

INVESTIGATION OF THE DEPENDENCE OF ATMOSPHERIC  
TRANSMITTANCE FOR BEAM RADIATION ON CLEARNESS INDEX

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INVESTIGATION OF THE DEPENDENCE OF ATMOSPHERIC  
TRANSMITTANCE FOR BEAM RADIATION ON CLEARNESS INDEX

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## TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS.....	iii
LIST OF TABLES.....	vii
LIST OF FIGURES.....	viii
SUMMARY.....	xi
Chapter	Page
I. INTRODUCTION.....	1
1.1 Problem Statement	
1.2 Objective	
II. PREVIOUS WORK.....	3
III. DATA BASE PREPARATION.....	8
3.1 The Solar Total Energy Project	
3.2 Calibration of the Instruments	
3.3 Qualitative Control	
3.3.1 Automatic Quality Controls	
3.3.2 Manual Quality Controls	
3.4 Data Validation Procedures	
3.5 Five-Year Data Base	
IV. SOLAR ASTRONOMY.....	24
4.1 Principles	
4.1.1 Determination of the Sun's Position	
4.1.2 Calculation of the Earth's Elliptic Motion	
4.2 The Celestial Vault	
4.2.1 Celestial Coordinate System	
4.2.2 Conversions Between the Equatorial and Ecliptic System	
4.2.3 Conversions Between the Hour Angle and Equatorial Systems	
4.2.4 Conversions Between the Horizontal and Hour Angles System	
4.3 Algorithm for Calculating the Position of the Sun	
4.3.1 Basic Equations for Calculating the Position of the Sun	
4.3.2 Results Using Subroutine HELGO	



Chapter	Page
V. STATISTICAL ANALYSIS.....	67
5.1 Annual and Five-Year Models	
5.2 Monthly Models	
5.3 Regression Analysis	
5.3.1 Statistical Procedures	
5.3.2 Results from Statistical Analysis	
VI. MODEL VALIDATION.....	106
6.1 Model Comparison	
6.2 Verification of Data Processing Procedures	
VII. CONCLUSIONS AND RECOMMENDATIONS.....	121
Appendix	Page
A.....	124
CREATE3: Program to Compute Monthly Data Files.....	125
B.....	129
HELGO: Subroutine Calculating the Position of the Sun....	130
TABLE3: Comparison of HELGO with DAILY and Nautical Almanac.....	134
CKTTB2: Calculations of $k_T$ and $\tau_b$ Using Subroutine Helgo.....	140
LSMAIN7: Sorting of Date Data According to $k_T$ .....	144
SORTR: Sorting Subroutine.....	145
VSRTTP: Sorting Subroutine from IMSL Library.....	146
VSRTTU: Sorting Subroutine from IMSL Library.....	150
C.....	153
TBREG5: Model Development and Regression- Statistical Analysis.....	154
SUBI: Subroutine to Calculate $k_T$ and $\tau_b$ from Radiation Data.....	161
CLRL: Subroutine to Plot Regression Lines.....	163
MDFD: Subroutine to Calculate the Probability Distribution Function.....	165
Development of Total Variation Identity.....	170
D.....	171
VERIF: Clearness Index versus Beam Normal Fraction Verification of Model Development.....	172

BIBLIOGRAPHY.....	177
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## LIST OF TABLES

Table	Page
4.1. Daily Values of the Declination, Hour Angle, and Equation of Time from Subroutines DAILY, HELGO, and the <u>Nautical Almanac</u> for the month of January, 1983.....	57
4.2. Comparison of Error Coefficients Between Subroutines HELGO and DAILY.....	58
5.1. Coefficients for the Piecewise Linear Function, $\tau_b = A_i * k_T + B_i$ .....	68
5.2. Model Comparison.....	70
5.3. Annual and Five-Year Regression Coefficients for Shenandoah STEP.....	72
5.4. Monthly Slope Coefficients for Shenandoah STEP.....	82
5.5. Model Coefficients of Determination and Correlation.....	101
5.6. Model Comparison Based on the Residual Regression, f-Statistic, and Probability Values.....	103
6.1. Monthly Output Format for January 1, 1980.....	118

## LIST OF FIGURES

Figure	Page
3.1. Flowchart for Algorithm CREATE3.....	15
3.2. Daily Radiation Chart for January 15, 1979.....	21
3.3. Daily Radiation Chart for December 4, 1979.....	22
4.1. Earth's Elliptical Orbit Around the Sun.....	26
4.2. Earth's Ecliptic Plane.....	28
4.3. Variation in the Motion of the Mean and Eccentric Earths...	29
4.4. The Basic Lines and Points of the Celestial Vault.....	34
4.5. The Ecliptic System of Coordinates ( $\beta$ and $\lambda$ ).....	36
4.6. The Equatorial System of Coordinates ( $\delta$ and RA).....	37
4.7. The Hour Angle System of Coordinates ( $\delta$ and $\omega$ ).....	39
4.8. The Horizontal System of Coordinates ( $\alpha$ and $\gamma_s$ ).....	40
4.9. Relations Between the Equatorial and Ecliptic Systems.....	42
4.10. The Ecliptic Triangle.....	43
4.11. Relations Between the Hour Angle and Equatorial Systems....	45
4.12. Relations Between the Horizontal and Hour Angle Systems....	47
4.13. The Astronomic Triangle.....	48
4.14. Comparison of the Calculated Annual Values of Declination, from Subroutines HELGO (distorted curve), DAILY (curve identified with "o") with 1983 <u>Nautical Almanac</u> (solid smooth curve).....	59
4.15. Comparison of the Model Produced Using Subroutine HELGO (curve identified with rhombi) with the One Using DAILY (curve identified with crosses).....	66
5.1. Scatter Plot of and Piecewise Regression on Shenandoah	

Figure	Page
STEP Data for 1979. The Randall-Whitson Model is Shown by the Plain-Line.....	73
5.2. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1980. The Randall-Whitson Model is Shown by the Plain-Line.....	74
5.3. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1981. The Randall-Whitson Model is Shown by the Plain-Line.....	75
5.4. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1983. The Randall-Whitson Model is Shown by the Plain-Line.....	76
5.5. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1984. The Randall-Whitson Model is Shown by the Plain-Line.....	77
5.6. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the 5-Years. The Randall-Whitson Model is Shown by the Plain-Line.....	78
5.7. The 5-Year Shenandoah STEP Regression Model Compared With Randall-Whitson Model (plain line).....	79
5.8. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of January The Randall-Whitson Model is Shown by the Plain-Line.....	83
5.9. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of February The Randall-Whitson Model is Shown by the Plain-Line.....	84
5.10. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of March The Randall-Whitson Model is Shown by the Plain-Line.....	85
5.11. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of April The Randall-Whitson Model is Shown by the Plain-Line.....	86
5.12. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of May The Randall-Whitson Model is Shown by the Plain-Line.....	87



Figure	Page
5.13. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of June The Randall-Whitson Model is Shown by the Plain-Line.....	88
5.14. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of July The Randall-Whitson Model is Shown by the Plain-Line.....	89
5.15. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of August The Randall-Whitson Model is Shown by the Plain-Line.....	90
5.16. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of September The Randall-Whitson Model is Shown by the Plain-Line.....	91
5.17. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of Octomber The Randall-Whitson Model is Shown by the Plain-Line.....	92
5.18. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of November The Randall-Whitson Model is Shown by the Plain-Line.....	93
5.19. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of December The Randall-Whitson Model is Shown by the Plain-Line.....	94
6.1. Beam Normal Fraction-Clearness Index Models.....	107
6.2. Daily Irradiation Limits.....	111
6.3. Clearness Index vs. Beam Normal Transmittance Model Verification for 1980.....	119

## SUMMARY

An accurate computation of the atmospheric transmittance for beam radiation is necessary to predict the beam normal solar irradiation. The object of this work is to expand the present knowledge about the dependence of beam normal fraction and clearness index using the information collected at Shenandoah, Georgia since 1979. The result is vital for predicting the performance of concentrators, for which the pertinent resource is the beam irradiation and is necessary to accurately predict the total irradiation on a surface of general orientation.

The main goals of this work are:

1. Develop a five-year data base to be used for the model development. Close screening of the collected pyranometer and pyrhelimeter data will result to usable hourly irradiation data (8112 hourly values).
2. Develop an algorithm to accurately compute the solar astronomy angles. This is presented in a form of a subroutine and computes the declination, equation of time and hour angle.
3. Process the irradiation data on an hourly basis to calculate the corresponding hourly extraterrestrial normal irradiation and extraterrestrial horizontal irradiation. Thus, the hourly clearness index and hourly beam transmittance can be calculated and used for statistical analysis. There are nine

bands of data defined, based on hourly clearness index values.

4. Perform the statistical analysis on the five-year data and develop a five-year model. The principal result of the statistical analysis on the two characteristics of the population, clearness index and beam transmittance, is a piecewise continuous linear regression model. This model was prepared by performing homogeneous least square fits for each band of data. Its continuous format provides for an easy-to-use model which makes it the most attractive (compared to Randall-Whitson model, piecewise linear regression model and a polynomial regression model). The five-year model is shown to be preferable to any annual model from a constituent year. It is also similar to the well known Randall-Whitson model except in the highest range of clearness indices.
5. Verify the developed model and the data processing procedures. The Shenandoah model was compared to other major models, The results indicate general agreement between the different models, but at higher clearness indices the Shenandoah model should be preferred. Finally, the data processing procedures are verified by conducting a numerical experiment.



## CHAPTER I

### INTRODUCTION

#### 1.1 Problem Statement

Hourly values for the beam normal solar irradiation are needed for such purposes as calculating the irradiation on tilted surfaces and assessing the performance of concentrating collectors. The most direct method of gaining knowledge about beam normal radiation is by measuring it, using a pyrhelimeter.

The consistently adequate operation of tracking pyrhelimeters is demanding on time and other resources (i.e. frequent adjustment). This is the most important problem that develops when one is trying to obtain accurate information in this fashion. As a result exact and reliable beam-normal radiation data is not so readily available as global, pyranometer, data. Historically many meteorological stations have not recorded beam normal radiation, probably due to the instrument complexity. Thus, great gaps appear in many of the historical data bases.

This situation has made the development of models for estimation of beam radiation from global radiation a high priority among solar energy researchers.

## 1.2 Objective

The main objective of this thesis is to develop a function which most accurately correlates the hourly beam normal function and the hourly clearness index. This will be done by using a selected set of well screened and validated beam normal and global radiation measurements, from the Shenandoah STEP site, over a five year period. From this correlation then, the beam normal radiation can be simply and reliably calculated given a reliable global radiation measurement.

## CHAPTER II

### PREVIOUS WORK

This thesis deals mainly with hourly solar radiation relations. Following is a summary of several categories of models available in the literature and related to this work.

Many studies have produced equations for hourly beam normal irradiation as a function of various meteorological variables such as sunshine duration, surface pressure, precipitable water, turbidity, total ozone content and relative humidity. Such equations can be found in the works of Hoyt [1], Atwater and Ball [2], Davies and McKay [3], and Sherry and Justus [4].

There have been models, however, which do not require that amount of data as input. Thus, a number of investigators have chosen to correlate the hourly fraction of diffuse horizontal radiation against the hourly clearness index (originally referred to by Liu and Jordan [5] as cloudiness index) to obtain relationships of the form:

$$F_1 = I_d / I = f_1(k_T), \quad (2.1)$$

where

$I_d$  = hourly diffuse horizontal irradiation,

$I$  = hourly global irradiation,

$I_0$  = hourly extraterrestrial horizontal irradiation.

$k_T$  = hourly clearness index,  $(I/I_0)$ , and

Although the idea originated by Liu and Jordan and their daily correlation has been used on hourly basis, according to [6] it is not suitable for this purpose. A widely used model of this form is due to Orgill and Hollands [7] and also Bruno [8], more recent results have been presented by Erbs, Klein, and Duffie [9] and by Spencer [10].

An alternative presentation is to consider the ratio of the hourly beam normal irradiation to the hourly extraterrestrial normal irradiation. This ratio should probably be called (according to [5] and [11]), the "hourly beam transmittance of the atmosphere", and can be correlated against the hourly clearness index. Correlations of this form:

$$\tau_b = I_{bn} / I_{0n} = f_2(k_T), \quad (2.2)$$

have special intuitive appeal since one expects the beam transmittance to increase monotonically with clearness index. Possibly the foremost model of this type is the result of work by Randall and Whitson [12] which has been concisely restated in [13].

The Randall-Whitson model is also called the Aerospace model. The algorithm estimates the direct normal solar radiation. It attempts to characterize the statistical variations of actual data from a correlation and it has been used to fill in the direct normal field in SOLMET [14] data tapes. A model to predict the beam normal irradiation from measured global solar radiation is also available by Turner and Mujahid [15]. In the development of the model, statistical regression tests were conducted over a range of solar altitude angles. The model was compared to the Randall-Whitson model, and overall the two models were found very similar. It is indicated though in [15] that the Aerospace model is the best available model.

It can be shown that models in the form of either Equation (2.1) or Equation (2.2) are approximately algebraically equivalent. For hourly data the beam normal irradiation can be related to the global and diffuse horizontal irradiances by defining an hourly average incident cosine,  $\cos \hat{\theta}_z$ , such that

$$I_{bn} = (I - I_d) / \cos \hat{\theta}_z. \quad (2.3)$$

Substituting this result into the definition for the hourly beam transmittance one has:

$$\tau_b = (1 - F_v) \cdot k_T. \quad (2.4)$$

Such an algebraically transformed relationship probably should not be considered as a rigorously equivalent statistical result, because the manipulation has altered the dependent variable. However such transformed relations are useful at least for qualitative comparisons.

Other correlations on the clearness index are possible. The beam transmittance may be expected to follow a Bouguer's Law dependence on atmospheric extinction (due to absorption and scattering) and air mass [16], such that:

$$\tau_b = \exp(-K \cdot m), \quad (2.5)$$

where

$K$  = extinction coefficient, and

$m$  = standard air mass.

The extinction coefficient, or some suitably normalized function, could then be correlated against the clearness index as has been done in [17].

An important alternative model is constructed by defining a modified clearness index based on an independent model for the clear day global irradiance. Correlations in this format, with quite similar results, have been presented by Stauter and Klein [18] and by Turner and Salim [19].



Correlations of the hourly diffuse fraction,  $I_d/I$ , to the ratio of the hourly global radiation to an estimate of hourly clear sky radiation,  $I/I_0$  have also been developed by Bugler [20], for a series of correlations over zenith-angle bands. Clear day models and comparisons of these different models are included in Mujahid and Turner [21]. Diffuse radiation correlations were investigated in [6].

In this thesis the development of a model in the form of Equation (2.2) will be presented, verified and compared to some other models, which were previously presented. This model is based on five years of data from the STEP site, beginning in 1979. The resulting model is an improved solar radiation model for determining the amount of beam normal irradiation when only the data for global irradiation is present.

## CHAPTER III

### DATA BASE PREPARATION

#### 3.1 The Solar Total Energy Project

The Solar Total Energy Project (STEP) at Shenandoah, Georgia ( $33.4042^{\circ}$  N,  $84.7478^{\circ}$  W) is a cooperative effort between the United States Department of Energy and the Georgia Power Company, to further the search for new sources of energy. The project is a prototype solar thermal total energy plant, being in operation since early 1982. The site is composed of 114 parabolic solar dish collectors (each, 7 meters in diameter).

The Shenandoah plant employs concentrating collectors. Each parabolic dish acts as a concentrator producing a concentration ratio of 250. The concentrated rays heat the circulating silicone transfer fluid to  $750^{\circ}$  F. The heat transfer fluid is then pumped to a heat exchanger, where it boils water and superheats steam. The superheated steam drives a turbine generator, producing electricity. Medium pressure steam is extracted from the turbine for knitwear pressing at the near-by factory. Low-pressure steam exhausted from the turbine is used to produce chilled water for air-conditioning.



### 3.2 Calibration of Instruments

A meteorological station at the site, operated by Georgia Institute of Technology, constantly monitors the amount of solar energy available. The solar insolation and surface weather instruments make it one of the most sophisticated stations in America for gathering data about the sun and is considered to be a pioneer modern automated station.

The basic data set assembled at the STEP includes of irradiation values integrated over fifteen-minute periods and recorded at the end of each period. The pertinent instruments at the site are an Epply precision spectral pyranometer (PSP), to measure global irradiation and two Epply normal incidence pyrhemliometers (NIP) on a common polar mount to measure beam normal irradiation.

During 1984 the solar monitoring station was reconfigured. It now includes two global pyranometers for redundancy. Redundancy in the beam normal measurements was enhanced by a third pyrhemliometer on the common mount being converted from measurements in the infrared band to full-spectrum measurements.

A fourth pyrhemliometer was added on a separate mount for complete redundancy, and in late 1984 this mount was converted to reliable PV power via a DC to AC inverter from an adjacent PV array with battery storage. One should note that the inverter powered unit shows poor performance, due to poor temperature stability.

The pyranometer and the NIP are not self-checking or absolute instruments. Their sensitivity should be determined by comparing them with some other "standard" instrument. Thus, all instruments have been periodically calibrated. The NIP's were calibrated by comparison with a TMI MK VI absolute cavity radiometer (SN 67812) traceable to the World Radiation Reference (WRR). No significant calibration adjustments have been necessary for any of the NIP's deployed in this station since operations began in 1977.

Calibration adjustments from the original calibration for the two principal instruments average only 0.8% and -0.3% respectively. The PSP for the global irradiation measurement has been recalibrated by comparison with a carefully maintained NBS-traceable Epply PSP (SN 18044). Its average deviation from initial calibration has been -1.5%. The PSP has shown a slight trend of degradation in response, which has been fully compensated by recalibration. The NIP's show no trend in response degradation.

### 3.3 Quality Control

The accuracy of a statistical model is strongly affected by its underlying data base. This is especially true for solar radiation data since one expects that systematic errors resulting from substandard operation or maintenance of the instruments will introduce low values, especially for the pyr heliometer data, and thereby introduce a one-sided bias in the data. Consequently, an effective data quality

control procedure and elimination of questionable data is essential to produce a reliable model.

### 3.3.1 Automatic Quality Controls

A routine quality-control procedure has been implemented for the data from the STEP site, since its inception. The procedure first involves an automated quality-control algorithm which computes a set of redundancy, limit and consistency checks between instruments. Its purpose is to efficiently check the data in order to indicate suspicious data, which then will be flagged. The quality control algorithm is described in [22]. Briefly the checks for beam normal data comprise the following:

1. Redundancy checks; NIP data are compared and deviations exceeding  $\pm 45 \text{ KJ/m}^2$  per period (  $\pm 5\%$  of clear sky value of  $900 \text{ KJ/m}^2$  per period) are flagged. The NIP data are also compared with the beam normal radiation inferred from the global irradiation and the horizontal diffuse irradiation inferred from the global irradiation and the horizontal diffuse irradiation measured by an Epply PSP with shading disc. Disagreement exceeding  $45 \text{ KJ/m}^2$  per period is flagged.
2. Limit check; NIP data are compared with a clear sky model, described in [23], which constitutes a practical upper bound. All data within  $45 \text{ KJ/m}^2$  per period of this limit are flagged.
3. Model check; NIP data are compared with the value predicted by

the Randall-Whitson model from the prevailing global irradiation. Values deviating more than 45 KJ/m<sup>2</sup> per period, possibly indicating poor tracking, are flagged.

The global irradiation data which employ a wide aperture instrument and no tracking are much more reliable than the beam normal data. The quality control algorithm still includes a consistency check (comparison of the global with the sum of diffuse horizontal and calculated beam horizontal irradiation), a limit check (comparison with the clear day model), and currently a redundancy check among the two instruments now deployed. The flags from the automated checks are called "internal flags" and denote only suspicious, not necessarily invalid, data. The vast majority of such data is reliable. An additional manual check will be introduced in the following section to assure that all spurious data has been detected.

### 3.3.2 Manual Quality Controls

The second step is a manual inspection of all data in the form of computer generated graphs with special attention paid to all data flagged by the quality-control algorithm. This is necessary since the "internal flags" were assigned with very broad limits. That is to say that in most cases the internal error flags represented only suspicious data and not actual faults in the data.

No data is eliminated on the basis of the automated check alone. Instead, daily graphs of all the radiation data and the pertinent



models are inspected by an experienced investigator. Special attention is given to all previously flagged data. Systematic problems can be identified by inspection of the daily plots. For example, an error in the beam normal data caused by poor tracking can be identified by the presence of low beam normal data simultaneously with low diffuse horizontal data. With the aid of the site operator's daily log, most unreliable data can be identified and flagged for exclusion from further analysis. These final flags resulting from manual verification of internal flags or manual identification of spurious data are called "external flags". Consequently, the data bases of this work were judged on the "external flags" only.

#### 3.4 Data Validation Procedures

At this point the data was assembled in monthly files including the external error flags. The unflagged data is expected to be highly reliable. However, there are some periods or even days that data were not recorded. These gaps can be due to station failure, periodic calibration, or routine maintenance.

In order to complete the monthly files with the exact number of periods and days, an algorithm was developed called CREATE3. The gaps will be filled by keeping track of the time (month, day, hour, minute) and by inserting dummy values of nine's for all other variables. As a result the data are automatically flagged and are not used in any following analysis. This procedure will complete a file with 96

periods a day and for every day of the month. This is an advantage for the programmer, who then has to deal with a known standard amount of data.

Using this program, one has also the opportunity to check for the correctness of the data. The experience that the author gained from processing the data base, boils down to the fact that despite all the previous checks, some "garbage" can still exist in the data (i.e. repeated periods, misrecorded dates, overflow in the hexadecimal external flags or a period of less than 15 minutes).

As it can be seen from Figure 3.1, the program operates as follows; it reads the data and based on the recorded time of the next period can specify if a period is missing. A warning message will come to your attention in a case that a reasonable looping time was spend looking for the expected next period without any success. The user then has to cross examine the periods of the completed data file (with the dummy variables) with the ones from the original data file. Special attention should be given to the area where a great number of dummy periods are recorded. This kind of problem would occur when a period that was read included something erroneous and as a result did not agree with the expected standard period format. This for the algorithm, is an indication of missing periods and the time counters are incremented trying to reach an agreement between the created period and the expected one.

The process of detecting problems of this nature is rather tedious, but the result reassures the user that the data does not include anything erroneous. It is also necessary to have available a

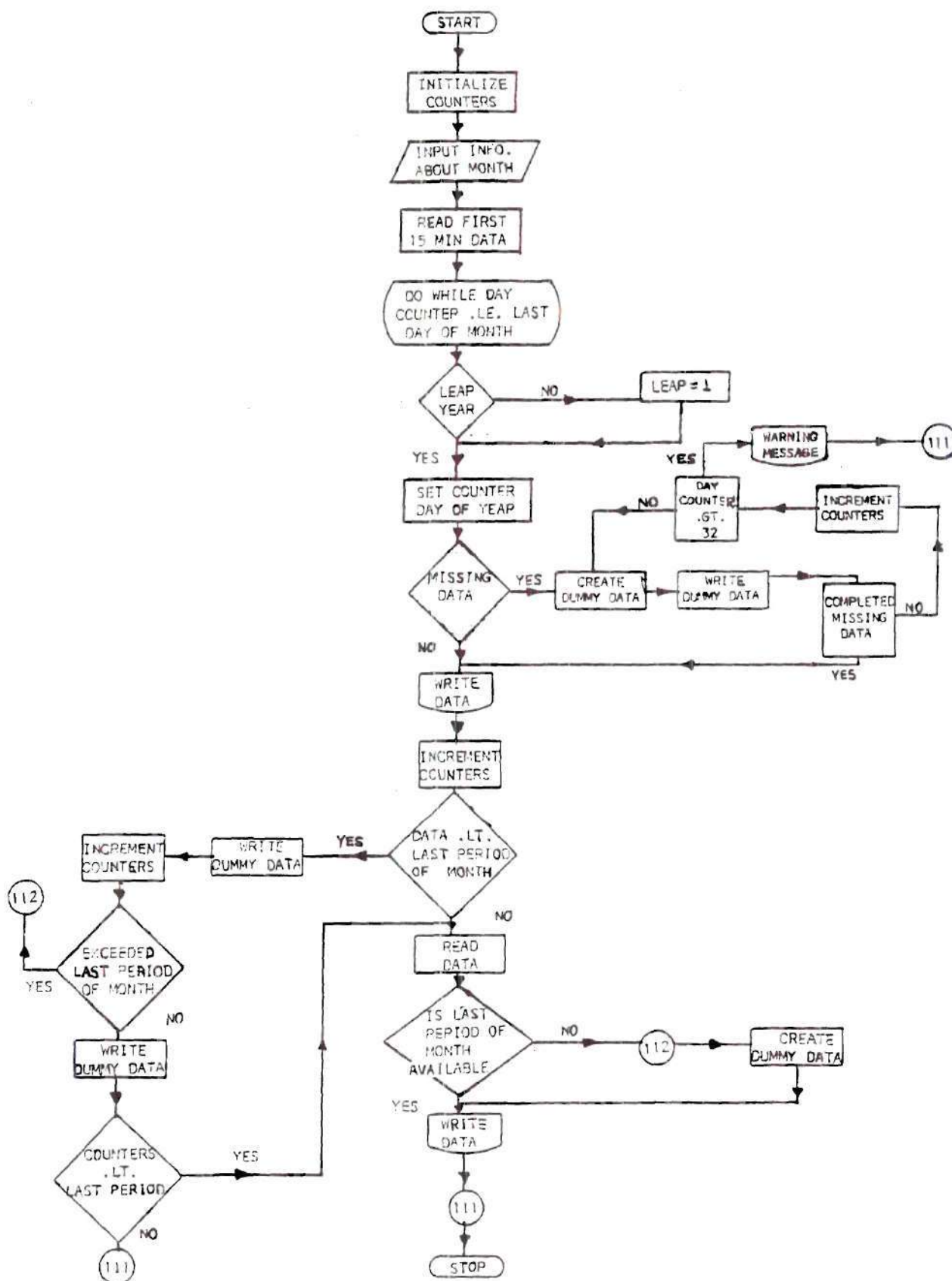


Figure 3.1. Flowchart for Algorithm CREATE3

complete data file before proceeding with the following analysis. The discovery of these problems gave a strong initiative to review the procedures of processing the data up to this point, locate the prospective causes of the problems and resolve them. A commented listing of CREATE3 can be found in APPENDIX A.

To prevent any residual poor data from contaminating the results, three additional screening checks were instituted for the present analysis:

1. Daily validation checks,
2. Hourly validation checks, and
3. Empirical error bound checks.

The daily validation test was instituted to eliminate certain days from further consideration. Days that were mostly overcast were rejected for two reasons: primarily because little beam radiation occurs on such days and secondarily because it is difficult to verify the pyrheliometer data on such days. Additionally, days with one-half or more of their periods flagged as unreliable were totally excluded as a conservative measure to preclude erroneous data. For this daily screening only periods with solar altitudes greater than  $6^\circ$  were considered. No data with lower altitudes is used in the beam radiation model to avoid the consequent refraction effects on tracking accuracy. Also it is felt that beam radiation at low solar altitudes has little practical significance but might confuse the model because of the effects of the large intervening air-mass.

The next step was to plot the good daily data for each year and to compare it with published models (Collares-Pereira and Rabl [24],



Liu and Jordan [1] and Speigel [25])). All relate  $H_d/H$ , the daily diffuse fraction, to  $k_T$ , the ratio of daily global to daily extraterrestrial radiation,  $H/H_0$ . The general agreement indicated was an encouraging verification of the quality check procedures used thus far. The result of the above was the compilation of all the reasonably reliable days for each year.

The next step was a closer examination of the data on an hourly basis the monthly files were processed again excluding all previously identified unreliable, or uninteresting, days. An hourly data base was assembled from the fifteen-minute data. The criterion used in this step is that at least three of the four intervals used in calculating the hourly value passed the previous quality checks.

Additionally, the data are screened based on the pyranometer readings. If the pyranometer data are less than 10% of clear day data, then these values are considered invalid due to inconsistencies. On the other hand, it might occur that unusually high pyranometer data are recorded (greater than the clear day total horizontal irradiation). These data exceed possible pyranometer values and being erroneous are discarded. The result of this procedure is the development of a new data base containing only good hourly irradiation values for the year.

The final check on the hourly data was a comparison of the calculated beam transmittance against empirical upper and lower bounds for a given clearness index. This step was instituted as a final verification of the previous checks. As detailed in [17], a scatter plot of the hourly beam transmittances versus clearness indices for 1980 was used to establish empirical bounds for hourly data. Upper and

lower boundary curves were estimated and then adjusted until data just outside the curves were found on close inspection likely to be spurious and any data just inside the curves were found likely to be reliable.

Four types of isolated errors were found to create such spurious data:

1. A pyranometer "glitch". A sudden drop in global irradiation with steady beam and diffuse data. Probably caused by temporary shading (e.g. during cleaning or by a resting bird) of the pyranometer. This causes a spuriously low clearness index.
2. A pyrliometer "glitch". A steady and high global irradiation, accompanying an isolated low pyrliometer reading. Also caused by apparent temporary shading. This causes a spuriously low beam transmittance.
3. Tracking failure. A sudden sustained drop in the beam radiation data (close to zero) while global and diffuse irradiation fluctuate normally. This is caused by a power failure or slippage in the drive mechanism. Most such data is detected routinely but residual errors at the beginning of such intervals could be overlooked. Again, such faults cause spuriously low beam transmittances.
4. Partial tracking. A lower than expected beam radiation value caused by imperfect tracking. Usually this is a result of poor alignment of the mount or slippage in the drive. This fault can be detected by viewing an entire day's data as it

tends to smoothly increase or decrease.

The most direct way of measuring beam normal radiation is by using a pyrheliometer. It should be clear by the above discussion that since we are dealing with a tracking instrument, there is always the possibility of a malfunction which would produce suspicious data. The addition of the fourth pyrheliometer, mounted on an independent tracking base (since 1984) at the STEP site, was indeed necessary. It will increase the confidence on the pyrheliometer data and decrease the possibility of malfunctions causing missing data. The data though used for this work included only two measurements from the common mount pyrheliometers. To account for a pyrheliometer malfunction, the following have to be done:

1. If one of the pyrheliometer measures a very low beam normal radiation (less than  $10 \text{ KJ/m}^2$ ) then the value of that reading is changed to equal that of the other pyrheliometer.
2. If both pyrheliometers measure a low beam normal radiation, then both these values are set to zero and the period is flagged.
3. If both pyrheliometers are functioning satisfactorily, then the value used for farther analysis is the average of the two measurements.

The check for the pyrheliometer malfunctions is done only during the day time, while during the night these checks are ignored. A similar process can easily be applied in the future for four

instruments to account for the measurements of the additional pyrheliometers. The empirical error bound test was instituted primarily as a proof against grossly erroneous data. Only eighteen hours from 2,477 in the entire set were excluded for 1980.

Later in this thesis (Chapter V) the data is used in a monthly fashion, to develop monthly models. Despite the screening of the data up to this point, it was found that there were still some outliers included. A close examination of these points is desirable to determine whether or not are spurious. These points were first identified and then the corresponding daily radiation charts were examined. Only two points were justified to be spurious:

1. On January 15, 1979 during the hourly period ending at 9:30.

Looking at Figure 3.2 one can note that during this period the global value (symbolized by a cross) remains steady while the beam normal values (symbolized by a square and a circle) experience a dramatic drop. This is considered as a pyrheliometer glitch and results to a lower value of  $\tau_b$  (equal to 0.444) for a high clearness index (equal to 0.783).

2. On December 4, 1979 during the hourly period ending at 10:15.

Looking at Figure 3.3 one can identify a similar occurrence of a pyrheliometer glitch. There is an identifiable difference in the values of the two pyrheliometers which indicates that there was a problem associated with the instrument (and its tracking). Again, the result is a decrease of the beam normal value from the expected value for



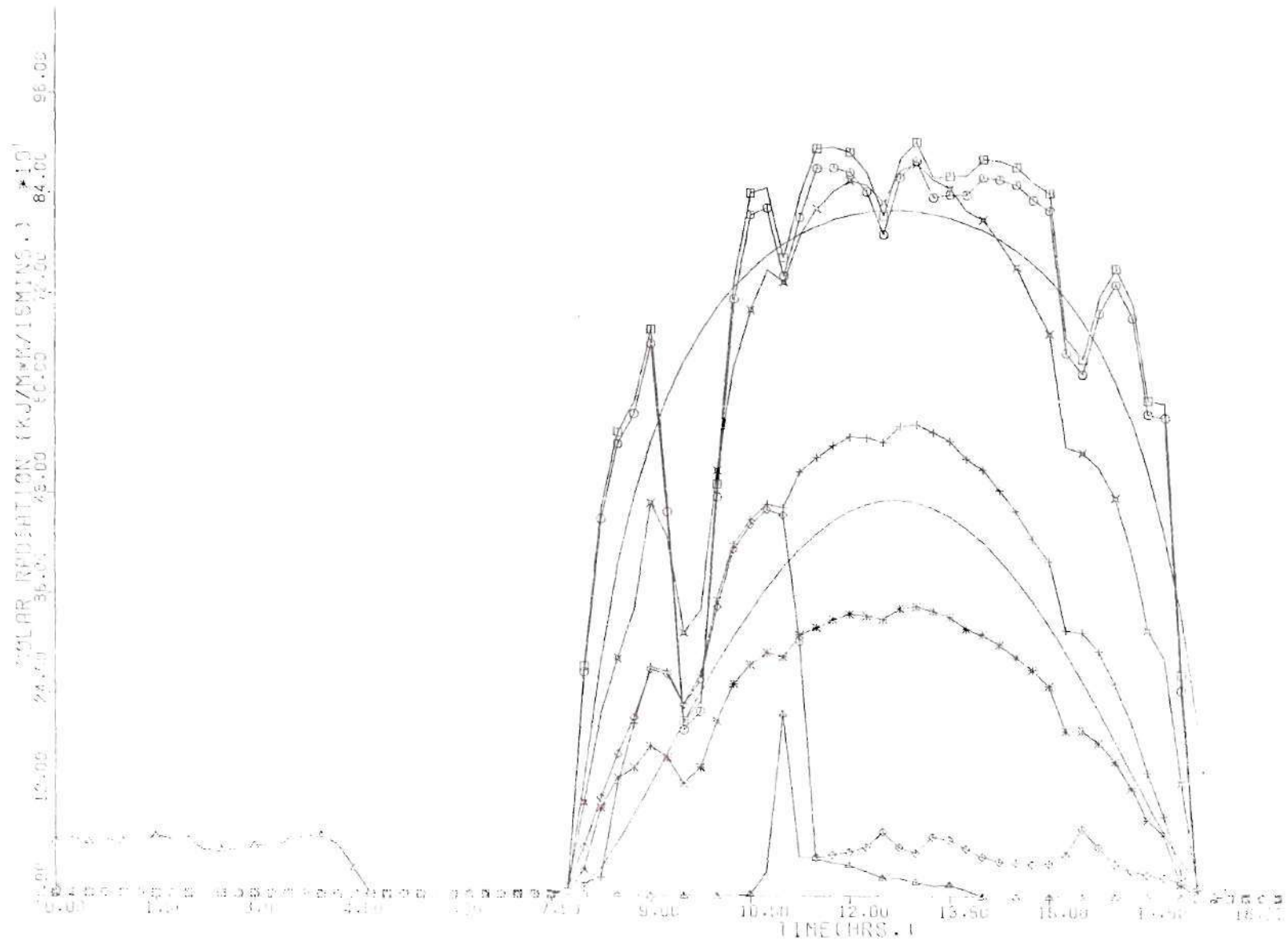


Figure 3.2. Daily Radiation Chart for January 15, 1979

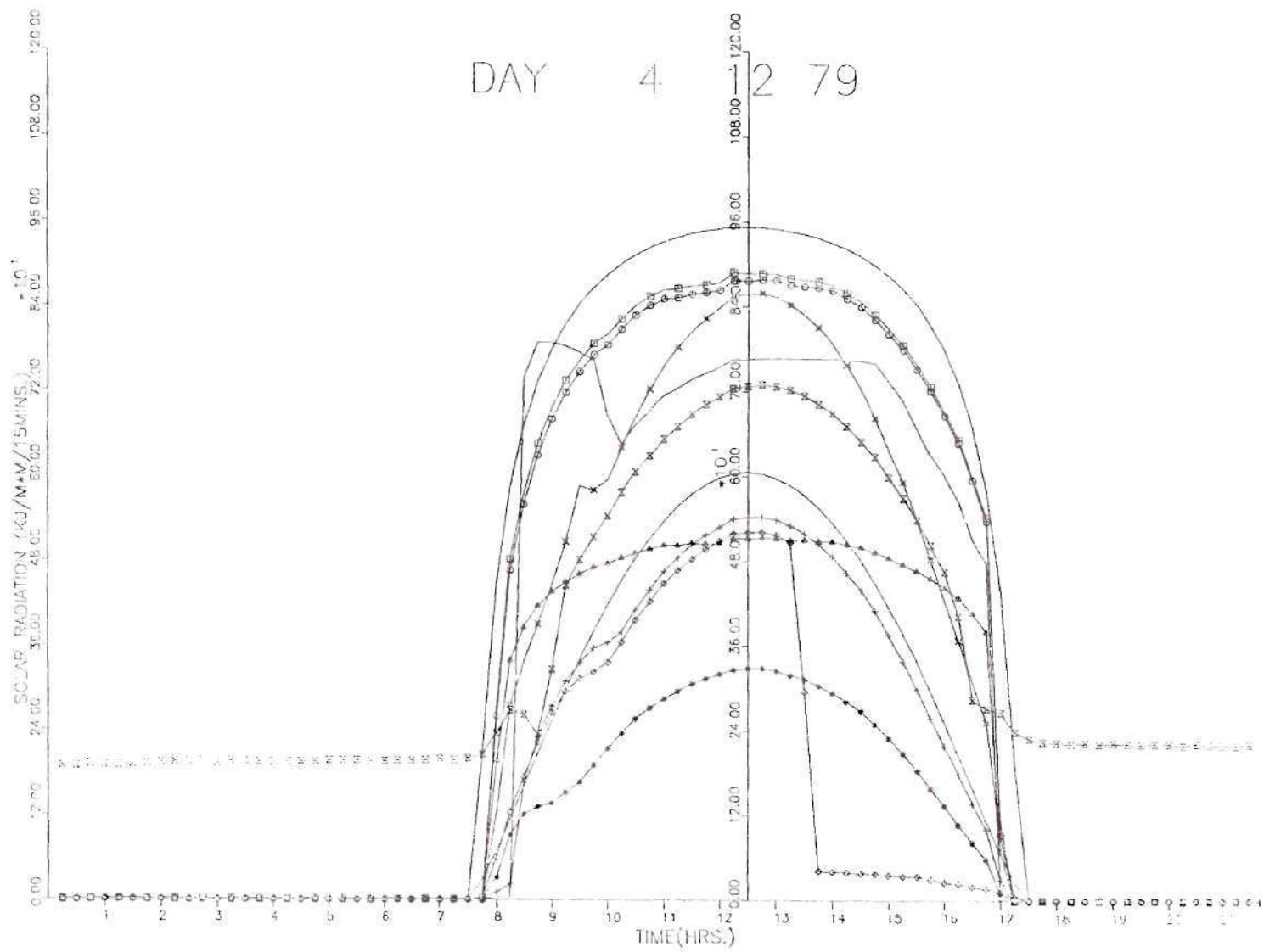


Figure 3.3. Daily Radiation Chart for December 4, 1979

a given clearness index. The expected value was about 0.9 while it was recorded as 0.615 for a clearness index of 0.754.

This close inspection confirms the reliability of the data.

### 3.5 Five Year Data Base

The resulting data base is a set of hourly irradiation values closely screened for reliability excluding data from predominantly overcast days and excluding data for very low solar altitudes (i.e. less than  $6^{\circ}$ ). Data from year 1982 was excluded due to a series of electronic and mechanical failures which degraded the performance of the monitoring system substantially. Only 41 days out of the whole year were classified as good days and from these 270 hourly periods passed all the checks and were available as usable periods. Consequently, five annual data sets were available for further analysis, which combined generate the 5-Year usable hourly data base (with a total of 8112 periods).

The important information in this data are:

1. The date, namely year, month, day, hour, and minute,
2. The radiation data, namely the direct beam and hourly global irradiation,
3. The clearness index and beam normal transmittance values, and
4. The percent of 15-minute periods and their identification, that were missing from the hour of interest.

## CHAPTER IV

## SOLAR ASTRONOMY

The availability of solar energy at the earth's surface is not uniform; it depends primarily on the optical state of the atmosphere and the apparent daily motion of the sun across the celestial vault. Thus, it is understandable that it is of vital importance to present how the angular position of the sun (relative to the center of the earth) can be expressed in terms of easily calculated declination and hour angles. The degree of accuracy for these calculations depends on the requirements of the particular application. For the purpose of this work, where we are dealing with solar radiation analysis, an accuracy of  $\pm 0.5 - 1.0$  degrees is satisfactory. A FORTRAN subroutine to implement these calculations will be described below. The algorithm provides acceptable precision and accuracy but is much more simplified compared to the one used for generating the tabular values in The American Ephemeris and Nautical Almanac which has very high accuracy (0.1 seconds of the arc). In general one should always consider the accuracy versus simplicity trade-off.

In order to fully understand this algorithm, one first needs to explain the sun's apparent motion about an observer on earth by studying both, the revolution of the earth about the sun, and the



rotation of the earth on its axis.

