta + D_H \cos^2 \frac{S}{2} [(1 + \sin^2 \frac{S}{2})(1 + \cos^2 \theta) \sin^3 z] \\ + \rho(B_H + D_H) \sin^2 \frac{S}{2} [(1 + \sin^2 \frac{S}{2})(|\cos A|)]$$

For south facing surfaces $A = \omega$, and above equation can be written as follows:

$$\therefore G_{TC} = (G_H - D_H) \frac{\cos \theta}{\sin \alpha} + D_H \cos^2 \frac{S}{2} [(1 + \sin^2 \frac{S}{2})(1 + \cos^2 \theta) \sin^3 z] \\ + \rho G_H \sin^2 \frac{S}{2} [(1 + \sin^2 \frac{S}{2}) |\cos \omega|] \\ = (290 - 135) \frac{\cos 22}{\sin 34} + 135 \cos^2 \frac{34.7}{2} [(1 + \sin^2 \frac{34.7}{2})(1 + \cos^2 22) \sin^3 56] \\ + 0.2(290) \sin^2 \frac{34.7}{2} (1 + \sin^2 \frac{56}{2}) \cos 6.25 \\ = 397.0 \\ \Delta\% = \frac{G_{TC} - G_{TM}}{G_{TM}} \times 100 \\ = \frac{397 - 443}{443} \times 100 \\ = -10.37$$

In the T&C method it is noted that the calculated value, G_{TC} , becomes smaller in relation to the measured value, G_{TM} , near midday (see Table V h). This results from the $\sin^3 z$ factor which becomes small as the zenith angle becomes small near noon. When diffuse radiation, D_H , is a significant proportion of the global radiation, G_H , the calculated radiation, G_{TC} , is too low, resulting in large negative differences $-\Delta\%$. There is some question from Reference 20 as to whether the $\sin^3 z$ should be multiplied by $(1 + \cos^2 \theta)$, as used here, or multiplied only by $\cos^2 \theta$. Private communication from Dr. Coulson confirmed that the equation is used here as the authors intended. Reference 20 states that measurements were made for clear sky conditions, so with cloudy skies when the proportion of diffuse radiation is large, the results shown in the Tables are not surprising.

BECKER & BOYD

$$G_{TC} = G_H [a + b (90 - s) + c (90 - s)^2]$$

$$= 1837 [1.510 + .013339 (90 - 34.7) + .0002112 (90 - 34.7)^2]$$

$$= 2943$$

$$\Delta\% = \frac{G_{TC} - G_{TM}}{G_{TM}} \times 100$$

$$= \frac{2943 - 2851}{2851} \times 100$$

$$= 3.2$$

KONDRATYEV & MANOLOVA

The K&M₁ and K&M₂ method for daily value is computed as shown on page 11.

$$K\&M_1 \Delta\% = \frac{2551 - 2851}{2851} \times 100 = -10.5$$

$$K\&M_2 \Delta\% = \frac{2688 - 2851}{2851} \times 100 = -5.7$$

CONCLUSIONS

From the analysis performed with several methods and different sources of data several conclusions may be expressed with confidence.

- a. All of the various methods follow the same basic calculations except the Becker & Boyd method which is based on an empirical polynomial and the coefficients are provided for various latitudes and times of year.
- b. With careful measurements of global (G_H), direct (B_H) and diffuse (D_H), one may expect a 10% error in resolving differences in the direct (B_H) and diffuse (D_H) totaling the global (G_H) value. Some errors reached 20%.

- c. The accuracy of computing solar radiation on an inclined surface compared with measurements varies considerably for individual cases but reasonable for averaged data.
- d. The error to be expected with averaged data is only slightly greater than that expected with the measurements at tilt angles.
- e. The Liu & Jordan method provides the most satisfactory results of hourly calculations. However, the accuracy of any of the methods depends largely on the accuracy of the data (see b. above). Averaging the data reduced differences between calculated (G_{TC}) and measured (G_{TM}) data to about 3 to 5%. This is about the error to be expected in the measurements. Very small sun elevation angles with corresponding low radiation values yield much larger percent errors.
- f. When the diffuse radiation (D_H) is greater than half of the global radiation (G_H , cloudy or partly cloudy) the L&J method (G_{TC}) agrees more closely with the measured tilted values (G_{TM}) than does the T&C anisotropic approximation. When the diffuse radiation (D_H) is less than half of the global radiation (G_H , clear or mostly clear) both methods (G_{TC}) are in close agreement with each other, with the best agreement when the diffuse is 20% or less of the global radiation. The T&C method calculates much too low on cloudy days ($G_H \approx D_H$) with the sun at small zenith angles. This results from the very small values of $\sin^2 z$ in the second term (Appendix "B"), the anisotropic approximation for diffuse radiation. Tables V d through V j and VII b show the increase in $\Delta\%$ as the zenith angle decreases near solar noon.
- g. While the methods appeared to yield the largest differences with low radiation values, this is because the same absolute difference will show a larger percent with small values.
- h. The Becker & Boyd method for daily values is the easiest to use and provides the most consistent results except with cloudy days in winter months. In these cases, January and February, the daily solar radiation on an inclined surface was less than that on a horizontal surface. This situation was not accounted for in the Becker & Boyd method. However, considering all days in January and February the Becker & Boyd method was satisfactory.

