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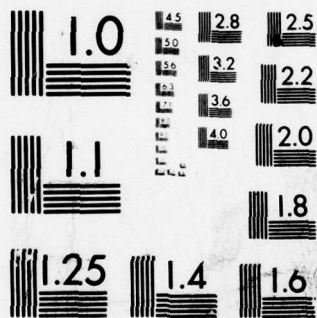
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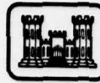


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SPECIAL REPORT E-155  
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INVESTIGATION OF THE INTERRELATIONSHIP  
BETWEEN DIRECT, DIFFUSE, AND TOTAL  
SOLAR RADIATION

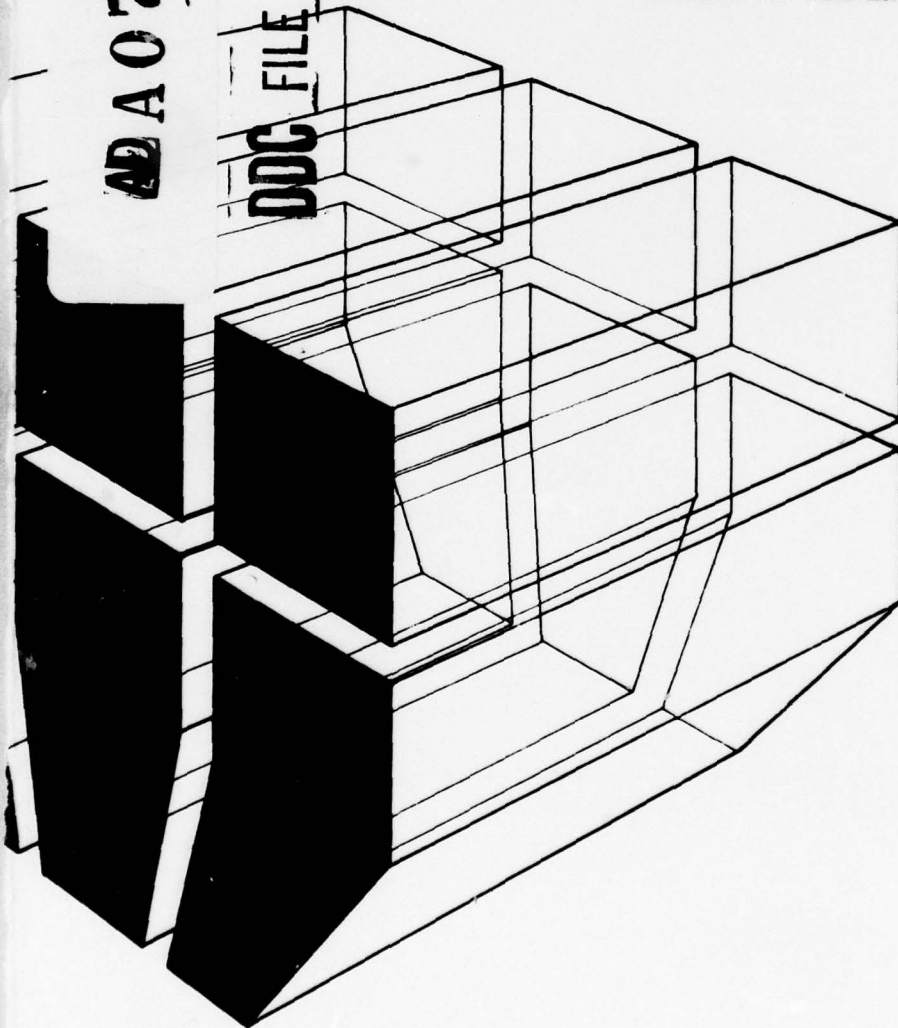
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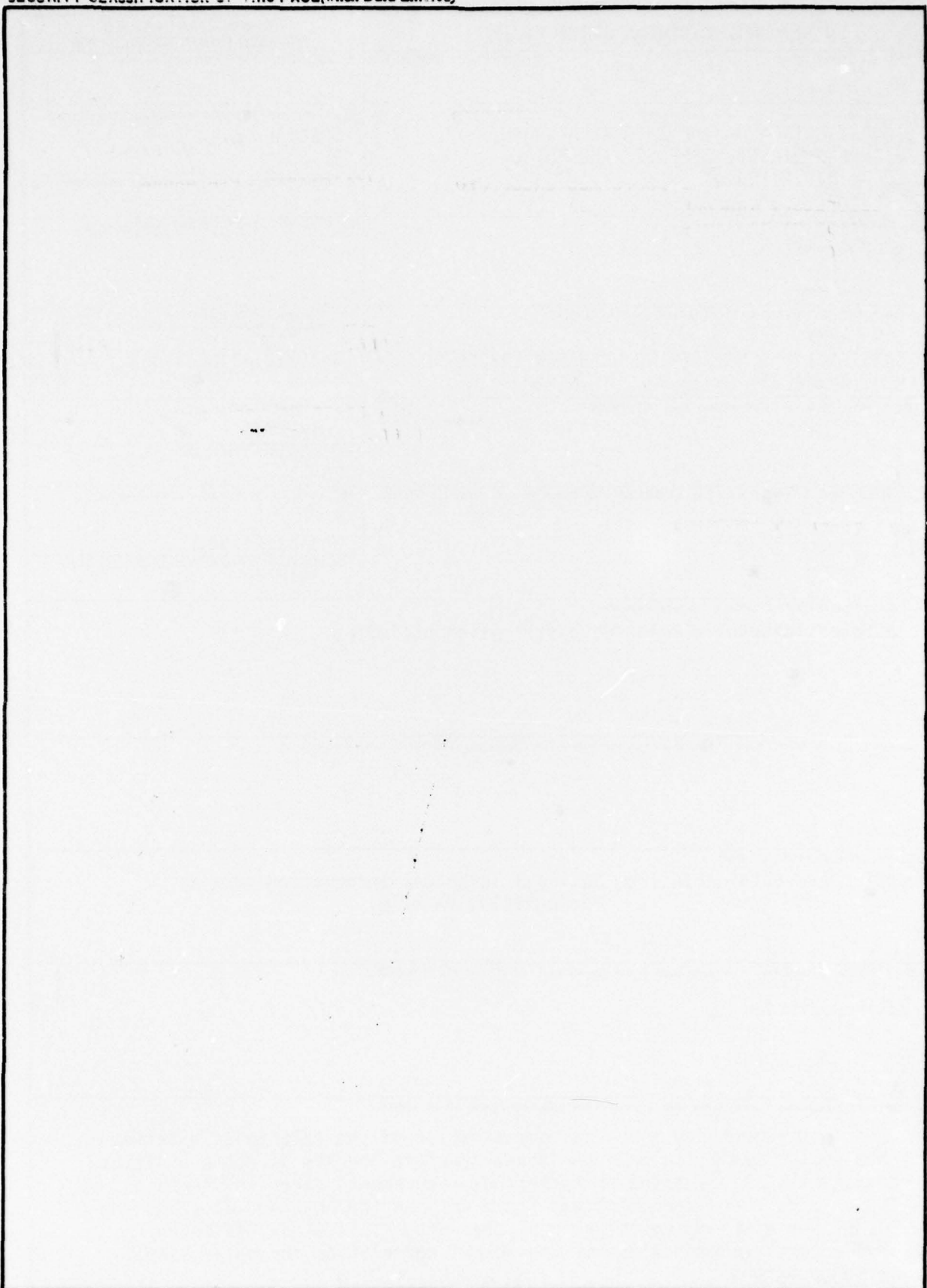
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes an investigation of the relationship between total solar radiation on a horizontal surface and its direct and diffuse components. It is based on radiation measurements taken in Champaign, IL in 1978. Good agreement was found between the observed data and the SOLMET correlation, which was published after this study was begun. This report recommends use of the SOLMET correlation for solar simulation programs. 405 279		