#### 4.1 Principles

##### 4.1.1 Determination of the Sun's Position

The position of the sun relative to a specific point on the earth varies throughout the day and season due to the spin of the earth around its axis and to its orbiting around the sun. The earth revolves around the sun in an elliptical orbit of small eccentricity. The earth's motion about the sun is affected primarily by the gravitational attraction between the earth and the sun. For simplicity, we will ignore any other influences by other planets and assume that the earth is the only celestial object orbiting about the sun. Since the sun has a much greater mass than the planets, one can assume that the sun remains approximately stationary as the earth moves in its orbit. According to Kepler's First Law (Law of Ellipses-1609) the orbit of each planet is an ellipse, with the sun at the one of the focuses, as it is indicated in Figure 4.1. The amount by which the orbit deviates from circularity, that is the eccentricity ( $e$ ) of the ellipse, is very small, and can be defined as:

$$e=c/\alpha, \quad (4.1)$$

where

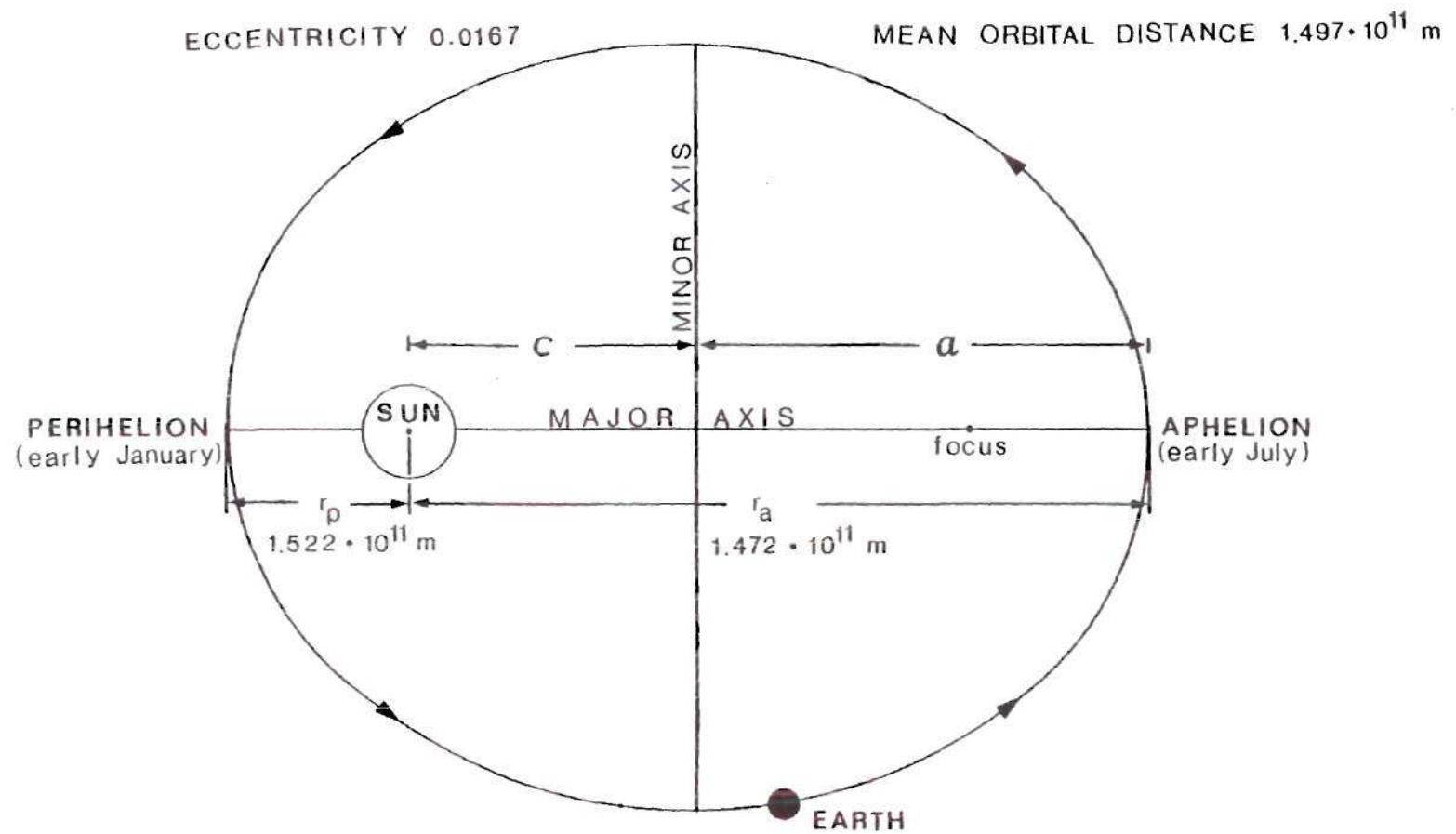


Figure 4.1. Earth's Elliptical Orbit Around the Sun

$c$  = distance from the center to a focus, and

$\alpha$  = semimajor axis.

In Figure 4.1 of course, the eccentricity of the earth's orbit is exaggerated, for illustration purposes.

The fixed plane containing the earth's orbit is called the ecliptic plane. The earth's axis of rotation is tilted at  $23^{\circ}26.5'$  (1984 value) with respect to the ecliptic plane (Figure 4.2). This angle is called the obliquity of the ecliptic,  $\epsilon$ , and it can be considered fixed for our purposes (there is an actual decrease of approximately 47 arc-sec per century).

#### 4.1.2 Calculations of the Earth's Elliptic Motion

Let  $S$  be the sun's center and  $OEO'$  the ellipse, with  $S$  at one focus, in which the earth makes its annual revolution (Figure 4.3). Consider the circle  $CE'C'$  (same area) with its center at  $S$  and its radius  $SE' = 1/2 \cdot (OO') =$  . This is a hypothetical circular orbit. The earth,  $E$ , orbiting the sun elliptic orbit is called eccentric earth, while  $E'$  orbiting the sun on a circular motion is called "mean earth". The "mean earth" is assumed to revolve about the sun with the same period as the eccentric earth.

According to Kepler's Third Law (1618) a planet moves more slowly the greater its distance from the sun in a particular fashion. One can assume that the two earths are at the same position, aligned with the sun, at the Perihelion. Starting from that point, as time

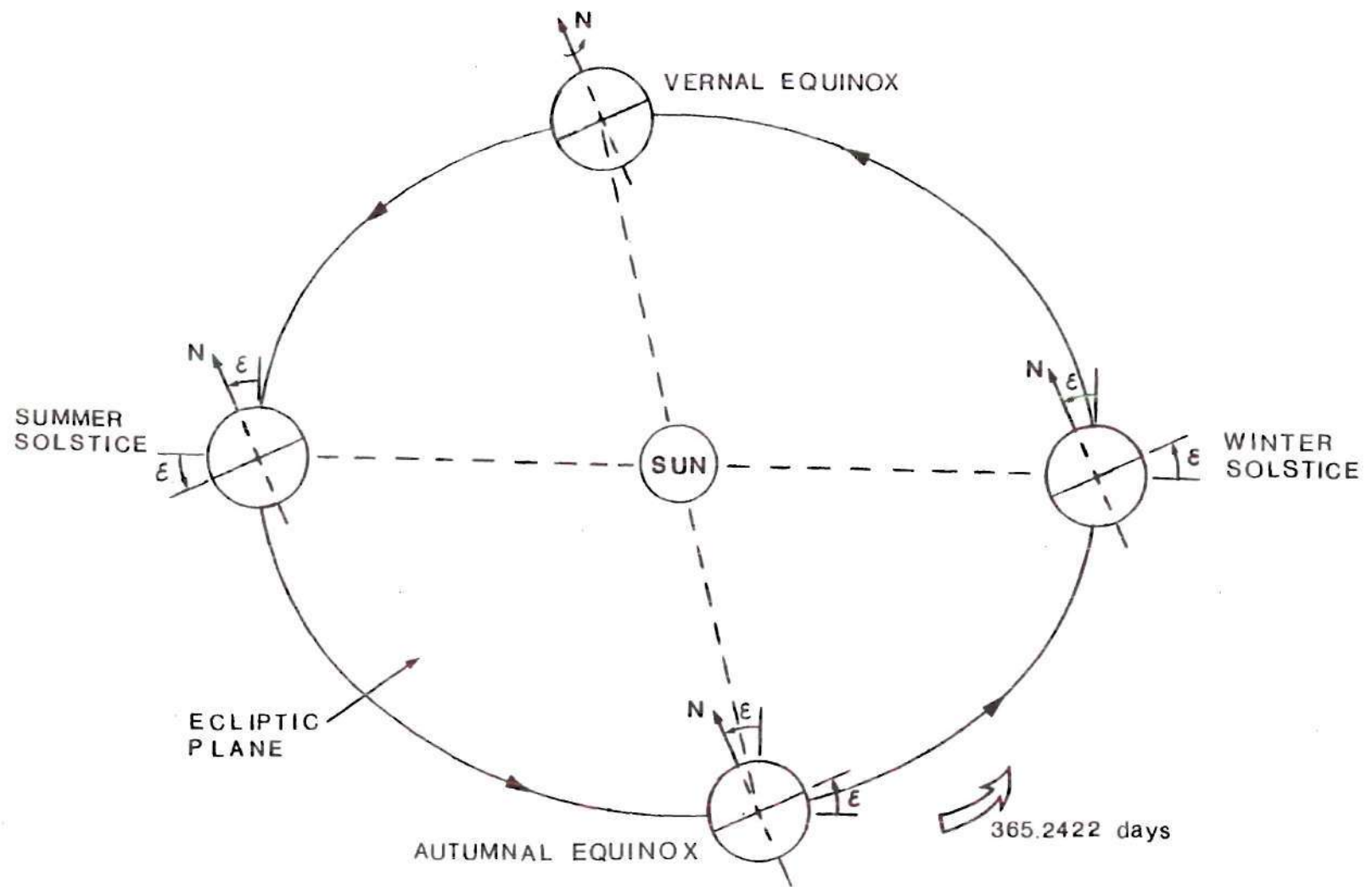
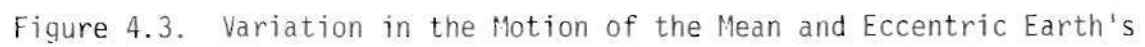


Figure 4.2. Earth's Ecliptic Plane





progresses, the "mean earth" is behind the eccentric earth. Close to the Aphelion the "mean earth" leads the eccentric earth and from there returning back towards the Perihelion, the eccentric earth progresses faster.

There are two angles of interest:  $\hat{O}SE$  and  $\hat{C}SE'$ . These angles are called respectively eccentric anomaly (TM) and mean anomaly (M). The orbital velocities according to Kepler's Second Law are non-uniform but vary in a regular fashion (Law of Equal Areas-1609). The farther the earth is from the sun, the more slowly it moves in its orbit. The speed of the planet is actually inversely proportional to the square distance at the Aphelion and the Perihelion.

The eccentric earth returns to the Perihelion in an interval called the anomalistic year (365.2596 mean solar days), which is slightly longer than the time it takes for earth to make one complete circuit of its orbit ( $360^\circ$ ) relative to the stars (sidereal year). Earth's sidereal year is equal to 365.25634 ephemeris days (or  $3.155815 \cdot 10^7$  seconds). This is due to the influence of the planets on the axis of the earth's orbit. The mean earth completes its orbit during the same period but it travels at a constant angular rate. As a result, when both the eccentric and mean earth make a complete revolution around the sun, they are again aligned with the sun's position at the Perihelion. Since the anomalistic year is 365.2596 days, the mean anomaly (M) is:

$$M = M_0 + (360/365.2596 \text{ days}) \cdot d, \quad (4.2)$$

where

$M_0$  = mean anomaly at standard epoch, and

$d$  = time in days in Universal time since the standard epoch.

An epoch is simply another aspect of time, and it is no more than a point of time selected as a fixed reference. It so happens that a scholar named Joseph Scaliger in 1582 first conceived the idea and proposed the Julian System. This system takes as the arbitrary initial epoch 12:00 UT January 1, 4713 BC. The Julian Date (JD) at this instant was by definition zero. It is obvious that such an early starting epoch creates large numbers laborious to handle in calculations. Various other fundamental epochs have been suggested and in many cases the standard epoch is considered to be 12:00 UT, January 1, 2000 (or indicated as J 2000). Then Equation 4.2 becomes:

$$M = 357.528 + 0.985600 \cdot d. \quad (4.3)$$

Equation (4.3) is equivalent to the "low precision" formulas given in Reference [27] and [28] and should be accurate to  $0.01^\circ$  until year 2050.

The time of a phenomenon in days since 0 January 0<sup>h</sup> UT,  $d$ , is calculated from:

$$d=N+(6^h-\lambda)/24 \quad (\text{morning}), \text{ or} \quad (4.4)$$

$$d=N+(29^h-\lambda)/24 \quad (\text{evening}), \quad (4.5)$$

where

$N$  - day of the year, and

$\lambda$  = sun's true longitude, in hours.

The true longitude,  $\lambda$ , is just

$$\lambda = TM + \beta, \quad (4.6)$$

where

$\beta$  = longitude of Perihelion.

It is desirable that we have available an expression to calculate the earth-sun distance, since the solar radiation arriving on the top of the earth's atmosphere varies with the square of the distance to the sun. Reference [29] provides a relation based on the mean anomaly ( $M$ ):

$$R_M = 1.00014 - 0.01671 \cdot \cos(M) - 0.00014 \cdot \cos(2 \cdot M). \quad (4.7)$$

The units of  $R_m$  (the mean distance between the earth and the sun) are in astronomical units (AU). The astronomical unit is defined as the length of the radius of the unperturbed circular orbit of a body of negligible mass (compared to the sun) moving around the sun with a sidereal angular velocity of 0.017202098950 radian per day of 86,400 ephemeris seconds ( $1\text{AU}=1.4959787 \cdot 10^{11}\text{m}$ ).

#### 4.2 The Celestial Vault

For many purposes, star positions may be represented by points on the surface of an imaginary sphere of arbitrary radius, centered on the earth's center. Such a unit sphere is called the Celestial Vault. The rotation axis of the earth intersects this sphere at the north and south celestial poles. The projection of the earth's equatorial plane onto the celestial vault and containing the center, is called the celestial equator or the equinoctial (Figure 4.4). The equator's plane is perpendicular to the axis of apparent rotation of the celestial vault and it is everywhere  $90^\circ$  from both celestial poles. The intersection of the great circle of the celestial sphere, in which the sun appears to perform its annual movement (the ecliptic), with the celestial equator provides two fixed points on the celestial equator,  $180^\circ$  apart (since both are great circles). These intersections are the equinoctial points (Vernal and Autumnal equinoctial points) or equinoxes. The points on the ecliptic that are  $90^\circ$  from the equinoxes are the solstitial points or solstices. An alternative term for the

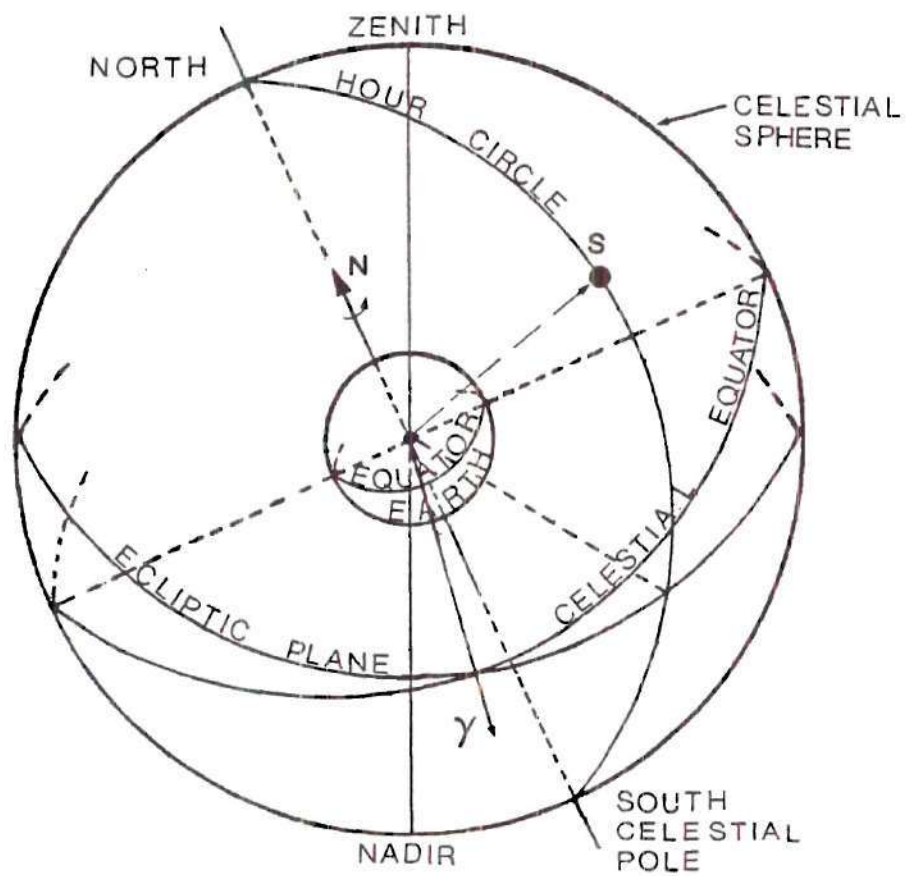


Figure 4.4. The Basic Lines and Points of the Celestial Vault



Vernal equinox is the First Point of Aries ( $\gamma$ ). The great circle normal to the celestial equator and passing through the sun, is called the hour circle.

#### 4.2.1 Celestial Coordinate Systems

The position of the stars on the celestial vault can be defined by two perpendicular or curvilinear coordinates. There are four available reference planes:

- A. The Ecliptic System,
- B. The Equatorial System,
- C. The Hour Angle System, and
- D. The Horizontal System.

A. The Ecliptic System. The primary reference plane is the ecliptic and the secondary is the ecliptic meridian of Aries (Figure 4.5). The direction of the sun, point S, can be defined by the ecliptic latitude and the ecliptic longitude. The ecliptic latitude,  $\beta$ , is the angular distance between the direction of the observer to the sun and the ecliptic measured in the ecliptic meridian of S from  $0^\circ$  to  $90^\circ$ . It is positive when measured northward and negative southward the complement of the true latitude is the true polar distance. The true (or ecliptic) longitude,  $\lambda$ , is the angle between the ecliptic meridian of the sun and that of the equinox measured from the vernal equinox,  $\gamma$ , to the east, in the ecliptic from  $0^\circ$  to  $360^\circ$ .

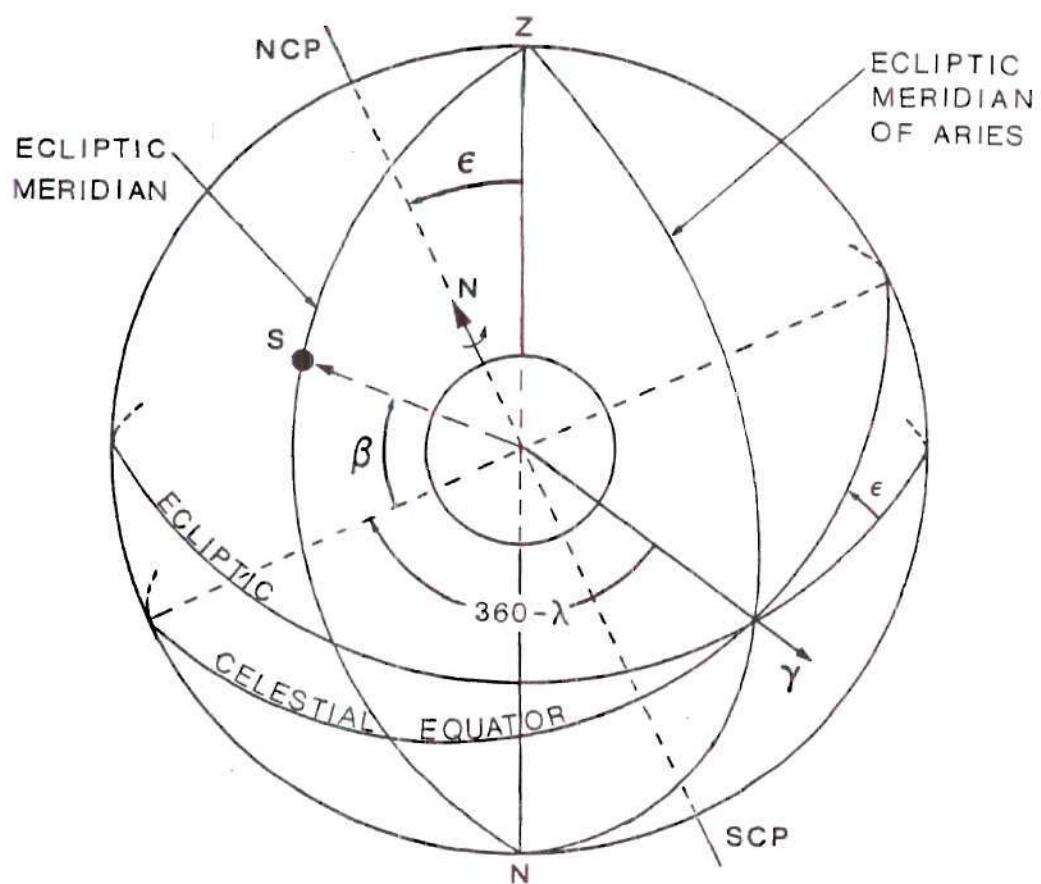


Figure 4.5. The Ecliptic System of Coordinates ( $\beta$  and  $\lambda$ )

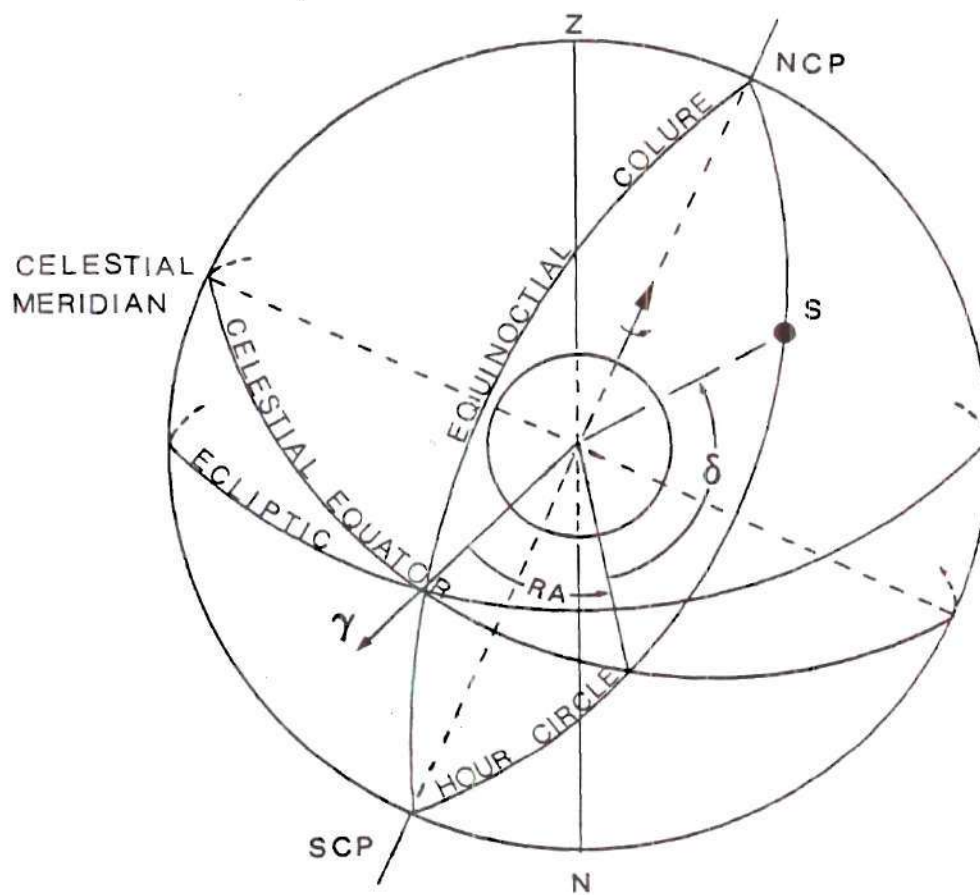


Figure 4.6. The Equatorial System of Coordinates ( $\delta$  and RA)

B. The Equatorial System. The primary reference plane is the celestial equator and the secondary is the plane defined by the NCP and SCP on the celestial vault - the equinoctial colure (Figure 4.6). Let S be the arbitrary position of the sun on the celestial vault. Its direction is given by the declination,  $\delta$ , and the right ascension, RA. The right ascension is the angle between the hour angle of S and the equinoctial colure, measured from the vernal equinox,  $\gamma$ , to the east in the plane of the celestial equator from  $0^h$  to  $24^h$  or from  $0^\circ$  to  $360^\circ$ .

C. The Hour Angle System. The primary reference is the celestial equator and the secondary is the hour circle containing the observer's celestial meridian (Figure 4.7). The direction of the sun, point S, can be defined by the hour angle and declination. The hour angle,  $\omega$ , is the angular distance between the hour circle and the observer's meridian. It is positive when measured westward from the observer. The declination,  $\delta$ , is the angular distance from the celestial equator to the sun measured on the hour circle. It is taken with a positive sign on the northern half of the celestial sphere and with a negative sign on the southern half.

D. The Horizontal System. The primary plane is the celestial meridian (Figure 4.8). The direction of the sun, point S, can be defined by the elevation and the azimuth. The elevation,  $\alpha$ , is the





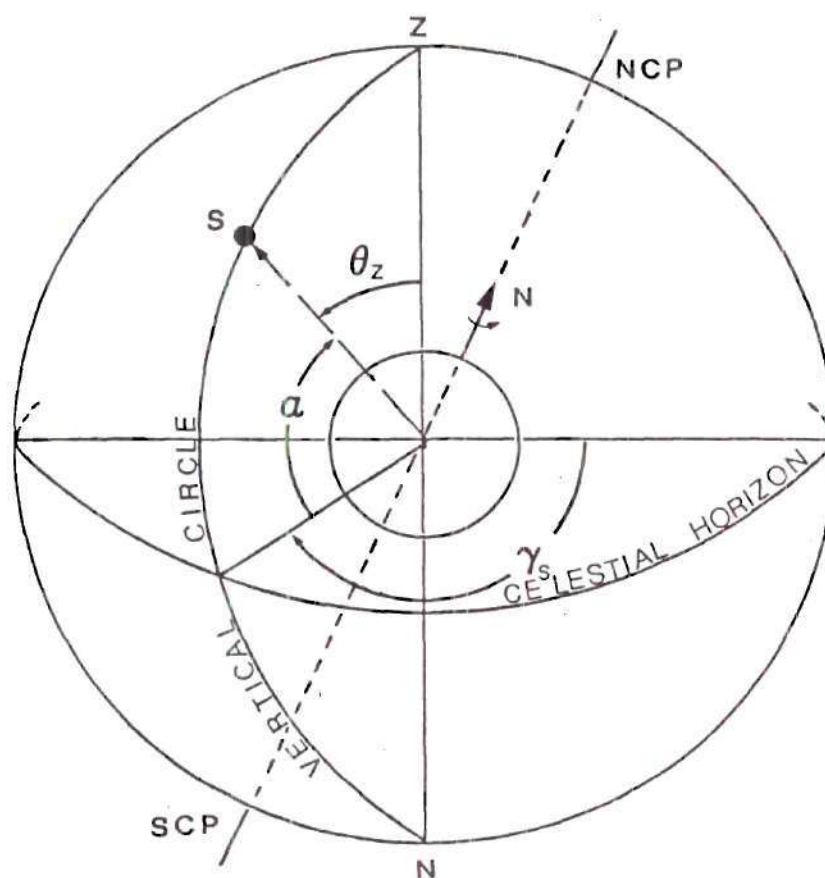


Figure 4.8. The Horizontal System of Coordinates ( $a$  and  $\gamma_s$ )

angular distance between the direction of the observer and the sun and the celestial horizon measured from  $0^\circ$  to  $90^\circ$  in the plane of the vertical circle through the position of the sun. It is considered positive above the horizon and with a negative sign below. Its complement is called zenith angle,  $\theta_z$ . The azimuth angle,  $\gamma_s$ , is the angular distance between the vertical plane of the sun and the celestial meridian of the observer measured from the direction of the north point to the east in the celestial horizon from  $0^\circ$  to  $360^\circ$ .

#### 4.2.2 Conversions Between the Equatorial and Ecliptic Systems

Consider the celestial vault in Figure 4.9 where the equatorial and ecliptic systems are shown together. We can note immediately that for the north ecliptic pole  $RA=270^\circ$  and the longitude of the north celestial pole is  $90^\circ$ . The following relations may be obtained by applying the laws of sine, cosine and the five elements of spherical trigonometry on the spherical triangle (Figure 4.10). The resulting sets of equations are [30]:

$$\cos\delta \cdot \cos(RA) = \cos\beta \cdot \cos\lambda, \quad (4.8)$$

$$\sin\delta = \cos\beta \cdot \sin\lambda \cdot \sin\epsilon + \sin\beta \cdot \cos\epsilon, \quad (4.9)$$

$$\cos\delta \cdot \sin(RA) = \cos\beta \cdot \sin\lambda \cdot \cos\epsilon - \sin\beta \cdot \sin\epsilon, \quad (4.10)$$

$$\cos\beta \cdot \cos\lambda = \cos\delta \cdot \cos(RA), \quad (4.11)$$

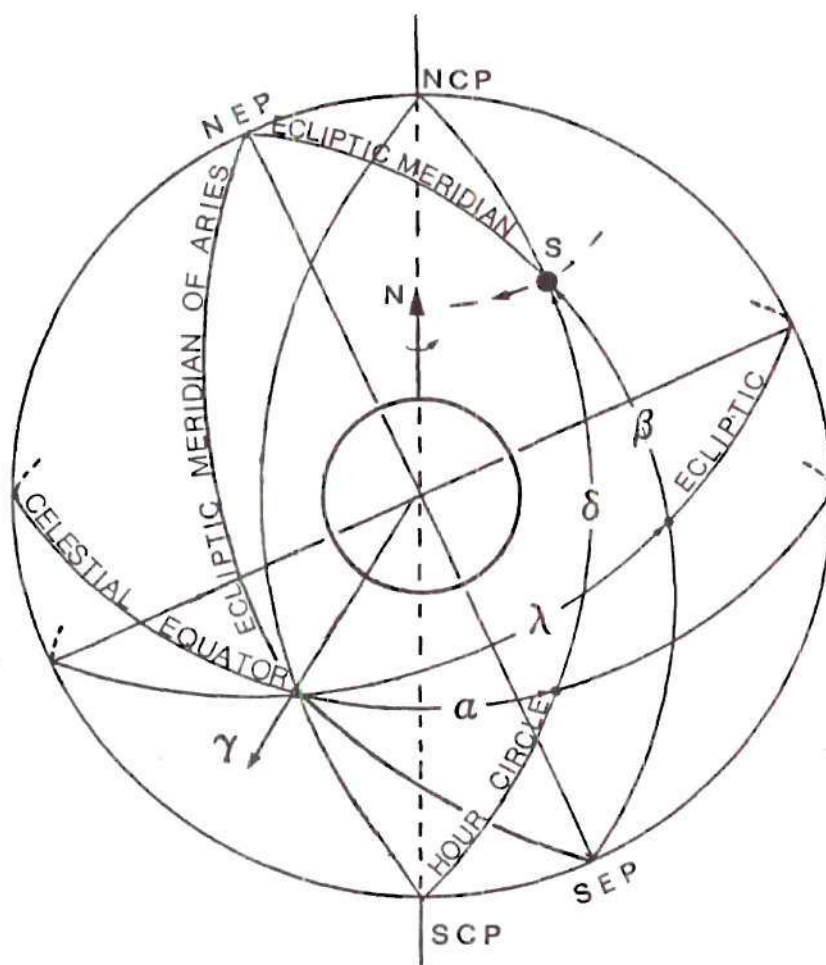


Figure 4.9. Relations Between the Equatorial and Ecliptic System

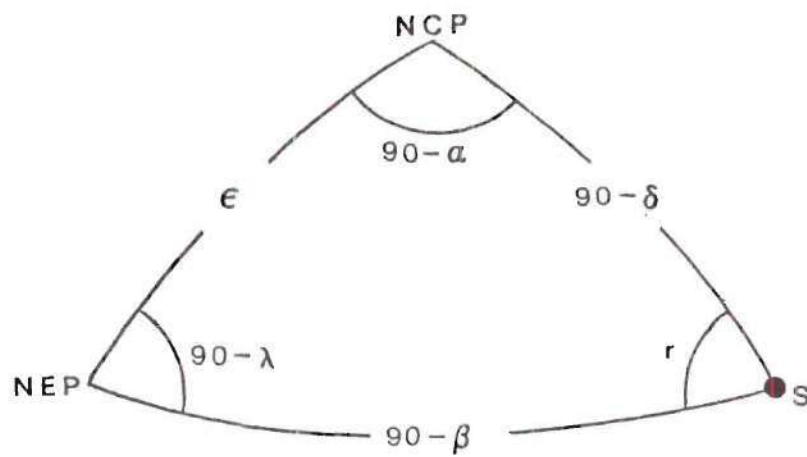


Figure 4.10. The Ecliptic Triangle

$$\sin\beta = -\cos\delta \cdot \sin(RA) \cdot \sin\epsilon + \sin\delta \cdot \cos\epsilon, \text{ and} \quad (4.12)$$

$$\cos\beta \cdot \sin\lambda = \cos\delta \cdot \sin(RA) \cdot \cos\epsilon + \sin\delta \cdot \sin\epsilon. \quad (4.13)$$

If the ecliptic parameters  $\epsilon, \lambda, \beta$  are known, then RA is found by dividing Equation 4.10 by Equation 4.8, i.e.

$$\tan(RA) = \tan\lambda \cdot \cos\epsilon - \tan\beta \cdot \sin\epsilon / \cos\lambda, \quad (4.14)$$

and  $\delta$  is given by Equation 4.9.

If the equatorial parameters RA,  $\delta, \epsilon$  are known, then  $\lambda$  is found by dividing Equation 4.13 by 4.11, i.e.

$$\tan\lambda = \tan(RA) \cdot \cos\epsilon + \tan\delta \cdot \sin\epsilon / \cos(RA), \quad (4.15)$$

and  $\beta$  is given by Equation 4.12. To determine the appropriate quadrant of RA or  $\lambda$  one can check the corresponding sines and the signs of the cosines.

#### 4.2.3 Conversions Between the Hour Angle and Equatorial Systems

For practical calculations the hour angle is more useful than the right ascension, since it accounts for the observer's local



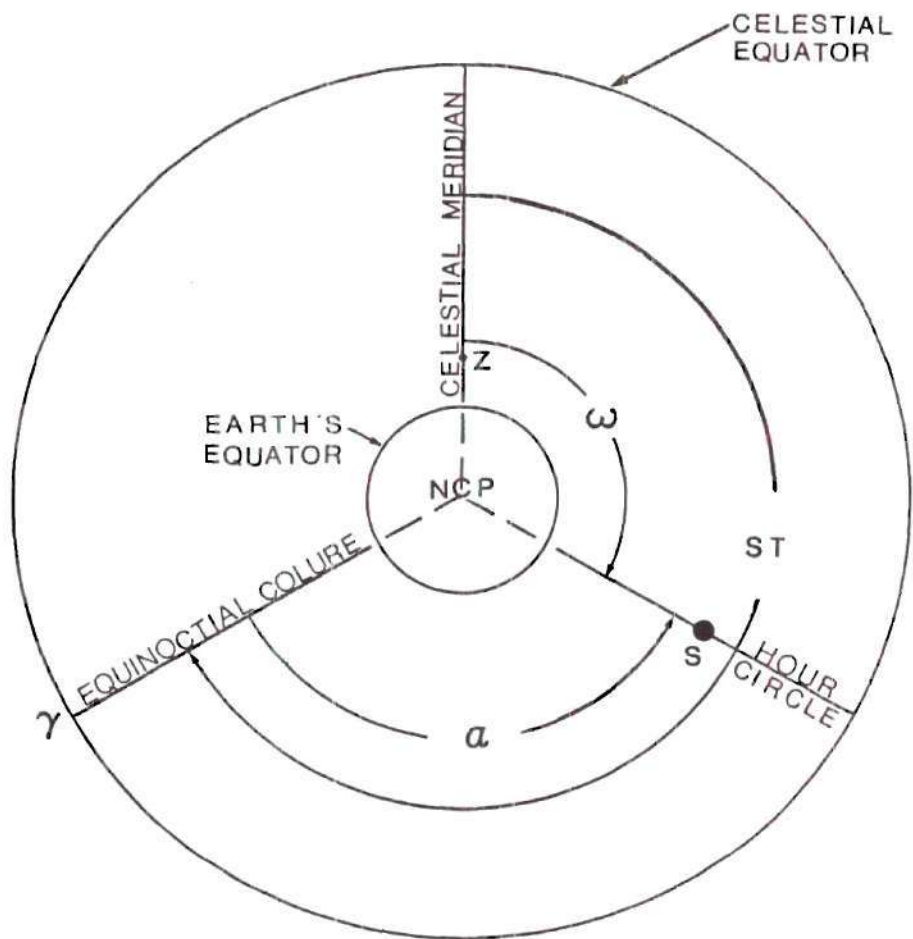


Figure 4.11. Relations Between the Hour Angle and Equatorial Systems

meridian and changes with the diurnal motion of the rotating earth. Both systems though use the equatorial plane as their primary reference thus, the declination is a common parameter.

Let us consider the celestial equator, viewed from the north celestial pole. From Figure 4.11 one can identify the Local Sidereal Time (LST) defined as the hour angle of the vernal equinox:

$$\text{LST} = \omega + \text{RA}. \quad (4.16)$$

If LST and hour angle parameter,  $\omega$ , are known, then RA is found by:

$$\text{RA} = \text{LST} - \omega. \quad (4.17)$$

If the equatorial parameter (RA) is known, then  $\omega$  is found by:

$$\omega = \text{LST} - \text{RA}. \quad (4.18)$$

#### 4.2.4 Conversions Between the Horizontal and Hour Angles System

Consider the northern half of the celestial vault as shown in Figure 4.12. The relations between the parameters of the horizon and the hour angle may be derived again by using the astronomic triangle

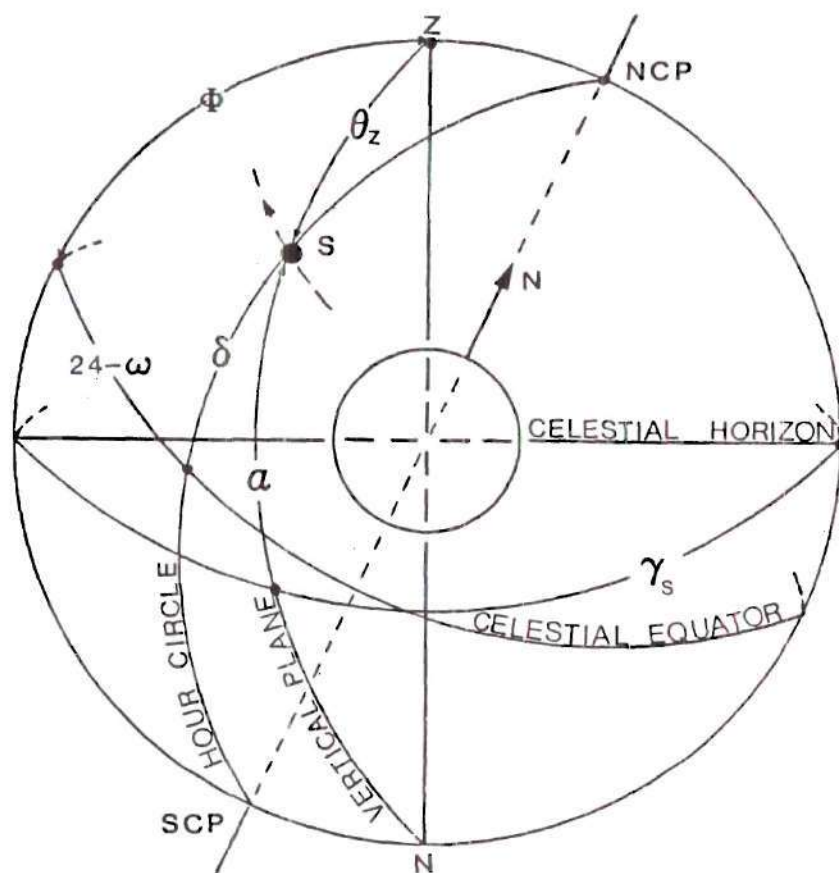


Figure 4.12. Relations Between the Horizontal and Hour Angle Systems

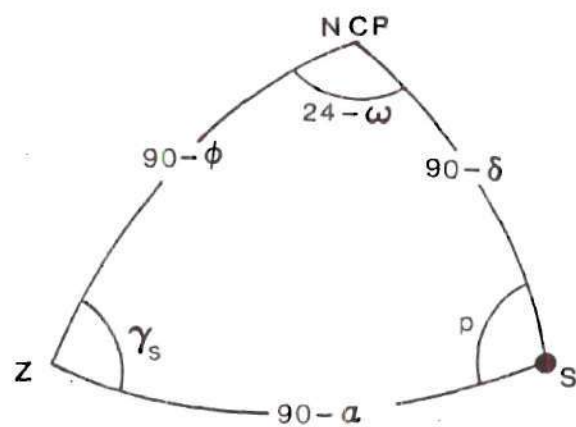


Figure 4.13. The Astronomical Triangle

$\triangle$   
ZNCPS and the basic laws of spherical trigonometry [30].

This analysis will result to the following transformation equations applied to Figure 4.13:

$$\sin \theta_Z \cdot \sin \gamma_S = -\cos \delta \cdot \sin \omega, \quad (4.19)$$

$$\cos \theta_Z = \sin \delta \cdot \sin \phi + \cos \delta \cdot \cos \omega \cdot \cos \phi, \quad (4.20)$$

$$\sin \theta_Z \cdot \cos \gamma_S = \sin \delta \cdot \cos \phi - \cos \delta \cdot \cos \omega \cdot \sin \phi, \quad (4.21)$$

$$\cos \delta \cdot \sin \omega = -\sin \theta_Z \cdot \sin \gamma_S, \quad (4.22)$$

$$\sin \delta = \cos \theta_Z \cdot \sin \phi + \sin \theta_Z \cdot \cos \gamma_S \cdot \cos \phi, \text{ and} \quad (4.23)$$

$$\cos \delta \cdot \cos \omega = \cos \theta_Z \cdot \cos \phi - \sin \theta_Z \cdot \cos \gamma_S \cdot \sin \phi. \quad (4.24)$$

where

$\phi$  = astronomical or geographical latitude of a plane on the earth's surface, which is the complement of the acute angle between the astronomical vertical and the earth's axis of rotation, positive (negative) in the northern (southern) hemisphere.