RECOMMENDATIONS

The conclusions lead to the following recommendations:

- a. It follows from conclusion e. that if one desires to use any model, carefully recorded data must be used. If one desires to design or modify a model the data must also be representative of several locations with various atmospheric conditions and zenith and incident angles.

b. It follows from conclusions e., f., and h. that certain procedures or methods are best suited for certain results desired.

(1) If hourly values of solar radiation on an inclined surface are desired it is recommended that measurements be taken. Reference 27 should be used as a guide.

(2) If hourly averaged values for a month are desired, the T&C method may be used when there is a preponderance of direct solar radiation. The L&J method will generally yield satisfactory results and should be used when the diffuse radiation is one-half or greater than the global radiation.

(3) If daily averaged values are desired, the Becker & Boyd method is recommended. It is the most reliable of all methods studied but must be used with average data for the month rather than with special weather cases.

N.B. As this report is being finalized WHO Report 467 [Ref. 28] was acquired. The reader is invited to review this report for a comprehensive treatment of the solar radiation received on inclined surfaces.

TABLE Va

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'N$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

January 1978, $s = 34.7^{\circ}$

Hour ending, solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0755	86	70	18.2	32.8	31.4	39.9	21.6	26.2	23.5	29.9
0855	76	57	13.5	37.4	12.8	24.7	5.2	10.1	8.2	16.4
0955	67	44	2.1	23.9	-7.3	3.3	-10.0	-6.3	-6.4	-1.4
1055	60	32	23.0	43.2	-8.4	-1.5	-12.5	-9.8	-8.9	-3.9
1155	57	23	20.4	32.6	-8.4	-1.6	-14.4	-12.6	-11.3	-7.8
1255	56	22	27.9	40.7	-8.1	-3.1	-16.5	-14.8	-13.1	-10.4
1355	59	30	24.3	43.3	-10.1	-3.0	-18.1	-16.0	-14.0	-10.0
1455	65	41	24.5	50.2	-21.6	-11.3	-21.4	-19.1	-19.2	-14.2
1555	74	54	21.9	48.5	-22.8	-12.0	-28.3	-25.1	-25.2	-19.4
DAILY			K&M ₁ 16.5 B&B 103.5	K&M ₂ 35.5	K&M ₁ -9.0 B&B 23.1	K&M ₂ 0.9	K&M ₁ -14.0 B&B -12.4	K&M ₂ -11.5	K&M ₁ -10.5 B&B 3.2	K&M ₂ -5.7

* sky cover sunrise to sunset $\geq .9$ (7 days)

** sky cover sunrise to sunset .4 to .8 (6 days)

*** sky cover sunrise to sunset $\leq .3$ (7 days)

TABLE Vb

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. 34°44'N, Long. 86°40'W, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

February 1978, $s = 54.7^\circ$

Hour ending, solar time	Zenith $\angle (z)^\circ$	Incident $\angle (\theta)^\circ$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0801	80	65	47.7	62.5	61.4	28.9	77.0	80.4	75.2	81.7
0901	70	51	42.7	77.0	52.8	18.9	74.8	53.0	31.9	69.7
1001	60	37	47.4	71.4	7.3	15.7	24.3	28.0	19.8	25.4
1101	53	23	41.3	46.0	-10.9	-9.0	13.2	14.7	6.2	7.9
1201	49	10	37.1	28.3	-15.0	-16.7	15.5	16.0	5.2	4.7
1301	49	9	45.7	36.8	-16.5	-18.5	13.8	14.2	4.8	4.1
1401	53	22	39.0	43.6	-15.0	-13.2	7.0	8.5	.7	2.3
1501	60	36	34.6	56.8	-13.7	-7.0	12.5	16.0	4.4	9.5
1601	69	50	30.8	62.3	-9.7	0.0	11.6	16.9	5.1	12.6
DAILY			K&M ₁ 33.3	K&M ₂ 47.0	K&M ₁ -4.0	K&M ₂ 2.8	K&M ₁ 17.8	K&M ₂ 23.0	K&M ₁ 12.5	K&M ₂ 17.3
			B&B 140		B&B 18.7		B&B 18.3		B&B 22.1	

* sky cover sunrise to sunset $\geq .9$ (8 days)

** sky cover sunrise to sunset .4 to .8 (4 days)

*** sky cover sunrise to sunset $\leq .3$ (6 days)

TABLE Vc

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'N$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