The astronomical vertical (ZN) is a line determined by the direction of the local gravitational field.

If the hour angle parameters  $\omega$ ,  $\delta$ ,  $\phi$  are known then the azimuth angle is found by dividing Equation 4.19 by Equation 4.21, i.e.

$$\tan \theta_Z = -\cot \delta \cdot \sin \omega / \cos \phi + \tan \omega \cdot \sin \phi, \quad (4.25)$$



and the zenith angle is given by Equation 4.20.

If the horizon parameters are available  $\theta_z, \gamma_s, \phi$  then the hour angle is found by dividing Equation 4.22 by 4.24, i.e.

$$\tan \omega = -\tan \theta_z \cdot \sin \gamma_s / \cos \phi + \tan \gamma_s / \sin \phi, \quad (4.26)$$

and the declination is given by Equation 4.23.

#### 4.3 Algorithm for Calculating the Position of the Sun

The preceeding discussion should help the reader to understand and use the fundamental relations in the FORTRAN subprograms included in APPENDIX B. Subroutine HELGO (named after the Greek words Heliaci-Gonia, Solar Angle) is primarily based on subprograms written at the McDonnell Douglas Corporation [31], to control the tracking of a high performance modular dish collector system with an advanced heat engine receiver.

##### 4.3.1 Basic Equations for Calculating the Position of Sun

The basic equations used in this subroutine (HELGO) are essentially the so-called "lower precision" formulae from the

Almanac for Computers . The incorporation of this subroutine in the present analysis was based on the desire to use a simple but accurate subroutine to perform the calculations for the position of the sun.

Some rather interesting refinements are included in HELGO, in order to obtain the most accurate results:

1. A polynomial expression in terms of  $\alpha$  is used for the correction for the atmospheric refraction. This correction is most valid for low elevations,  $\alpha$ , and is not applied for less than  $5^\circ$ . This should amount for nearly all cases of practical interest.
2. An expression for the change in the orbital eccentricity is included to refine the value computed for the ecliptic longitude.
3. An expression for the change in obliquity is also included.

The main part of subroutine HELGO computes the declination,  $\delta$ , the equation of time,  $E_T$ , and the distance of sun-earth. Function GAST, is a function subprogram that computes the Greenwich Apparent Siderial Time accurately using the equation of Equinoxes. Finally, Function XJDAY, is a function that computes the Julian date.

The irregularities in the earth's rate of rotation make Universal Time (the local mean time of the prime meridian) unsuitable for the comparison of theory with observation. This fact created the obvious need to be able to define with precision on a uniform time scale the instant of some phenomenon or observation. That was previously called an epoch (J 2000). The time interval elapsed between

two epochs measured in units of some time scale, is the so called time interval and for this system:

$$d = JD - TREF, \quad (4.27)$$

where

$$TREF = 2451545,$$

or

$$d = -5479.5 - N + UT/24, \quad (4.28)$$

where

$N$  = number of whole days since 0 UT, 0 January 1985.

The world is divided into twenty-four zones each having a width of 15 degrees (one hour) of longitude, in each of which the same standard time is kept. The meridian of Greenwich is taken as the reference point and namely zone zero. Zones to be east are numbered  $ZONE = -1, -2, -3, \dots$  and those to the west  $ZONE = 1, 2, 3, \dots$  according to the number of hours to be added to the local standard time (CVLT). Thus,

$$UT = CVLT + ZONE. \quad (4.29)$$

The STEP site is located west of Greenwich, five zones, which gives the Universal Time to be used for the locality as

$$UT = CVLT + 5 \quad (\text{in hours}). \quad (4.30)$$

In addition to the above, since 1966, for six months each year (from the last Sunday in April to the last Sunday in October) the time in each zone is advanced one hour, thus defining the daylight savings time (DST).

To determine  $\delta$  and  $\omega$  a change should be made from the horizontal plane to the equatorial reference system. The calculation of  $\omega$  from the RA was analyzed in the previous sections of this chapter. As a point of caution, one must always make sure that the hour angle is in the correct quadrant. To eliminate the ambiguity of sign or quadrant, use of the two argument arctangent function is suggested. Otherwise numerous problems would arise and certainly an error will be introduced in the following calculations. Once the value of  $\omega$  is calculated in degrees, one can easily obtain the apparent solar time (AST)

$$AST = \omega + 12^h, \quad (4.31)$$

so at  $\omega=0$ , AST=12 noon. Similarly the mean solar time (MST)

$$\text{MST} = \text{LST} + (\mathcal{L}_{\text{st}} - \mathcal{L}), \quad (4.32)$$

where

LST = local standard time,

$\mathcal{L}_{\text{st}}$  = standard longitude,  $75^\circ\text{W}$ , and

$\mathcal{L}$  = longitude of the locality,  $84.7076^\circ\text{W}$ .

All the necessary parameters to calculate the equation of time ( $E_T$ ) are available at this point. The  $E_T$  is defined as the difference between the apparent and mean solar time:

$$E_T = \text{AST} - \text{MST} \quad (\text{in minutes}). \quad (4.33)$$

The equation of time may also be defined as the quantity which must be added to the mean longitude of the sun to give the sun's right ascension. What causes the necessity to define the principle of  $E_T$  is:

1. The eccentricity of earth's orbit, and
2. The obliquity of earth's orbit,

namely



$$E_T = E_1(\text{eccentricity}) + E_2(\text{obliquity}). \quad (4.34)$$

At Greenwich, apparent solar noon varies between  $11^h 44^m 05^s$  and  $12^h 14^m 19^s$ . Maximum contribution from earth's orbital eccentricity is approximately eight minutes; from earth's obliquity is approximately ten minutes. AST and MST agree four times a year. An approximate expression for  $E_T$  (Watt's equation) is also available

$$E_T = 9.87 \cdot \sin(2 \cdot D) - 7.53 \cdot \cos(D) - 1.5 \cdot \sin(D) \quad (\text{in minutes}), \quad (4.35)$$

where

$$D = 360 \cdot (n - 81) / 364, \text{ and}$$

$$n = \text{day of the year } 1 < n < 365.$$

The results are valid for any year reasonably close to the present.

The apparent solar time, numerically measured by the hour angle of the sun plus  $12^h$ , is no longer of importance in time keeping. In the American Ephemeris and the British Astronomical Ephemeris, since 1965, the equation of time was eliminated and replaced by the Ephemeris Time of transit of the sun, and no reference was any longer made to apparent solar time. However, in applications to solar engineering, navigation and surveying, there is still need for means to determine the hour angle of the sun. In such cases one should recall that AST is

a time scale paced according to the apparent sun such that:

$$\omega = (\text{AST} - 12.0) \cdot 15^\circ/\text{hr.} \quad (4.36)$$

In this time scale  $\omega$  equals zero when AST equals 12:00 (solar noon) or when the apparent sun is due south.

#### 4.3.2 Results Using Subroutine Helgo

Subroutine HELGO was developed in order to replace the one used in [17], in an attempt to improve the accuracy of the modeling procedures. The results from both subroutines were compared against the 1983 Nautical Almanac [32] at 12:00 noon local Greenwich time. Program TABLE3 utilizes both methods and compares the corresponding values with the ones from the Almanac. A commented copy of the program is included in APPENDIX B. A part of the results from the above comparison, for January 1983, is given in Table 4.1. There are three groups of results, each including the declination, the hour angle and equation of time. The first set of data includes the results from subroutine DAILY used in [17], namely the declination by Cooper's equation and the equation of time by Watt's method. The second set of data includes the results from subroutine HELGO and the last set of data is from the Nautical Almanac. Annual results of the comparison of

Table 4.1. Daily Values of the Declination, Hour Angle, and Equation of Time from Subroutines DAILY, HELGO, and the Nautical Almanac for the month of January 1983

DAY	DAILY (17)					HELGO					NAUTICAL ALMANAC (32)				
	DELTA		OMEGA		EOT	DELTA		OMEGA		EOT	DELTA		OMEGA		EOT
	(DEGR-MIN)	(COOPER)	(DEGR-MIN)	(WATT)		(DEGR-MIN)	(DEGR-MIN)	(DEGR-MIN)	(DEGR-MIN)		(DEGR-MIN)	(DEGR-MIN)	(DEGR-MIN)	(DEGR-MIN)	(MIN-SEC)
1	-23	70	0	-47.82	-3 11.27	-23	1.60	0	-51.47	-3 25.86	-23	1.6	359	8.9	-3 24.0
2	-22	55.83	0	-53.67	-3 34.69	-22	56.55	0	-58.54	-3 54.15	-22	56.5	359	1.9	-3 52.0
3	-22	50.56	0	-59.48	-3 57.93	-22	51.04	-1	5.52	-4 22.09	-22	51.0	358	54.9	-4 20.0
4	-22	44.88	-1	5.25	-4 20.99	-22	45.08	-1	12.42	-4 49.66	-22	45.0	358	48.1	-4 47.0
5	-22	38.80	-1	10.96	-4 43.84	-22	38.66	-1	19.21	-5 16.83	-22	38.6	358	41.3	-5 14.0
6	-22	32.31	-1	16.61	-5 6.46	-22	31.80	-1	25.89	-5 43.57	-22	31.8	358	34.6	-5 41.0
7	-22	25.42	-1	22.21	-5 28.83	-22	24.49	-1	32.46	-6 9.86	-22	24.5	358	28.0	-6 7.0
8	-22	18.14	-1	27.74	-5 50.94	-22	18.74	-1	38.91	-6 35.65	-22	18.7	358	21.6	-6 33.0
9	-22	10.45	-1	33.19	-6 12.77	-22	8.56	-1	45.24	-7 9.94	-22	8.5	358	15.2	-6 59.0
10	-22	2.38	-1	38.58	-6 34.31	-21	59.94	-1	51.42	-7 25.69	-21	59.9	358	9.0	-7 23.0
11	-21	53.91	-1	43.88	-6 55.52	-21	50.88	-1	57.47	-7 49.88	-21	50.9	358	3.0	-7 48.0
12	-21	45.05	-1	49.10	-7 16.40	-21	41.41	-2	3.37	-8 13.49	-21	41.4	357	57.1	-8 11.0
13	-21	35.81	-1	54.23	-7 36.94	-21	31.51	-2	9.12	-8 36.49	-21	31.5	357	51.3	-8 34.0
14	-21	26.18	-1	59.28	-7 57.10	-21	21.20	-2	14.71	-8 58.86	-21	21.2	357	45.7	-8 57.0
15	-21	16.17	-2	4.22	-8 16.89	-21	10.48	-2	20.15	-9 20.58	-21	10.5	357	40.2	-9 19.0
16	-21	5.78	-2	9.07	-8 36.28	-20	59.35	-2	25.41	-9 41.64	-20	59.4	357	35.0	-9 40.0
17	-20	55.02	-2	13.81	-8 55.25	-20	47.82	-2	30.50	-10 2.01	-20	47.8	357	29.9	-10 0.0
18	-20	43.88	-2	18.45	-9 13.79	-20	35.89	-2	35.42	-10 21.68	-20	35.9	357	25.0	-10 20.0
19	-20	32.38	-2	22.97	-9 31.89	-20	23.57	-2	40.16	-10 40.63	-20	23.6	357	20.2	-10 39.0
20	-20	20.51	-2	27.38	-9 49.54	-20	10.87	-2	44.71	-10 58.85	-20	10.9	357	15.7	-10 57.0
21	-20	8.28	-2	31.68	-10 6.71	-19	57.79	-2	49.08	-11 16.33	-19	57.8	357	11.3	-11 14.0
22	-19	55.69	-2	35.85	-10 23.39	-19	44.34	-2	53.26	-11 33.04	-19	44.4	357	7.1	-11 31.0
23	-19	42.75	-2	39.89	-10 39.58	-19	30.52	-2	57.25	-11 48.99	-19	30.6	357	3.2	-11 47.0
24	-19	29.46	-2	43.81	-10 55.25	-19	16.34	-3	1.04	-12 4.16	-19	16.4	356	59.4	-12 2.0
25	-19	15.82	-2	47.60	-11 10.40	-19	1.80	-3	4.64	-12 18.54	-19	1.9	356	55.8	-12 16.0
26	-19	1.84	-2	51.25	-11 25.01	-18	46.92	-3	8.03	-12 32.13	-18	47.0	356	52.4	-12 30.0
27	-18	47.52	-2	54.77	-11 39.07	-18	31.70	-3	11.23	-12 44.92	-18	31.8	356	49.3	-12 43.0
28	-18	32.86	-2	58.14	-11 52.58	-18	16.13	-3	14.22	-12 56.90	-18	16.2	356	46.3	-12 55.0
29	-18	17.88	-3	1.38	-12 5.51	-18	1.24	-3	17.02	-13 8.06	-18	1.3	356	43.5	-13 6.0
30	-18	2.57	-3	4.46	-12 17.86	-17	44.03	-3	19.60	-13 18.41	-17	44.1	356	41.0	-13 16.0
31	-17	46.94	-3	7.40	-12 29.62	-17	27.50	-3	21.99	-13 27.95	-17	27.6	356	38.6	-13 25.0

HELGO and DAILY with the values from the Nautical Almanac are given in Table 4.2 in terms of maximum error and root mean square error (RMS).

Table 4.2. Comparison of the Error Coefficients Between Subroutines HELGO and DAILY

VARIABLE	ERRORS COMPARED TO 1983 NAUTICAL ALMANAC			
	HELGO		DAILY	
	MAXIMUM	RMS	MAXIMUM	RMS
$\delta$	0.006°	0.002	1.196°	0.548
E	0.057 min	0.028	1.581 min	0.634

The annual results for the declination calculated by the two subroutines are compared with the values from the Almanac in Figure 4.14. The error using HELGO is:

$$\epsilon_1 = \delta - \delta_h, \quad (4.37)$$

where

$\delta$  = declination value from Almanac, and

$\delta_h$  = declination predicted by HELGO.

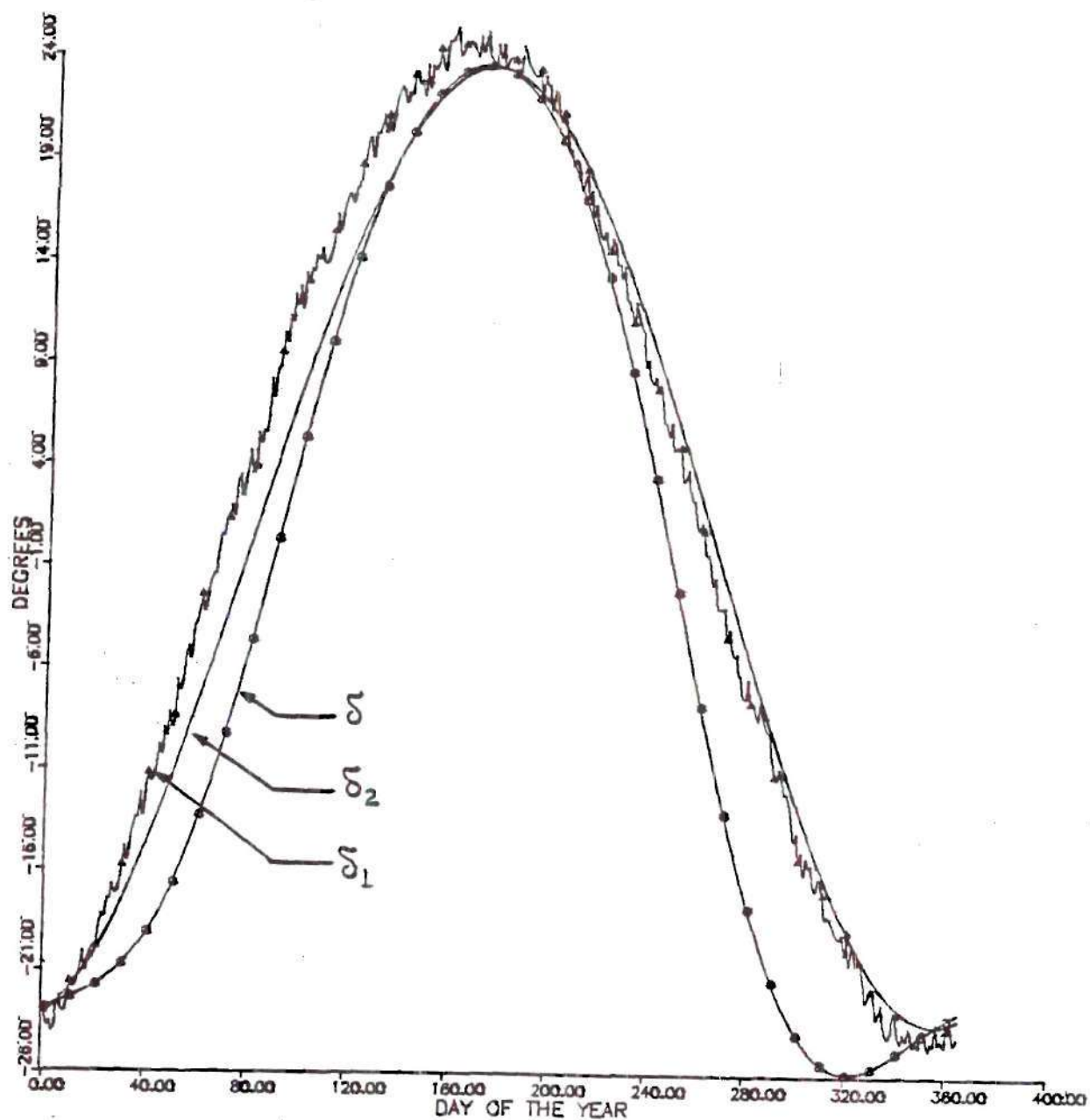


Figure 4.14. Comparison of the Calculated Annual Values of Declination, from Subroutines HELGO (distorted curve), DAILY (curve identified with "o") with 1983 Nautical Almanac (solid smooth curve)



The error using DAILY is

$$\epsilon_2 = \delta - \delta_c, \quad (4.38)$$

where

$\delta$  = declination value from Almanac, and

$\delta_c$  = declination predicted by Coopers

formula.

The Almanac declination is plotted in Figure 4.14. To illustrate the annual pattern, the subroutine results are plotted with the errors exaggerated, so that the plotted values are as follow:

1. to illustrate HELGO such that

$$\delta_1 = \delta - 1000 \cdot \epsilon_1, \text{ and}$$

2. to illustrate DAILY such that

$$\delta_2 = \delta - 10 \cdot \epsilon_2.$$

It was necessary to exaggerate the error using HELGO by a factor of 1000 to make it distinguishable from the Almanac values. Results from DAILY were exaggerated by only a factor of 10 to be distinguishable. Also note that results from DAILY are uniformly low,

whereas results from HELGO are slightly above and below the Almanac results.

Figure 4.14 indicates that for the month of March for example (between the 59<sup>th</sup> and 90<sup>th</sup> day of the year) declination by HELGO is higher than the value calculated by DAILY. Then, the azimuth angle would be lower or  $\cos \theta_z$  would have a higher value for HELGO (than DAILY). This would affect the calculated value of  $I_0$  (increase) and as a consequence the clearness index would decrease. Such behavior was observed when the data were plotted for both cases and cross compared. The data points were shifted to the left (towards lower  $k_T$  values on the plots of  $k_T$  versus  $\tau_b$ ) when subroutine HELGO was used.

In addition to the improvement of the calculation of the declination, hour angle and equation of time, the mean distance of sun-earth,  $R_m$ , in (AU) can be an additional advantage. For 1983 the daily values of  $R_m$  were calculated, with the following characteristic values:

$$(R_m)_{\min} = 0.983290 \text{ AU} \quad \text{on (January 3, 1983), and} \quad (4.39)$$

$$(R_m)_{\max} = 1.01699 \text{ AU} \quad \text{on (July 6, 1983).} \quad (4.40)$$

The variation of the sun-earth distance,  $\pm 1.685\%$ , is due to the eccentricity of the earth's orbit around the sun, as it was previously discussed. The principal result is a  $\pm 3.4\%$  variation in the amount of extraterrestrial radiation reaching the earth.

The results from the comparison with the precise values from the Nautical Almanac are substantial evidence that allow us to conclude that subroutine HELGO produces extremely small error and for engineering applications should be preferred and can be used with confidence. For this study, the three main improvements, namely in declination, equation of time and the mean sun-earth distance, along with a very accurate latitude and longitude for the site, allow more accurate calculations of extraterrestrial radiation values.

For each hour it is possible to calculate the extraterrestrial normal irradiation as follows:

$$I_{on} = G_{sc} \cdot (1/R_m)^2 \cdot \Delta t, \quad (4.41)$$

where

$G_{sc}$  = solar constant,  $1367 \text{ W/m}^2$ ,

$R_m$  = mean sun-earth distance,  $R/R_{ave}$ ,

$R$  = prevailing sun-earth distance,

$R_{ave}$  = average sun-earth distance, and

$\Delta t$  = time interval, 1.0 hour.

One should note the value of the solar constant ( $1367 \text{ W/m}^2$ ) used in this work. Several publications are available in the literature about the seasonal variation of the solar constant but there is still disagreement between researchers on its absolute value [35].

Since though, the radiometers used at Shenandoah STEP site are traceable to the WRR, it was decided for consistency to employ the solar constant of  $1367 \text{ W/m}^2$  adopted by the World Meteorological Organization (WMO). In the present analysis the solar constant is only a normalizing factor, and the model depends only on surface observations. The actual value of the solar constant is not fundamentally important, and the adopted value should be continued to be used in applying this model.

The extraterrestrial horizontal irradiation was calculated according to the formula:

$$I_0 = (12/\pi) \cdot G_{sc} \cdot (R_{ave}/R)^2 \cdot \{ \cos \phi \cos \delta (\sin \omega_2 - \sin \omega_1) + (\omega_2 - \omega_1) \sin \phi \sin \delta \}, \quad (4.42)$$

where

$\phi$  = latitude of the locality,

$\delta$  = solar declination, and

$\omega_2, \omega_1$  = hour angle at start, end of hour.

Thus, an easy to use subroutine (HELGO) is now available, for calculating the position of the sun and can be used in the modeling process to calculate more accurately the desired radiation parameters.

In Equations (4.41) and (4.42) the earth-sun distance, the declination, and the equation of time used to compute the hour angles

were computed at the middle of each hour (in [17] the calculations are made at the beginning of each day). In APPENDIX B a commented program called CKTTB2 is presented, that illustrates the use of subroutine HELGO. CKTTB2 is used to recalculate the  $k_T$  and  $\tau_b$  values at the midpoint of the hourly intervals, using only the radiation data from the 5-Year data base. This program is more accurate and is much simpler in organization than the one used in [17], although the basic equations are the same. For example, the solar constant was used as  $1377 \text{ W/m}^2$  and the values for Longitude and Latitude were not that accurate. Again in CKTTB2 the calculations (for  $R_m$ ,  $\omega$ ,  $E_T$ ) are performed at the beginning of each day, for comparison reasons. The results from the calculations showed that one can use CKTTB2 to reproduce the values of  $k_T$  and  $\tau_b$  (the maximum difference was 0.3%, which can be attributed to round off error).

Once the results from CKTTB2 were verified, CKTTB1 was developed, with the only difference being that it performs the calculations (through HELGO) at the middle of each hourly period. As a result, a simple and accurate way for calculating  $k_T$  and  $\tau_b$  is now available. Realizing that  $\omega$  and  $\delta$  do not change substantially during the day, a difference of about 1.1% was noticed in comparison to the results obtained in [17] (or in other words 1.1% improvement in the accuracy of the calculated values).

The 5-Year data was sorted based on the  $k_T$  value calculated by CKTTB1 in order to reach its final form. There were actually two programs, LSMAN6 and LSMAN7 (APPENDIX B), which performed the sorting of the data. This was necessary due to the use of large numbers of



arrays. LSMAIN7, sorts the date data values for each hourly period and the value of the old  $k_T$ . Similarly, LSMAIN6 sorts the remaining data. Combining the two outputs, one has the final form of the 5-Year data (8112 cases, listed in ascending order based on  $k_T$ ) which can be used in all the following calculations. Note that LSMAIN7 precedes LSMAIN6 in the executing procedure since one would like to keep the permutation vector developed after the first sorting in order to make sure that the same one is used for the sorting of the second group of data. The sorting subroutines are implemented through subroutines VSRTTP and VSRTU (APPENDIX B) from the IMSL Library [36].

One can compare the present subroutine (HELGO) with the earlier one (DAILY [17]) by developing the corresponding models, based on the 5-Year data, as indicated in Figure 4.15. The line with the crosses indicates that subroutine DAILY was used, while the squares indicate subroutine HELGO was incorporated in the modeling analysis. The shift to the left and upwards (lower  $k_T$ , higher  $\mathcal{Z}_b$ ) is obvious for the square line (the situation was previously discussed).

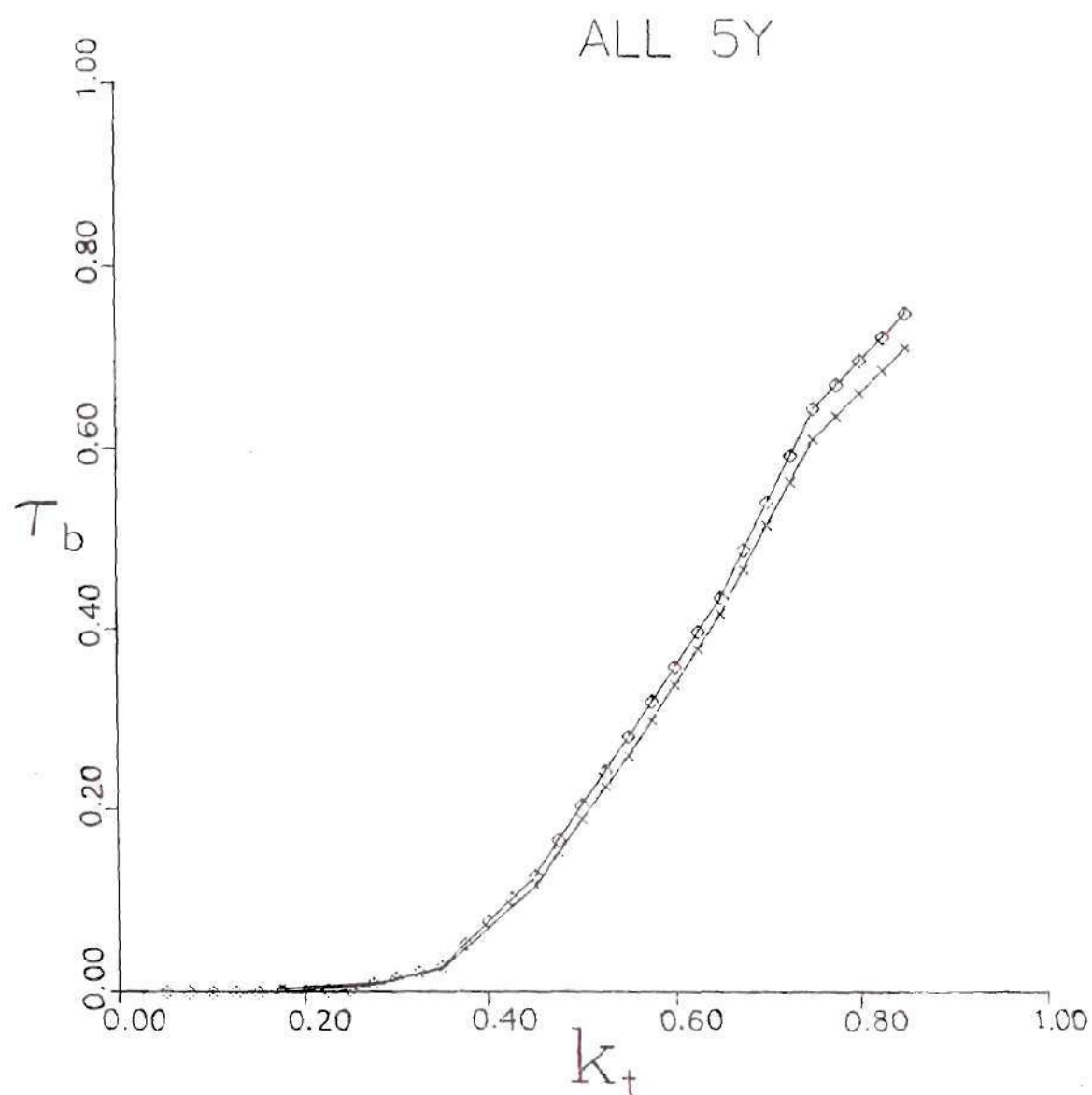


Figure 4.15. Comparison of the Model Produced Using Subroutine HELGO (curve identified with rhombi) With the One Using DAILY (curve identified with crosses)

## CHAPTER V

## STATISTICAL ANALYSIS

A 5-Year data base was previously developed. From these hourly data,  $k_T$  and  $\tau_b$  can be easily calculated following the procedures indicated in the previous chapters. Processing of these data is done in a similar fashion as the annual data. Thus, the 5-Year model can be obtained. In this chapter, the available models will be compared, on a statistical, to determine the best model for the Shenandoah data.

5.1 Annual and Five-Year Models

The available data for the 5-Year model are data that have passed all previous tests and contain only hourly observed data. The 5-Year model was prepared by performing homogeneous least square fits for each band of data. For consistency the same bands were selected as were used by Randall and Whitson. The coefficients for the piecewise linear function  $\tau_b = A_i \cdot k_T + B_i$  are shown in Table 5.1 according to [33]:

Table 5.1 Coefficients for the Piecewise  
Linear Function  $\mathcal{Z}_b = A_i k_T + B_i$

INTERVAL FOR $k_T$	$A_i$	$B_i$
0.00 - 0.05	0.04	0.00
0.05 - 0.15	0.01	0.002
0.15 - 0.25	0.06	-0.006
0.25 - 0.35	0.32	-0.071
0.35 - 0.45	0.82	-0.246
0.45 - 0.55	1.56	-0.579
0.55 - 0.65	1.69	-0.651
0.65 - 0.75	1.49	-0.521
0.75 - 0.85	0.27	0.395

The initial screening already excluded data with very low clearness indices ( $k_T < 0.05$ ). Thus, the regression analysis was conducted for the eight remaining bands in sequence. For each band the regression model which assures simple continuity is:

$$(\tau_{bj} - y_{oi}) = \beta_i (k_{Tj} - x_{oi}) + \epsilon_j, \quad (5.1)$$

where

$x_{oi}$  = lower limit of bound  $i$ ,

$y_{oi}$  = regression model at  $x_{oi}$ ,

$\beta_i$  = regression coefficient, and

$\epsilon_j$  = residual error for data  $(k_{Tj} - \tau_{bj})$ .

Each individual year as well as the aggregate 5-Year set was analyzed separately. Reference [17] suggests that the best model for the Shenandoah data is the piecewise continuous linear regression. Its continuous format provides for an easy-to-use model which makes it the most attractive. Let us look at Table 5.2 where the annual results for 1980 are tabulated, comparing different types of models.

The Randall-Whitson model produces the largest sum of square errors (SSE). This represents the accuracy with which the Randall-Whitson model describes the data and is the value with which to compare the other regression results. The piecewise linear regression produces the smallest SSE, which makes it attractive from a statistical

Table 5.2 Model Comparison

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TYPE OF MODEL	SUM OF SQUARE ERROR
<hr/>	
Randall-Whitson, Piecewise Continuous Linear Equations	15.76
Piecewise Linear Regressions	13.67
Piecewise Continuous Linear Regressions	13.73
Polynomial Regression 2nd Degree	13.81
Polynomial Regression 3rd Degree	13.76
Polynomial Regression 4th Degree	13.76

---



standpoint. The slope discontinuities of this model have no physical basis, and therefore, this model can not be recommended. The polynomial regressions produce higher SSE values and they would tend to over predict the beam normal fraction at high clearness indices. Similar observations were made for the other four annual models and 5-Year model.

The obvious choice for the Shenandoah model, that is the set of piecewise continuous linear regressions, was verified. The coefficients for all annual models and the 5-Year model, can be found in Table 5.3. Scatter plots for each year and the combined 5-Years are shown in Figures 5.1 through 5.6, with the resulting regression models superimposed along with the Randall-Whitson model (solid line). An extra plot, Figure 5.7, is included for the 5-Year case, without the data, in order to assist the reader in distinguishing the corresponding model and Randall-Whitson model.

Several observations are pertinent relative to the annual models and the 5-Year model. All six models are qualitatively similar with one exception. The 1984 model has an anomalous coefficient, actually zero, in the highest band. This seems to represent a seasonal effect since no data were collected due to operational problems during the winter and early spring. These seasons account for essentially all of the clearest weather experienced in northern Georgia. At these times cold, dry continental air masses penetrate this transitional region which is otherwise most strongly influenced by neighboring tropical maritime air masses originating over the mid-Atlantic and the Gulf of Mexico. In the absence of these clear weather patterns a very few

Table 5.3. Annual and Five-Year Regression Coefficients for Shenandoah STEP

INTERVALS OF CLEARNESS INDEX	1979 ( $\beta_i$ )	1980 ( $\beta_i$ )	1981 ( $\beta_i$ )	1983 ( $\beta_i$ )	1984 ( $\beta_i$ )	5-YEAR ( $\beta_i$ )
0.00 < k < 0.05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.05 < k < 0.15	0.0000	0.0004	0.0032	0.0000	0.0000	0.0007
0.15 < k < 0.25	0.0168	0.0317	0.0511	0.0301	0.0310	0.0297
0.25 < k < 0.35	0.2564	0.2337	0.2591	0.2879	0.1733	0.2490
0.35 < k < 0.45	0.8562	0.8796	0.8851	1.0713	1.174	0.9466
0.45 < k < 0.55	1.3511	1.3473	1.6430	1.5602	1.5111	1.4772
0.55 < k < 0.65	1.8084	1.3314	1.5253	1.4959	1.6393	1.5680
0.65 < k < 0.75	2.0174	2.1214	2.3527	2.0059	1.9325	2.0773
0.75 < k < 0.85	1.4478	2.2664	1.3337	0.8439	0.0000	1.3778

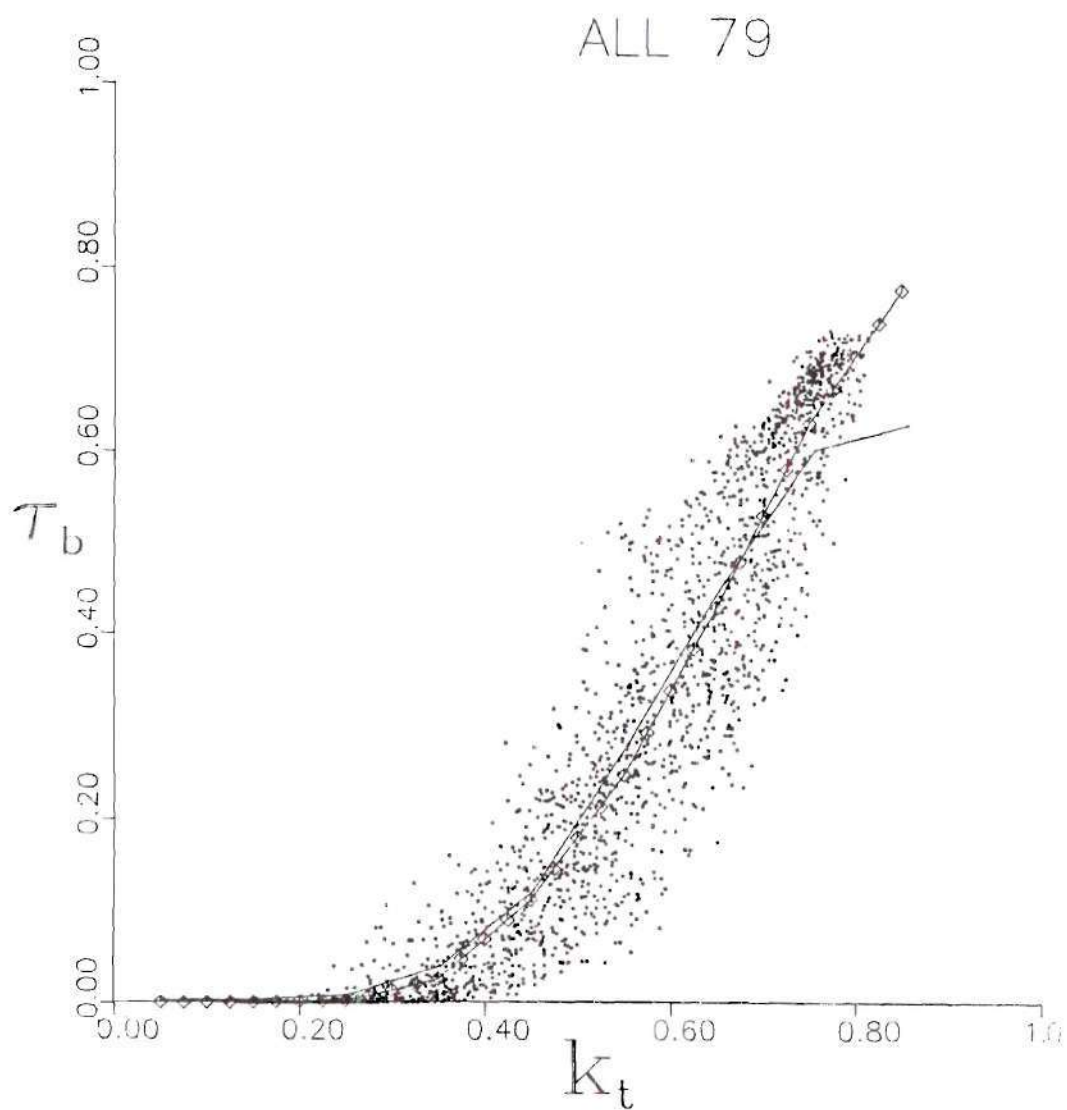


Figure 5.1. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1979. The Randall-Whitson Model is shown by the Plain Line

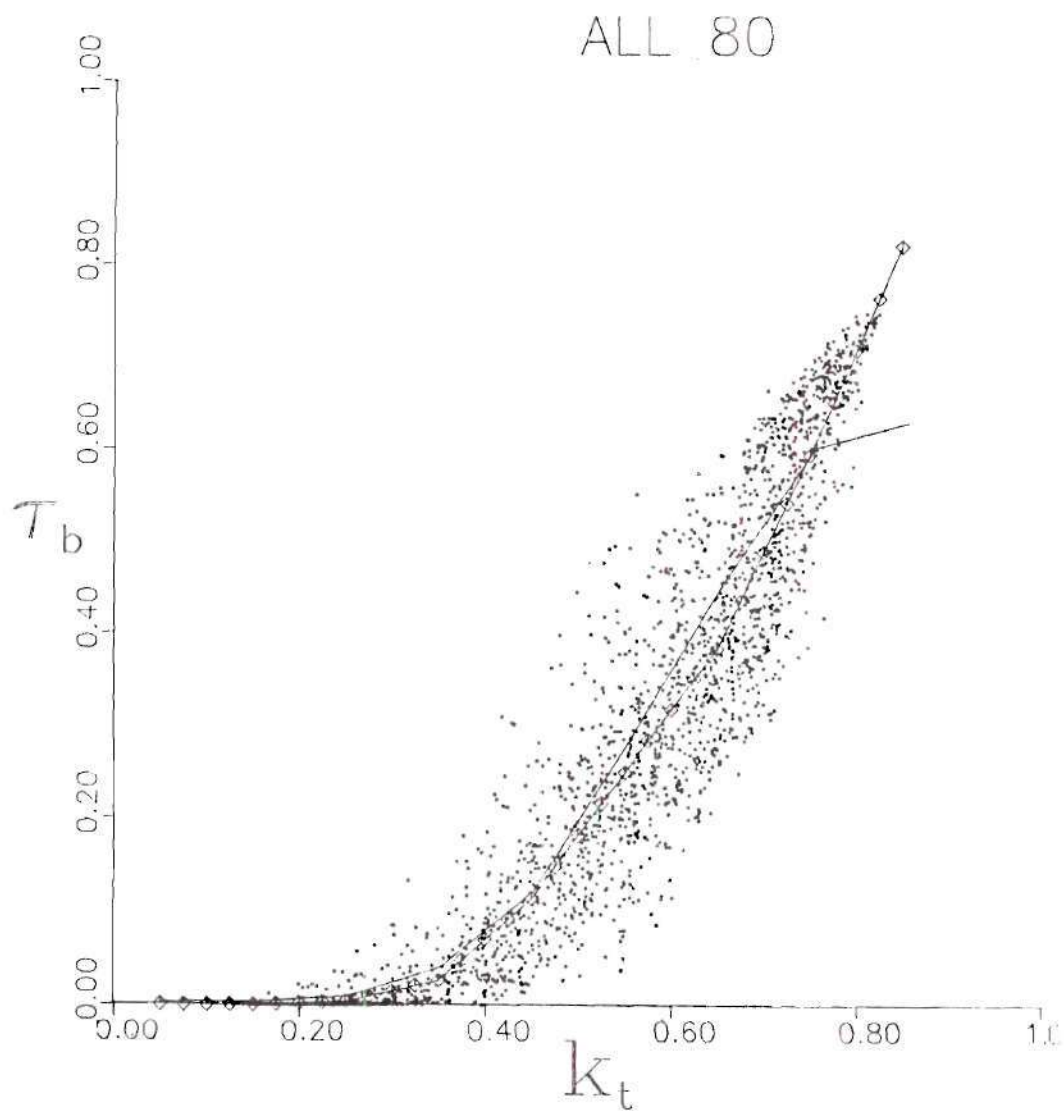


Figure 5.2. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1980. The Randall-Whitson Model is shown by the Plain Line

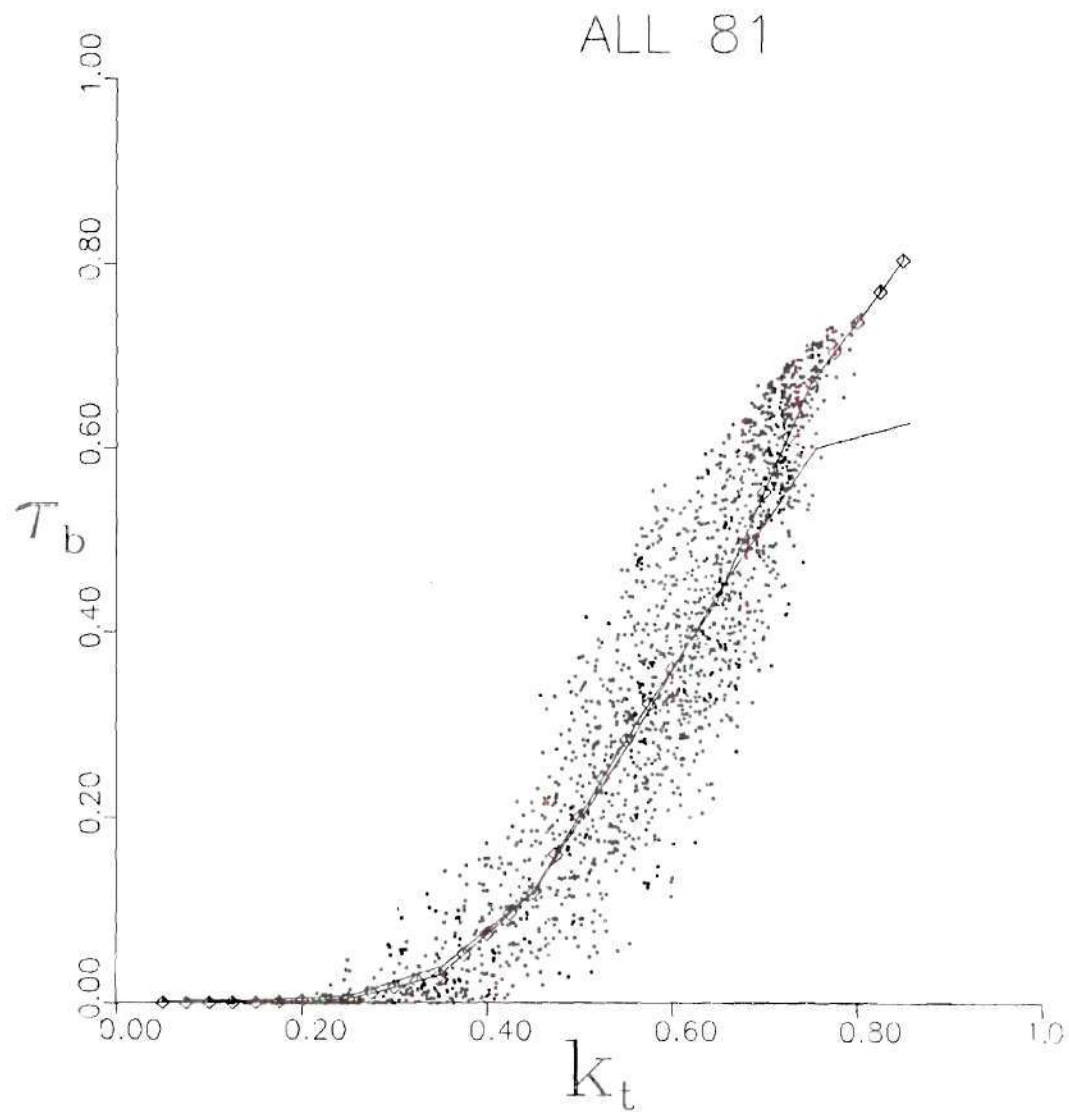


Figure 5.3. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1981. The Randall-Whitson Model is shown by the Plain Line



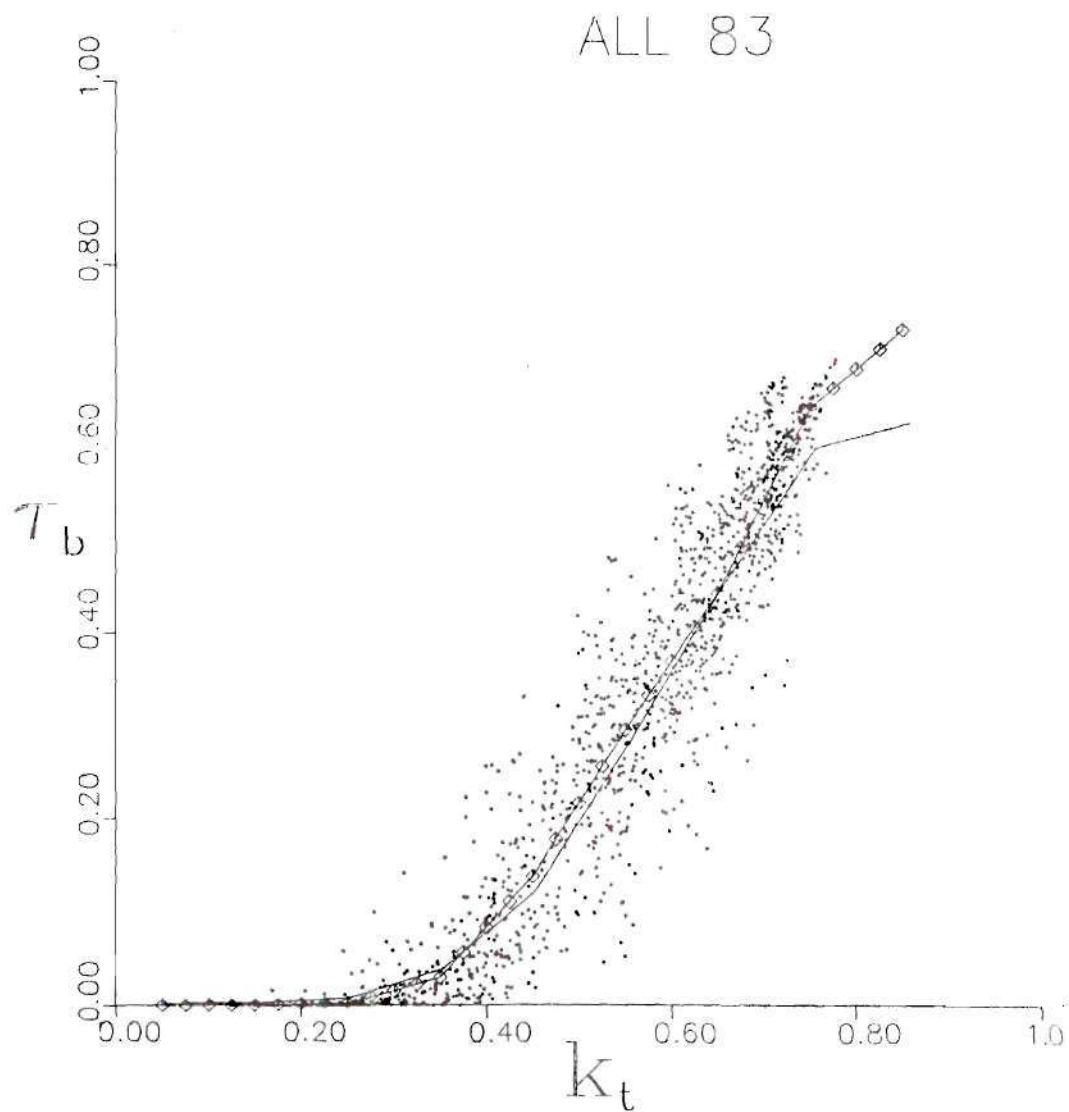


Figure 5.4. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1983. The Randall-Whitson Model is shown by the Plain Line

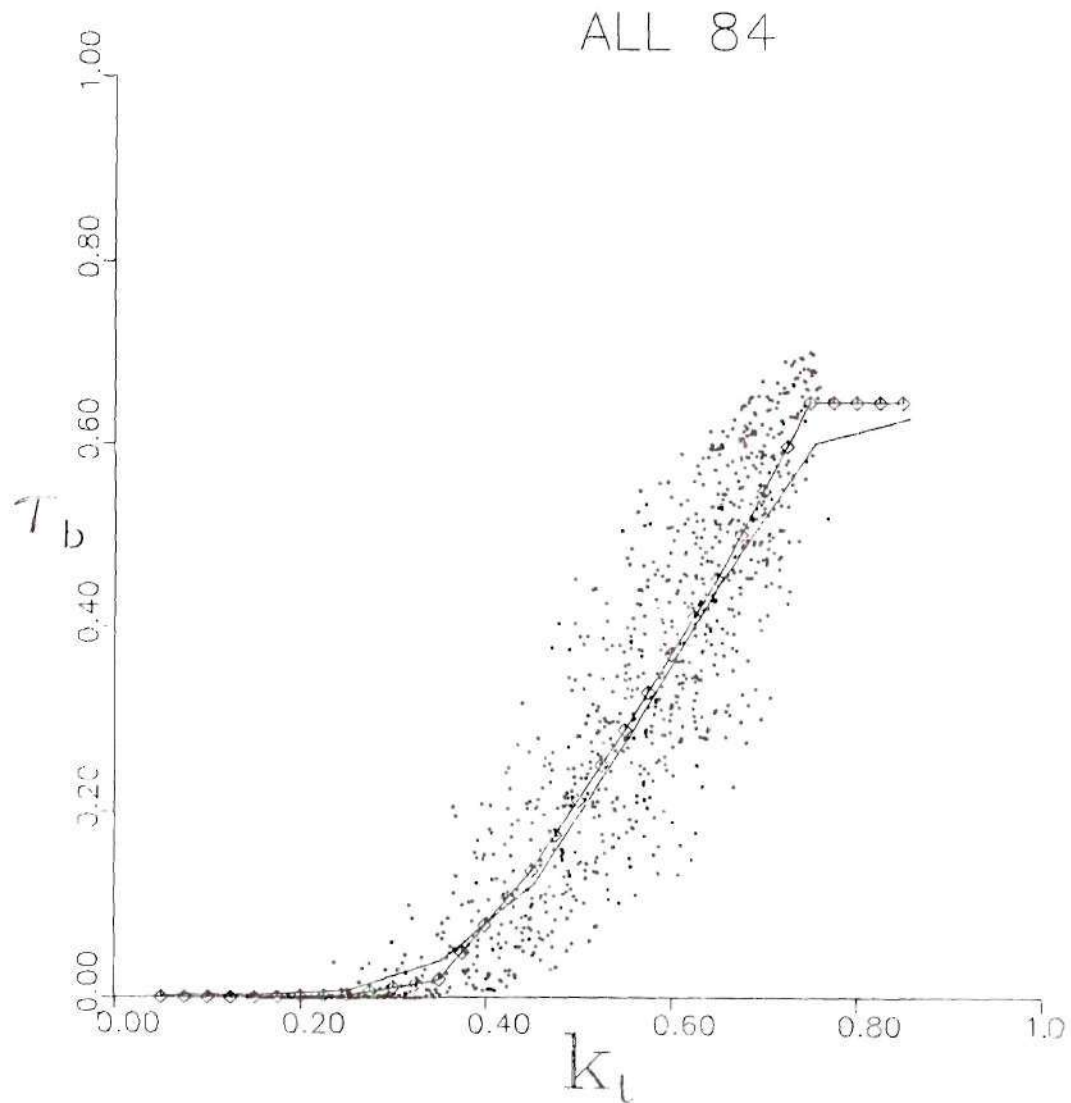


Figure 5.5. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for 1984. The Randall-Whitson Model is shown by the Plain Line

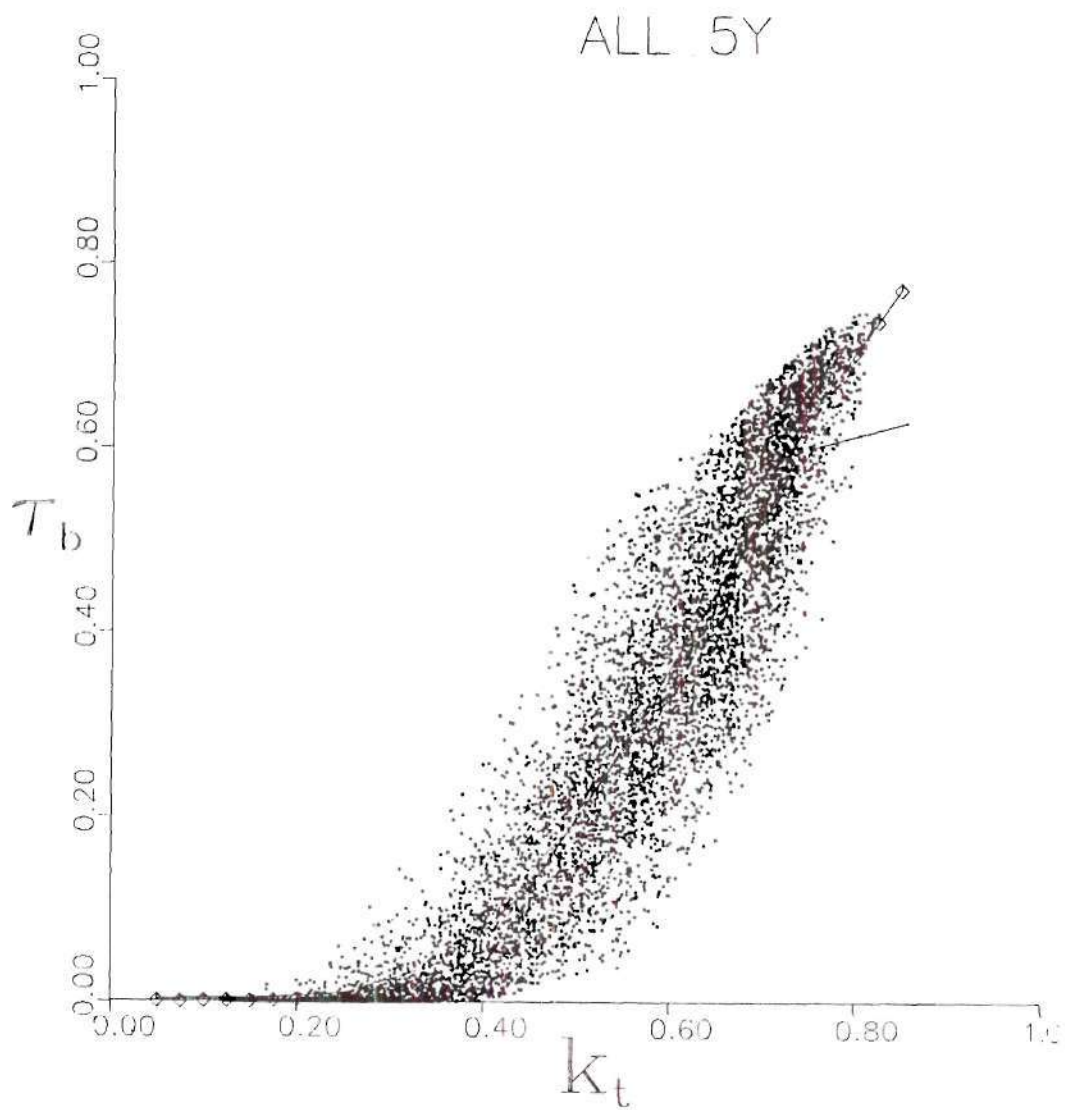


Figure 5.6. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the 5-Years. The Randall-Whitson Model is Shown by the Plain-Line

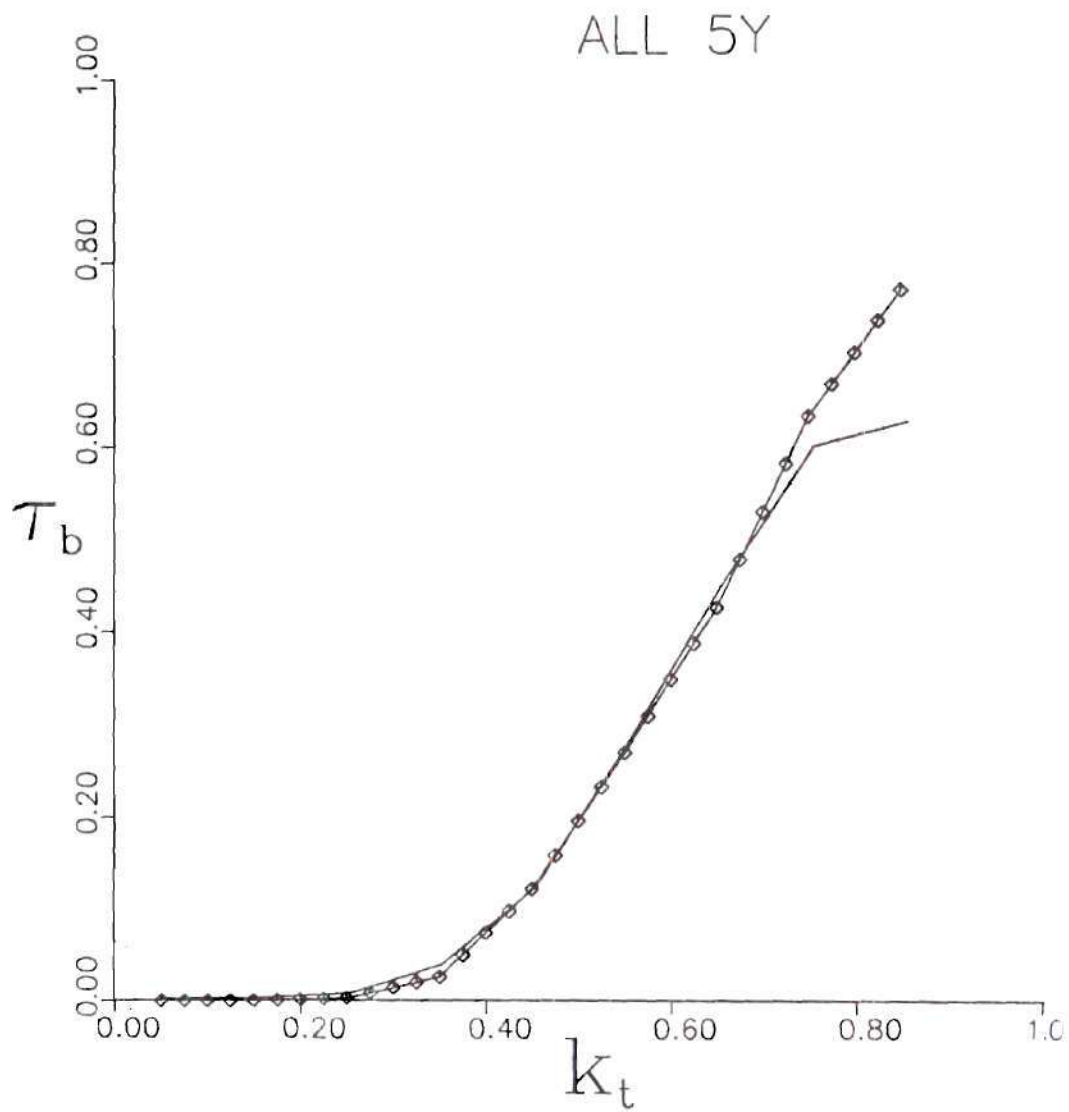


Figure 5.7. The 5-Year Shenandoah STEP Regression Model Compared With the Randall-Whitson Model (plain line)

spurious outliers, dominate the regression.

There is an obvious contrasting behaviour of the models at high clearness indices. The anomalous character of the regression for 1984 demonstrates two possible explanations. The entire regression for  $k_T > 0.75$  is determined by only nine data, one of which is a possible spurious outlier. Our 1984 data is truncated because no winter data is included. This sparsity of clear sky data makes our 1984 model the least reliable of all tested, much less reliable than even the Randall-Whitson model.

Several of the data sets employed by Randall-Whitson (e.g. Raleigh, North Carolina Fort Hood, Texas and Maynard, Massachusetts) seem similarly depleted. Additionally, the two data sets available to Randall-Whitson with the largest number of clear sky data (both for Albuquerque, New Mexico) were deemed by them, less reliable and only "limited use" of these data were made in their model development. The limited data for clearest skies are reason enough to question such data. Additionally, the possibility that an outlier (an exceptional or spurious datum) could overly influence the data is enhanced when only a few data are available. Again, at least two of their data sets (Raleigh, North Carolina and Fort Hood, Texas) include many outliers, some of which, based on our experience, might be identifiable as spurious on closer examination.



## 5.2 Monthly Models

The data are grouped in such a way that would be easy to further examine them and proceed from the annual models to monthly models. The only requirement is to group the 5-Year data (8112 periods) in periods that belong to the same month. The monthly data were used to create monthly models and plot them against the 5-Year model. The monthly model coefficients are listed in Table 5.4 and all 12 plots are illustrated in Figures 5.8 to 5.20. The 5-Year model is the solid line while the corresponding monthly model is the line identified with squares.

Examining these figures one can see that there is a difference in the data distribution during different seasons. The data are grouped at higher clearness index values during the winter months, compared with the summer months where there is a much more uniform distribution. The seasonal dependence is quite obvious. During the summer months the corresponding models are below the 5-Year model. As we move along towards the winter months the over all slope of the model increases, moving closer to the 5-Year model, and during the winter months it clearly has higher values.

The model is very sensitive to outliers, especially at the last band where only a few data points exist (i.e. four data points out of 389, in the case of January). A closer examination of these points, presented in Chapter III, determined that some of them were spurious outliers and were removed from the 5-Year monthly data.

Table 5.4. Monthly Regression Coefficients for Shenandoah STEP

INTERVALS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CLEARNESS INDEX	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$	$\{b_i\}$
0.00<k <0.05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.05<k <0.15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0048	0.0018	0.0032	0.0000	0.0000	0.0000	0.0000
0.15<k <0.25	0.0014	0.0071	0.0275	0.0533	0.0816	0.0167	0.0463	0.0946	0.0131	0.0048	0.0209	0.0023
0.25<k <0.35	0.1269	0.2070	0.3030	0.1697	0.2649	0.2900	0.3086	0.2999	0.3024	0.1561	0.1811	0.2614
0.35<k <0.45	0.9220	0.6790	0.5494	0.9933	0.7879	1.0202	0.8972	0.8247	0.9619	1.2836	1.1203	1.0712
0.45<k <0.55	2.0783	2.1504	1.7033	1.4098	1.1973	1.2579	1.1189	1.2985	1.4974	1.7171	1.9164	1.7879
0.55<k <0.65	1.8841	1.3939	1.8319	1.7250	1.2811	1.5605	1.5005	1.1026	1.0991	1.6099	1.7854	2.1550
0.65<k <0.75	1.5831	2.0938	1.7841	1.9386	2.3147	1.9811	1.7797	1.8003	2.1719	1.7813	1.7918	1.6335
0.75<k <0.85	1.7992	1.1585	1.8942	1.1985	1.1549	0.0000	1.3783	6.8126	0.0000	1.3909	0.3836	0.1128

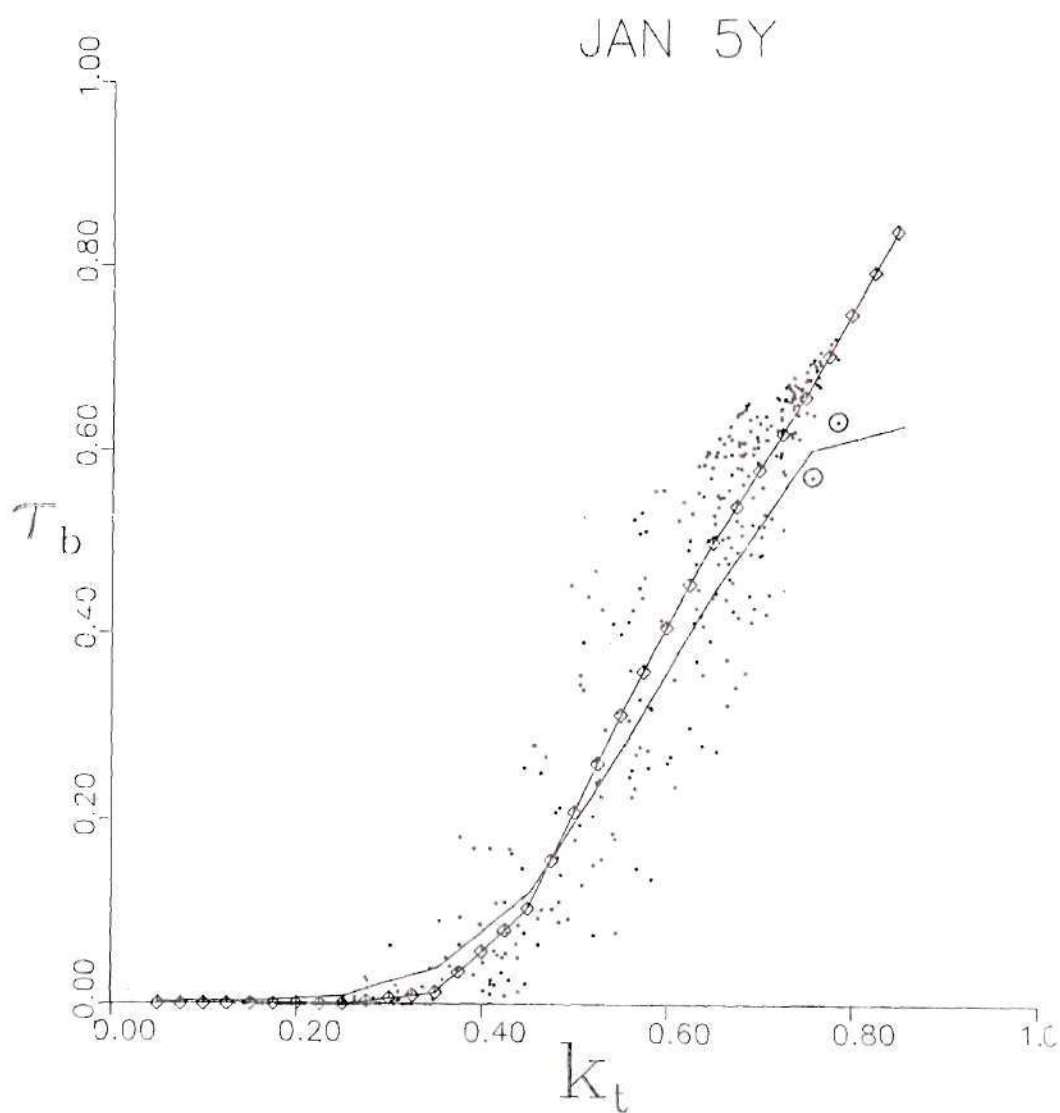


Figure 5.8. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of January. The Randall-Whitson Model is Shown by the Plain-Line

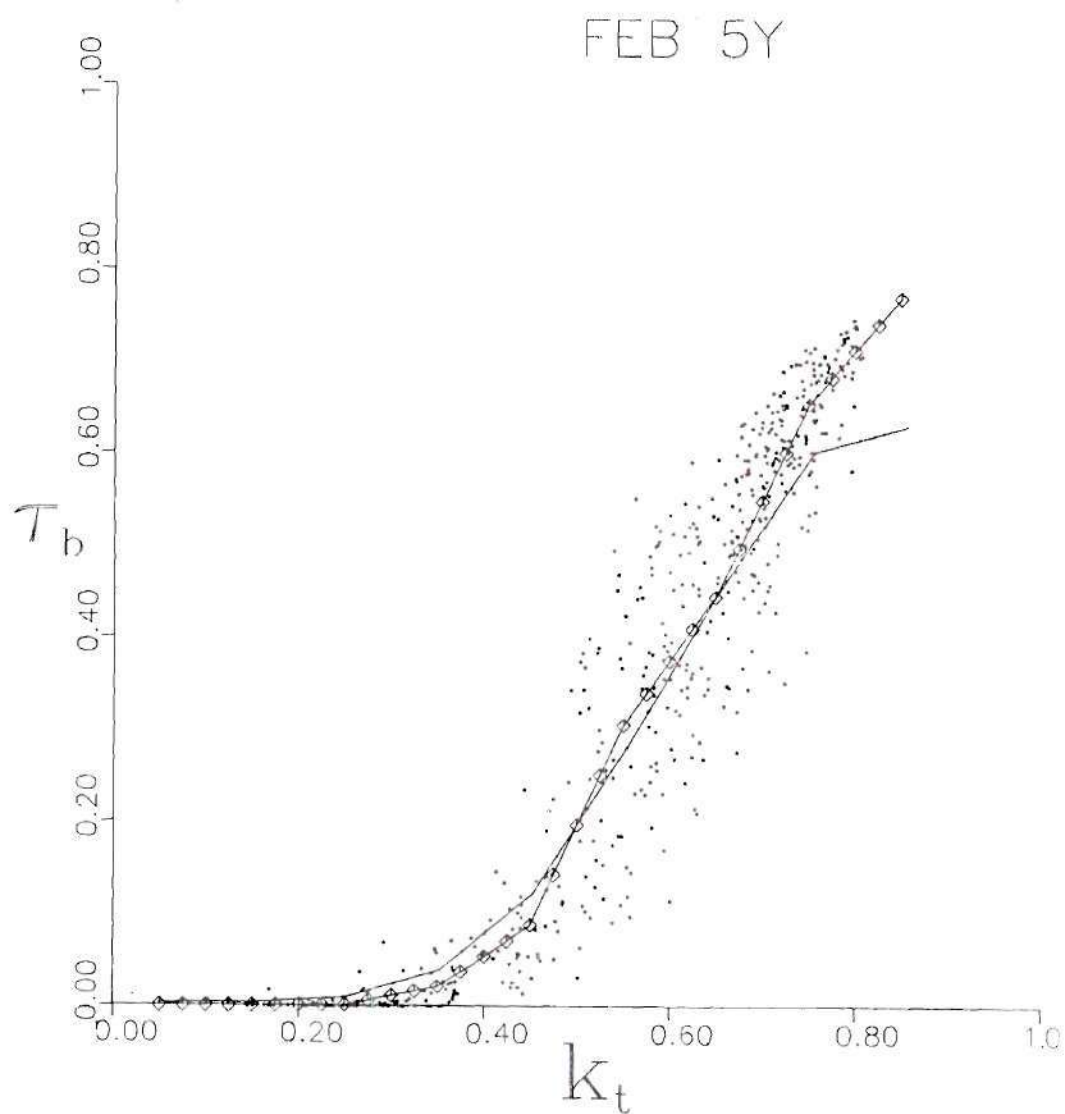


Figure 5.9. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of February. The Randall-Whitson Model is Shown by the Plain-Line

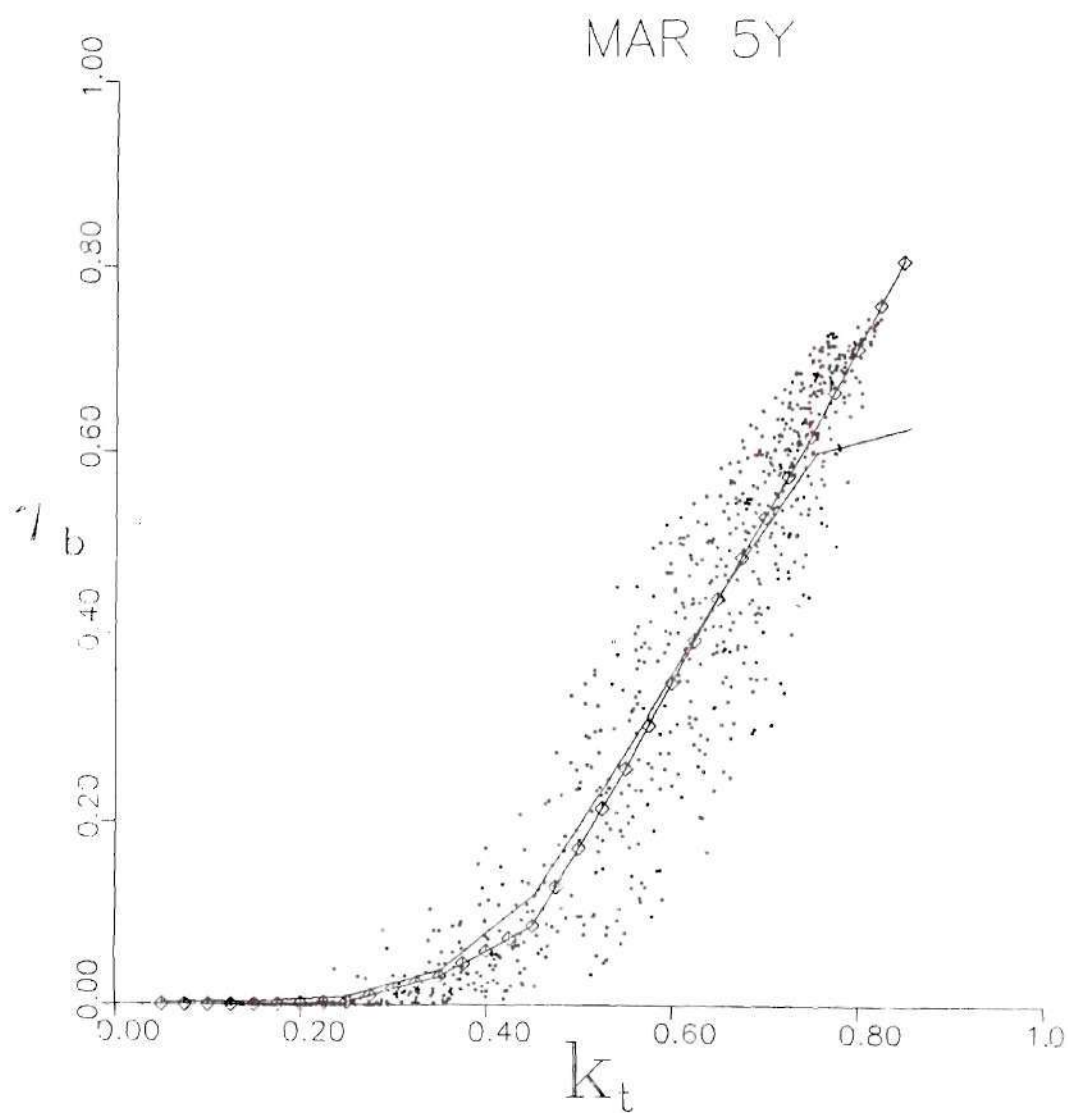


Figure 5.10. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of March. The Randall-Whitson Model is Shown by the Plain-Line



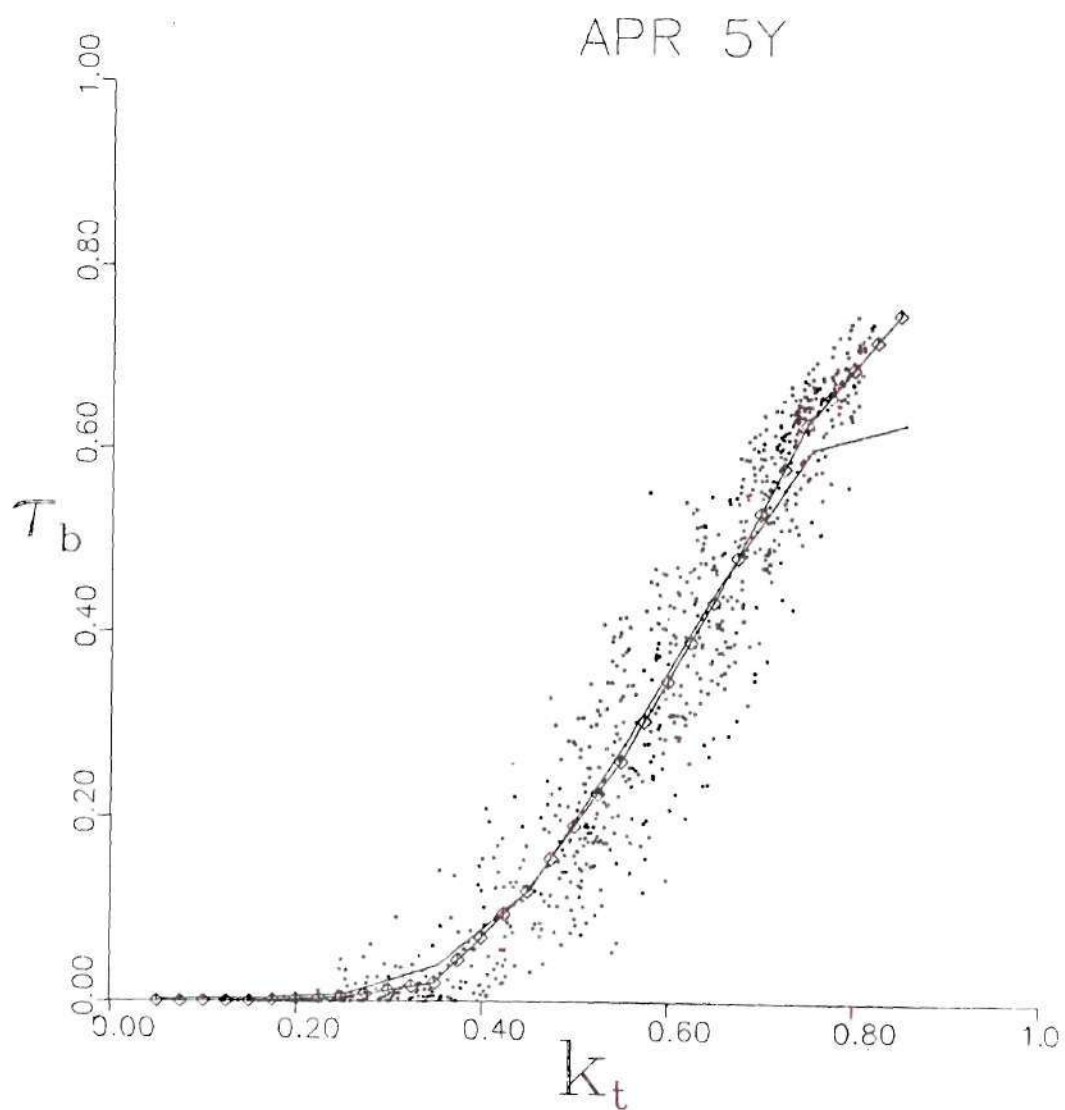


Figure 5.11. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of April. The Randall-Whitson Model is Shown by the Plain-Line

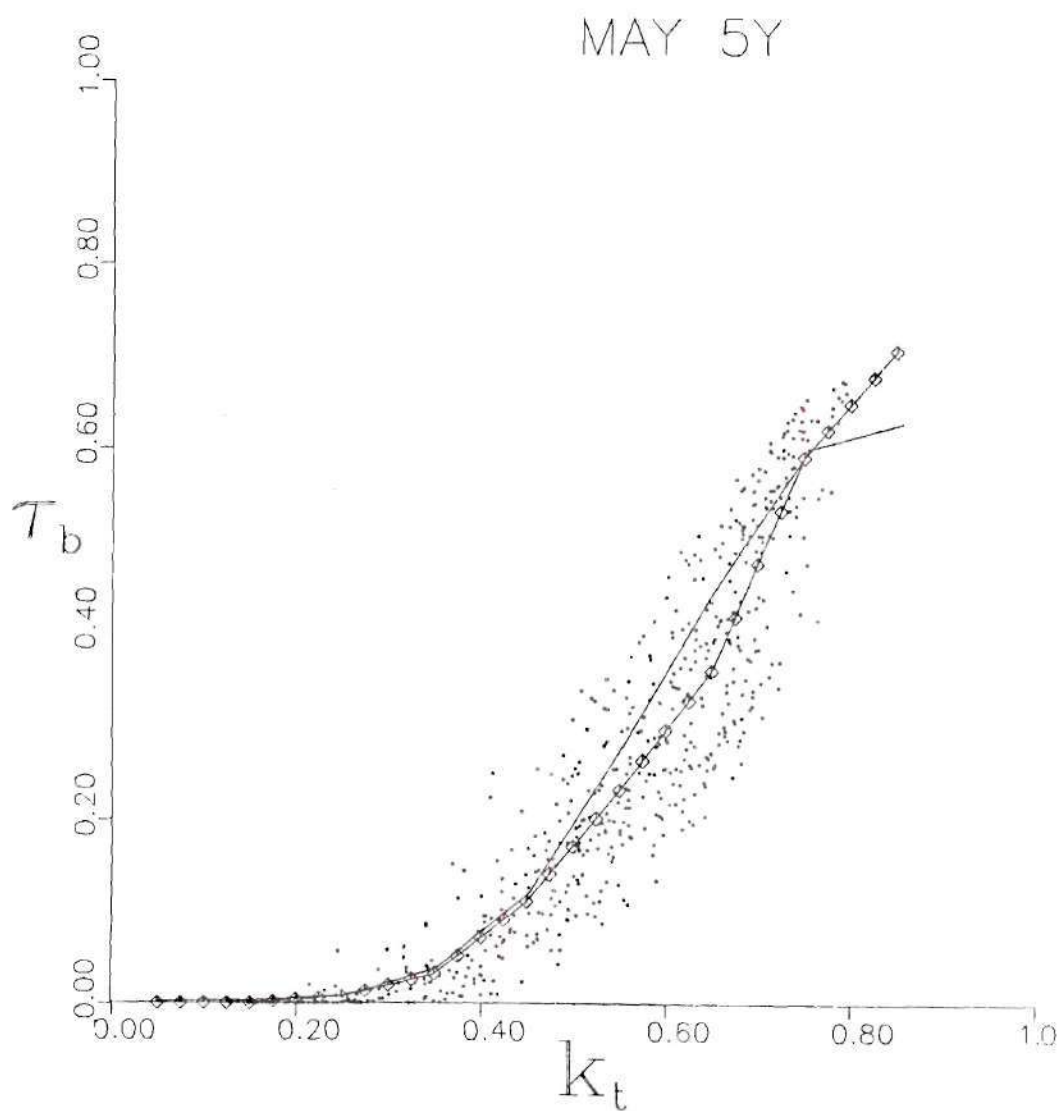


Figure 5.12. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of May. The Randall-Whitson Model is Shown by the Plain-Line