March 1978, $s = 54.7^{\circ}$

Hour ending, solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0756	74	69	-13.0	-53.5	-60.8	-12.0			15.9	-43.1
0856	63	55	-47.7	-49.1	-7.6	-13.5			-34.1	-37.1
0956	52	41	-25.1	-34.8	-10.2	-21.1			-19.6	-29.8
1056	44	29	-35.4	-57.7	-9.8	-39.6	no clear days with tilt measurements at 54.7°		-28.9	-53.1
1156	38	19	-37.5	-66.8	-14.5	-50.2			-30.9	-62.3
1256	38	18	-47.1	-72.6	-14.1	-49.4			-36.9	-65.4
1356	43	27	-42.1	-63.8	-15.5	-28.7			-29.8	-47.0
1456	51	40	-44.6	-54.5	-11.7	-19.4			-26.0	-34.7
1556	61	53	-30.4	-31.0	-12.5	-19.9			-21.6	-26.2
1656	73	67	.7	7.8	-14.5	-24.3			-9.1	-13.8
1756	85	81	16.8	11.6	51.7	6.8			19.1	2.3
DAILY			K&M ₁ -39.5	K&M ₂ -56.7	K&M ₁ -6.9	K&M ₂ -27.7	K&M ₁	K&M ₂	K&M ₁ -27.2	K&M ₂ -45.7
			B&B -19.0		B&B -7.0		B&B		B&B -13.9	

* sky cover sunrise to sunset $\geq .9$ (5 days)

** sky cover sunrise to sunset .4 to .8 (1 day)

*** sky cover sunrise to sunset $\leq .3$

TABLE Vd

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'W$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

March 1978, $s = 34.5^{\circ}$

Hour ending, solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0756	74	69	2.7	5.2	1.6	3.5	27.4	28.9	18.8	20.5
0856	63	53	2.3	-1.0	-24.2	-4.0	8.6	8.4	6.3	5.4
0956	52	39	3.5	-15.4	-3.3	-13.4	4.5	2.3	3.2	-1.7
1056	44	24	3.4	-34.1	-3.4	-16.7	2.8	-1.4	1.7	-7.0
1156	38	9	.9	-48.3	-4.1	-29.2	2.2	-4.1	1.0	-11.9
1256	38	7	1.7	-48.6	1.1	-33.0	5.1	-0.4	4.1	-10.0
1356	42	22	.4	-37.7	9.6	-30.9	9.1	4.5	5.6	-4.2
1456	51	37	1.6	-19.1	1.3	-19.3	10.7	6.0	8.4	.4
1556	61	52	1.9	-2.8	12.7	7.3	17.1	16.7	13.8	12.3
1656	73	67	1.7	4.0	4.6	6.9	28.7	30.1	22.2	23.8
1756	85	82	1.8	3.8	-5.4	-3.4	35.5	39.3	20.5	-23.0
DAILY			K&M ₁ -6	K&M ₂ -23.7	K&M ₁ -5.7	K&M ₂ -21.0	K&M ₁ 6.9	K&M ₂ 3.6	K&M ₁ 4.5	K&M ₂ -3.1
			B&B 29.0		B&B 13.2		B&B 5.0		B&B 13.0	

* sky cover sunrise to sunset $\geq .9$ (3 days)

** sky cover sunrise to sunset .4 to .8 (1 day)

*** sky cover sunrise to sunset $\leq .3$ (3 days)

TABLE Ve

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. 34°44'N, Long. 86°40'W, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

April 1978, $s = 30^\circ$

Hour ending, solar time	Zenith $\angle (z)^\circ$	Incident $\angle (\theta)^\circ$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0647	81	85			-0.9	-3.1	4.4	2.1	1.4	-0.8
0747	69	70			-13.3	-17.8	10.0	7.2	-4.4	-8.3
0847	57	55			-1.5	-17.8	7.7	3.4	2.5	-9.0
0947	45	41	no cloudy days with tilt measurements at 30°		-2.2	-36.0	4.4	-2.1	0.8	-19.7
1047	35	26			-1.0	-57.1	2.1	-6.5	0.5	-33.8
1147	27	12			-2.2	-62.5	2.2	-8.2	-0.5	-40.0
1247	26	6			-1.7	-66.1	2.2	-8.9	0.0	-42.1
1347	31	20			-0.9	-67.2	1.4	-8.6	1.0	-39.3
1447	40	34			1.8	-45.9	2.0	-5.8	1.9	-27.4
1547	51	49			4.2	-29.6	7.0	0.3	5.5	-17.4
1647	64	64			6.3	-2.9	21.1	16.5	11.1	3.4
DAILY			K&M ₁	K&M ₂	K&M ₁	K&M ₂	K&M ₁	K&M ₂	K&M ₁	K&M ₂
			B&B		B&B		B&B		B&B	
					-3.0	-44.6	2.7	-3.9	-0.5	-26.8
					5.08		-1.2		2.08	

* sky cover sunrise to sunset $\geq .9$

** sky cover sunrise to sunset .4 to .8 (3 days)

*** sky cover sunrise to sunset $\leq .3$ (1 day)

TABLE VF

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'N$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