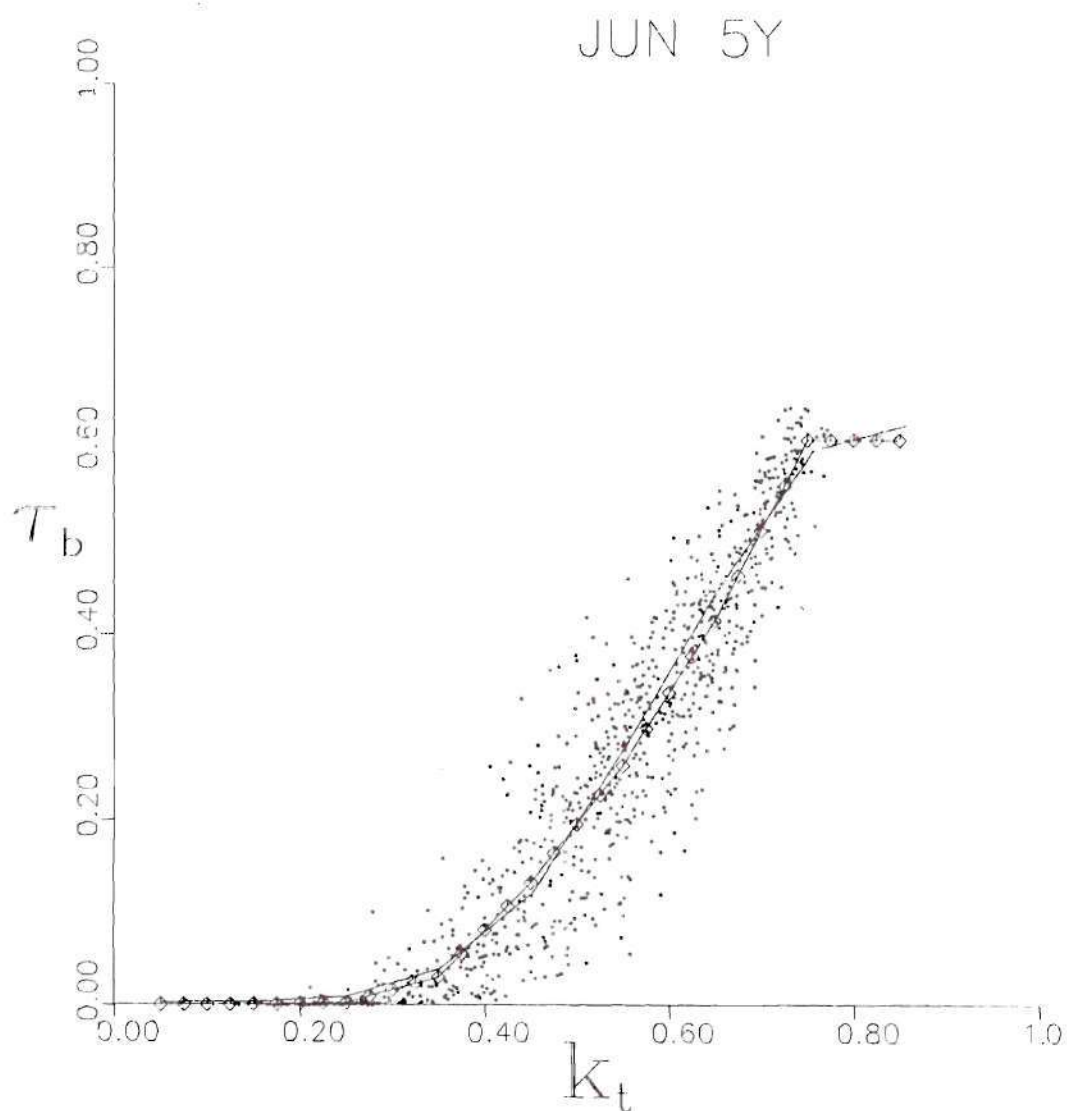


Figure 5.13. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of June. The Randall-Whitson Model is Shown by the Plain-Line

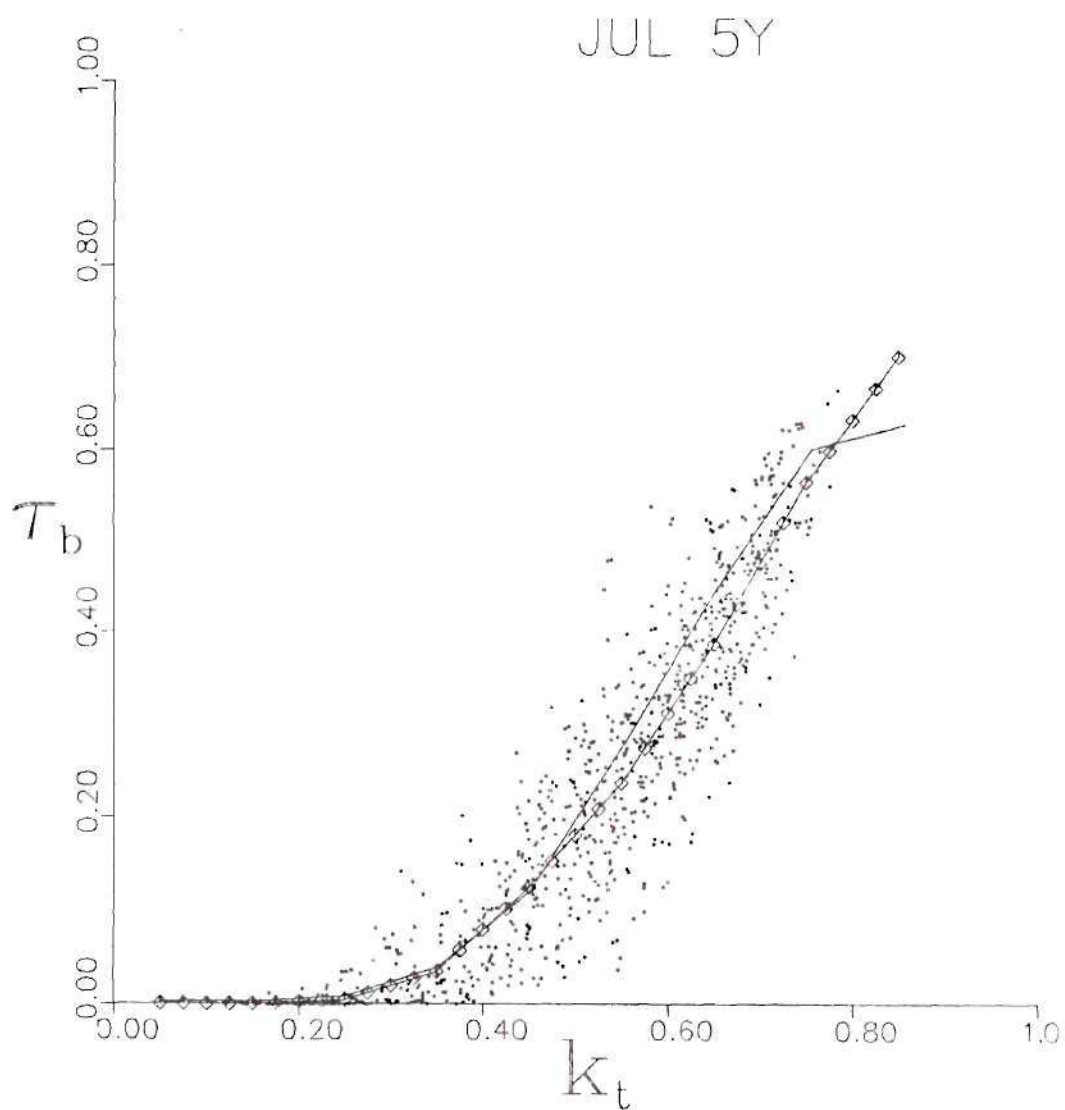


Figure 5.14. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of July. The Randall-Whitson Model is Shown by the Plain-Line

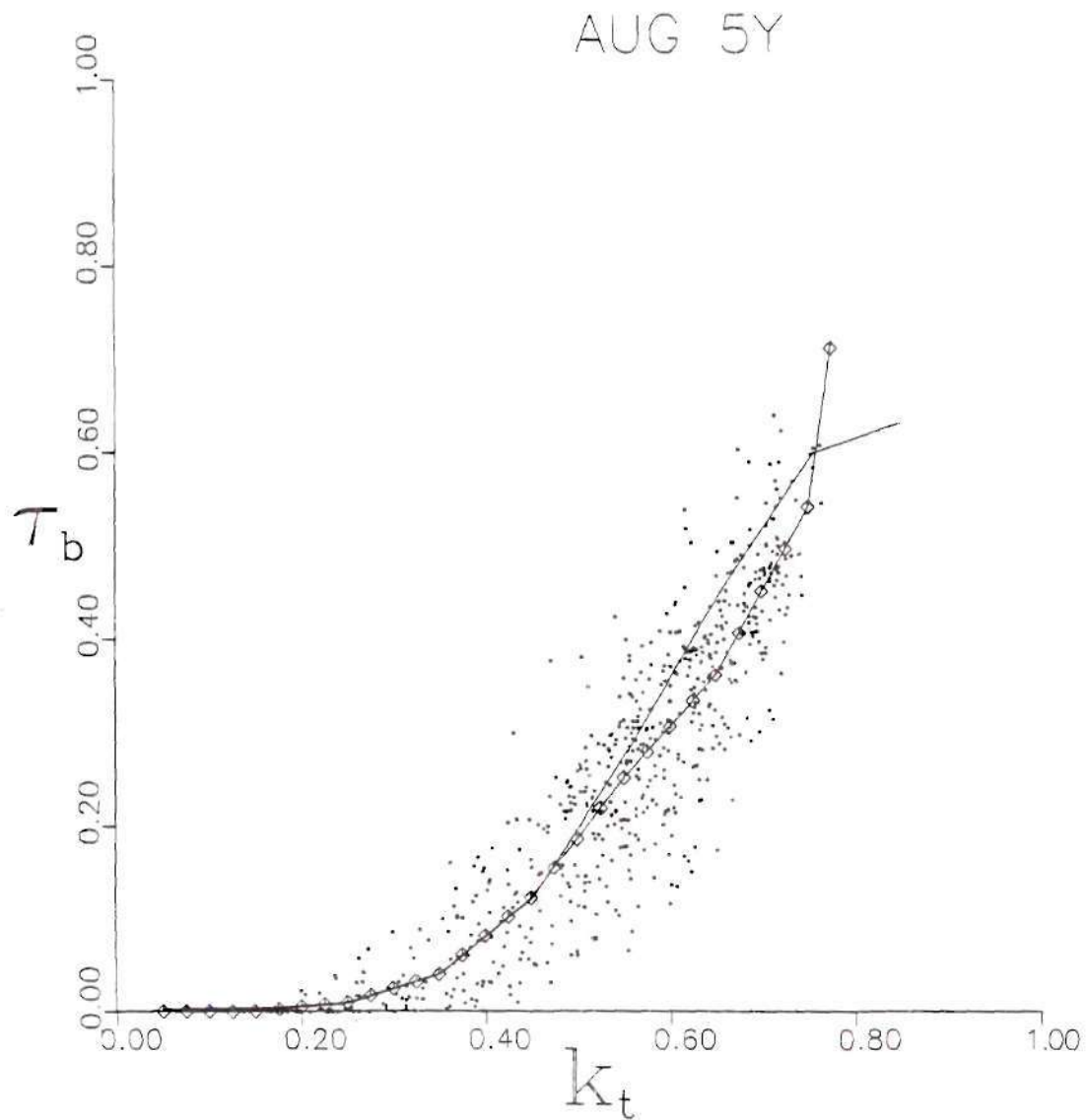


Figure 5.15. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of August. The Randall-Whitson Model is Shown by the Plain-Line

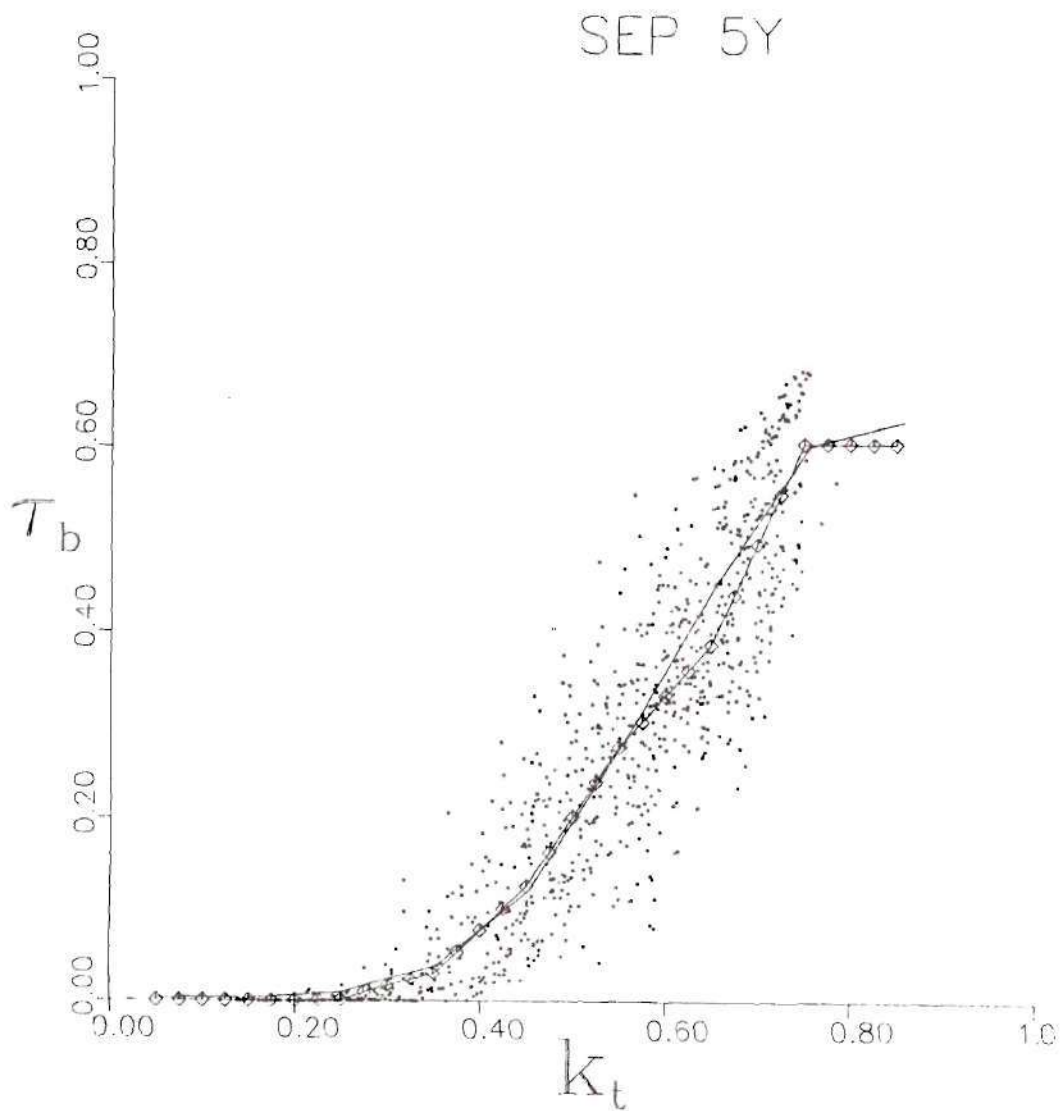


Figure 5.16. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of September. The Randall-Whitson Model is Shown by the Plain-Line



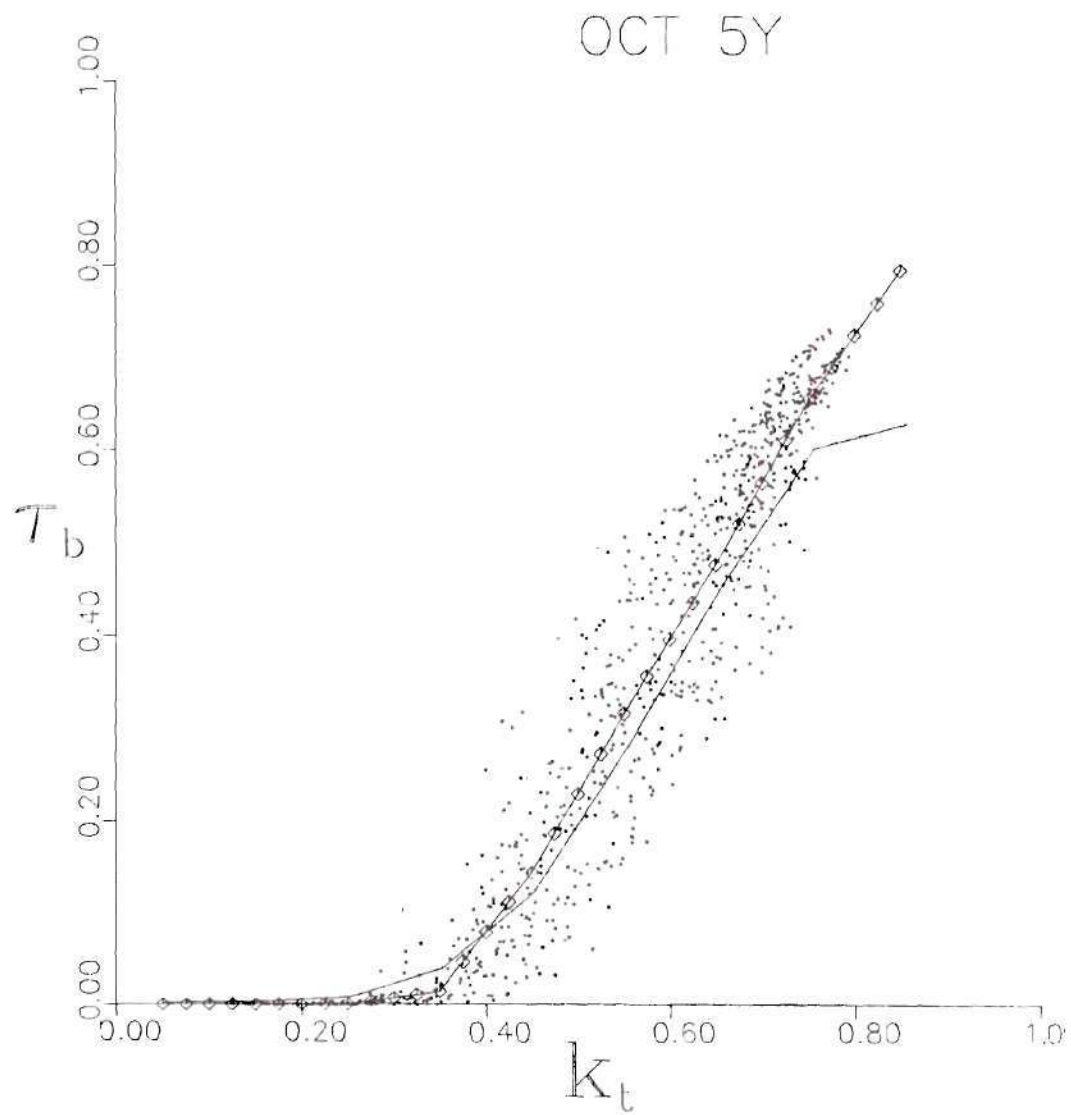


Figure 5.17. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of October. The Randall-Whitson Model is Shown by the Plain-Line

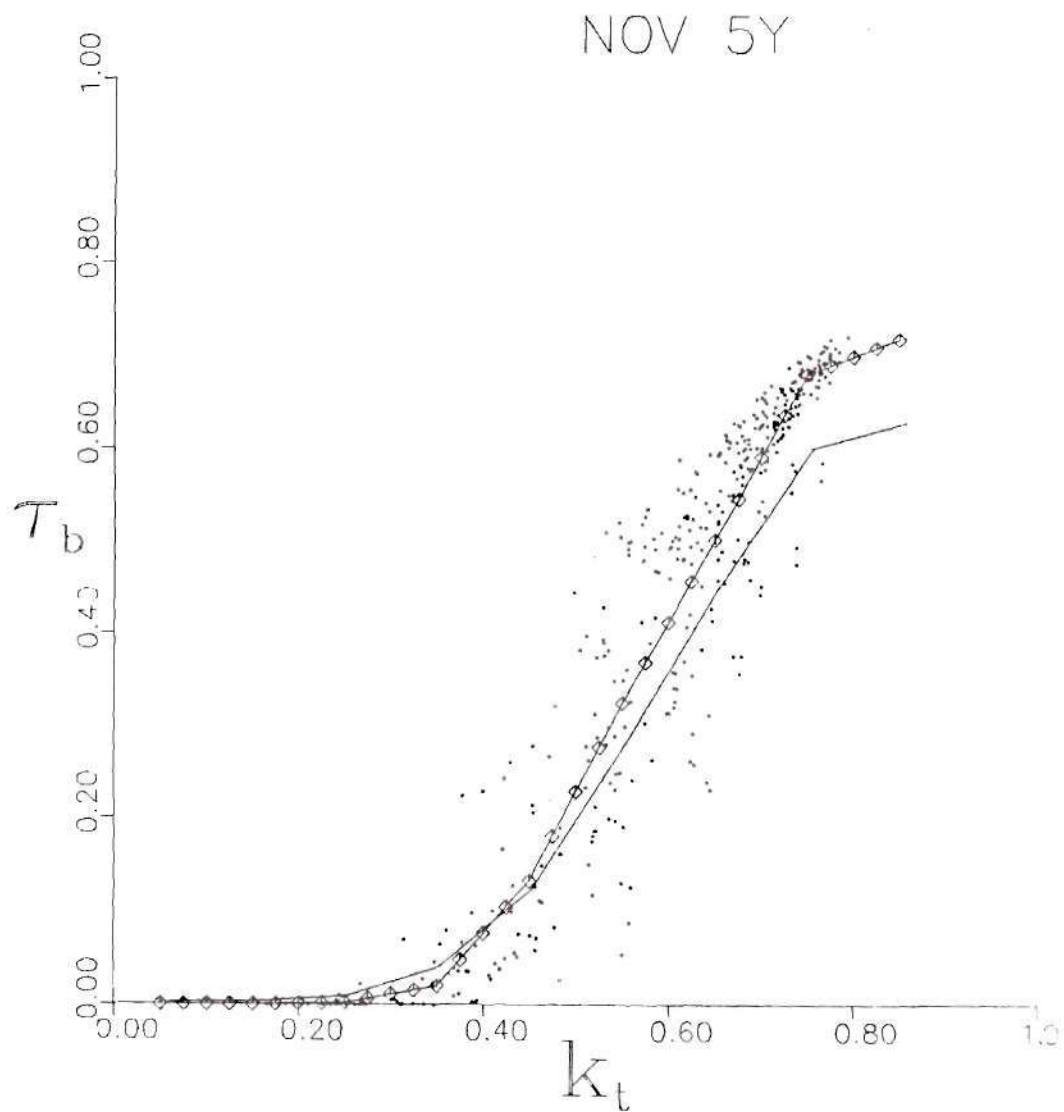


Figure 5.18. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of November. The Randall-Whitson Model is Shown by the Plain-Line

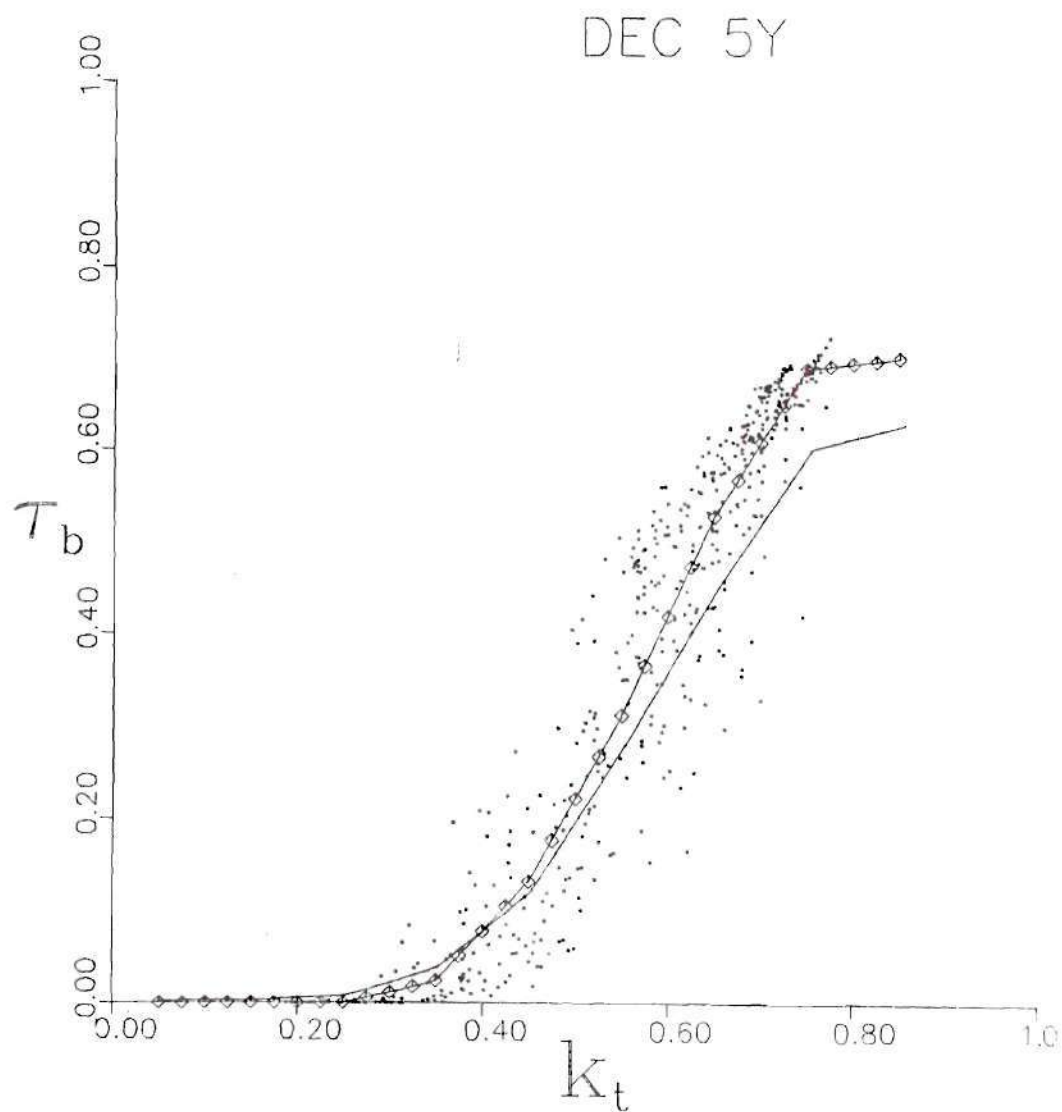


Figure 5.19. Scatter Plot of and Piecewise Regression on Shenandoah STEP Data for the Five Year Months of December. The Randall-Whitson Model is Shown by the Plain-Line

The identified spurious point in January was the only one, in the last band, but certainly for the other months there are some more suspicious outliers. These points (identified with a circle) were not taken off due to lack of justification; there was not any indication of instrument malfunction of any type, in order to prove the measured data, erroneous.

The seasonal dependence is currently under an extensive investigation. From the preliminary results, one can conclude that the model tends to underpredict the beam normal irradiation during the winter months and overpredict it during the summer months, which supports the model's seasonal dependence. This seasonal dependence though, averages out when considering the whole year.

### 5.3 Regression Analysis

Statistics may be regarded as the study of populations. The initial meaning of populations referred to human beings. It is evident though, that if a measurement is to be repeated for a large number of times, the aggregate of the results is a population of measurements. For our purposes we are considering a population that consists of two variables: clearness index  $k_T$ , and beam transmittance  $\tau_b$ . The populations which are the object of any statistical study, always display variation in one or more respects. Their distribution, though generally tends to the normal form as the size of the population is increased. For this study we have a very high number of measurements

and it is reasonable to assume that such statistics are normally distributed and limit consideration of their variability to calculations of the standard error (the theory of large samples [34]). Various data distribution plots were previously presented ( $k_T$  versus  $\mathcal{Z}_b$ ) as scatter diagrams. Each dot represents a pair of observations. These diagrams usually suggest whether or not any significant correlation exists between the variables and in general, how good the model represents the data. It is not possible, though, to determine by inspection which one of the annual models, the 5-Year model or the Randall-Whitson is the best for the corresponding data base. The following analysis will provide the necessary tools to accomplish the task of determining a way to compare these models and justify the general acceptance of one of them, if possible.

### 5.3.1 Statistical Procedures

To determine how well a linear model can explain a relationship between two variables,  $k_T$  and  $\mathcal{Z}_b$ , in a case of scatter data, we have to use what is called "measures of correlation". The least square line approximating the set of points  $(x, y)$   $i=1, 2, \dots, n$  has the equation:

$$y = a_0 + a_1 \cdot x, \quad (5.2)$$

where

$x$  = independent variable,  $k_T$ ,

$y$  = dependent variable,  $\tau_b$ , and  
 $a_0, a_1$  = constants to be determined.

For this statistical analysis, the International Mathematical and Statistical Libraries [36] will be used, to determine constants  $a_0$  and  $a_1$ .

Program TBREG5, included in APPENDIX C, was developed to perform the statistical analysis. It is a compact program that actually summarizes a lot of the previously presented analysis. TBREG5 can be used with the 5-Year data base, to produce the annual models as well as the 5-Year model. In the form of a subroutine, SUBI in APPENDIX C, it can be used to recalculate the  $k_T$  and  $\tau_b$  from the radiation data. There is an option if one prefers to perform the calculations at the mid-period (using SUBI) or at the beginning of each day. It can provide the slopes of the linear regression models, create the corresponding plots and perform the statistical analysis by comparing the 5-Year models with any annual or the Randall-Whitson model.

A summary of the most important statistical parameters is presented. The total sum of squares error (SUME2) is calculated as the summation of all the sum of square errors for each band (SSE1, SSE2,....., SSE8). These sums were calculated using subroutine RLONE from [36].

The total variation of  $y$ ,  $S_{yy}$ , is a measure of the scatter in the data, and is defined as [37]:



$$S_{yy} = \sum_{i=1}^n (y_i - \bar{y})^2 = SS_R + SS_E, \quad (5.3)$$

where

$SS_E$  = unexplained variation,  $\sum_{i=1}^n (y_i - \hat{y}_i)^2$  and measures the residual variation left unexplained by the regression line,

$SS_R$  = explained variation,  $\sum_{i=1}^n (\hat{y}_i - \bar{y})^2$  and measures the amount of variability in the  $y_i$  accounted by the regression line,

$\hat{y}$  = estimated regression model, and

$\bar{y} = (1/n) \sum_{i=1}^n y_i$ .

The development of equation (5.3) is presented in APPENDIX C.

In order judge the adequacy of a regression model, a quantity called the coefficient of determination ( $r^2$ ), can be of help. It is defined as the ratio of the explained variation to the total variation:

$$r^2 = SS_R / S_{yy} = 1 - (SS_E / S_{yy}). \quad (5.4)$$

The coefficient of determination is a measure of how much of the variation in the beam transmittance is accounted for by the piecewise linear dependence on  $k_T$ , established in the regression analysis. In the case that we have  $S_{yy} = SS_R$  or the total variation of  $(y)$  to equal

the explained variation, then the coefficient of determination equals one (perfect positive relationship between the two variables). On the other hand, if the total variation of (y) equals the unexplained variation, then the  $r^2$  equals zero (no relationship between the two variables). Clearly  $0 < r^2 < 1$ .

Caution is advised, though, regarding the use of the statistic  $r^2$ . It is possible to make  $r^2$  equal to unity, that is 100 percent of the variability in the data will be accounted for by the model, by simply adding enough terms to the model. That would result to the misleading conclusion that the fit of the data to the model is "perfect". The  $r^2$  statistic must be used with caution when comparing the results obtained from analyses of different models.

It is convenient that we have chosen the case with a linear relationship between a dependent and an independent variable, so that one can be concerned with the linear regression of  $\mathcal{Z}_b$  on  $k_T$ . Thus, in this case that the variables are linearly related, the correlation coefficient is a measure of the degree of relationship present. The correlation coefficient may be defined as :

$$r = \pm \sqrt{SS_R / S_{yy}} = \pm \sqrt{r^2}. \quad (5.5)$$

The ratio of the explained variation to the total variation (or the coefficient of determination) is always positive, while the correlation coefficient lies between  $-1 < r < 1$ . The sign of  $r$  is the

same as the sign of slope in the regression equation. It follows that, a value of  $r=0$ , would mean no linear relationship between  $k_T$  and  $\mathcal{Z}_b$ . If the value is nonzero then that means that a large number of  $k_T$  values tends to be associated with a large number of  $\mathcal{Z}_b$  values. The results of the analysis for all six models are listed in Table 5.5. For all the years there is a positive relationship between  $k_T$  and  $\mathcal{Z}_b$  but it is not perfect. The correlation coefficient for 1984 is 0.9222 which is related to the scatter of the plotted points about the line representing their trend (Figure 5.5).

The next step in our analysis is to determine the significance of the difference observed between the 5-Year and annual models, and between the 5-Year and the Randall-Whitson model. All previously developed parameters will be used to test whether the 5-Year continuous linear model can adequately describe the annual models. For this work the null hypothesis is that the Randall-Whitson model or an annual model is tenable. The alternative hypothesis is that the 5-Year model is more tenable based on the 5-Year data base.

The most appropriate test statistic for comparing regression lines is the Fisher F-statistic, which is computed according to the formula [38]:

$$F = \{ (RSS_{NH} - RSS_{AH}) / (df_{NH} - df_{AH}) \} / (RSS_{AH} / df_{AH}), \quad (5.6)$$

where

Table 5.5 Model Coefficients of Determination and Correlation

---

MODEL	COEFFICIENT OF DETERMINATION ( $r^2$ )	COEFFICIENT OF CORRELATION ( $r$ )
<hr/>		
1979	0.9070	0.9524
1980	0.8933	0.9451
1981	0.8823	0.9393
1983	0.9116	0.9548
1984	0.8504	0.9222
5-YEAR	0.8865	0.9415

---

$RSS_{NH}$  = unexplained variation for the hypothesized model  
 (i.e. an annual model or the Randall-Whitson),  
 $RSS_{AH}$  = unexplained variation for the alternative model  
 (i.e. the five-year model),  
 $df_{NH}$  = degrees of freedom for the hypothesized model,  $n$ ,  
 $df_{AH}$  = degrees of freedom for the alternative model  $n-p$ ,  
 $n$  = total number of observations for the five-years,  
 8112, and  
 $p$  = number of parameters  $\{\beta_i\}$ , 8.

The F statistic gives evidence against the null hypotheses if the value of F calculated by Equation 5.4 is large when compared to the percentage points of  $F(df_{NH}-df_{AH}, df_{AH})$ . For example,  $F(8,\infty)=2.64$  with a confidence of 0.09. Then the model provided by the null hypotheses is not as good as the one provided by the alternative hypothesis. On the other hand, if the model is adequate when compared to the general model F will be small.

### 5.3.2 Results from Statistical Analysis

Results from the analysis of variation are given in Table 5.6. The 5-Year model has the lowest RSS since its parameters were calculated to minimize the residual error. The annual models were computed from a subset of data while the Randall-Whitson model is

Table 5.6 Model Comparison Based on the Residual Regression,  
F-Statistic, and Probability Values

Model	RSS	F	P(Z<F)
1979	48.40	20.000	1.00
1980	54.84	157.454	1.00
1981	49.49	43.325	1.00
1983	49.12	35.392	1.00
1984	49.83	50.410	1.00
R-W	50.26	59.601	1.00
5-YEAR	47.46	0.000	0.00



independent of this data so their RSS's are higher. A higher value of the F-statistic tends to support the 5-Year model as a better alternative to the hypothesized less inclusive models. As can be seen from the table the F-statistics for every hypothesized model is quite large. Consequently, one would tend to reject all of these in favor of the 5-Year model.

Also shown in Table 5.6 are the probabilities  $P(Z < F)$  that a random variable Z would have a value less than the computed value of F. Again, all the hypothesized models have  $P=1.0$ . The literal interpretation is that there is essentially no chance that a long-period would have the same regression model as any of the short-period, annual models or as the Randall-Whitson model. As a practical matter the F distribution should not be trusted implicitly in this application. The F distribution assumes that the errors in Equation (5.1) are randomly distributed about the regression line with uniform, although unknown, variance [38].

Observation of the scatter plot, Figure 5.6, for the 5-Year set reveals that while the distribution does have a random appearance at any given  $k_T$  the variance is by no means constant. It is obvious that the variance is small both for large  $k_T$  ( $>c.0.75$ ) and small  $k_T$  ( $<c.0.4$ ). In contrast, the variance as manifested by the breadth of the scatter plot is large for intermediate clearness indices. Nevertheless, the high probabilities that an adequate model would have lower RSS than the observed for the limited models is convincing evidence that all, including the Randall-Whitson model, should be rejected in favor of the new 5-Year model.

As a practical matter, however, inspection of Figure 5.7, shows that the Randall-Whitson model hardly differs from the 5-Year model except in the highest  $k_T$  band ( $0.75 < k_T < 0.85$ ). Otherwise the correlations are nearly identical. Even at  $k_T = 0.75$  the models differ by only 5.1 percentage points. One can conclude on the basis of the STEP data that the Randall-Whitson model is a tenable correlation for  $k_T < 0.65$ . For higher clearness indices the 5-Year correlation is preferred.

## CHAPTER VI

## MODEL VALIDATION

6.1 Model Comparison

The Shenandoah solar radiation models were developed in the previous chapters, for determining the amount of beam normal irradiation when only the data for global irradiation is present. The recommended models were piecewise continuous linear models correlating two variables, clearness index and beam normal fraction. The Shenandoah model for 1980 was compared with other models, like the Randall-Whitson model and the Orgill-Hollands, Erbs-Klein-Duffie and Spencer transformed diffused fraction models. The transformation used was :  $\tau_b = \{1 - (I_o/I) \cdot k_T\}$ .

The results, as indicated in Figure 6.1, showed that the Shenandoah model follows the other models up to a clearness index of about 0.7. After this point the other models tend to drop in slope, while the Shenandoah model does not follow that pattern. The bend of the other models is due to a lack of data in the high clearness index regions. The Shenandoah data included high clearness index values, upto 0.82. One can be confident that the Shenandoah model provides accurate information at the most important region of high  $k_T$  values.

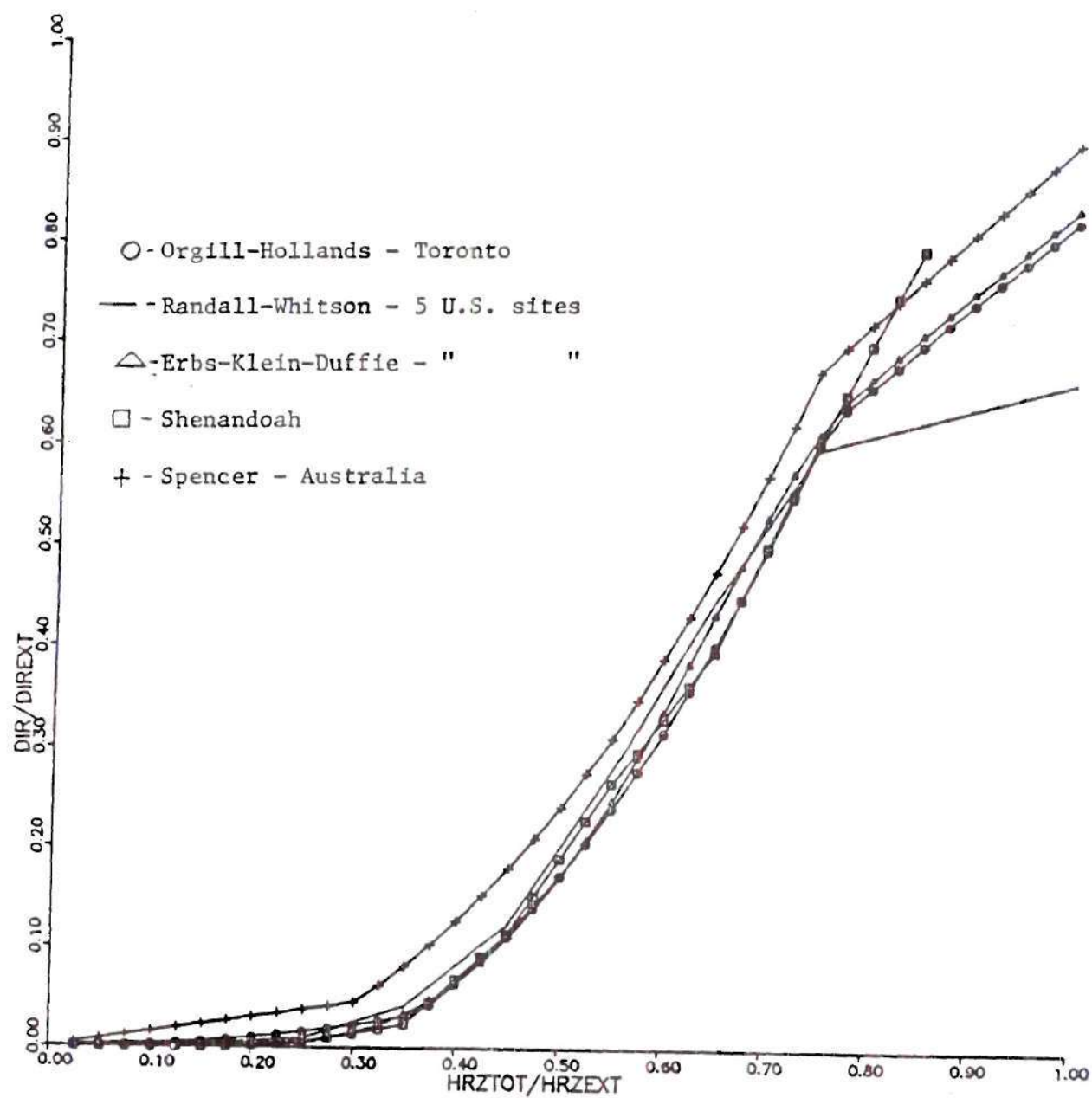


Figure 6.1. Beam Normal Fraction - Clearness Index Models

## 6.2 Verification of Data Processing Procedures

An additional check was performed in order to provide an overall verification of the data processing procedures used to produce the Shenandoah models. This was done by conducting the following numerical experiment: create an artificial data base containing a synthesized global and beam irradiation with a predefined relationship between  $\tau_b$  and  $k_T$ . If the data processing procedures are working correctly they should detect the predefined relationship precisely.

For this purpose a FORTRAN program was developed to create a data base by recalculating the radiation data. The necessary information inputs are the coordinates of the site ( $33.4046^\circ$  N and  $84.7478^\circ$  W). The main features of this algorithm are:

- A. Calculate daily sunrise and sunset hour angles, and standard time of sunrise and sunset.
- B. Calculate the irradiation values for each period.
- C. Calculate the global irradiation and clearness index for each period.
- D. Calculate the beam normal irradiation from (C) using the predefined relation between  $\tau_b$  and  $k_T$ .

It is important that the calculations are performed between sunrise and sunset, in order to obtain meaningful results. Fundamental equations are used to calculate the declination, hour angle, equation of time and standard time of sunrise and sunset. Declination,  $\delta$ , is given from Cooper's equation (1969):

$$\delta = 23.45 \cdot \sin(360 \cdot (284 + n) / 365), \quad (6.1)$$

where

$n$  = day of the year.

Duffie and Beckman [26] propose that for the sunset hour angle,  $\omega_{ss}$ , one can use:

$$\omega_{ss} = -\tan \phi \cdot \tan \delta, \quad (6.2)$$

where

$\phi$  = latitude of the location.

The sunrise hour angle is simply,

$$\omega_{sr} = -\omega_{ss}. \quad (6.3)$$

The equation of time,  $E_T$ , is given by (Watt, 1978):

$$E_T = -14.2 \cdot \sin\{(n-7) \cdot 0.028303\} \quad 1 < n < 106 \quad (6.4)$$

$$E_T = 4 \sin\{(n-106) \cdot 0.053247\} \quad 107 < n < 166 \quad (6.5)$$



$$E_T = -6.5 \cdot \sin\{(n-166) \cdot 0.03927\} \quad 167 < n < 246 \quad (6.6)$$

$$E_T = 16.4 \cdot \sin\{(n-247) \cdot 0.027802\} \quad 247 < n \quad (6.7)$$

The relation of solar time to standard time can be used to calculate the standard time of solar noon [26]:

$$\text{STDTSN} = 12 - E_T - (\text{STMER} - \text{LONG}), \quad (6.8)$$

where

STDTSN = standard time of solar noon,

STMER = standard meridian for the local time zone,

75°W, and

LONG = longitude of the location, 84.7478° W.

The sunrise (SRTIME) and sunset (SSTIME) standard time are then simply:

$$\text{SRTIME} = \text{STDTSN} - \omega_{SS} \quad \text{and} \quad (6.9)$$

$$\text{SSTIME} = \text{STDTSN} + \omega_{SS} \quad (6.10)$$

The irradiation for each period is the area under the curve (shaded area in Figure 6.2), obtained by performing an integration

between start-end of the period. Let time  $(t-\Delta t)$  represent the time that a period starts and  $(t)$  the ending time. The integration limits of the first and last period, within the usable part of the day (between sunrise-sunset) have to be specified. One can use the sunrise time  $(t_{sr})$  to determine the lower integration limit:

1. If  $t_{sr} > t$  then that period is neglected since irradiation equals zero.
2. If  $t_{sr} < t - \Delta t$  then sunrise occurred before the start time of the period. Then the lower integration limit,  $\tau_l$ , is set equal to the starting time of the period or  $\tau_l = t - \Delta t$ .
3. If  $t - \Delta t < t_{sr} < t$  then  $\tau_l = t_{sr}$ .

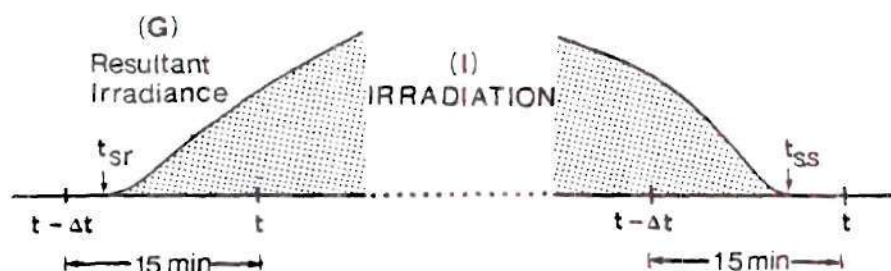


Figure 6.2. Daily Irradiation Limits

A similar analysis should also be performed for the last period:

1. If  $t_{ss} < t - \Delta t$  then all the periods after sunset are neglected,

since all irradiation equals zero.

2. If  $t_{SS} > t$  then the sunset occurred after the end of the last period. The higher integration limit,  $\tau_2$ , is set equal to the ending time of the period  $\tau_2 = t$ .
3. If  $t - \Delta t < t_{SS} < t$  then the higher integration limit becomes  $\tau_2 = t_{SS}$ .

For all other periods within  $t_{sr}$  and  $t_{ss}$ , it is obvious that  $\tau_1 = t - \Delta t$  and  $\tau_2 = t$ . The times considered here are the standard times.

The integration limits,  $\tau_1$  and  $\tau_2$ , are now available. At the average value ( $\tau_{ave} = (\tau_1 + \tau_2) / 2$ ) that is at the middle of each period one can calculate:

1. The hour angle,  $\bar{\omega}$  negative in the morning, positive in the afternoon,
2. The zenith angle,  $\bar{\theta}_z$ , [26]

$$\cos \bar{\theta}_z = \cos \delta \cdot \cos \phi \cdot \cos \omega + \sin \omega \sin \phi, \quad (6.11)$$

3. The solar altitude angle,  $\bar{\alpha}$ ,

$$\bar{\alpha} = 90^\circ - \bar{\theta}_z, \quad (6.12)$$

4. The air mass,  $\overline{AM}$ ,

$$\overline{AM} = 1/\sin(\alpha), \quad (6.13)$$

5. The extraterrestrial radiation,  $G_{on}$ , which remains constant during a day [26],

$$G_{on} = G_{sc} \cdot (1 + 0.033 \cdot \cos(360 \cdot n/365)), \quad (6.14)$$

where

$G_{sc}$  = solar constant,  $1367 \text{ W/m}^2$ ,

$n$  = day of the year,

and finally,

6. The beam normal radiation. For this analysis one can ignore atmospheric refraction and then can assume that the air mass value is constant, i.e.

$$\overline{G}_{bn} = G_{on} \cdot \exp(-K \cdot \overline{AM}), \quad (6.15)$$

where

$K$  = extinction coefficient, 0.25.

The global irradiation (I) can be computed by integrating the irradiance (G) with respect to time, between  $\tau_1$  and  $\tau_2$ , namely

$$I = \int_{\tau_1}^{\tau_2} G(\tau) d\tau = \int_{\tau_1}^{\tau_2} \bar{G}_{bn} \cos \bar{\theta}_z(\tau) d\tau. \quad (6.16)$$

If one assumes no diffuse irradiation (ignoring refraction), then G can be brought out of the integral and the global irradiation becomes

$$I = \bar{G}_{bn} \int_{\tau_1}^{\tau_2} \cos \theta_z d\tau. \quad (6.17)$$

Equivalently the integration can be performed between the hour angles  $\omega_1$  and  $\omega_2$  for a period. The hour angle for the low integration limit  $\omega_1$ , is the difference between the starting standard time ( $\tau_1$ ) of the period of interest and the time of solar noon. The value of  $\omega_1$  is negative in the morning and positive in the afternoon. Similarly the higher integration limit,  $\omega_2$ , is the difference between the ending standard time ( $\tau_2$ ) of the period in interest and the solar noon time.

One can substitute Equation 6.11 in Equation 6.17 to obtain:

$$I = \bar{G}_{bn} \int_{\tau_1}^{\tau_2} (\cos \delta \cdot \cos \phi \cdot \cos \omega + \sin \delta \cdot \sin \phi) d\tau, \quad (6.18)$$

or in terms of integration between  $\omega_1$  and  $\omega_2$ ,

$$I = \bar{G}_{bn} \int_{\omega_1}^{\omega_2} (\cos \delta \cdot \cos \phi \cdot \cos \omega + \sin \delta \sin \phi) d\omega. \quad (6.19)$$

Equation 6.19 yields:

$$I = (12/\pi) \cdot 3600 \cdot \bar{G}_{bn} \cdot \{ \cos \delta \cdot \cos \phi \cdot (\sin \omega_2 - \sin \omega_1) + (\omega_2 - \omega_1) \cdot \sin \delta \sin \phi \}. \quad (6.20)$$

The extraterrestrial horizontal irradiation can similarly be defined as:

$$I_o = (12/\pi) \cdot 3600 \cdot G_{on} \cdot \{ \cos \delta \cdot \cos \phi \cdot (\sin \omega_2 - \sin \omega_1) + (\omega_2 - \omega_1) \cdot \sin \delta \cdot \sin \phi \}. \quad (6.21)$$

The extraterrestrial normal irradiation is simply,

$$I_{on} = 3600 \cdot G_{on} \cdot (\tau_2 - \tau_1). \quad (6.22)$$



The clearness index,  $k_T$ , is defined as the ratio of the global irradiation to the extraterrestrial horizontal irradiation, i.e.

$$k_T = I/I_0. \quad (6.23)$$

The beam normal transmittance is defined as the ratio of the beam normal irradiation to the extraterrestrial normal irradiation

$$\tau_b = I_{bn}/I_{0n}, \quad (6.24)$$

or

$$I_{bn} = \tau_b \cdot I_{0n}. \quad (6.25)$$

The test one would like to perform is to define an arbitrary relation between  $k_T$  and  $\tau_b$  and to observe if the output is the same as the input relation. Let  $\tau_b = (1/2) \cdot k_T$ . Then by substituting in Equation 6.25

$$I_{bn} = (1/2) \cdot k_T \cdot I_{0n}. \quad (6.26)$$

All the desired radiation data needed are now available. An artificial data file was created including only the data that are necessary and used from the algorithms that is, the time variables, the direct beam irradiation and the global irradiation. This file was used to test all FORTRAN programs used in this work. The format of the artificial data files is shown in Table 6.1. The first group of data is part of the artificial monthly file constructed for this test, and below it a group of data from the original Shenandoah data. The odd lines provide the year, day of the year, month, day of the month, hour, minute and the error flags. For the purposes of this test, the error flags were set arbitrarily to zero. The same was done for all other instruments in the even lines except the two beam normal and global irradiation values. A commented listing of the program called VERIF can be found in APPENDIX D.

The result of the procedures described above is an artificial data base covering one year, but with a predefined relationship between the beam normal and global irradiation, such that  $\tau_b = 0.5 \cdot k_T$ . This data base was then analyzed using the same data processing procedures.

Figure 6.3 shows a plot of  $k_T$  versus  $\tau_b$  as computed from the artificial data base using the developed data processing procedures. As expected the result is a straight line with a slope of 0.5 and a zero intercept. Actually it looks like there is some small dispersion. First, consider the resultant line is not fine but actually includes some small dispersion. This arises from two sources. First, the created radiation data was formatted in a way such that it would be similar to the format of the true data files. By doing so, a round off

Table 6.1. Monthly Output Format for January 1, 1980

[illegible][illegible]

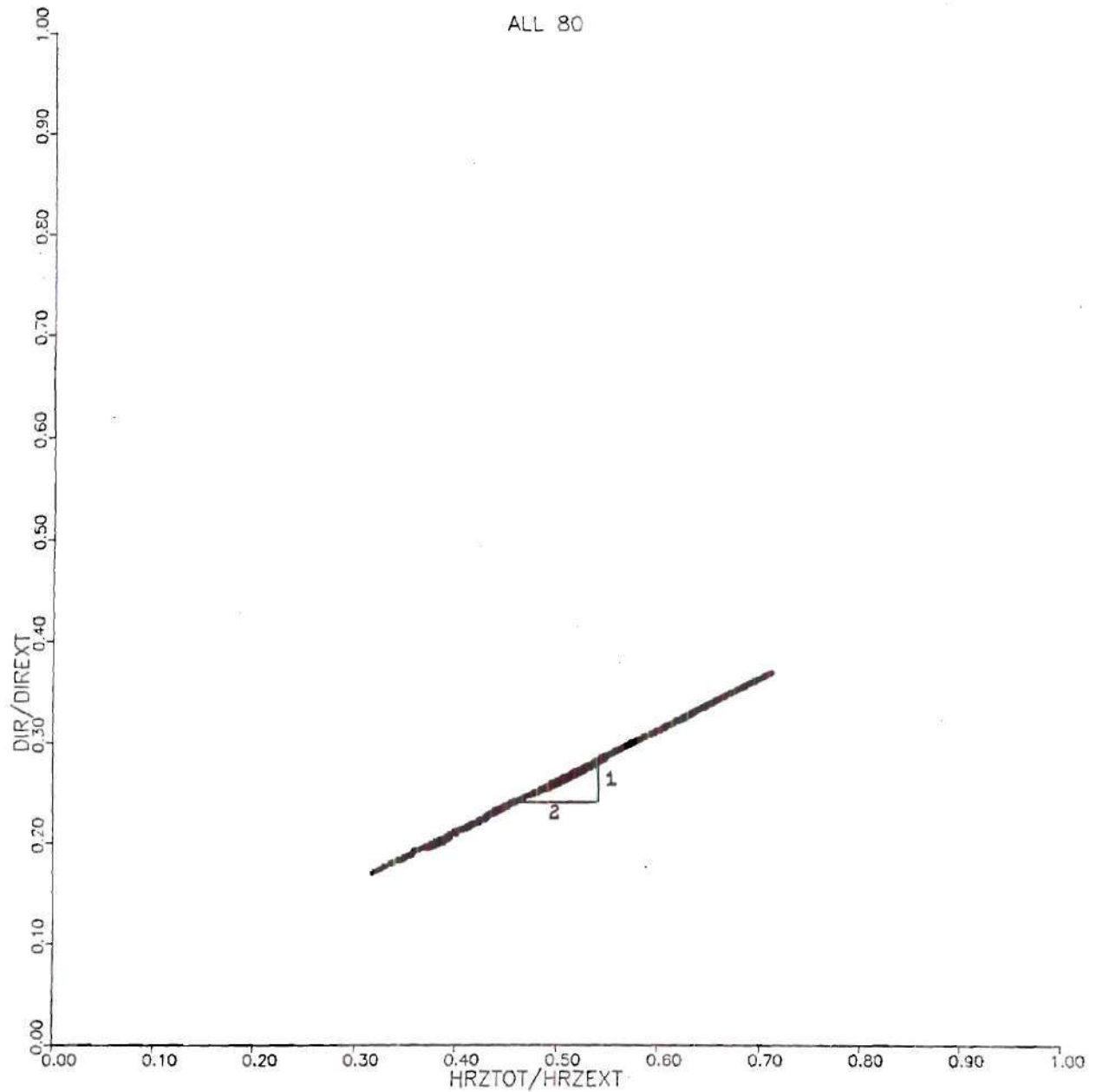


Figure 6.3. Clearness Index Versus Beam Normal Transmittance  
Model Verification for 1980

error was introduced, creating some inaccuracies. Secondly, each "data" point is actually represented by a sizeable dot. In any case the results are satisfactory and sufficient to support confidence in the conclusion that the data processing procedures operate correctly.

## CHAPTER VII

## CONCLUSIONS AND RECOMMENDATIONS

The main goal of this work has been the development of an improved model for estimating the amount of beam normal irradiation when only global irradiation data is available. In Chapter V it was shown that a 5-Year model, based on all of the available data from the Shenandoah STEP, is clearly preferable to any annual model from a constituent year. The resulting model is shown to be similar to the well-known Randall-Whitson model except in the highest range of clearness indices. The evidence previously presented tends to support a preference for the new model in the region of disagreement. One should note that the highest clearness index in the data base is 0.82, and therefore under no circumstances would it be appropriate to extrapolate the results beyond this value. The 5-Year model reported in this work may be preferred for all similar sites.

Many of the comparisons in this work were based on detailed statistical analyses of the Shenandoah STEP data base. An analysis similar to the one used for the 5-Year can be used to compare the monthly models presented in Chapter V as well. Algorithm TBREG5 can easily be extended and be used for a seasonal analysis.



Statistics can be a powerful tool, but the user must be extremely careful because it is easy to find accidental correlations in data as diverse and varied as meteorological records. Adherence to critical standards in handling statistical data could avoid some of the confusion that has often characterized research in this area. These standards should include the following:

1. Understanding the properties of the data: errors, biases, scatter, autocorrelation, spatial coherence, frequency distribution, and stationarity,
2. Choosing statistical methods appropriate both to properties of the data and the purpose of the analysis,
3. Critically examining the statistical significance of the results and making proper allowance for spatial coherence, autocorrelations and smoothing and data selection, and
4. Testing the result on one or more independent data sets, or subsets, of the original data.

While the coefficient of determination for the proposed model is high (89%), there is evidence of considerable seasonal influence. The model could likely be improved either by including the effect of atmospheric conditions (e.g. relative or specific humidity, turbidity) or by disaggregating the data to support seasonal models. One should also consider the investigation of the air-mass dependence and the development of a model using 15 minute data.

An interesting point is to investigate the effect, if any, that the eruption of El Chicon in 1982, could have had on the presented

correlations, based on the collected data at the Shenandoah STEP site. Additionally, the recent strong El Niño events in the Pacific [43] should also be of interest. In general, El Niño events are known to produce major changes on the climate, since it is now recognized as part of a global pattern of anomalies in the atmosphere. The fact that the 1982 - 1983 El Niño is considered as being the strongest in the century, could have very well effected the Shenandoah data and thus the developed model between Fall 1982 and Fall 1983. Studies that have already been conducted on the subject [44], conclude that the combination of El Chichon and El Niño created substantial climatic disturbances, & that in fact do produce a small change in the global correlations.

One could investigate the correlation of  $(\tau_U)$  versus  $(k_T)$  resulted, by using the Shenandoah data broken into optimally adjusted number of linear bands (for different  $k_T$  values). This is believed to produce a better fit model. Calculations should be performed for each year and the entire 5-Year sample, in a similar fashion as this concluded analysis.

Finally, as an alternate method that one can investigate, is a non-parametric statistical analysis, such as a cumulative distribution and a random number generator. This is an attempt to actually account for the dispersion of the data and produce a more realistic model.

## APPENDIX A

CREATE3 : Program to Complete the Monthly Data Files

```

PROGRAM CREATE3(INPUT,OUTPUT,TAPE10,TAPE6=OUTPUT,TAPE5=INPUT,
&TAPE3)
C
C
C      C. BALARAS      12-20-84
C
C...THIS PROGRAM READS THE Q-FILE, LOCATES THE MISSING DAYS
C OR PERIODS FOR THE MONTH AND SUBSTITUTES THEM WITH DUMMY
C VARIABLES.  A NEW Q-FILE WILL BE CREATED, INCLUDING ALL
C 96 PERIODS FOR EVERY DAY OF THE MONTH.
C FOR EACH PARTICULAR MONTH HAVE TO ACCOUNT FOR THE NUMBER
C OF DAYS (THE MONTH-LENGTH 31-28-31-30-31-30-31-31-30-31-30-31).
C
C...DECLARATIONS
      INTEGER JDAYC, DAYC, HRC, MINC, DAY, HR, MIN, MODAY, YR, JDAY, MONTH,
&FLAG1, FLAG2, FLAG3, FLAG4, FLAG5, FLAG6, A1, A2, A3, A4, A5, A6,
&A7, A8, A9, A10, A11, A12, A13, A14, A15, A16, DAYF, HRF, MINF, LEAP
C
C
C...DEFINITIONS
      JDAYC : JULIAN DAY COUNTER
      DAYC  : DAILY COUNTER
      HRC   : HOURLY COUNTER
      MINC  : MINUTE COUNTER
      JDAY  : JULIAN DAY
      DAY   : DAY OF THE MONTH
      HR    : HOUR IN THE DAY
      MIN   : MINUTES IN THE HOUR FOR EVERY PERIOD
      MODAY : THE LAST DAY OF EACH MONTH
      DAYF  : LAST RECORDED DAY IN THE MONTH QFILE
      HRF   : LAST RECORDED HOUR IN THE MONTH QFILE
      MINF  : LAST RECORDED MINUTE IN THE MONTH QFILE
C
C...INITIALIZE VARIABLES AND SET COUNTERS
      DAYC=1
      HRC=0
      MINC=15
      LEAP=0
      WRITE(6,*) 'INPUT NUMBER OF DAYS IN MONTH'
      READ(5,*) MODAY
      WRITE(6,*) 'THE LAST PERIOD OF THE MONTH:DAY,HR,MIN'
      READ(5,*) DAYF,HRF,MINF
C...READ THE FIRST LINE OF THE Q-FILE
      READ(10,1) YR, JDAY, MONTH, DAY, HR, MIN, FLAG1, FLAG2, FLAG3, FLAG4,
&FLAG5, FLAG6
1      FORMAT(I2,1X,I3,1X,I2,1X,I2,1X,I2,1X,I2,1X,Z11,Z11,Z10,1X,Z11,
&Z11,Z10)
      READ(10,2) A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16
2      FORMAT(I3,I5,I4,I5,I6,I5,I5,I5,I5,I5,I5,I5,I5,I5,I5,I5)
C

```





```

END IF
IF (DAYC.GT.32) THEN
WRITE(6,*) 'SOMETHING IS WRONG COSTA THE LIMIT WAS OVERUNNED'
GO TO 111
END IF
IF (DAYC.GT.MODAY) GO TO 112
END WHILE
WRITE(3,7) YR,JDAY,MONTHC,DAY,HR,MIN,FLAG1,FLAG2,FLAG3,FLAG4,
&FLAG5,FLAG6
7   FORMAT(I2,1X,I3,1X,I2,1X,I2,1X,I2,1X,I2,1X,Z11,Z11,Z10,1X,Z11,
&Z11,Z10)
WRITE(3,8) A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16
8   FORMAT(I3,I5,I4,I5,I6,I5,I5,I5,I5,I5,I5,I5,I5,I5,I5)
END IF

C
C...INCREMENT THE COUNTERS FOR THE CORRECT DATA
MINC=MINC+15
IF (MINC.GE.60) THEN
MINC=0
HRC=HRC+1
END IF
IF (HRC.GE.24) THEN
HRC=0
DAYC=DAYC+1
END IF
IF (DAY.EQ.DAYF.AND.HR.EQ.HRF.AND.MIN.EQ.MINF) THEN
WRITE(3,100) YR,JDAYC,MONTHC,DAYC,HRC,MINC,'999999999999999999',
&'999999999999','999999999999999999999999999999999999'
100  FORMAT(I2,1X,I3,1X,I2,1X,I2,1X,I2,1X,I2,1X,A20,A12,1X,A32)
WRITE(3,101) '999','99','99','999','9999','999','999','999',
&'999','999','999','999','999','999','999','999'
101  FORMAT(A3,3X,A2,2X,A2,2X,A3,2X,A4,2X,A3,2X,A3,2X,A3,2X,A3,2X,A3,
&2X,A3,2X,A3,2X,A3,2X,A3,2X,A3,2X,A3)
WHILE (DAYC.LE.MODAY.AND.HRC.LE.23.AND.MINC.LE.45) DO
C...INCREMENT THE COUNTERS FOR THE "DUMMY" DATA
MINC=MINC+15
IF (MINC.GE.60) THEN
MINC=0
HRC=HRC+1
END IF
IF (HRC.GE.24) THEN
HRC=0
DAYC=DAYC+1
JDAYC=JDAYC+1
END IF
IF (DAYC.EQ.MODAY+1.AND.HRC.EQ.0.AND.MINC.EQ.0) GO TO 112
WRITE(3,102) YR,JDAYC,MONTHC,DAYC,HRC,MINC,'999999999999999999',
&'999999999999','999999999999999999999999999999999999'
102  FORMAT(I2,1X,I3,1X,I2,1X,I2,1X,I2,1X,I2,1X,A20,A12,1X,A32)
WRITE(3,103) '999','99','99','999','9999','999','999','999',

```



```

&'999','999','999','999','999','999','999'
103  FORMAT(A3,3X,A2,2X,A2,2X,A3,2X,A4,2X,A3,2X,A3,2X,A3,2X,A3,
&2X,A3,2X,A3,2X,A3,2X,A3,2X,A3,2X,A3)
      END WHILE
      IF (DAYC.EQ.MODAY.AND.HRC.EQ.23.AND.MINC.EQ.45) THEN
      DAYC=DAYC+1
      GO TO 200
      END IF
      END IF
C
C...READ THE NEXT LINE OF THE Q-FILE
200  READ(10,9) YR,JDAY,MONTH,DAY,HR,MIN,FLAG1,FLAG2,FLAG3,FLAG4,
&FLAG5,FLAG6
9    FORMAT(I2,1X,I3,1X,I2,1X,I2,1X,I2,1X,I2,1X,Z11,Z11,Z10,1X,Z11,
&Z11,Z10)
      READ(10,10) A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16
10   FORMAT(I3,I5,I4,I5,I6,I5,I5,I5,I5,I5,I5,I5,I5,I5,I5,I5)
      END WHILE
C
C...COMPLETE THE LAST PERIOD OF THE MONTH
      IF (DAY.EQ.DAYF.AND.HR.EQ.HRF.AND.MIN.EQ.MINF) THEN
      WRITE(3,11) YR,JDAY,MONTH,DAY,HR,MIN,FLAG1,FLAG2,FLAG3,FLAG4,
&FLAG5,FLAG6
11   FORMAT(I2,1X,I3,1X,I2,1X,I2,1X,I2,1X,I2,1X,Z11,Z11,Z10,1X,Z11,
&Z11,Z10)
      WRITE(3,12) A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16
12   FORMAT(I3,I5,I4,I5,I6,I5,I5,I5,I5,I5,I5,I5,I5,I5,I5,I5)
      ELSE
112  DAYC=1
      HRC=0
      MINC=0
      MONTHC=MONTHC+1
      IF (MONTHC.EQ.13) THEN
      MONTHC=1
      YR=YR+1
      JDAYC=1
      END IF
      WRITE(3,104) YR,JDAYC,MONTHC,DAYC,HRC,MINC,'99999999999999999999',
&'99999999999999999999','99999999999999999999999999999999'
104  FORMAT(I2,1X,I3,1X,I2,1X,I2,1X,I2,1X,I2,1X,A20,A12,1X,A32)
      WRITE(3,105) '999','99','99','999','9999','999','999','999',
&'999','999','999','999','999','999','999','999'
105  FORMAT(A3,3X,A2,2X,A2,2X,A3,2X,A4,2X,A3,2X,A3,2X,A3,2X,A3,2X,A3,
&2X,A3,2X,A3,2X,A3,2X,A3,2X,A3,2X,A3)
      END IF
111  CONTINUE
      END

```

## APPENDIX B

HELGO : Subroutine for Calculating the Position of the Sun  
TABLE3 : Comparison of HELGO with DAILY and Nautical Almanac  
CKTTB2 : Calculations of k and Using Subroutine HELGO  
LSMAIN7 : Sorting of Date Data According to k  
SORTR : Sorting Subroutine  
VS RTP : Sorting Subroutine from IMSL Library  
VS RTU : Sorting Subroutine from IMSL Library

SUBROUTINE HELGO (IYEAR, MONTH, IDAY, CVLT, ALONGD, ALATD, ALONST, ZONE,  
&ALTR, DECL, EOT, HANG, RADIUS)

```

C
C C. BALARAS      1-31-85
C
C...THIS IS THE LATEST VERSION OF THE SUBROUTINE USED IN PROGRAMS (DY104)
C AND (HOUR5). THE INPUTS IN THIS SUBROUTINE ARE INTEGER VALUES UNDER
C THE FOLLOWING VARIABLE NAMES: IYEAR (CURRENT YEAR, I.E. 83)
C                               MONTH (CURRENT MONTH, I.E. 3 FOR MARCH)
C                               IDAY  (THE CURRENT DAY IN THE MONTH)
C                               CVLT  (THE CIVIL LOCAL TIME)
C                               ALONGD (LONGITUDE IN DEGREES)
C                               ALATD  (LATITUDE IN DEGREES)
C                               ALONST (STANDARD LONGITUDE IN DEGREES)
C                               ZONE  (TIME ZONE OF THE LOCALITY
C                                   E-W OF GREENWICH)
C THE OUTPUTS ARE: ALTR  (ALTITUDE UNITS ARE RADIAN)
C                  DECL  (DECLINATION UNITS ARE RADIAN)
C                  EOT   (EQUATION OF TIME UNITS ARE MINUTES)
C                  HANG  (HOUR ANGLE UNITS ARE RADIAN)
C                  RADIUS (RADIUS OF EARTH'S ORBIT IN ASSTRONOMICAL UNITS)
C FOR OTHER POSSIBLE OUTPUTS COULD CONSIDER THE CALCULATED HOUR ANGLE,
C THE ALTITUDE AND AZIMUTH ANGLES (IN RADIAN).
C FOR SOME OF THE FOLLOWING CALCULATIONS, LOW PRECISION EQUATIONS ARE
C USED (TAKEN FROM THE ALMANAC FOR COMPUTERS 1984) AS PRESENTED BY
C R.L. JOHNSON OF MCDONNELL DOUGLAS
C
C THIS SUBROUTINE WAS TESTED BY COMPARING ITS COMPUTED VALUES WITH THE
C ALMANAC OF COMPUTERS (PROGRAM (MCDON) FOR THE YEAR OF 1983 AND THE
C LOCALITY OF GREENWICH).
C
C...DEFINITIONS OF VARIABLES
C  ANGR  : MEAN ANOMALY
C  AZIM  : AZIMUTH, UNITS ARE RADIAN
C  ALONGH : LONGITUDE IN HOURS
C  ALONST : STANDARD LONGITUDE IN DEGREES
C  ALATR  : LATITUDE, UNITS ARE RADIAN
C  ALT    : ALTITUDE, UNITS ARE DEGREES
C  CVLT   : LOCAL TIME, UNITS ARE HOURS
C  DECL   : DECLINATION, UNITS ARE RADIAN
C  DRCONV : DEGREES TO RADIAN CONVERSION
C  ECLL   : ECLIPTIC LONGITUDE OR TRUE GEOCENTRIC LONGITUDE,
C          UNITS ARE RADIAN
C  ECLO   : OBLIQUITY OF THE ECLIPTIC, UNITS ARE RADIAN
C  GAST   : GREENWICH ACTUAL SIDERAL TIME, UNITS ARE HOURS
C  HANG   : LOCAL HOUR ANGLE OF THE SUN, UNITS ARE RADIAN
C  RADIUS : THE DISTANCE OF SUN TO EARTH IN ASTRONOMICAL UNITS
C  RTAS   : RIGHT ASCENSION, UNITS ARE RADIAN
C  SMALAL : SMALLEST ALTITUDE ALLOWED
C  TREF   : STANDARD EPOCH JANUARY 2000.0

```



```

C          WHICH IS 12 UT, 1 JANUARY 2000.0
C    UT      : UNIVERSAL TIME, LOCAL TIME FROM GREENWICH MIDNIGHT IN HOURS
C    XCON     : STANDARD EPOCH 0 UT, 0 JANUARY 1984
C              WHICH IS MIDNIGHT UT STARTING 31 DECEMBER 1983
C    XD       : DAYS SINCE STANDARD EPOCH TREF
C    XL1      : MEAN LONGITUDE
C    XN       : DAYS SINCE STANDARD EPOCH XCON
C
C...CONSTANTS
C...CONSTANTS FOR LOW PRECISION EQUATIONS FOR ECLL AND ECLO
C    DATA  A1,A2,A3,A4,A5,A6,A7,A8,A9,TREF,XCON/6.2400408,
C            &1.720197E-2,4.8934184,1.7202536E-2,3.3479055E-2,
C            &2.2936565E-9,3.7606585E-4,4.0911372E-1,6.21199E-9,
C            &2451545.0,2445699.5/
C...CONSTANTS FOR ATMOSPHERIC REFRACTION EQUATION
C    DATA  B1,B2,B3,B4,B5/-9.036938093E-5,-1.600076095E-5,
C            &2.948314656E-4,-3.278909E-6,-1.234081940E-8/
C    PI=4.0*ATAN(1.0)
C    TWOPI=2.0*PI
C    DRCONV=PI/180.0
C    ALONGH=ALONGD/15.
C    ALATR=ALATD*DRCONV
C    CLAT=COS(ALATR)
C    SLAT=SIN(ALATR)
C    SMALAL=0.008
C    HRCONV=15.0*DRCONV
C    IYEAR2=IYEAR+1900
C
C    CALL JDAY(XJUDAT,IYEAR2,MONTH,IDAY)
C
C...CALCULATE THE UNIVERSAL TIME FOR THE LOCATION (EAST US: 5)
C    UT=CVLT+ZONE
C...CALCULATE THE MEAN ANOMALY
C    TD=XJUDAT-TREF+UT/24.0
C    ANGCR=A1+A2*TD
C    ANGCR=(ANGCR/TWOPI-aint(ANGCR/TWOPI))*TWOPI
C...CALCULATE THE DISTANCE OF SUN FROM EARTH IN ASTRONOMICAL UNITS
C    RADIUS=1.00014-0.01671*COS(ANGCR)-0.00014*COS(ANGCR)
C...CALCULATE THE MEAN LONGITUDE
C    XL1=A3+A4*TD
C...CALCULATE THE TRUE LONGITUDE
C    ECLL=XL1+(A5-A6*TD)*SIN(ANGCR)+A7*SIN(2.0*ANGCR)
C    ECLL=(ECLL/TWOPI-aint(ECLL/TWOPI))*TWOPI
C...CALCULATE THE OBLIQUITY
C    ECLO=A8-A9*TD
C...CONVERT TO RT ASCENSION AND DECINATION
C    RTAS=ATAN2(SIN(ECLL)*COS(ECLO),COS(ECLL))
C    SLSE=SIN(ECLL)*SIN(ECLO)
C    DECL=ATAN2(SLSE,SQRT(1.0-SLSE**2.0))
C...CALCULATE THE HOUR ANGLE

```

```

      XN=XJUDAT-XCON
      DAY=XN+UT/24.0
      HANG=HRCONV*(GAST(XN,UT,DAY)-ALONGH)-RTAS
      HANG=AMOD(HANG,TWOPI)
      IF (HANG.GT.PI.AND.HANG.LT.TWOPI) HANG=HANG-TWOPI
      IF (HANG.LT.-PI) HANG=HANG+TWOPI
C...CONVERT TO ELEVATION AND AZIMUTH
      ALT=ASIN(SLAT*SIN(DECL)+COS(DECL)*COS(HANG)*CLAT)
      IF (ALT.LT.SMALAL) ALT=SMALAL
      AZIM=-ATAN2(SIN(HANG),(COS(HANG)*SLAT-TAN(DECL)*CLAT))
C...REFRACTION, RC=0.0, IF ALT<=5 DEGREES=0.08727 RADIAN
C NO CORRECTION FOR REFRACTION IS MADE FOR ALTITUDES LESS THAN 5 DEGREES
      RC=0.0
      IF (ALT.GT.0.08727)
&RC=B1*(ALT)+B2+B3*(1/ALT)+B4*((1/ALT)**2.0)+B5*((1/ALT)**3)
      ALTR=ALT+RC
C...CALCULATE THE HOUR ANGLE IN DEGREES
      HANGDE=HANG/DRCONV
      HANGDE=AMOD(HANGDE,360.)
      IF (HANGDE.GT.180.0.AND.HANGDE.LT.360.0) HANGDE=HANGDE-360.
      IF (HANGDE.LT.-180.0.AND.HANGDE.GT.-360.0) HANGDE=HANGDE+360.
C...CALCULATE THE APARENT SOLAR TIME
      AST=HANGDE/15.+12.
C...CALCULATE THE MEAN SOLAR TIME
      AMST=CVLT+(ALONST-ALONGD)/15.0
C...CALCULATE THE EQUATION OF TIME
      EOT=(AST-AMST)*60.
      IF (HANGDE.GT.180) EOT=-EOT
      EOT=AMOD(EOT,1440.)
      RETURN
      END
      FUNCTION GAST(XN,UT,DAY)
C...CALCULATE THE GREENWICH ACTUAL SIDERAL TIME
C BASED ON EQUATIONS IN ALMANAC FOR COMPUTERS 1984
C
C...DEFINITIONS
C DAY : XN+UT/24.0
C DRCONV : CONVERSION FROM DEGREES TO RADIAN
C E : EQUATION OF THE EQUINOXES, IN HOURS
C GAST : GREENWICH ACTUAL SIDERAL TIME, IN HOURS
C GMST : GREENWICH MEAN SIDERAL TIME (VERNAL EQUINOX ANGLE FROM
C GREENWICH), IN HOURS.
C UT : LOCAL TIME (FROM GREENWICH MIDNIGHT), UNITS ARE HOURS
C XN : DAYS SINCE STANDARD EPOCH XCON
C XOMEGA : MEAN LONGITUDE OF ASCENDING NODE OF THE MOON'S ORBIT,
C & IN RADIAN
C
      DATA G1,G2,G3,G4,G5,G6/6.5905966,0.0657098242,
& 1.00273791,74.5658,-0.0529539,-0.00029/
      PI=4.0*ATAN(1.0)

```

```

      DRCONV=PI/180.
      GMST=G1+G2*XN+G3*UT
      GMST=24.0*(GMST/24.0-AINT(GMST/24.0))
      XOMEGA=DRCONV*(G4+G5*DAY)
      E=G6*SIN(XOMEGA)
C...IN THE NEXT STATEMENT GMST IS CORRECTED
C  FOR PERTUBATIONS INDUCED BY MOTION OF THE MOON TO
C  YIELD AN ACCURATE VALUE FOR GAST
      GAST=GMST+E
      RETURN
      END
      SUBROUTINE JDAY(XJUDAT,IYEAR2,MONTH,IDAY)
C...SUBROUTINE JDAY CALCULATES THE STANDARD JULIAN DATE
C  NOTE: VARIOUS STANDARD EPOCHS ARE USED IN APPLICATIONS
      JD=IDAY+1461*(IYEAR2+4800+(MONTH-14)/12)/4
      &  +367*(MONTH-2-(MONTH-14)/12*12)/12
      JD=JD-32075-3*((IYEAR2+4900+(MONTH-14)/12)/100)/4
      XJUDAT=JD-0.5D0
      RETURN
      END

```



```

PROGRAM TABLE3 (INPUT, OUTPUT, TAPE4=OUTPUT, TAPE3=INPUT, TAPE8,
&TAPE7, TAPE5, TAPE2)
C
C      C. BALARAS      11-12-84
C
C...THIS PROGRAM TABULATES VALUES FOR THE DECLINATION, THE
C      ALTITUDE OF THE SUN AND THE EQUATION OF TIME, CALCULATED
C      AT 12.0 NOON STANDARD TIME, 1983.
C      THESE PARAMETERS ARE CALCULATED BY TWO METHODS AND
C      COMPARED TO THE NAUTICAL ALMANAC.
C      FIRST METHOD : EQUATION OF TIME BY WATT AND DECLINATION
C      BY COOPER.
C      SECOND METHOD : ACCORDING TO SUBROUTINE HELGO
C      THE 1983 DATA FROM THE ALMANAC IS IN TAPE7.
C
C...DEFINITIONS
C
C...VARIABLES USED IN THE FIRST METHOD
C      DELTA  : DECLINATION ANGLE IN RADIANS
C      EQOT   : EQUATION OF TIME IN MINUTES
C      OMEGA   : HOUR ANGLE IN RADIANS
C      DELTAD  : DECLINATION IN DEGREES
C      OMEGAD  : HOUR ANGLE IN DEGREES
C      IDELTAD, DELTAM :DECLINATION IN DEGREES, MINUTES
C      IEQOT, EQOTS   : EQUATION OF TIME IN MINUTES, SECONDS
C      IOMEGAD, OMEGAM : HOUR ANGLE IN DEGREES, MINUTES
C      DRCONV : DEGREES TO RADIANS CONVERSION FACTOR
C
C...VARIABLES USED IN THE SECOND METHOD
C      DECL   : DECLINATION ANGLE IN RADIANS
C      EOT     : EQUATION OF TIME IN MINUTES
C      HANG    : HOUR ANGLE IN RADIANS
C      DECLD   : DECLINATION IN DEGREES
C      HANGD   : HOUR ANGLE IN DEGREES
C      IDECLDE, DECLM : DECLINATION IN DEGREES, MINUTES
C      IEOTM, EOTS    : EQUATION OF TIME IN MINUTES, SECONDS
C      IHANGDR HANGM  : HOUR ANGLE IN DEGREES AND MINUTES
C
C...VARIABLES FROM THE NAUTICAL ALMANAC
C      IDELTAO DELATOM : THE DECLINATION IN DEGREES AND MINUTES
C      IEOTOM EOTOS    : EQUATION OF TIME IN MINUTES AND SECONDS
C      IHANGO HANGOM   : HOUR ANGLE IN DEGREES AND MINUTES
C
C      DATA  AMAXE1,AMAXE2,AMAXE3,AMAXE4,AMAXE5,AMAXE6,SUM1,SUM2,
&SUM3,SUM4,SUM5,SUM6,MONTH/0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,
&0.0,0.0,0.0,0.0,1/
      IYEAR=1983
      CVLT=12.0
      WRITE(8,101) 'YEAR=',IYEAR,'LOCAL TIME=',CVLT
101  FORMAT(1X,A5,I4,5X,A11,F4.1,/)