April 1978, $s = 34.5^{\circ}$

Hour ending solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0647	81	86			-6.3	-8.4	-17.2	-39.2	-15.6	-17.6
0747	69	71			-7.7	-12.6	-13.2	-1.7	-12.1	-16.2
0847	57	56			-7.9	-17.5	-11.2	-18.0	-10.6	-17.8
0947	45	42			-8.6	-25.8	-8.8	-21.7	-8.8	-22.5
1047	35	27	no cloudy days with tilt measurements at 34.5°		-7.5	-25.2	-9.1	-28.5	-8.8	-27.8
1147	27	14			-5.3	-56.6	-8.4	-28.0	-8.0	-31.9
1247	26	10			-7.0	-67.1	-8.7	-26.6	-8.5	-30.6
1347	31	21			-4.3	-64.9	-5.7	-28.0	-5.7	-32.0
1447	40	35			-1.4	-45.1	-3.3	-17.3	-3.0	-20.2
1547	51	50			-2.4	-25.6	-2.6	-9.3	-1.2	-11.7
1647	64	65			-8.8	-15.2	-6.6	-6	-3.3	-3.7
DAILY			K&M ₁	K&M ₂	K&M ₁	K&M ₂	K&M ₁	K&M ₂	K&M ₁	K&M ₂
			B&B		B&B		B&B		B&B	
					-8.6	-35.1	-7.9	-22.5	-7.7	-24.3
					-4.7		-8.4		-6.9	

* sky cover sunrise to sunset $\geq .9$

** sky cover sunrise to sunset .4 to .8 (2 days)

*** sky cover sunrise to sunset $\leq .3$ (4 days)

TABLE Vg

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'N$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

May 1978, $s = 14.5^{\circ}$

Hour ending solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0643	77	81	0.0	-71.4	-6.5	-41.7	-4.6	-60.7	-5.5	-49.8
0743	65	67	.5	-14.1	-.5	-7.7	-.6	-7.4	-.4	-7.9
0843	52	53	1.0	-31.3	-1.7	-15.0	-1.3	-13.2	-1.5	-15.2
0943	40	39	.5	-55.8	-2.3	-23.1	-1.9	-21.3	-2.0	-23.7
1043	29	25	-.9	-76.8	-2.0	-32.0	-2.4	-28.2	-2.0	-33.2
1143	19	11	-1.6	-78.1	-2.3	-44.2	-2.6	-35.2	-2.4	-43.8
1243	16	3	-3.0	-87.2	-2.2	-42.6	-2.7	-40.9	-2.5	-45.4
1343	22	17	-.6	-84.6	-1.5	-42.2	-2.5	-31.9	-1.9	-41.7
1443	33	31	-1.8	-63.6	-1.2	-38.4	-1.5	-23.0	-1.4	-34.8
1543	45	45	-2.7	-46.0	-.3	-27.0	-.2	-18.6	-.2	-25.3
DAILY			K&M ₁ -1.0 B&B -1.5	K&M ₂ -62.8	K&M ₁ -4.0 B&B -3.2	K&M ₂ -31.1	K&M ₁ -5.2 B&B -3.5	K&M ₂ -25.4	K&M ₁ -1.1 B&B -3.2	K&M ₂ -31.2

* sky cover sunrise to sunset $\geq .9$ (1 day)

** sky cover sunrise to sunset .4 to .8 (7 days)

*** sky cover sunrise to sunset $\leq .3$ (5 days)

TABLE Vh

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'N$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

May 1978, $s = 20^{\circ}$

Hour ending, solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0643	77	82	-1.6	-7.4	-6.7	-10.8	-4.6	-9.0	-4.7	-9.4
0743	65	69	1.3	-13.8	-2.9	-10.2	-4.4	-12.3	-2.6	-11.7
0843	52	54	.2	-31.4	-3.3	-17.3	-4.1	-14.1	-3.1	-19.2
0943	40	40	.4	-51.7	-2.3	-31.8	-4.9	-24.7	-2.6	-35.0
1043	29	26	-1.5	-72.0	-1.1	-60.5	-4.1	-27.1	-2.5	-50.8
1143	19	12	-1.5	-79.1	-2.4	-85.9	-4.3	-19.4	-2.9	-54.6
1243	16	5	-.1	-85.0	-3.6	-71.6	-5.0	-23.8	-3.1	-55.4
1343	22	18	1.9	-83.5	-1.0	-86.1	-6.1	-37.1	-2.7	-59.8
1443	33	32	.9	-62.7	-2.5	-67.0	-3.7	-19.5	-1.9	-44.8
1543	45	46	1.6	-39.0	-1.5	-28.0	-2.8	-13.7	-.6	-27.2
DAILY			K&M ₁ 0.0 B&B -.8	K&M ₂ -61.7	K&M ₁ -2.6 B&B -2.9	K&M ₂ 23.3	K&M ₁ -4.5 B&B -7.3	K&M ₂ -22.6	K&M ₁ -2.5 B&B -4.1	K&M ₂ -41.7

* sky cover sunrise to sunset $\geq .9$ (3 days)

** sky cover sunrise to sunset .4 to .8 (1 day)

*** sky cover sunrise to sunset $\leq .3$ (1 day)

TABLE Vi

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'N$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