```

```

        WRITE(8,111) 'DAY','DELTA','OMEGA','EOT','DELTA','OMEGA','EOT',
        &'DELTA','OMEGA','EOT'
111  FORMAT(1X,A3,8X,A5,10X,A5,9X,A3,10X,A5,8X,A5,8X,A3,13X,
        &A5,8X,A5,9X,A3)
        WRITE(8,114) '(DEGR-MIN)', '(DEGR-MIN)', '(MIN-SEC)', '(DEGR-MIN)',
        &'(DEGR-MIN)', '(MIN-SEC)', '(DEGR-MIN)', '(DEGR-MIN)', '(MIN-SEC)'
114  FORMAT(9X,A10,5X,A10,4X,A9,5X,A10,3X,A10,2X,A9,7X,A10,3X,
        &A10,4X,A9,/)
        WRITE(8,113) '(COOPER)', '(DAILY)', '(WATT)', '(HELGO)',
        &'(NAUTICAL ALMANAC)'
113  FORMAT(11X,A8,6X,A7,20X,A7,13X,A18,/)
C
        DO 100 I=1,365
            IDAY=I
            T1=11.875
            T2=12.125
            READ(7,*) IHANGO,HANGOM,IDELTAO,DELTAOM,IEOTOM,EOTOS
C
            CALL SOTIME(DELTA,EQOT,I,T1,T2,OMEGAV)
C...CALCULATE THE DECLINATION IN DEGREES AND MINUTES
            PI=4.0*ATAN(1.0)
            DRCONV=PI/180.0
            DELTAD=DELTA/DRCONV
            IDELTAD=INT(DELTAD)
            DELTAM=(DELTAD-IDELTAD)*60.
            IF (DELTAD.LT.-1.0) DELTAM=(IDELTAD-DELTAD)*60.0
C...CALCULATE THE EQUATION OF TIME IN MINUTES AND SECONDS
            IEQOT=INT(EQOT)
            EQOTS=(EQOT-IEQOT)*60.
            IF (EQOT.LT.-1.0) EQOTS=(IEQOT-EQOT)*60.0
C...CALCULATE THE HOUR ANGLE IN DEGREES AND MINUTES
            OMEGAD=OMEGAV/DRCONV
            IOMEGAD=INT(OMEGAD)
            OMEGAM=(OMEGAD-IOMEGAD)*60.
            IOMEGAD=MOD(IOMEGAD,360)
            IF (OMEGAD.LT.-1.0) OMEGAM=(IOMEGAD-OMEGAD)*60.0
C
            CALL HELGO(IYEAR,MONTH,IDAY,CVLT,DECL,HANG,EOT)
C...CALCULATE THE DECLINATION IN DEGREES AND MINUTES
            DECLD=DECL/DRCONV
            IDECLDE=INT(DECLD)
            DECLM=(DECLD-IDECLDE)*60.
            IF (DECLD.LT.-1.0) DECLM=(IDECLDE-DECLD)*60.0
C...CALCULATE THE HOUR ANGLE IN DEGREES AND MINUTES
            HANGD=HANG/DRCONV
            HANGD=AMOD(HANGD,360.)
            IHANGDR=INT(HANGD)
            HANGM=(HANGD-IHANGDR)*60.
            IHANGDR=MOD(IHANGDR,360)
            IF (HANGD.LT.-1.0) HANGM=(IHANGDR-HANGD)*60.0

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      HANGD=AMOD(HANGD,360.)
C...CALCULATE THE EQUATION OF TIME IN MINUTES AND SECONDS
      IEOTM=INT(EOT)
      EOTS=(EOT-IEOTM)*60.0
      IF (EOT.LT.-1.0) EOTS=(IEOTM-EOT)*60.0
C...CALCULATE THE MAXIMUM ERROR IN COMPARISON WITH THE
C   NAUTICAL ALMANAC
      DELTAO=IDELTAO+DELTAOM/60.
      IF (IDELTAO.LT.0) DELTAO=IDELTAO-DELTAOM/60.
      HANGO=IHANGO+HANGOM/60.
      EOTO=IEOTOM+EOTOS/60.
      IF (IEOTOM.LT.0) EOTO=IEOTOM-EOTOS/60.
      OMEGA1=OMEGAD
      OMEGA2=HANGO
      OMEGA3=HANGD
      IF (OMEGAD.GT.180.) OMEGA1=OMEGAD-360.
      IF (HANGD.GT.180.) OMEGA3=HANGD-360.
      IF (HANGO.GT.180.) OMEGA2=HANGO-360.
      E1=ABS(DELTAO-DELTAD)
      E2=ABS(OMEGA2-OMEGA1)
      E3=ABS(EOTO-EQOT)
      E4=ABS(DELTAO-DECLD)
      E5=ABS(OMEGA2-OMEGA3)
      E6=ABS(EOTO-EOT)
      IF (E1.GT.AMAXE1) AMAXE1=E1
      IF (E2.GT.AMAXE2) AMAXE2=E2
      IF (E3.GT.AMAXE3) AMAXE3=E3
      IF (E4.GT.AMAXE4) AMAXE4=E4
      IF (E5.GT.AMAXE5) AMAXE5=E5
      IF (E6.GT.AMAXE6) AMAXE6=E6
C...CALCULATE THE TOTAL SQUARE ERROR
      SUM1=SUM1+E1*E1
      SUM2=SUM2+E2*E2
      SUM3=SUM3+E3*E3
      SUM4=SUM4+E4*E4
      SUM5=SUM5+E5*E5
      SUM6=SUM6+E6*E6
      WRITE(5,*) 'I=',IDAY,'E1=',E1,'E2=',E2,'E3=',E3,'E4=',E4,
&'E5=',E5,'E6=',E6
      WRITE(8,103) I,IDELTAD,DELTAM,IOMEGAD,OMEGAM,IEQOT,EQOTS,
&IDDECLDE,DECLM,IHANGDR,HANGM,IEOTM,EOTS,
&IDELTAO,DELTAOM,IHANGO,HANGOM,IEOTOM,EOTOS
103  FORMAT(1X,I3,5X,I4,1X,F6.2,3X,I3,2X,F6.2,1X,I4,1X,F6.2,
&4X,I4,1X,F6.2,2X,I4,1X,F6.2,2X,I4,1X,F6.2,
&6X,I4,1X,F5.1,3X,I4,1X,F5.1,3X,I3,2X,F5.1)
100  CONTINUE
C...CALCULATE THE ROOT MEAN SQUARE ERROR (RMS)
      RMS1=SQRT(SUM1/I)
      RMS2=SQRT(SUM2/I)
      RMS3=SQRT(SUM3/I)

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RMS4=SQRT(SUM4/I)
RMS5=SQRT(SUM5/I)
RMS6=SQRT(SUM6/I)
WRITE(8,*) ' '
WRITE(8,115) 'MAXIMUM ERRORS COMPARED TO THE NAUTICAL ALMANAC'
115 FORMAT(23X,A47,/)
WRITE(8,116) 'DELTA','OMEGA','EOT','DELTA','OMEGA','EOT',
116 FORMAT(12X,A5,8X,A5,8X,A3,10X,A5,8X,A5,8X,A3,/)
WRITE(8,117) AMAXE1,AMAXE2,AMAXE3,AMAXE4,AMAXE5,AMAXE6
117 FORMAT(11X,F6.3,7X,F7.3,5X,F6.3,8X,F6.3,6X,F7.3,5X,F7.3,/)
WRITE(8,118) 'SQUARE ROOT MEAN SQUARE ERROR'
118 FORMAT(32X,A29,/)
WRITE(8,119) RMS1,RMS2,RMS3,RMS4,RMS5,RMS6
119 FORMAT(11X,F6.3,7X,F7.3,5X,F6.3,8X,F6.3,6X,F7.3,5X,F7.3,/)
END
SUBROUTINE SOTIME(DELTA,EQOT,IDAY,T1,T2,OMEGAV)
C...DEFINITIONS OF VARIABLES
C   ALAT   : LATITUDE IN DEGREES
C   ALON   : LONGITUDE IN DEGREES
C   ALONSM : STANDARD MERIDIAN FOR THE LOCAL TIME ZONE
C           (15 DEGREES FOR EVERY TIME ZONE E-W FROM GREENWICH)
C   ALPHAV : CORRESPONDING AVERAGE OF THE SOLAR ALTITUDE
C   DELTA  : DECLINATION ANGLE IN RADIANS
C   DRCONV : CONVERSION FACTOR FROM DEGREES TO RADIANS
C   EQOT   : EQUATION OF TIME IN MINUTES
C           NORMAL TO THE RADIATION ON THE NTH DAY OF THE YEAR
C   GSC    : SOLAR CONSTANT(W/M/M)
C   HANGSS : HOUR ANGLE AT SUNSET(STANDARD TIME)
C   HRCONV : CONVERSION FACTOR FROM HRS TO RAD
C   ISHR   : APPARENT SOLAR TIME OF THE HOUR
C   ISMIN  : APPARENT SOLAR TIME FOR THE MIN.
C   OMEGA  : HOUR ANGLE IN RADIANS
C   OMEGA1 : HOUR ANGLE CORRESPONDING TO THE LOWER INTIGRATION LIMIT
C   OMEGA2 : HOUR ANGLE CORRESPONDING TO THE HIGHER INTIGRATION LIMIT
C   OMEGAV : CORRESPONDING AVERAGE OF THE HOUR ANGLE-SOLAR TIME
C   SRTIME : SUNRISE STANDARD TIME
C   SSTIME : SUNSET STANDARD TIME
C   STDTSN : STANDARD TIME OF SOLAR NOON
C   T1     : STANDARD TIME AT WHICH EACH PERIOD STARTS
C   T2     : STANDARD TIME AT WHICH EACH PERIOD ENDS
C   TAU1   : INTEGRATION LOWER LIMIT FOR EVERY PERIOD (STD.TIME)
C   TAU2   : INTEGRATION UPPER LIMIT FOR EVERY PERIOD (STD.TIME)
C   TAUAV  : INTEGRATION AVERAGE TIME (STD. TIME)
C   THETAZ : ZENITH ANGLE OF THE SUN IN RADIANS
C
C   COMMON/WHERE/ALAT,ALON,ALONSM
C
C   PI=4.0*ATAN(1.0)
C   ALON=0.0
C   ALAT=51.47

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ALONSM=0.0
DRCONV=PI/180.0
SLAT=ALAT*DRCONV
HRCONV=15.0*DRCONV
C...CALCULATE THE DECLINATION
    DELTA=23.45*SIN(2.0*PI*(284.0+IDAY)/365.0)*DRCONV
C...CALCULATE THE SUNSET HOUR ANGLE
    HANGSS=ACOS(-TAN(SLAT)*TAN(DELTA))
C...CALCULATE THE EQUATION OF TIME
    IF (IDAY.GT.106) GO TO 10
    EQOT=-14.2*SIN((IDAY+7.0)*0.028303)
    GO TO 40
10  IF (IDAY.GT.166) GO TO 20
    EQOT=4.0*SIN((IDAY-106.0)*0.053247)
    GO TO 40
20  IF (IDAY.GT.246) GO TO 30
    EQOT=-6.5*SIN((IDAY-166.0)*0.03927)
    GO TO 40
30  EQOT=16.4*SIN((IDAY-247.0)*0.027802)
C...CALCULATE THE STANDARD TIME OF SOLAR NOON
40  STDTSN=12.0-(EQOT/60.0)-(ALONSM-ALON)/15.0
C...CALCULATE THE SUNRISE STANDARD TIME
    SRTIME=STDTSN-(HANGSS/HRCONV)
C...CALCULATE THE SUNSET STANDARD TIME
    SSTIME=STDTSN+(HANGSS/HRCONV)
C...CALCULATE TAU1
C.....FOR PERIODS BEFORE SUNRISE
    IF (SRTIME.GT.T2) THEN
        ALPHAV=0.0
        GO TO 101
    ELSE
C.....FOR PERIODS BETWEEN SUNRISE AND SUNSET
        IF (SRTIME.LT.T1) TAU1=T1
        IF (SRTIME.GT.T1) TAU1=SRTIME
        END IF
C...CALCULATE TAU2
C.....FOR PERIODS AFTER SUNSET
    IF (SSTIME.LT.T1) THEN
        ALPHAV=0.0
        GO TO 101
    ELSE
C.....FOR PERIODS BETWEEN SUNRISE AND SUNSET
        IF (SSTIME.GT.T2) TAU2=T2
        IF (SSTIME.LT.T2) TAU2=SSTIME
        END IF
C...CALCULATE THE AVERAGE INTEGRATION LIMITS(STD. TIME)
    TAUAV=(TAU1+TAU2)/2.0
C...CALCULATE THE CORRESPONDING AVERAGE OF THE
C.....HOUR ANGLE
    IF (TAUAV.LE.STDTSN) THEN

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```
OMEGAV=-(STDTSN-TAUAV)*HRCONV
ELSE
OMEGAV=(TAUAV-STDTSN)*HRCONV
END IF
C.....SOLAR ALTITUDE
THETAZ=(ACOS(COS(DELTA)*COS(SLAT)*COS(OMEGAV)+SIN(DELTA)*
&SIN(SLAT)))
ALPHAV=(PI/2.0)-THETAZ
101 RETURN
END
```



```

      PROGRAM CKTTB2 (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT, TAPE26,
&TAPE30)
C
C   C. BALARAS      4-30-85
C   C. BALARAS      5-13-85
C   C. BALARAS      5-20-85
C
C...THIS PROGRAM RECALCULATES THE KT AND TB FROM THE RADIATION DATA
C   INCLUDED IN TAPE26. THE CALCULATIONS WILL BE PERFORMED USING
C   SUBROUTINE HELGO AT 0:00 HRS AND THE SCREENED DATA SET (SDS).
C   THE RESULTS WILL BE COMPARED WITH THE CORRESPONDING VALUES
C   WE ARE CURRENTLY USING (FROM SDS), AND REPORT ANY
C   SUBSTANTIAL DEVIATIONS OR AGREEMENT.
C
C...FOR CKTTB1 THE ONLY CHANGE IS INDICATED WHEN CALLING
C   SUBROUTINE HELGO, IN SUCH A WAY THAT THE CALCULATIONS
C   ARE PERFORMED AT THE MID-PERIOD.
C
C...DEFINITIONS
C
C...DECLARATIONS
C   ALATD  : LATITUDE OF THE LOCALITY IN DEGREES
C   ALONGD : LONGITUDE OF THE LOCALITY IN DEGREES
C   ALONST : STANDRD LONGITUDE IN DEGREES
C   AMAXKT : MAXIMUM ERROR OF KT VALUES
C   AMAXTB : MAXIMUM ERROR OF TB VALUES
C   CVLT   : LOCAL TIME IN HOURS
C   DIR    : BEAM IRRADIATION IN KJ/M/M
C   EKT    : ABSOLUTE VALUE OF ERROR BETWEEN KT VALUES
C   ETB    : ABSOLUTE VALUE OF ERROR BETWEEN TB VALUES
C   F1     : SOLAR CONSTANT IN KJ/M/M/RAD
C   F2     : SOLAR PARAMETER DEPENDING ON RADIUS EARTH SUN KJ/M/M/RAD
C   GSC    : SOLAR CONSTANT IN W/M/M
C   HRZTOT : GLOBAL IRRADIATION IN KJ/M/M
C   IO     : EXTRATERRESTRIAL HORIZONTAL IRRADIATION IN KJ/M/M
C   KT1    : CLEARNESS INDEX FROM SDS
C   KT2    : RECALCULATED CLEARNESS INDEX
C   TB1    : BEAM NORMAL TRANSMITTANCE FROM SDS
C   TB2    : RECALCULATED BEAM NORMAL TRANSMITTANCE
C   ZONE   : TIME ZONE OF LOCALITY
C           INTEGER YR, DAY, HR, BADPER
C           REAL KT1, KT2, ION, IO, IO2, ION2
C
C
C...CONSTANTS
C   PI=4.0*ATAN(1.0)
C   DRCONV=PI/180.0
C   ALATD=33.4046
C   ALAT=33.4046*DRCONV
C   ALONGD=84.7478

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```

ALONST=75.
ZONE=5.
GSC=1367.
F1=GSC*12.0*3600.0/PI/1000.0
C
DATA AMAXKT,AMAXTB/0.0,0.0/
DATA AMKTPR/0.0/
C
WRITE(30,*) ' '
WRITE(30,*) ' '
WRITE(30,40) 'YR','MO','DAY','HR','MIN','HRZTOT','DIR','KT1',
&'KT2','ERROR','TB1','TB2','ERROR','PCT','BADPER','DIFF1'
40  FORMAT(1X,A2,2X,A2,2X,A3,1X,A2,2X,A3,5X,A6,4X,A3,9X,A3,4X,A3,
&5X,A5,6X,A3,4X,A3,4X,A5,5X,A3,2X,A6,2X,A5)
WRITE(30,*) ' '
DO 30 I=1,1963
C
IO2=0.0
ION2=0.0
OMEG1A=0.
OMEG2A=0.
OMEG3A=0.
OMEG4A=0.
C
C...READ ONE HOURS DATA ENDING AT HR+MIN/60
READ(26,10) YR,MO,DAY,HR,MIN,KT1,TB1,HRZTOT,DIR,PCT,BADPER
10  FORMAT(1X,I2,2X,I2,2X,3(I2,1X),1X,F5.3,2X,F5.3,2(2X,F7.1),
&2X,F4.2,2X,I2)
C
C...CALL SUBROUTINE HELGO FOR 0:00 HOURS
CALL HELGO(YR,MO,DAY,0.,ALONGD,ALATD,ALONST,ZONE,ALPHA,
&DELTA,EOT,OMEGA,R)
YR=YR-1900
C...TO PRFORM CALCULATIONS AT THE MID-PERIOD FOR CKTTB1
C MUST CALCULATE THE CIVIL LOCAL TIME
C CVLT=(HR+MIN/60.)-0.5
C AND CALL HELGO FOR TIME-0.5 HOURS
C CALL HELGO(YR,MO,DAY,CVLT,ALONGD,ALATD,ALONST,ZONE,ALPHA,
C DELTA,EOT,OMEGA,R)
C
C...CALCULATE OMEGA AT THE MIDDLE OF THE PERIOD
ALONGD=84.7478
AMST=CVLT+(ALONST-ALONGD)/15.
AST=AMST+EOT/60.
OMEGA=(AST-12.0)*15.*DRCONV
C
C...CALCULATE THE HOUR ANGLES AT THE START END OF THE PERIOD
OMEGA1=OMEGA-15.0/2.*DRCONV
OMEGA2=OMEGA+15.0/2.*DRCONV
C...CORRECT HOUR ANGLES FOR FIRST AND LAST PERIODS OF DAY

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WSS=ACOS(-TAN(ALAT)*TAN(DELTA))
IF(OMEGA2.GT.WSS) OMEGA2=WSS
IF(OMEGA1.LT.-WSS) OMEGA1=-WSS
C
C...DETERMINE MISSING PERIOD
      IPD=IFIX(AMOD(FLOAT(BADPER),10.))
C...DETERMINE HOUR ANGLES
C  IF FIRST PERIOD IS MISSING
      IF (IPD.EQ.1) OMEGA1=OMEGA1+15./4.*DRCONV
C  IF LAST PERIOD IS MISSING
      IF (IPD.EQ.4) OMEGA2=OMEGA2-15./4.*DRCONV
C  IF SECOND PERIOD IS MISSING
      IF (IPD.EQ.2) THEN
        OMEG1A=OMEGA1+15./4.*DRCONV
        OMEG2A=OMEG1A+15./4.*DRCONV
C  CALCULATE THE EXTRATER. HORIZONTAL IRRADIATION
C  FOR THE MISSING PERIOD
      IO2=(F1/R**2)*((COS(DELTA)*COS(ALAT)*(SIN(OMEG2A)-SIN(OMEG1A)))
        &+((OMEG2A-OMEG1A)*SIN(DELTA)*SIN(ALAT)))
C  CALCULATE THE EXTRATER. NORMAL IRRADIATION
C  FOR THE MISSING PERIOD
      ION2=3.6*GSC/R**2*(OMEG2A-OMEG1A)*180./PI/15.
      END IF
C  IF THIRD PERIOD IS MISSING
      IF (IPD.EQ.3) THEN
        OMEG3A=OMEGA1+15./2.*DRCONV
        OMEG4A=OMEG3A+15./4.*DRCONV
C  CALCULATE THE EXTRATER. HORIZONTAL IRRADIATION
C  FOR THE MISSING PERIOD
      IO2=(F1/R**2)*((COS(DELTA)*COS(ALAT)*(SIN(OMEG4A)-SIN(OMEG3A)))
        &+((OMEG4A-OMEG3A)*SIN(DELTA)*SIN(ALAT)))
C  CALCULATE EXTRATER. NORMAL IRRADIATION
      ION2=3.6*GSC/R**2*(OMEG4A-OMEG3A)*180./PI/15.
      END IF
C
C...CALCULATE EXTRATERRESTRIAL NORMAL RADIATION
      GON=GSC/R**2
C
C...CALCULATE EXTRATERRESTRIAL NORMAL IRRADIATION
      ION=3.6*GON*(OMEGA2-OMEGA1)*180.0/PI/15.
C...ACCOUNT FOR A MISSING PERIOD
      ION=ION-ION2
C
C...CALCULATE EXTRATERRESTRIAL HORIZONTAL IRRADIATION
      F2=F1/R**2
      IO=F2*((COS(DELTA)*COS(ALAT)*(SIN(OMEGA2)-SIN(OMEGA1)))
        &+((OMEGA2-OMEGA1)*SIN(DELTA)*SIN(ALAT)))
C...ACCOUNT FOR A MISSING PERIOD
      IO=IO-IO2
C

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C
C...CALCULATE CLEARNESS INDEX
      KT2=HRZTOT/IO
C
C...CALCULATE BEAM NORMAL TRANSMITTANCE
      TB2=DIR/ION
C
C...CALCULATE ERROR BETWEEN THE NEW AND OLD VALUES OF KT, TB
      EKT=ABS(KT2-KT1)
      ETB=ABS(TB2-TB1)
C
C...CALCULATE % DIFFERENCE BETWEEN THE TWO VALUES
      DIFF1=((KT1-KT2)/KT1)*100.
C
C...CALCULATE MAXIMUM CORRESPONDING ERRORS
      IF (EKT.GT.AMAXKT) AMAXKT=EKT
      IF (ETB.GT.AMAXTB) AMAXTB=ETB
C
C...CALCULATE MAXIMUM % ERROR
      IF (DIFF1.GT.AMKTPR) AMKTPR=DIFF1
C
      WRITE(30,20) YR,MO,DAY,HR,MIN,HRZTOT,DIR,KT1,KT2,EKT,TB1,TB2,
&ETB,PCT,BADPER,DIFF1
20  FORMAT(1X,I2,4(2X,I2),4X,2(F7.1,2X),4X,2(F5.3,2X),F9.5,
&3X,2(F5.3,2X),F9.5,2X,F4.2,2X,I2,5X,F6.3)
C
30  CONTINUE
      WRITE(30,*) ' '
      WRITE(30,*) ' '
      WRITE(30,31) 'MAXIMUM ERROR FOR KT =',AMAXKT
31  FORMAT(1X,A22,1X,F6.5)
      WRITE(30,32) 'MAXIMUM ERROR FOR TB =',AMAXTB
32  FORMAT(1X,A22,1X,F6.5)
C
      WRITE(30,33) 'MAXIMUM % ERROR FOR KT=',AMKTPR
33  FORMAT(1X,A23,1X,F6.3)
      END

```

```

        PROGRAM LSM7 (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT, TAPE26,
&TAPE13, TAPE25)
C
C      C. BALARAS      4-8-85
C      C. BALARAS      4-22-85
C
C...IN THIS UPDATED VERSION THE DATA THAT WILL ALLOW US TO RECALCULATE
C  THE KT AND TB, IS INCLUDED IN TAPE25.
C...THIS PROGRAM PUTS THE DATA FROM TAPE26 IN ORDER, BASED ON THE
C  INCREASING CLEARNESS INDEX. OUTPUT DATA FILE IS IN TAPE25.
C...
        DIMENSION KT2(8114),KT1(8114,1),YR(8114,1),MO(8114,1),
&DAY(8114,1),HR(8114,1),MIN(8114,1)
        COMMON /RAD/ KT1,KT2,NPAIRS,TAPE,YR,MO,DAY,HR,MIN
        INTEGER YR,MO,DAY,HR,MIN
        REAL KT1,KT2
C...ENTER DATA FROM 5-YEAR PROCESSING
        NPAIRS=8114
        DO 100 J=1,8114
            READ(26,33) YR(J,1),MO(J,1),DAY(J,1),HR(J,1),MIN(J,1),KT1(J,1),
&KT2(J)
33      FORMAT(1X,I2,4(2X,I2),26X,2(F5.3,2X))
100     CONTINUE
C...SORT THE DATA
        CALL SORTR
        STOP
        END

```

```

      SUBROUTINE SORTR
C...ARRANGES CLEARNESS AND TRANSMITTANCE DATA IN ASCENDING ORDER
      COMMON /RAD/ KT1,KT2,NPAIRS,TAVE,YR,MO,DAY,HR,MIN
      DIMENSION KT2(8114),IRVS(8114),KT1(8114,1),WK(1),YR(8114,1),
&MO(8114,1),DAY(8114,1),HR(8114,1),MIN(8114,1)
      DIMENSION IRVS2(8114),IRVS3(8114),IRVS4(8114),IRVS5(8114),
&IRVS6(8114),IRVS7(8114)
      INTEGER YR,MO,DAY,HR,MIN
C...
      DO 10 I=1,NPAIRS
10    IRVS(I)=I
C...
      CALL VSRTU(KT2,NPAIRS,IRVS)
      WRITE(13,*) IRVS
C...
      DO 200 I=1,NPAIRS
200    IRVS2(I)=IRVS(I)
      DO 201 I=1,NPAIRS
201    IRVS3(I)=IRVS(I)
      DO 202 I=1,NPAIRS
202    IRVS4(I)=IRVS(I)
      DO 203 I=1,NPAIRS
203    IRVS5(I)=IRVS(I)
      DO 204 I=1,NPAIRS
204    IRVS6(I)=IRVS(I)
      CALL VSRTU(KT1,8114,NPAIRS,1,1,IRVS,WK)
      CALL VSRTU(YR,8114,NPAIRS,1,1,IRVS2,WK)
      CALL VSRTU(MO,8114,NPAIRS,1,1,IRVS3,WK)
      CALL VSRTU(DAY,8114,NPAIRS,1,1,IRVS4,WK)
      CALL VSRTU(HR,8114,NPAIRS,1,1,IRVS5,WK)
      CALL VSRTU(MIN,8114,NPAIRS,1,1,IRVS6,WK)
      WRITE(6,*) 'ARRAYS ARE SORTED'
      DO 101 K=1,8114
      WRITE(25,21) YR(K,1),MO(K,1),DAY(K,1),HR(K,1),MIN(K,1),KT1(K,1),
&KT2(K)
101  CONTINUE
21    FORMAT(1X,I2,2X,I2,2X,I2,1X,I2,1X,I2,3(2X,F5.3))
C...
      RETURN
      END

```



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IMSL ROUTINE NAME - VS RTP

COMPUTER - CDCFT5/SINGLE

LATEST REVISION - JANUARY 1, 1978

PURPOSE - SORTING OF ARRAYS BY ABSOLUTE VALUE -  
PERMUTATIONS RETURNED

USAGE - CALL VS RTP (A, LA, IR)

ARGUMENTS    A    - ON INPUT, A CONTAINS THE ARRAY TO BE SORTED.  
ON OUTPUT, A CONTAINS THE SORTED ABSOLUTE  
VALUES OF THE ARRAY.  
LA    - INPUT VARIABLE CONTAINING THE NUMBER OF  
ELEMENTS IN THE ARRAY TO BE SORTED.  
IR    - VECTOR OF LENGTH LA.  
ON INPUT, IR CONTAINS THE INTEGER VALUES  
1, 2, ..., LA. SEE REMARKS.  
ON OUTPUT, IR CONTAINS A RECORD OF THE  
PERMUTATIONS MADE ON THE VECTOR A.

PRECISION/HARDWARE - SINGLE/ALL

REQD. IMSL ROUTINES - NONE REQUIRED

NOTATION - INFORMATION ON SPECIAL NOTATION AND  
CONVENTIONS IS AVAILABLE IN THE MANUAL  
INTRODUCTION OR THROUGH IMSL ROUTINE UHELP

REMARKS    THE VECTOR IR MUST BE INITIALIZED BEFORE ENTERING  
VS RTP. ORDINARILY, IR(1)=1, IR(2)=2, ...,  
IR(LA)=LA. FOR WIDER APPLICABILITY, ANY INTEGER  
THAT IS TO BE ASSOCIATED WITH A(I) FOR I=1, 2, ..., LA

```

C          MAY BE ENTERED INTO IR(I).
C
C  COPYRIGHT          - 1978 BY IMSL, INC. ALL RIGHTS RESERVED.
C
C  WARRANTY          - IMSL WARRANTS ONLY THAT IMSL TESTING HAS BEEN
C                    APPLIED TO THIS CODE. NO OTHER WARRANTY,
C                    EXPRESSED OR IMPLIED, IS APPLICABLE.
C
C-----
C
C  SUBROUTINE VSRTP  (A,LA,IR)
C                    SPECIFICATIONS FOR ARGUMENTS
C  INTEGER          LA,IR(LA)
C  REAL             A(LA)
C                    SPECIFICATIONS FOR LOCAL VARIABLES
C  INTEGER          IU(21),IL(21),I,M,J,K,IJ,IT,L,ITT
C  REAL             T,TT,R
C                    FIRST EXECUTABLE STATEMENT
C                    FIND ABSOLUTE VALUES OF ARRAY A
C  IF (LA.LE.0) RETURN
C  DO 5 I=1,LA
C    IF (A(I) .LT. 0.0) A(I)=-A(I)
5  CONTINUE
C  M=1
C  I=1
C  J=LA
C  R=.375
10 IF (I .EQ. J) GO TO 55
15 IF (R .GT. .5898437) GO TO 20
C  R=R+3.90625E-2
C  GO TO 25
20 R=R-.21875
25 K=I
C                    SELECT A CENTRAL ELEMENT OF THE
C                    ARRAY AND SAVE IT IN LOCATION T
C  IJ=I+(J-I)*R
C  T=A(IJ)
C  IT=IR(IJ)
C                    IF FIRST ELEMENT OF ARRAY IS GREATER
C                    THAN T, INTERCHANGE WITH T
C  IF (A(I) .LE. T) GO TO 30
C  A(IJ)=A(I)
C  A(I)=T
C  T=A(IJ)
C  IR(IJ)=IR(I)
C  IR(I)=IT
C  IT=IR(IJ)
30 L=J
C                    IF LAST ELEMENT OF ARRAY IS LESS THAN
C                    T, INTERCHANGE WITH T

```

	IF (A(J) .GE. T) GO TO 40	
	A(IJ)=A(J)	
	A(J)=T	
	T=A(IJ)	
	IR(IJ)=IR(J)	
	IR(J)=IT	
	IT=IR(IJ)	
C		IF FIRST ELEMENT OF ARRAY IS GREATER
C		THAN T, INTERCHANGE WITH T
	IF (A(I) .LE. T) GO TO 40	
	A(IJ)=A(I)	
	A(I)=T	
	T=A(IJ)	
	IR(IJ)=IR(I)	
	IR(I)=IT	
	IT=IR(IJ)	
	GO TO 40	
35	IF (A(L) .EQ. A(K)) GO TO 40	
	TT=A(L)	
	A(L)=A(K)	
	A(K)=TT	
	ITT=IR(L)	
	IR(L)=IR(K)	
	IR(K)=ITT	
C		FIND AN ELEMENT IN THE SECOND HALF OF
C		THE ARRAY WHICH IS SMALLER THAN T
40	L=L-1	
	IF (A(L) .GT. T) GO TO 40	
C		FIND AN ELEMENT IN THE FIRST HALF OF
C		THE ARRAY WHICH IS GREATER THAN T
45	K=K+1	
	IF (A(K) .LT. T) GO TO 45	
C		INTERCHANGE THESE ELEMENTS
	IF (K .LE. L) GO TO 35	
C		SAVE UPPER AND LOWER SUBSCRIPTS OF
C		THE ARRAY YET TO BE SORTED
	IF (L-I .LE. J-K) GO TO 50	
	IL(M)=I	
	IU(M)=L	
	I=K	
	M=M+1	
	GO TO 60	
50	IL(M)=K	
	IU(M)=J	
	J=L	
	M=M+1	
	GO TO 60	
C		BEGIN AGAIN ON ANOTHER PORTION OF
C		THE UNSORTED ARRAY
55	M=M-1	

```
IF (M .EQ. 0) RETURN
I=IL(M)
J=IU(M)
60 IF (J-I .GE. 11) GO TO 25
IF (I .EQ. 1) GO TO 10
I=I-1
65 I=I+1
IF (I .EQ. J) GO TO 55
T=A(I+1)
IT=IR(I+1)
IF (A(I) .LE. T) GO TO 65
K=I
70 A(K+1)=A(K)
IR(K+1)=IR(K)
K=K-1
IF (T .LT. A(K)) GO TO 70
A(K+1)=T
IR(K+1)=IT
GO TO 65
END
```

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\* AS THE BASIS FOR ANY SOFTWARE DEVELOPMENT.  
\*

C IMSL ROUTINE NAME - VSRTU  
C  
C -----

C COMPUTER - CDCFT5/SINGLE  
C

C LATEST REVISION - JANUARY 1, 1978  
C

C PURPOSE - INTERCHANGE THE ROWS OR COLUMNS OF A MATRIX  
C USING A PERMUTATION VECTOR SUCH AS THE ONE  
C OBTAINED FROM IMSL ROUTINES VSRTU OR  
C VSRTU  
C

C USAGE - CALL VSRTU (Z,IZ,N,M,IND,IR,WK)  
C

C ARGUMENTS Z - INPUT MATRIX OF DIMENSION N BY M TO BE  
C INTERCHANGED. ON OUTPUT, Z CONTAINS  
C THE INTERCHANGED MATRIX.  
C IZ - ROW DIMENSION OF MATRIX Z EXACTLY AS  
C SPECIFIED IN THE DIMENSION STATEMENT IN THE  
C CALLING PROGRAM. (INPUT)  
C N - NUMBER OF ROWS IN Z. (INPUT)  
C M - NUMBER OF COLUMNS IN Z. (INPUT)  
C IND - INPUT OPTION PARAMETER.  
C IF IND IS GREATER THAN ZERO, THE ROWS OF Z  
C WILL BE INTERCHANGED ACCORDING TO THE  
C INFORMATION IN VECTOR IR.  
C OTHERWISE, THE COLUMNS OF Z WILL BE  
C INTERCHANGED ACCORDING TO THE  
C INFORMATION IN VECTOR IR.  
C IR - INPUT INTEGER PERMUTATION VECTOR OF LENGTH  
C N, IF IND IS POSITIVE, AND OF LENGTH M  
C OTHERWISE. IR CONTAINS THE FIRST N OR M  
C POSITIVE INTEGERS. SEE PROGRAMMING NOTES.  
C IR IS DESTROYED ON OUTPUT.  
C WK - WORK VECTOR OF LENGTH M IF IND IS POSITIVE



```

C                                     AND OF LENGTH N OTHERWISE.
C
C PRECISION/HARDWARE - SINGLE/ALL
C
C REQD. IMSL ROUTINES - NONE REQUIRED
C
C NOTATION - INFORMATION ON SPECIAL NOTATION AND
C             CONVENTIONS IS AVAILABLE IN THE MANUAL
C             INTRODUCTION OR THROUGH IMSL ROUTINE UHELP
C
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C
C WARRANTY - IMSL WARRANTS ONLY THAT IMSL TESTING HAS BEEN
C             APPLIED TO THIS CODE. NO OTHER WARRANTY,
C             EXPRESSED OR IMPLIED, IS APPLICABLE.
C -----
C
C SUBROUTINE VSRTU (Z, IZ, N, M, IND, IR, WK)
C
C DIMENSION Z(IZ, 1), WK(1), IR(1)
C             FIRST EXECUTABLE STATEMENT
C IPTR = 1
C IF (IND .GT. 0) GO TO 45
C             SORT Z BY COLUMNS
C             CHECK IF ALL COLUMNS ARE SORTED
C 5 IF (IPTR .GE. M) GO TO 85
C             CHECK IF COLUMN IPTR HAS BEEN SORTED
C IF (IR(IPTR) .GT. 0) GO TO 15
C 10 IPTR = IPTR + 1
C GO TO 5
C             CHECK IF COLUMN IPTR NEED BE MOVED
C 15 IF (IR(IPTR) .EQ. IPTR) GO TO 10
C K = IPTR
C             STORE COLUMN IPTR IN TEMPORARY VECTOR
C DO 20 I = 1, N
C WK(I) = Z(I, K)
C 20 CONTINUE
C 25 L = IR(K)
C             CHECK IF TEMPORARY VECTOR NEEDED HERE
C IF (L .EQ. IPTR) GO TO 35
C             INSERT COLUMN L INTO COLUMN K
C DO 30 I = 1, N
C Z(I, K) = Z(I, L)
C 30 CONTINUE
C             MARK COLUMN K AS ALREADY SORTED
C IR(K) = 0
C K = L
C GO TO 25
C             INSERT TEMPORARY VECTOR IN COLUMN K

```

```

35 DO 40 I = 1,N
    Z(I,K) = WK(I)
40 CONTINUE
    IR(K) = 0
    GO TO 10
C
                                SORT Z BY ROWS
45 IF (IPTR .GE. N) GO TO 85
    IF (IR(IPTR) .GT. 0) GO TO 55
50 IPTR = IPTR + 1
    GO TO 45
55 IF (IR(IPTR) .EQ. IPTR) GO TO 50
    K = IPTR
    DO 60 I = 1,M
        WK(I) = Z(K,I)
60 CONTINUE
65 L = IR(K)
    IF (L .EQ. IPTR) GO TO 75
    DO 70 I = 1,M
        Z(K,I) = Z(L,I)
70 CONTINUE
    IR(K) = 0
    K = L
    GO TO 65
75 DO 80 I = 1,M
    Z(K,I) = WK(I)
80 CONTINUE
    IR(K) = 0
    GO TO 50
85 RETURN
    END

```

## APPENDIX C

TBREG5 : Model Development and Regression-Statistical Analysis

SUBI : Subroutine to Calculate  $k$  and  $\sigma$  from Radiation Data

CLRL : Subroutine to Plot Regression Lines

MDFD : Subroutine to Calculate the Probability Distribution Function

Development of Total Variation Identity

```

      PROGRAM TBREG5 (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT, TAPE26, TAPE2)
C
C   C. BALARAS   31-5-85
C   C. BALARAS   6-6-85
C
C...PIECEWISE REGRESSION OF TB ON KT
C...ASSUMES INPUT FILE IS SORTED BY KT
C.
C..VARIABLE DICTIONARY
C   SYY=TOTAL VARIATION
C   RSST= RESIDUAL VARIATION
C   RSS(IB)= RESIDUAL VARIATION FOR BAND IB
C   NPTST= TOTAL NUMBER OF DATA POINTS
C..MODIFICATIONS NEEDED
C..OPEN PLOT FILE, PLOT AND LABEL AXES
C..AFTER EACH DATUM IS READ PLOT THAT POINT
C..AFTER PROCESSING PLOT THE REGRESSION LINES
C..AFTER PROCESSING CALCULATE THE F-STATISTIC
C...DECLARATIONS
      DIMENSION BETA(9),XO(10),HBETA(9)
      DIMENSION RSS(9)
      DIMENSION IBUF(512)
      DIMENSION KTARR(8112),TBARR(8112),IRVS(8112),WK(1)
      REAL KT,K,KT1,TB1,TB,ION,IO,IO2,ION2
      REAL KTARR
      INTEGER BADPER,YR,DAY,MO,HR,MIN
      WRITE(6,*) 'WHAT IS THE TITLE (ALL 80)'
      READ(5,10) TITLE
10  FORMAT(A6)
      WRITE(6,*) 'PERFORM CALCULATIONS AT MID-PERIOD? 1 YES, 0 NO'
      READ(5,5) ICAL
      IF (ICAL.EQ.1) THEN
        WRITE(6,*) 'KT CALCULATED AT CURRENT TIME'
      ELSE
        WRITE(6,*) 'KT FROM DATA FIE'
      ENDIF
      WRITE(6,*) 'PERFORM CALCULATIONS FOR ALL 5YEARS? 1 YES, 0 NO'
      READ(5,6) IALL
6   FORMAT(I1)
      WRITE(6,*) 'CALCULATIONS FOR SEASONAL ANALYSIS? 1=YES, 0=NO'
      READ(5,14) ISEASO
14  FORMAT(I1)
      IF (ISEASO.EQ.1) THEN
        WRITE(6,*) 'PERFORM CALCULATIONS FOR WHAT MONTHS ?'
        WRITE(6,*) '01=JAN, 02=FEB, ... 12=DEC'
        READ(5,15) IMO
15  FORMAT(I2)
      END IF
      IF (IALL.EQ.0) THEN
        WRITE(6,*) 'PERFORM CALCULATIONS FOR WHAT YEAR? (I.E. 80)'

```

```

      READ(5,7) IYR
7      FORMAT(I2)
      ELSE
      IYR=0
      END IF
5      FORMAT(I1)
      WRITE(6,*) 'SYMBOL FOR PLOTTING REGRESSION LINES (5)'
      READ(5,9) ISYM
9      FORMAT(I1)
      WRITE(6,*) 'SYMBOL FOR PLOTTING RANDALL WHITSON MODEL (15)'
      READ(5,12) ISYMRW
12     FORMAT(I2)
      WRITE(6,*) 'SHOW DATA POINTS? 1 YES, 0 NO'
      READ(5,11) ISHOW
11     FORMAT(I1)
      WRITE(6,*) 'WHAT IS THE HYPOTHEZIZED MODEL?'
      WRITE(6,*) '1=79, 2=80, 3=81, 4=83, 5=84, 6=5Y, 7=R-W'
      READ(5,13) IHYP0
13     FORMAT(I1)
C...GLOBAL INITIALIZATIONS
      DATA BETA/9*0.0/
      DATA XO/0.0,0.05,0.15,0.25,0.35,0.45,0.55,0.65,0.75,0.85/
      IB=1
      IFRST=1
      SUMTSQ=SUMT=0.0
C
C...CONSTANTS
      ALATD=33.4046
      ALONGD=84.7478
      ALONST=75.0
      ZONE=5.0
      GSC=1367.0
      NPAIRS=0
C
C...INITIALIZE VARIABLES FOR FIRST BAND
      YO=0.0
      SUMX=SUMY=SUMXSQ=SUMYSQ=SUMXY=0.0
      NPTS=NPTST=0
C...**OPEN PLOT FILES, DRAW AND LABEL AXES, SET SCALES
      CALL PLOTS(IBUF,512,2,40)
      CALL PLOTMX(18.5)
      CALL FACTOR(1.5)
      CALL PLOT(3.0,1.0,-3)
C...DRAW X-AXIS
      CALL AXIS(0.0,0.0,'',-10,5.0,0.0,0.0,0.2)
C...DRAW Y-AXIS
      CALL AXIS(0.0,0.0,'',10,5.0,90.0,0.0,0.2)
C...TITLE GRAPH
      CALL SYMBOL(2.5,5.15,0.2,TITLE,0.0,6)
C...INSERT LABELS

```



```

      CALL SYMBOL(2.4,-0.5,0.30,'&<K;T',0.0,5)
      CALL SYMBOL(-0.6,2.5,0.30,'&<#S;B',0.0,6)
C...BEGIN ANALYSIS
C...ENTER HOURLY LOOP
      DO 200 IDA=1,8112
C...READ ONE HOURS DATA
      READ(26,20) YR,MO,DAY,HR,MIN,HRZTOT,DIR,KT1,
      &KT,TB1,TB,PCT,BADPER
20   FORMAT(1X,I2,4(2X,I2),4X,2(F7.1,2X),4X,2(F5.3,2X),
      &4X,2(F5.3,2X),4X,F4.2,2X,I2)
C...TEST FOR SEASONAL CALCULATIONS
      IF (ISEASO.EQ.1) THEN
      IF (MO.NE.IMO) THEN
      GO TO 200
      END IF
      END IF
C...TEST FOR ANNUAL CALCULATIONS
      IF (IALLEQ.0) THEN
      IF (YR.NE.IYR) THEN
      GO TO 200
      END IF
      END IF
C
      NPAIRS=NPAIRS+1
      IF(ICAL.EQ.1) THEN
C...CALL SUBROUTINE HELGO FOR TIME-0.5 HOURS
      CVLT=(HR+MIN/60.)-0.5
      CALL HELGO(YR,MO,DAY,CVLT,ALONGD,ALATD,ALONST,ZONE,ALPHA,
      &DELTA,EOT,OMEGA,R)
C
C...CALL SUBROUTINE IRRADIATION
      CALL SUBI(OMEGA,ALATD,DELTA,BADPER,GSC,IFRST,R,HRZTOT,DIR,
      &KT,TB)
      ELSE
      KT=KT1
      TB=TB1
      ENDIF
      IF (ISHOW.EQ.0) GO TO 703
C...***PLOT THIS DATUM USING 'CALL SYMBOL'
      K=KT/.2
      T=TB/.2
      CALL SYMBOL(K,T,0.035,19,0.0,-1)
C..PLACE DATA IN ARRAYS
703  KTARR(NPAIRS)=KT
      TBARR(NPAIRS)=TB
      IRVS(NPAIRS) =NPAIRS
200  CONTINUE
      WRITE(6,*) 'NPAIRS=',NPAIRS
C...CALL IMSL SORTING ROUTINES
      END IF

```

```

CALL VSRTTP(KTARR,NPAIRS,IRVS)
CALL VSRTTU(TBARR,NPAIRS,NPAIRS,1,1,IRVS,WK)
DO 300 IDA=1,NPAIRS
KT=KTARR(IDA)
TB=TBARR(IDA)
IF( (KT.GT.XO(IB+1)).OR.(IDA.EQ.NPAIRS) ) THEN
  IF(SUMXY.GT.0.0) THEN
    BETA(IB)=SUMXY/SUMXSQ
  ELSE
    BETA(IB)=0.0
  ENDIF
  YO=YO+BETA(IB)*(XO(IB+1)-XO(IB) )
  RSS(IB)=SUMYSQ-2.0*BETA(IB)*SUMXY+BETA(IB)*BETA(IB)*SUMXSQ
  NPTST=NPTST+NPTS
  IB=IB+1
C....REINITIALIZE VARIABLES FOR NEXT BAND
  SUMX=SUMY=SUMXSQ=SUMYSQ=SUMXY=0.0
  NPTS=0
C....BRANCH IF DATA IS EXHAUSTED
  ENDIF
C....ANALYSIS OF BAND NO. IB CONTINUES
  XBND=KT-XO(IB)
  YBND=TB-YO
  SUMT=SUMT+TB
  SUMTSQ=SUMTSQ+TB*TB
  SUMX=SUMX+XBND
  SUMY=SUMY+YBND
  SUMXSQ=SUMXSQ+XBND*XBND
  SUMYSQ=SUMYSQ+YBND*YBND
  SUMXY =SUMXY +XBND*YBND
  NPTS=NPTS+1
C....THIS HOUR'S COMPUTATIONS COMPLETED
C   WRITE(6,988) NPTS,KT,TB,SUMXSQ,SUMXY
C988   FORMAT(I7,2F7.4,2F10.3)
C....ALL HOURLY COMPUTATIONS COMPLETED
300   CONTINUE
C...PLOT THE REGRESSION LINES
C   FOR THE SHENANDOAH AND R-W MODEL
  CALL CLRL(BETA,XO,ISYM,ISYMRW)
C...COMPLETE THE PLOTTING JOB
  CALL PLOT(7.0,0.0,3)
  CALL PLOT(7.0,0.0,999)
C...SUMMARY COMPUTATIONS
  TAVE=SUMT/FLOAT(NPTST)
  SYX=SUMTSQ-2.0*TAVE*SUMT+NPTST*TAVE*TAVE
  WRITE(6,*) BETA
  WRITE(6,*) RSS
  WRITE(6,*) SYX
C...REPEAT SUMMARY COMPUTATIONS
  RSST=0.0

```

```

SYY=0.0
YO=0.0
IB=1
DO 600 JK=1,NPAIRS
KT=KTARR(JK)
TB=TBARR(JK)
  IF(KT.GT.XO(IB+1) ) THEN
    YO=YO+BETA(IB)*(XO(IB+1)-XO(IB) )
    IB=IB+1
  ENDIF
  YEST=YO+BETA(IB)*(KT-XO(IB))
  RSST=RSST+(TB-YEST)**2
  SYY=SYY+(TB-TAVE)**2
600  CONTINUE
C...CALCULATE THE EXPLAINED VARIATION
  SSREG=SYY-RSST
C...CALCULATE THE COEFFICIENT OF CORRELATION
  AR=SQRT(SSREG/SYY)
C...CALCULATE THE COEFFICIENT OF DETERMINATION
  AR2=AR*AR
  WRITE(6,*) SSREG,AR2
C...REPEAT CALCULATIONS FOR THE HYPOTHESIZED
C  MODEL, ANNUAL MODEL OR THE RANDAL WHITSON MODEL
C...SCF = SOLAR CONSTANT FACTOR, TO ACCOUNT FOR THE DIFFERENCE
C  IN THE SOLAR CONSTANT VALUE BETWEEN OUR VALUE 1367.0
C  AND THE VALUE USED FOR THE R-W MODEL (1377 W/M/M)
C  IN ALL OTHER CASES SCF=1
SCF=1.0
IF (IHYP0.EQ.1) THEN
HBETA(2)=0.
HBETA(3)=0.01680610898376
HBETA(4)=0.2563727495389
HBETA(5)=0.856204541161
HBETA(6)=1.351087178326
HBETA(7)=1.80842889396
HBETA(8)=2.017398031243
HBETA(9)=1.447819544956
END IF
IF (IHYP0.EQ.2) THEN
HBETA(2)=0.0004458185646733
HBETA(3)=0.03166244709482
HBETA(4)=0.2337467649286
HBETA(5)=0.8796391441972
HBETA(6)=1.347261835858
HBETA(7)=1.331416536751
HBETA(8)=2.121394821706
HBETA(9)=2.266402906436
END IF
IF (IHYP0.EQ.3) THEN
HBETA(2)=0.003190779476716

```

```

HBETA(3)=0.05111871536509
HBETA(4)=0.2590704091887
HBETA(5)=0.8850880372326
HBETA(6)=1.643031036335
HBETA(7)=1.525337244653
HBETA(8)=2.352748816485
HBETA(9)=1.333663078997
END IF
IF (IHYP0.EQ.4) THEN
HBETA(2)=0.0
HBETA(3)=0.03098476893561
HBETA(4)=0.2879876505518
HBETA(5)=1.071358223407
HBETA(6)=1.560173112096
HBETA(7)=1.495866981226
HBETA(8)=2.005941455909
HBETA(9)=0.8438980215066
END IF
IF (IHYP0.EQ.5) THEN
HBETA(2)=0.0
HBETA(3)=0.03098057710589
HBETA(4)=0.1733451088209
HBETA(5)=1.174526276132
HBETA(6)=1.511159104577
HBETA(7)=1.639333183761
HBETA(8)=1.932529200337
HBETA(9)=0.0
END IF
IF (IHYP0.EQ.6) THEN
HBETA(2)=0.0007178049038916
HBETA(3)=0.02972517920018
HBETA(4)=0.2490303701482
HBETA(5)=0.9466134865964
HBETA(6)=1.477191594315
HBETA(7)=1.56801154
HBETA(8)=2.077319493401
HBETA(9)=1.377810138749
END IF
IF (IHYP0.EQ.7) THEN
HBETA(2)=0.01
HBETA(3)=0.06
HBETA(4)=0.32
HBETA(5)=0.82
HBETA(6)=1.56
HBETA(7)=1.69
HBETA(8)=1.49
HBETA(9)=0.27
C...ACCOUNT FOR THE SOLAR CONSTANT DIFFERENCE
SCF=1367.0/1377.0
END IF

```



```

C
  HRSST=0.0
  HSY Y=0.0
  YO=0.0
  IB=1
C
  DO 601 JL=1,NPAIRS
    KT=KTARR(JL)*SCF
    TB=TBARR(JL)*SCF
    IF (KT.GT.XO(IB+1)) THEN
      YO=YO+HBETA(IB)*(XO(IB+1)-XO(IB))
      IB=IB+1
    END IF
    HYEST=YO+HBETA(IB)*(KT-XO(IB))
    HRSST=HRSST+(TB-HYEST)**2
    HSY Y=HSY Y+(TB-TAVE)**2
601  CONTINUE
C
C...CALCULATE THE F-STATISTIC
C    HRSST=RESIDUAL VARIATION FOR THE HYPOTHEZIZED MODELS
C        (ANNUAL MODEL OR R-W)
C    RSST=RESIDUAL VARIATION FOR THE ALTERNATIVE HYPOTHESIS
C        (FIVE YEAR MODEL)
C    DFH=DEGREES OF FREEDOM FOR HYPOTHEZIZED MODEL, N
C    DFA=DEGREES OF FREEDOM FOR THE ALTERNATIVE MODEL, N-P
C    N=NUMBER OF DATA POINTS, 8112
C    P=NUMBER OF PARAMETERS, 8
C
    DFH=8112
    DFA=8112-8
    F=((HRSST-RSST)/(DFH-DFA))/(RSST/DFA)
C...CALCULATE CONFIDENCE AND ALPHA
    N1=8
    N2=8112-8
    CALL MDFFD(F,N1,N2,P,IER)
    ALPHA=1.-P
C
    WRITE(6,*) RSST,HRSST,F,P,ALPHA
    WRITE(6,*) RSST,SY Y
    STOP
    END

```



```

      SUBROUTINE SUBI(OMEGA,ALATD,DELTA,BADPER,GSC,IFRST,R,HRZTOT,DIR,
&KT,TB)
C
C      C. BALARAS      5-31-85
C
C...SUBROUTINE TO RECALCULATE THE KT AND TB AT THE MIDPOINT OF
C EACH PERIOD.
C      INPUTS:
C          OMEGA : HOUR ANGLE IN RADIANS (FROM HELGO)
C          ALATD : LATITUDE OF LOCALITY IN DEGREES
C          DELTA : DECLINATION IN RADIANS (FROM HELGO)
C          BADPER : 15-MINUTE PERIOD MISSING
C          GSC : SOLAR CONSTANT, 1367 W/M/M
C          IFRST : TO PREVENT REPETITION OF CALCULATIONS
C          R : EARTH-SUN DISTANCE IN AU (FROM HELGO)
C          HRZTOT : HOURLY HORIZONTAL IRRADIATION
C          DIR : DIRECT BEAM IRRADIATION
C      OUTPUTS:
C          KT : CLEARNESS INDEX AT THE MID-PERIOD
C          TB : HOURLY BEAM TRANSMITTANCE AT THE MID-PERIOD
C
      INTEGER BADPER
      REAL KT,ION,IO,IO2,ION2
      IF (IFRST.LT.1) GO TO 333
      PI=4.0*ATAN(1.0)
      DRCONV=PI/180.0
      ALAT=ALATD*DRCONV
      F1=GSC*12.0*3600.0/PI/1000.0
      FA1=3.6*GSC*180.0/PI/15.0
      IFRST=0
333  CONTINUE
C...SUBROUTINE INITIALIZATIONS
      F2=F1/R**2
      FA2=FA1/R**2
      IO2=0.0
      ION2=0.0
      OMEG1A=0.0
      OMEG2A=0.0
      OMEG3A=0.0
      OMEG4A=0.0
C...CALCULATE THE HOUR ANGLES AT THE START END OF THE PERIOD
      OMEG1=OMEGA-15.0/2.*DRCONV
      OMEG2=OMEGA+15.0/2.*DRCONV
C...CORRECT HOUR ANGLES FOR FIRST AND LAST PERIODS OF DAY
      WSS=ACOS(-TAN(ALAT)*TAN(DELTA))
      IF(OMEGA2.GT.WSS) OMEGA2=WSS
      IF(OMEG1.LT.-WSS) OMEG1=-WSS
C
C...DETERMINE MISSING PERIOD
      IPD=IFIX(AMOD(FLOAT(BADPER),10.))

```

```

C...DETERMINE HOUR ANGLES
C  IF FIRST PERIOD IS MISSING
    IF (IPD.EQ.1) OMEGA1=OMEGA1+15./4.*DRCONV
C  IF LAST PERIOD IS MISSING
    IF (IPD.EQ.4) OMEGA2=OMEGA2-15./4.*DRCONV
C  IF SECOND PERIOD IS MISSING
    IF (IPD.EQ.2) THEN
        OMEGA1=OMEGA1+15./4.*DRCONV
        OMEGA2=OMEGA1+15./4.*DRCONV
C  CALCULATE THE EXTRATER. HORIZONTAL IRRADIATION
C  FOR THE MISSING PERIOD
    IO2=F2*((COS(DELTA)*COS(ALAT)*(SIN(OMEGA2)-SIN(OMEGA1)))
    &+((OMEGA2-OMEGA1)*SIN(DELTA)*SIN(ALAT)))
C  CALCULATE THE EXTRATER. NORMAL IRRADIATION
C  FOR THE MISSING PERIOD
    ION2=FA2*(OMEGA2-OMEGA1)
    END IF
C  IF THIRD PERIOD IS MISSING
    IF (IPD.EQ.3) THEN
        OMEGA3A=OMEGA1+15./2.*DRCONV
        OMEGA4A=OMEGA3A+15./4.*DRCONV
C  CALCULATE THE EXTRATER. HORIZONTAL IRRADIATION
C  FOR THE MISSING PERIOD
    IO2=F2*((COS(DELTA)*COS(ALAT)*(SIN(OMEGA4A)-SIN(OMEGA3A)))
    &+((OMEGA4A-OMEGA3A)*SIN(DELTA)*SIN(ALAT)))
C  CALCULATE EXTRATER. NORMAL IRRADIATION
    ION2=FA2*(OMEGA4A-OMEGA3A)
    END IF
C
C...CALCULATE EXTRATERRESTRIAL NORMAL RADIATION
    GON=GSC/R**2
C
C...CALCULATE EXTRATERRESTRIAL NORMAL IRRADIATION
    ION=FA2*(OMEGA2-OMEGA1)
C...ACCOUNT FOR A MISSING PERIOD
    ION=ION-ION2
C
C...CALCULATE EXTRATERRESTRIAL HORIZONTAL IRRADIATION
    IO=F2*((COS(DELTA)*COS(ALAT)*(SIN(OMEGA2)-SIN(OMEGA1)))
    &+((OMEGA2-OMEGA1)*SIN(DELTA)*SIN(ALAT)))
C...ACCOUNT FOR A MISSING PERIOD
    IO=IO-IO2
C
C...CALCULATE CLEARNESS INDEX
    KT=HRZTOT/IO
C
C...CALCULATE BEAM NORMAL TRANSMITTANCE
    TB=DIR/ION
    RETURN
    END

```

```

SUBROUTINE CLRL(BETA,XO,ISYM,ISYMRW)
C
C      C. BALARAS      5-31-85
C
C...SUBROUTINE TO PLOT THE REGRESSION LINES FOR THE
C  SHENANDOAH AND R-W MODELS
C      INPUTS:
C          BETA   : SLOPE COEFFICIENTS FOR EACH BAND
C          XO     : INITIAL KT VALUES AT THE BEGINNING OF
C                  EACH BAND
C          ISYM   : SYMBOL FOR THE REGRESSION LINE FOR
C                  SHENANDOAH MODEL
C          ISYMRW : SYMBOL FOR THE REGRESSION LINE FOR
C                  THE R-W MODEL
C
C      DIMENSION BETA(9),XO(10),X(9),Y(9),XRW(9),YRW(9),A(9),B(9)
C      X(6)=0.0
C      X(7)=0.2
C      Y(6)=0.0
C      Y(7)=0.2
C      XRW(6)=0.0
C      XRW(7)=0.2
C      YRW(6)=0.0
C      YRW(7)=0.2
C...INITIALIZE
C      YO=0.0
C...RANDALL WHITSON SLOPES FOR SEPARATE BANDS
C      A(2)=0.01
C      B(2)=0.002
C      A(3)=0.06
C      B(3)=-0.006
C      A(4)=0.32
C      B(4)=-0.071
C      A(5)=0.82
C      B(5)=-0.246
C      A(6)=1.56
C      B(6)=-0.579
C      A(7)=1.69
C      B(7)=-0.651
C      A(8)=1.49
C      B(8)=-0.521
C      A(9)=0.27
C      B(9)=0.395
C
C      DO 700 J=2,9
C      YO=(YO+(XO(J)-XO(J-1))*BETA(J-1))
C      W=XO(J+1)-XO(J)
C
C      DO 701 L=1,5
C...COORDINATES FOR THE SHENANDOAH MODEL

```

```
      X(L)=(XO(J)+W*(L-1)/4.0)
      Y(L)=(YO+(X(L)-XO(J))*BETA(J))
C...COORDINATES FOR THE R-W MODEL
      XRW(L)=X(L)
      YRW(L)=B(J)+XRW(L)*A(J)
      XRW(L)=XRW(L)*(1377.0/1367.0)
      YRW(L)=YRW(L)*(1377.0/1367.0)
701  CONTINUE
C
C...PLOT CONNECTED LINEAR REGRESSION LINES
      CALL LINE(X,Y,5,1,1,ISYM)
C...PLOT RANDALL WHITSON MODEL
      CALL LINE(XRW,YRW,5,1,1,ISYMRW)
C
700  CONTINUE
      RETURN
      END
```



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IMSL ROUTINE NAME - MDFD

COMPUTER - CDCFT5/SINGLE

LATEST REVISION - JUNE 1, 1981

PURPOSE - F PROBABILITY DISTRIBUTION FUNCTION

USAGE - CALL MDFD (F,N1,N2,P,IER)

ARGUMENTS F - INPUT CONSTANT TO WHICH INTEGRATION IS PERFORMED. F MUST BE GREATER THAN OR EQUAL TO ZERO.

N1 - INPUT FIRST DEGREE OF FREEDOM. A POSITIVE INTEGER.

N2 - INPUT SECOND DEGREE OF FREEDOM, A POSITIVE INTEGER.

P - OUTPUT PROBABILITY THAT A RANDOM VARIABLE FOLLOWING THE F DISTRIBUTION WITH DEGREES OF FREEDOM N1 AND N2 WILL BE LESS THAN OR EQUAL TO INPUT F.

IER - ERROR PARAMETER. (OUTPUT)

TERMINAL ERROR

IER = 129 INDICATES EITHER N1 OR N2 IS LESS THAN ONE OR N1+N2 IS GREATER THAN 20,000. P IS SET TO POSITIVE MACHINE INFINITY.

IER = 130 INDICATES F IS LESS THAN ZERO. P IS SET TO POSITIVE MACHINE INFINITY.

PRECISION/HARDWARE - SINGLE/ALL

REQD. IMSL ROUTINES - MERRC=ERFC,UERTST,UGETIO



```

C  NOTATION          - INFORMATION ON SPECIAL NOTATION AND
C                    CONVENTIONS IS AVAILABLE IN THE MANUAL
C                    INTRODUCTION OR THROUGH IMSL ROUTINE UHELP
C
C  COPYRIGHT          - 1978 BY IMSL, INC. ALL RIGHTS RESERVED.
C
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C                    APPLIED TO THIS CODE. NO OTHER WARRANTY,
C                    EXPRESSED OR IMPLIED, IS APPLICABLE.
C
C -----

```

```

C  SUBROUTINE MDFS   (F,N1,N2,P,IER)
C
C                    SPECIFICATIONS FOR ARGUMENTS
C
C  INTEGER            N1,N2,IER
C  REAL               F,P
C
C                    SPECIFICATIONS FOR LOCAL VARIABLES
C
C  INTEGER            I1,I2P,I2,I,L2,MNM,MXM
C  REAL               ACONS,A,BIGE,B,CBR1,CBR2,C,DPL,DP,F1F,F1,F2P,
1  F2,R1D3,R2D9,R2DPI,RINFP,STS,S,TEMP1,TEMP,
2  THETA,VP,X1,X2,XI
C  DATA              RINFP/.12650140831E+323/
C  DATA              R2D9/.2222222222222222/,R1D3/.3333333333333333/
C                    R2DPI = 2/PI
C  DATA              R2DPI/.63661977236758/
C  DATA              BIGE/741.6/,ACONS/1.E215/
C
C                    FIRST EXECUTABLE STATEMENT
C                    TEST FOR INVALID INPUT
C
MXM = MAX0(N1,N2)
MNM = MIN0(N1,N2)
IF (MNM.LT.1.OR.MXM.GT.(20000-MNM)) GO TO 100
IF (F.LT.0.0) GO TO 105
IER = 0
IF (F.EQ.0.0) GO TO 115
F1 = N1
F2 = N2
DP = 0.0
VP = F1+F2-2.0
F1F = F1*F
F2P = F2+F1F
X1 = F2/F2P
X2 = 1.0-X1
IF (X2.EQ.0.0) GO TO 115
IF ((N1/2)*2-N1.EQ.0.AND.N1.LE.500) GO TO 5
IF ((N2/2)*2-N2.EQ.0.AND.N2.LE.500) GO TO 30
IF (N1+N2.LE.500) GO TO 55
F1 = R2D9/F1
F2 = R2D9/F2
CBR1 = R1D3*ALOG(F)

```

```

IF (ABS(CBR1).GT.BIGE) GO TO 120
CBR1 = EXP(CBR1)
CBR2 = CBR1*CBR1
S = (CBR1*(1.0-F2)-1.0+F1)/SQRT(F1+CBR2*F2)
P=.70710678118655
P = .5*ERFC(-P*S)
GO TO 95

```

C N1 IS EVEN AND LESS THAN 500

```

5 TEMP1 = 0.
TEMP = .5*F2*ALOG(X1)
IF (N1.EQ.2) GO TO 25
I1 = N1-2
XI = F1
DO 10 I2=2,I1,2
    L2 = I2
    XI = XI-2.
    VP = VP-2.
    DP = X2*VP/XI*(1.+DP)
    IF (DP.GT.ACONS) GO TO 15
10 CONTINUE
GO TO 25
15 IF (L2.GE.I1) GO TO 25
DPL = ALOG(DP)
I2P = L2+2
XI = F1-I2P
DO 20 I2=I2P,I1,2
    VP = VP-2.
    DPL = DPL+ALOG(X2*VP/XI)
    XI = XI-2.
20 CONTINUE
TEMP = TEMP+DPL
IF (ABS(TEMP).LE.BIGE) TEMP1 = EXP(TEMP)
P = 1.-TEMP1
GO TO 95
25 IF (ABS(TEMP).LE.BIGE) TEMP1 = EXP(TEMP)
P = 1.0-TEMP1*(1.0+DP)
GO TO 95

```

C N2 IS EVEN AND LESS THAN 500

```

30 TEMP1 = 0.
TEMP = .5*F1*ALOG(X2)
IF (N2.EQ.2) GO TO 50
I1 = N2-2
XI = F2
DO 35 I2=2,I1,2
    L2 = I2
    XI = XI-2.
    VP = VP-2.
    DP = X1*VP/XI*(1.+DP)
    IF (DP.GT.ACONS) GO TO 40
35 CONTINUE

```

```

      GO TO 50
40  IF (L2.GE.I1) GO TO 50
      DPL = ALOG(DP)
      I2P = L2+2
      XI = F2-I2P
      DO 45 I2=I2P,I1,2
          VP = VP-2.
          DPL = DPL+ALOG(XI*VP/XI)
          XI = XI-2.
45  CONTINUE
      TEMP = TEMP+DPL
      IF (ABS(TEMP).LE.BIGE) TEMP1 = EXP(TEMP)
      P = TEMP1
      GO TO 95
50  IF (ABS(TEMP).LE.BIGE) TEMP1 = EXP(TEMP)
      P = TEMP1*(1.+DP)
      GO TO 95
C
                                     SUM OF DFS ARE LE 500 AND ODD
55  DP = SQRT(F1F/F2)
      THETA = ATAN(DP)
      STS = F1F/F2P
      A = 0.0
      B = 0.0
      IF (N2.EQ.1) GO TO 70
      IF (N2.EQ.3) GO TO 65
      I1 = N2-3
      XI = F2
      DO 60 I2=2,I1,2
          XI = XI-2.
          A = XI*(XI-1.0)/XI*(1.0+A)
60  CONTINUE
65  A = XI*DP*(1.0+A)
70  A = A+THETA
      IF (N1.EQ.1) GO TO 90
      IF (N1.EQ.3) GO TO 80
      I1 = N1-3
      XI = F1
      DO 75 I2=2,I1,2
          XI = XI-2.
          VP = VP-2.
          B = STS*VP/XI*(1.0+B)
75  CONTINUE
80  B = DP*XI*(1.0+B)
      IF (N2.EQ.1) GO TO 90
      I2 = N2/2
      C = 1.0
      DO 85 I=1,I2
          B = B*XI*C/(C-0.5)
          C = C+1.0
85  CONTINUE

```

```
90 P = R2DPI*(A-B)
95 IF (P.LT.0.0) P = 0.0
   IF (P.GT.1.0) P = 1.0
   GO TO 9005
100 IER = 129
   GO TO 110
105 IER = 130
110 P = RINFP
   GO TO 9000
115 P = 0.0
   GO TO 9005
120 P = .5
   GO TO 9005
9000 CONTINUE
   CALL UERTST (IER,'MDFD ')
9005 RETURN
END
```

Equation 5.3 states:

$$S_{yy} = SS_R + SS_E,$$

$$\text{or } \sum_1^n (y_i - \bar{y})^2 = \sum_1^n (\hat{y}_i - \bar{y})^2 + \sum_1^n (y_i - \hat{y}_i)^2.$$

$$\begin{aligned} \text{Note: } \sum_1^n (y_i - \bar{y})^2 &= \sum_1^n [(y_i - \hat{y}_i) - (\hat{y}_i - \bar{y})]^2 \\ &= \sum_1^n (y_i - \hat{y}_i)^2 + \sum_1^n (\hat{y}_i - \bar{y})^2 - 2 \sum_1^n (\hat{y}_i - \bar{y})(y_i - \hat{y}_i) \end{aligned}$$

One must show the last term  $\sum (\hat{y}_i - \bar{y})(y_i - \hat{y}_i) = 0$ , or

$$\sum (\hat{y}_i - \bar{y})(y_i - \hat{y}_i) = \sum y_i \cdot \hat{y}_i - \sum \bar{y} \cdot y_i - \sum \hat{y}_i^2 + \sum \bar{y} \cdot \hat{y}_i.$$

Term by term,

$$\begin{aligned} \sum y_i \cdot \hat{y}_i &= \sum [\hat{\alpha}' \cdot y_i + \hat{\beta} \cdot (x_i - \bar{x}) \cdot y_i] = \hat{\alpha}' \cdot n \cdot \bar{y} + \hat{\beta} \cdot S_{xy} - \sum \bar{y} \cdot y_i \\ &= -\bar{y} \sum y_i = -n \cdot \bar{y}^2. \end{aligned}$$

$$\begin{aligned} -\sum \hat{y}_i^2 &= -\sum [\hat{\alpha}' + \hat{\beta} \cdot (x_i - \bar{x})]^2 = -\sum_1^n [\hat{\alpha}'^2 + 2 \hat{\alpha}' \hat{\beta} \cdot (x_i - \bar{x}) + \hat{\beta}^2 (x_i - \bar{x})^2] \\ &= -n \hat{\alpha}'^2 - 2 \cdot \hat{\alpha}' \cdot \hat{\beta} \cdot 0 - \hat{\beta}^2 S_{xx} \\ &= -n \hat{\alpha}'^2 - \hat{\beta}^2 S_{xx}. \end{aligned}$$

$$\sum_1^n y_i \cdot \hat{y}_i = \bar{y} \sum_1^n \hat{y}_i = \bar{y} \sum_1^n [\hat{\alpha}' + \hat{\beta} \cdot (x_i - \bar{x})] = \bar{y} \cdot n \cdot \hat{\alpha}'.$$

Substituting  $\hat{\alpha}' = \bar{y}$ , and  $\hat{\beta} = S_{xy}/S_{xx}$

$$n \cdot \bar{y}^2 - n \cdot \bar{y}^2 - n \bar{y}^2 + n \cdot \bar{y}^2 + (S_{xy}^2/S_{xx}) - (S_{xy}^2/S_{xx}) = 0$$

This concludes the proof of the identity.



## APPENDIX D

VERIF : Clearness Index vs. Beam Normal Fraction  
Verification of Model Development

```

PROGRAM VERIF(INPUT,OUTPUT,TAPE6=OUTPUT,TAPE5=INPUT)
C
C      C. BALARAS    6-29-84
C
C...THIS PROGRAM CALCULATES THE GLOBAL RADIATION AND BEAM
C  NORMAL IRRADIATION, FOR EVERY 15 MINUTES (96 PERIODS)
C  DURING EACH DAY OF THE YEAR, TO CREATE A DUMMY Q-FILE
C  FOR TESTING PURPOSES.
C
C...DEFINITIONS
C      ALAT   : SOLAR LATITUDE IN RADIANS
C      ALONG  : LONGITUDE OF THE LOCALITY IN DEGREES
C      ALPHAV : CORRESPONDING AVERAGE OF THE SOLAR ALTITUDE
C      AMV    : CORRESPONDING AVERAGE OF THE AIR MASS
C      DAY    : DAY OF THE MONTH
C      DELTA  : DECLINATION ANGLE, IN RADIANS
C      DRCONV : CONVERSION FACTOR FROM DEGREES TO RADIANS
C      EQOT   : EQUATION OF TIME, IN MINUTES
C      EXTC   : ATMOSPHERIC EXTINCTION COEFFICIENT
C      FACTOR : CONVERSION FACTOR FROM W TO KJ/15MIN
C      GBNV   : AVERAGE EXTRATERRESTRIAL BEAM NORMAL RADIATION
C      GLOBAL : GLOBAL RADIATION
C      GON    : EXTRATERRESTRIAL RADIATION MEASURED ON THE PLANE
C              NORMAL TO THE RADIATION ON THE NTH DAY OF THE YEAR
C      GSC    : SOLAR CONSTANT (W/M/M)
C      HANGSR : HOUR ANGLE AT SUNRISE (STANDARD TIME)
C      HANGSS : HOUR ANGLE AT SUNSET (STANDARD TIME)
C      HR     : HOURS DURING THE DAY, STARTING AT MIDNIGHT OF THE
C              PREVIOUS DAY OR AT 0 HOURS OF THE NEW DAY
C      HRCONV : CONVERSION FACTOR FROM HRS TO RAD
C      I      : MONTH OF THE YEAR
C      IBN    : BEAM NORMAL IRRADIATION
C      IO     : EXTRATERRESTRIAL HORIZONTAL IRRADIATION
C      ION    : EXTRATERRESTRIAL NORMAL IRRADIATION
C      KT     : CLEARNESS INDEX
C      MIN    : MINUTES (15 MINUTE INTERVAL)
C      MONLEN : THE NUMBER OF DAYS IN A MONTH
C      N      : DAY OF THE YEAR
C      OMEGA1 : HOUR ANGLE CORRESPONDING TO THE LOWER INTEGRATION LIMIT
C      OMEGA2 : HOUR ANGLE CORRESPONDING TO THE HIGHER INTEGRATION LIMIT
C      OMEGAV : CORRESPONDING AVERAGE OF THE HOUR ANGLE-SOLAR TIME
C      PHI    : LATITUDE (DEGREES) OF THE LOCALITY
C      SHANGL : HOUR ANGLE IN SOLAR TIME
C      SRTIME : SUNRISE STANDARD TIME
C      SSTIME : SUNSET STANDARD TIME
C      STDTSN : STANDARD TIME OF SOLAR NOON
C      STMER  : STANDARD MERIDIAN
C      T1     : STANDARD TIME AT WHICH EACH PERIOD STARTS
C      T2     : STANDARD TIME AT WHICH EACH PERIOD ENDS
C      TAU1   : INTEGRATION LOWER LIMIT FOR EVERY PERIOD (STD. TIME)

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C      TAU2      : INTEGRATION UPPER LIMIT FOR EVERY PERIOD (STD. TIME)
C      TAUAV     : INTEGRATION AVERAGE TIME (STD. TIME)
C      THETAZ    : ZENITH ANGLE OF THE SUN
C      YR        : YEAR OF INTEREST (1980)
C
C...VARIABLE DECLARATIONS
      INTEGER YR,HR,DAY
      REAL IBN,IO,ION,KT,OMEGA1,OMEGA2,OMEGAV,PHI,SHANGL
C
      DIMENSION MONLEN(12)
      DATA MONLEN/31,29,31,30,31,30,31,31,30,31,30,31/
C
C...INITIALIZE VARIABLES
      PI=4.0*ATAN(1.0)
      DRCONV=PI/180.0
      PHI=33.42
      ALAT=PHI*DRCONV
      FACTOR=3.6
      HRCONV=15.0*DRCONV
      ALONG=84.75
      STMER=75.0
      N=0
      YR=80
      DAY=0
C
C...PERFORM CALCULATIONS FOR EVERY DAY OF THE MONTH (I)
      DO 350 I=1,12
        L=MONLEN(I)
        DO 250 J=1,L
          N=N+1
          DAY=DAY+1
C
C...CALCULATE THE DECLINATION
          DELTA=23.45*SIN(2.0*PI*(284.0+N)/365.0)*DRCONV
C...CALCULATE THE SUNSET HOUR ANGLE
          HANGSS=ACOS(-TAN(SALT)*TAN(DELTA))
C...CALCULATE THE SUNRISE HOUR ANGLE
          HANGSR=-HANGSS
C
C...CALCULATE THE EQUATION OF TIME
          IF (N.GT.106) GO TO 100
          EQOT=-14.2*SIN((N+7.0)*0.028303)
          GO TO 400
100      IF (N.GT.166) GO TO 200
          EQOT=4.0*SIN((N-106.0)*0.053247)
          GO TO 400
200      IF (N.GT.246) GO TO 300
          EQOT=-6.5*SIN((N-166.0)*0.03927)
          GO TO 400
300      EQOT=16.4*SIN((N-247.0)*0.027802)

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C
C...CALCULATE THE STANDARD TIME OF SOLAR NOON
400  STDTSN=12.0-(EQOT/60.0)-(STMER-LONG)/15.0
C...CALCULATE THE SUNRISE STANDARD TIME
      SRTIME=STDTSN-(HANGSS/HRCONV)
C...CALCULATE THE SUNSET STANDARD TIME
      SSTIME=STDTSN+(HANGSS/HRCONV)
C...CALCULATE THE EXTRATERRESTRIAL NORMAL RADIATION
      GSC=1353.0
      GON=GSC*(1.0+0.033*COS(2.0*PI*N/365.0))
C
C...CALCULATE THE INTEGRATION LIMITS TAU1,TAU2 FOR EACH
C 15 MINUTE INTERVAL, STARTING AT MIDNIGHT OF THE PREVIOUS
C DAY OR AT 0:00 HOURS OF THE NEW DAY
      T1=0.0
      T2=15.0/60.0
      GLOBAL=0.0
      IBN=0.0
      HR=0
      MIN=15
C
      WRITE(6,20) YR,N,I,DAY,HR,MIN,'000000000000'
&'00000000000000000000 00000000000000000000000000000000'
20  FORMAT(I2,1X,I3,4(1X,I2),1X,A12,A53)
      WRITE(6,21) '0','0','0','0','0',IBN,IBN,'0',GLOBAL,'0',
&'0','0','0','0','0','0'
21  FORMAT(2X,A1,4X,A1,3X,A1,4X,A1,6X,A1,F5.0,F5.0,4X,A1,F5.0,
&7(4X,A1))
C
      DO 10 K=2,96
      T1=T1+15./60.
      T2=T2+15./60.
C...CALCULATE TAU1
C.....FOR PERIODS BEFORE SUNRISE
      IF (SRTIME.GT.T2) THEN
        GLOBAL=0.0
        IBN=0.
        GO TO 50
      ELSE
C.....FOR THE PERIODS BETWEEN SUNRISE SUNSET
        IF (SRTIME.LE.T1) TAU1=T1
        IF (SRTIME.GT.T1) TAU1=SRTIME
        END IF
C...CALCULATE TAU2
C.....FOR PERIODS AFTER SUNSET
        IF (SSTIME.LT.T1) THEN
          GLOBAL=0.
          IBN=0.
          GO TO 50
        ELSE

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C.....FOR PERIODS BETWEEN SUNRISE SUNSET
  IF (SSTIME.GE.T2) TAU2=T2
  IF (SSTIME.LT.T2) TAU2=SSTIME
  END IF

C
C...CALCULATE THE AVERAGE INTEGRATION LIMITS (STD. TIME)
  TAUAV=(TAU1+TAU2)/2.
C...CALCULATE THE CORRESPONDING AVERAGE OF THE
C.....HOUR ANGLE
  OMEGAV=(TAUAV-STDTSN)*HRCONV
C.....SOLAR ALTITUDE
  THETAZ=(ACOS(COS(DELTA)*COS(SLAT)*COS(OMEGAV)+SIN(DELTA)*
    &SIN(SLAT)))*180.0/PI
  ALPHAV=(90.0-THETAZ)*DRCONV
C.....AIR MASS
  AMV=1.0/SIN(ALPHAV)
C...CALCULATE THE AVERAGE BEAM NORMAL RADIATION
  EXTC=0.25
  GBNV=GON*EXP(-EXTC*AMV)

C
C...CALCULATE THE HOUR ANGLE FOR THE LOWER INTEGRATION LIMIT
  OMEGA1=(TAU1-STDTSN)*HRCONV
C...CALCULATE THE HOUR ANGLE FOR THE HIGHER INTEGRATION LIMIT
  OMEGA2=(TAU2-STDTSN)*HRCONV

C
C...CALCULATE THE GLOBAL RADIATION BETWEEN SUNRISE SUNSET
  GLOBAL=(12.0/PI)*GBNV
  &*(COS(DELTA)*COS(ALAT)*(SIN(OMEGA2)-SIN(OMEGA1)))
  &+(OMEGA2-OMEGA1)*SIN(DELTA)*SIN(ALAT))
  GLOBAL=GLOBAL*FACTOR
C...CALCULATE THE EXTRATERRESTRIAL HORIZONTAL IRRADIATION
  IO=(12.0/PI)*GON
  &*(COS(DELTA)*(COS(ALAT)*(SIN(OMEGA2)-SIN(OMEGA1)))
  &+(OMEGA2-OMEGA1)*SIN(DELTA)*SIN(ALAT))
  IO=IO*FACTOR
C...CALCULATE THE CLEARNESS INDEX
  KT=GLOBAL/IO
C...CALCULATE THE EXTRATERRESTRIAL NORMAL IRRADIATION
  ION=GON*(TAU2-TAU1)*FACTOR
C...CALCULATE THE BEAM NORMAL IRRADIATION
  Q=(1./2.)*KT
  IBN=Q*ION
50  MIN=MIN+15
  IF (MIN.EQ.60) GO TO 5
  GO TO 500
5   HR=HR+1
  MIN=0
  IF (HR.EQ.24.AND.MIN.EQ.0) THEN
    HR=0
    MIN=0

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      N=N+1
      DAY=DAY+1
      IF (DAY.EQ.L) DAY=1
      IF (DAY.EQ.1) I=I+1
      ELSE
      GO TO 500
      END IF
C
500  WRITE(6,22) YR,N,I,DAY,HR,MIN,'000000000000'
      &'00000000000000000000 00000000000000000000000000000000'
22   FORMAT(I2,1X,I3,4(1X,I2),1X,A12,A53)
      WRITE(6,23) '0','0','0','0','0','0',IBN,IBN,'0',GLOBAL,'0',
      &'0','0','0','0','0','0'
23   FORMAT(2X,A1,4X,A1,3X,A1,4X,A1,6X,A1,F5.0,F5.0,4X,A1,F5.0,
      &7(4X,A1))
C
10   CONTINUE
      N=N-1
      DAY=DAY-1
250  CONTINUE
350  CONTINUE
      END

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