June 1978, $s = 14.5^{\circ}$

Hour ending solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0647	74	79	3.6	-3.4	-1.7	-6.9	-2.1	-7.2	-.6	-6.2
0747	62	65	1.7	-14.0	.5	-12.2	-1.3	-9.3	-.3	-11.6
0847	50	52	-.2	-30.9	-2.4	-20.5	-1.4	-14.6	-1.5	-20.8
0947	37	38	-1.3	-48.9	-1.7	-33.7	-1.8	-19.9	-1.6	-32.5
1047	25	24	-2.3	-58.1	-2.6	-43.2	-2.2	-25.5	-2.3	-40.1
1147	15	11	-1.9	-59.6	-2.2	-48.1	-2.2	-28.4	-2.2	-43.7
1247	12	5	-2.4	-67.1	-1.6	-43.0	-2.6	-30.2	-2.2	-44.4
1347	20	18	-1.9	-52.3	-1.6	-36.0	-2.9	-28.6	-2.2	-38.0
1447	32	32	-1.6	-43.4	-.8	-31.1	-2.8	-27.3	-1.7	-33.0
1547	44	45	-2.4	-50.5	-3.6	-36.4	-2.8	-22.8	-2.9	-35.3
1647	56	59	-.1	-9.4	-2.5	-17.2	-2.1	-9.1	-1.5	-17.0
DAILY			K&M ₁ -1.9 B&B -3.6	K&M ₂ -47.4	K&M ₁ -1.9 B&B -4.4	K&M ₂ -33.1	K&M ₁ -2.3 B&B -4.7	K&M ₂ -23.0	K&M ₁ -1.9 B&B -4.3	K&M ₂ -33.0

* sky cover sunrise to sunset $\geq .9$ (4 days)

** sky cover sunrise to sunset .4 to .8 (4 days)

*** sky cover sunrise to sunset $\leq .3$ (4 days)

TABLE Vj

Johnson Environmental and Energy Center (JEEC), Huntsville, Alabama
 Lat. $34^{\circ}44'N$, Long. $86^{\circ}40'W$, Elev. 201 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) and incident angle (θ) are at the midpoint of the hour.

July 1978, $s = 14.5^{\circ}$

Hour ending, solar time	Zenith $\angle (z)^{\circ}$	Incident $\angle (\theta)^{\circ}$	Cloudy days*		Partly Cloudy days**		Clear days***		All days	
			L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$	L&J $\Delta\%$	T&C $\Delta\%$
0652	74	78	1.0	-7.8	11.1	-5.3	25.5	-5.4	14.4	-5.4
0752	62	64	1.0	-18.3	5.3	-12.2	9.6	-6.3	7.0	-9.9
0852	49	51	0.0	-26.3	2.2	-36.0	3.8	-9.9	2.7	-15.3
0952	37	37	-.2	-46.4	-.1	-23.4	.7	-13.4	.3	-21.2
1052	25	23	-.4	-63.1	-1.3	-30.8	-.5	-17.1	-1.0	-27.5
1152	16	9	-1.0	-90.6	-1.7	-29.6	-1.2	-18.4	-1.5	-27.4
1252	14	5	-1.1	-81.5	-2.0	-28.5	-1.2	-18.7	-1.6	-27.0
1352	22	19	-1.2	-69.5	-1.5	-25.5	-1.0	-15.8	-1.4	-24.5
1452	34	33	.2	-42.4	-.4	-23.0	.4	-13.7	-.2	-21.0
1552	46	47	3.2	-15.2	2.0	-16.1	2.7	-10.7	2.5	-13.9
1652	58	61	8.6	-12.0	6.7	-13.0	8.7	-10.8	7.7	12.0
1752	70	74	19.3	-.8	14.1	-4.5	17.5	-3.5	15.8	-4.0
DAILY			K&M ₁ 1.3 B&B .05	K&M ₂ -40.7	K&M ₁ 4.2 B&B -3.09	K&M ₂ -21.6	K&M ₁ 2.1 B&B -3.18	K&M ₂ -11.6	K&M ₁ 1.1 B&B -2.86	K&M ₂ -18.2

* sky cover sunrise to sunset $\geq .9$ (1 day)

** sky cover sunrise to sunset .4 to .8 (6 days)

*** sky cover sunrise to sunset $\leq .3$ (4 days)

TABLE VI

Laboratory of Climatology, Tempe, Arizona
 Lat. $33^{\circ}26'N$, Long. $111^{\circ}56'W$, Elev. 1160 ft. (354 m.)

Comparison of calculations of solar radiation on an inclined surface with measurements. $s = 45^{\circ}$.
 Zenith angle (z) is at the midpoint of the hour on the 15th day of the month.

Hour ending LST	November 1977			December 1977			January 1978			March 1978		
	Zenith $\angle (z)^{\circ}$	L&J $\Delta\%$	T&C $\Delta\%$	Zenith $\angle (z)^{\circ}$	L&J $\Delta\%$	T&C $\Delta\%$	Zenith $\angle (z)^{\circ}$	L&J $\Delta\%$	T&C $\Delta\%$	Zenith $\angle (z)^{\circ}$	L&J $\Delta\%$	T&C $\Delta\%$
08	85	-70.4	-51.6							80	-20.7	-21.6
09	74	-20.2	-26.9	79	-30.9	-38.7	79	-38.5	-45.9	68	3.1	1.2
10	64	-12.1	-18.1	70	-16.9	-21.9	69	-18.6	-24.1	56	14.6	9.0
11	57	-8.5	-14.2	63	-13.1	-16.4	62	-11.4	-16.7	46	8.7	-1.8
12	53	-21.9	4.2	58	-23.4	-23.7	56	-9.1	-14.5	39	0.1	-14.0
13	52	-4.3	27.4	57	-10.1	-14.8	55	-1.7	-7.8	36	8.0	-9.2
14	55	-30.2	-6.7	59	-7.0	-10.8	56	-8.0	-13.1	38	5.4	-11.7
15	62	-34.1	-10.7	64	-9.4	-13.7	62	-9.2	-13.7	45	10.2	-1.1
16	70	-36.3	-11.2	72	-7.5	-14.3	69	-11.1	-16.9	55	7.7	1.7
17	80	-44.0	-10.5	82	-2.3	-14.9	79	-25.7	-35.1	66	4.7	2.4
18										78	-3.0	-4.1
DAILY	B&B 1.1	K&M ₁ -23.4	K&M ₂ -7.1	B&B -1.6	K&M ₁ -15.3	K&M ₂ -19.5	B&B -1.3	K&M ₁ -14.4	K&M ₂ -19.9	B&B 14.1	K&M ₁ 6.27	K&M ₂ -4.1

TABLE VII a

Meteorological Research Station (MRS), Toronto, Canada
 Lat. $43^{\circ}48'N$, Long. $79^{\circ}33'W$, Elev. 192 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) is at the midpoint of the hour.

26 May 1977 - Clear Day

Hour ending, solar time	Zenith $\angle (z)^{\circ}$	$s = 30^{\circ}$			$s = 60^{\circ}$			$s = 90^{\circ}$		
		Incident angle θ	L&J	T&C	Incident angle θ	L&J	T&C	Incident angle θ	L&J	T&C
07	70	78	-1.6	-29.8	89	-3.7	97.0	100	-169.0	80.6
08	59	64	-1.7	-17.7	76	-1.8	27.6	91	-36.8	191.0
09	49	50	-1.4	-14.3	63	-4.6	11.1	82	-6.9	148.5
10	38	36	-1.3	-13.4	52	-2.5	7.3	75	-1.3	105.0
11	29	22	-1.0	-13.0	44	-1.8	4.8	70	0.6	90.0
12	24	11	-0.6	-12.1	38	-0.9	5.0	68	1.9	87.0
13	24	11	0.1	-11.3	38	.06	6.2	68	3.3	89.8
14	29	22	0.15	-11.4	44	-0.4	7.0	70	1.9	94.4
15	38	36	0.8	-10.5	52	-0.1	11.7	75	1.6	115.0
16	49	50	1.7	-10.7	63	-0.4	17.3	82	-2.4	157.0
17	59	64	1.6	-14.0	76	-0.4	31.7	91	-41.0	225.0
18	70	78	5.2	-25.1	89	-24.0	56.6	100	-168.0	75.5
DAILY		B&B 3.2	K&M ₁ 3.15	K&M ₂ -10.3	B&B 5.8	K&M ₁ 2.17	K&M ₂ 15.0	B&B -4.0	K&M ₁ -9.4	K&M ₂ 115

TABLE VII b

Meteorological Research Station (MRS), Toronto, Canada
 Lat. $43^{\circ}48'N$, Long. $79^{\circ}33'W$, Elev. 192 m.

Comparisons of calculations of solar radiation on an inclined surface with measurements.
 Zenith angle (z) is at the midpoint of the hour.

12 June 1977 - Cloudy Day

Hour ending solar time	Zenith $\angle(z)$	$s = 30^{\circ}$			$s = 60^{\circ}$			$s = 90^{\circ}$		
		Incident angle θ	L&J	T&C	Incident angle θ	L&J	T&C	Incident angle θ	L&J	T&C
06	79	91	-11.0	-20.4	103	-26.2	3.2	111	-39.7	79.2
07	69	77	4.7	-14.0	89	9.0	18.5	101	14.9	104.0
08	58	64	4.4	-27.8	77	10.1	-0.5	92	18.5	71.6
09	47	50	4.0	-67.0	64	8.3	-56.2	84	15.3	-28.0
10	37	36	6.2	-64.5	54	13.0	-50.7	77	21.7	-15.3
11	28	23	4.6	-81.3	45	10.4	-74.3	72	18.1	-56.4
12	22	12	7.2	-89.1	40	15.6	-84.8	70	24.3	-74.5
13	22	12	5.7	-89.3	40	13.6	-85.1	70	22.4	-74.8
14	28	23	3.4	-81.5	45	9.5	-74.5	72	17.4	-56.7
15	37	36	7.4	-64.0	54	15.9	-49.4	77	24.7	-13.2
16	47	50	1.6	-46.7	64	5.4	-27.8	84	10.8	21.4
17	58	64	2.3	-29.3	77	6.7	-3.6	92	12.8	63.3
18	69	77	-1.7	-19.8	89	-3.7	5.8	101	-5.1	75.2
19	79	91	-2.2	-9.7	103	-5.4	25.0	111	-6.1	125.7
DAILY		B&B 7.2	K&M ₁ 4.84	K&M ₂ -67.4	B&B 3.0	K&M ₁ 11.36	K&M ₂ -54.1	B&B -35.4	K&M ₁ 16.45	K&M ₂ -25.0

TABLE VIII

RIVERSIDE, CALIFORNIA
DISCREPANCIES BETWEEN ASHRAE SOLAR ALGORITHM
AND
LIU/JORDAN METHOD
TILTED SURFACE INSULATION (PERCENT)

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JLY	AUG	SEP	OCT	NOV	DEC
5	0.00	0.00	0.00	0.00	0.00	200.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	-200.00	-76.38	-43.03	-49.90	-53.76	-83.08	-135.48	-209.00	0.00	0.00
7	-200.00	-119.78	-31.98	16.16	-16.98	-20.96	-5.76	-7.42	-3.46	-13.08	1.38	-139.55
8	4.81	-9.69	-5.54	15.03	-17.45	-29.39	-3.78	-1.39	-4.59	11.58	22.60	21.61
9	19.99	-1.92	-3.34	12.56	-12.40	-15.47	0.20	2.00	-3.72	8.29	17.64	26.40
10	21.82	5.50	-0.78	13.72	-7.90	-9.50	1.68	1.79	-2.90	7.50	13.54	25.02
11	21.42	4.95	-2.36	10.98	-5.66	-8.84	1.69	0.20	-2.00	1.51	7.93	22.05
12	20.72	6.62	-3.48	9.88	-4.08	-7.74	-0.38	-1.11	-2.67	-3.28	2.47	16.01
13	22.53	8.10	-0.08	12.09	-2.14	-4.56	0.10	-0.87	-5.41	-4.05	5.64	17.98
14	22.71	11.45	3.14	13.65	-0.72	-5.77	0.03	-1.71	-3.49	-6.24	0.97	15.55
15	23.59	12.14	6.23	11.99	-3.68	-5.95	-0.93	-2.36	-5.85	-12.67	-6.99	8.71
16	12.48	16.02	9.49	10.28	-9.57	-8.12	-1.58	-4.49	-12.15	-30.02	-47.63	-37.77
17	-200.00	-15.19	-7.80	-6.55	-24.32	-18.17	-6.80	-11.64	-45.61	-179.45	-200.00	-200.00
18	0.00	0.00	-200.00	-170.59	-107.92	-76.29	-65.39	-110.68	-200.00	-200.00	0.00	0.00
DAILY	17.28	4.84	-2.05	10.68	-7.70	-10.00	-1.17	-2.10	-5.85	-7.22	2.72	14.13

ANNUAL = 7.037E-01

TILT = LAT = 34 DEG

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KAEMPFERT

KREITH

APPENDIX A

NOMENCLATURE, DEFINITIONS & ADOPTED CONVENTIONS

- α : Solar altitude (the angle between the beam from the sun and the horizontal equal to $90^\circ - z$)
- A : Azimuth of the sun, $A = \sin^{-1}(\cos\delta\sin\omega/\cos(90^\circ - z))$
- B : Turbidity coefficient
- B_H : Direct radiation on a horizontal plane
- B_N : Direct radiation on a plane normal to the solar beam
- B_T : Direct radiation on a tilted plane
- δ : Solar declination angle (the angular position of the sun at solar noon with respect to the plane of the equator, North positive)
- D_H : Diffuse radiation on a horizontal plane (measured with shadowband)
- D_T : Diffuse radiation on a tilted plane
- e : Water vapor pressure
- γ : The surface azimuth angle (the deviation of the normal to the plane from the local meridian, the zero point being due South, East positive, and West negative)
- G_H : Global radiation on a horizontal plane
- G_T : Global radiation on a tilted plane
- m : Air mass
- ω : Hour angle (solar noon being zero, and each hour equaling 15° of longitude with mornings positive and afternoons negative)
- ϕ : Latitude of site (North positive)
- ρ : Ground reflectance
- R_H : Reflected radiation on a horizontal plane
- R_T : Reflected radiation on a tilted plane
- s : Angle of Inclination of a surface with respect to horizontal plane
- θ : The angle of incidence of direct solar radiation (the angle being measured between the beam and the normal to the plane)
- z : Zenith angle (the angle between the beam from sun and the vertical)
- $()_c$: Subscript c indicates calculated data, example: B_{Hc}

DEFINITION OF SOLAR AND SURFACE ANGLES

FIGURE A-1

APPENDIX B

EQUATIONS OF VARIOUS METHODS

INSTANTANEOUS AND HOURLY DATA METHODS

1. ASHRAE

$$G_T = B_N \cos \theta + D_T + R_T$$

From ASHRAE Tables, the solar radiation on tilted surfaces can be interpolated using two sets of data. These tables are based on clear-sky conditions.

2. BASNETT - for vertical surfaces only

$$G_{T90} = B_N \cos \theta + \frac{1}{2} D_H + 0.1 G_H$$

3. EI & I

$$G_T = G_H \times R$$

where R is given in charts for different latitude, month, tilt angle and G_H/E_0 ratio. E_0 = average daily extraterrestrial radiation on a horizontal surface.

4. GARNIER & OHMURA

$$G_T = G_N \cos \theta + D_H \cos^2 \frac{\theta}{2} + \rho G_H \sin^2 \frac{\theta}{2}$$

5. KONDRATYEV - direct radiation only

$$B_T = B_N \cos \theta$$

6. KREITH - direct radiation only

$$B_T = B_N \cos \theta$$

7. LIU & JORDAN

$$G_T = (G_H - D_H) \frac{\cos \theta}{\sin \alpha} + D_H \cos^2 \frac{\theta}{2} + \rho G_H \sin^2 \frac{\theta}{2}$$

8. LOUDON

$$G_T = (G_H - D_H) \frac{\cos \theta}{\sin \alpha} + D_H \cos^2 \frac{\theta}{2} + \rho G_H \sin^2 \frac{\theta}{2}$$

9. TEMPS & COULSON

Isotropic approximation:

$$G_T = B_N \cos \theta + D_H \cos^2 \frac{\theta}{2} + (B_H + D_H) \rho \sin^2 \frac{\theta}{2}$$

Anisotropic approximation:

$$G_T = B_N \cos \theta + D_H \cos^2 \frac{\theta}{2} [(1 + \sin^2 \frac{\theta}{2})(1 + \cos^2 \theta) \sin^2 z] + \rho (B_H + D_H) \sin^2 \frac{\theta}{2} [(1 + \sin^2 \frac{\theta}{2})(|\cos \alpha|)]$$

(α = the azimuth angle of the tilted surface with respect to that of the sun, which approximates ω for south facing and is used as such since the last term is a small contribution.)

10. THRELKELD & JORDAN - direct radiation only

$$B_T = B_N \cos \theta$$

DAILY DATA METHODS

1. BECKER & BOYD

$$G_T = G_H[a + b(90 - s) + c(90 - s)^2]$$

The following table shows a tabulation of the coefficient, a, b, c of the above equation for various latitudes and seasons:

COEFFICIENTS OF THE POLYNOMIAL

$$G_T = G_H[a + b(90 - s) + c(90 - s)^2]$$

DATE	LATITUDE	COEFFICIENT		
		a	b	c
Dec. 21	30°	1.496	0.012657	-0.0002025
	35°	1.734	.014313	.0002502
	40°	2.132	.012366	.0002774
	45°	2.499	.010621	.0003033
Jan. 21 and Nov. 21	30°	1.322	0.014395	-0.0001999
	35°	1.510	.013339	.0002112
	40°	1.827	.013236	.0002500
	45°	2.154	.012117	.0002776
Feb. 21 and Oct. 21	30°	0.997	0.014531	-0.0001613
	35°	1.141	.015173	.0001860
	40°	1.312	.014250	.0001972
	45°	1.500	.013619	.0002139
Mar. 21 and Sep. 21	30°	0.638	0.016279	-0.0001361
	35°	.768	.015605	.0001445
	40°	.872	.015237	.0001532
	45°	1.011	.015365	.0001722
Apr. 21 and Aug. 21	30°	0.314	0.017447	-0.0001083
	35°	.400	.017659	.0001221
	40°	.492	.016878	.0001249
	45°	.571	.018014	.0001472
May 21 and Jul. 21	30°	0.186	0.016350	-0.0000806
	35°	.244	.016964	.0000944
	40°	.345	.015827	.0000944
	45°	.399	.016884	.0001132
Jun. 21	30°	0.105	0.016696	-0.0000744
	35°	.205	.016145	.0000805
	40°	.277	.016064	.0000889
	45°	.326	.017028	.0001055

2. FULLWOOD - for vertical surfaces only

$$G_{T90} = \Sigma(G_H - D_H) \frac{\cos\theta}{\sin\alpha} + 0.4 D_H \quad \text{---facing North}$$

$$= \Sigma(G_H - D_H) \frac{\cos\theta}{\sin\alpha} + 0.5 D_H \quad \text{---facing East or West}$$

$$= \Sigma[(G_H - D_H) \frac{\cos\theta}{\sin\alpha} + 0.5 D_H] \left(\frac{k}{\sqrt{\alpha_n}}\right) \quad \text{---facing South}$$

where α_n = mean solar altitude between 11 and 13 on the date in question .

k = 0.95 - the mean value of $\sqrt{\alpha_n}$ on 7th April and 7th September

3. KONDRATYEV & MANOLOVA

$$\Sigma(B + D + R)_T = \Sigma B_H (\cos\theta) + \cos^2 \frac{s}{2} \Sigma D_H + \rho \sin^2 \frac{s}{2} \Sigma G_H$$

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$$\left[\frac{\int B_H \frac{\cos\theta}{\sin\alpha} dt}{\int B_H dt} \right] B_H + D_H \cos^2 \frac{s}{2} + \rho G_H \sin^2 \frac{s}{2}$$

Monthly average data can be used in above equation.

5. RANKINS & WILSON

Percentage Table -- give the percentage of the solar radiation on tilted surface to that on a horizontal surface.

Monthly average data can be used in this method.

OTHER METHODS:

1. PORTIG: Set of tables for direct solar radiation.
2. ROBINSON: Treats direct radiation only.
3. TULLER: Does not discuss radiation on an inclined surface.
4. KAEMPFERT: Is not in English and is similar to other hourly data methods.
5. HAY: Analyzes radiation data for Alberta.
6. HEYWOOD: Defines function using previous data.
7. HOTTEL & WOERTZ: Discusses performance of the solar collectors.