FOREWORD

This work was performed under Project 4A161101A91D, "In-House Laboratory Independent Research," Task 04, Work Unit 058, "Investigation of the Interrelationship Between Direct, Diffuse, and Total Solar Radiation."

This study was performed by the Energy and Habitability Division (EH), U.S. Army Construction Engineering Research Laboratory (CERL). Mr. R. G. Donaghy is Chief of EH. Dr. R. Dinnat of CERL was the project manager.

Appreciation is expressed to Dr. David Joncich of CERL for his assistance in integrating this study's equipment with equipment contained in CERL's solar test facility.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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# INVESTIGATION OF THE INTERRELATIONSHIP BETWEEN DIRECT, DIFFUSE, AND TOTAL SOLAR RADIATION

## 1 INTRODUCTION

### Background

Solar radiation is commonly measured by its total intensity on a horizontal surface. Studies of solar heat gain in buildings and the performance of solar collectors require information about total radiation intensities on tilted surfaces. Horizontal radiation is transformed to tilted surface radiation by decomposing the total horizontal radiation into its direct and diffuse components and then recombining them in proper proportions. Direct radiation intensity on a surface is given by the direct intensity normal to the sun's rays times the cosine of the angle of incidence of the sun's rays on the surface. Diffuse radiation intensity on a surface is given by horizontal diffuse intensity times the radiation view factor between the surface and the sky.

When this study was begun, the only available algorithm for computing diffuse and beam radiation from the total horizontal radiation was based on daily totals of the three components listed above. Several computer simulations were in use or being developed which computed hourly building loads or solar performance. These programs required hourly values of beam and diffuse radiation, and only hourly horizontal radiation values were available. It was not known how accurately the daily algorithm was for computing hourly diffuse and beam radiation.

### Objective

The objective of this research was to determine a simple correlation between total radiation on a horizontal surface and its direct and diffuse components.

### Approach

Using two solar pyranometers, researchers measured total and diffuse radiation on a horizontal surface. Data collected during different seasons showed the effects of daily and seasonal changes in the sun's position and of seasonal weather changes. These data were recorded by an automatic digital system which created data tapes suitable for computer analysis. Several regression algorithms were used to find which one would best describe the measured data.

### Organization of Report

Chapter 2 describes the equipment and the procedure used to measure the horizontal and diffuse radiation. Chapter 3 presents the results in terms of the data points measured and the calculated correlation. Chapter 4 analyzes the results by comparing the correlation to published correlations. Chapter 5 gives conclusions and recommendations.

## 2 EXPERIMENTAL PROCEDURE

### Equipment and Its Use

Instrumentation for this project was incorporated into instrumentation that was already being used in the existing solar test facility. The solar facility had one pyranometer for measuring total radiation on a horizontal surface, as well as a system for automatically recording signals from sensors placed throughout the building. A second pyranometer and a shadow band were purchased to measure the diffuse radiation on a horizontal surface by the shadow band blocking the beam radiation. The band was oriented so that it was between the sun and the pyranometer as the sun moved across the sky during the day. The position of the shadow band was adjusted every few days by moving the shadow band until the pyranometer was centered in its shadow. These adjustments were made to account for the changes in solar position between summer and winter.

A mounting platform was installed at the peak of the solar facility next to the original pyranometer. This location provided a clear view to the horizon in all directions. The new pyranometer was connected to the solar facility data recording system.

The pyranometers were calibrated; the new pyranometer was the standard, since its calibration was at least 2 years more recent than that of the old one. The voltage signals from each pyranometer are fed through amplifiers to the solar facility's data-recording equipment. This equipment integrates and records these signals and 38 other signals every hour. Each data cassette holds approximately 1 week's data. Because of limited access to the transfer facilities, several cassettes were accumulated before their data were transferred to a large tape. This tape was then transferred to a computer facility.

### Procedure

A program was written to compute the solar position and the value of the solar constant (intensity of the sun's direct radiation outside the earth's atmosphere) for any hour of any day of the year. These values were combined with the measured horizontal and diffuse radiation values onto a single data file. This file contained all the data necessary to analyze and evaluate an estimating algorithm. Another program was written that would use plotting routines to generate simple plots of the data points. Other programs were written that would do regressions against different algorithm types to determine the best one to use. Several simple polynomial forms were tried, because polynomials are easy to implement in simulation programs.

### 3 RESULTS

The data-gathering technique twice allowed errors to go unnoticed; this resulted in the loss of several months' data. First, an intermittent amplifier failure was not observed until September 1977, and there was no spare amplifier available. Return to the manufacturer, repair, and reinstallation took until the end of January 1978. Second, an error in the setting of the cassette recording speed during April destroyed the next 3 months' data.

Experimental results are presented in terms of the following quantities:

Z = the angle between the sun and the zenith

H = the total radiation measured on a horizontal surface

B = the direct (beam) radiation measured normal to the direction of the sun's rays

D = the diffuse radiation measured on a horizontal surface

BO = the theoretical beam radiation on a surface outside the earth's atmosphere

HO = the theoretical radiation on a horizontal surface outside the earth's atmosphere

These values are related by the expressions

$$H = B * \cos(Z) + D \quad [\text{Eq 1}]$$

and

$$HO = BO * \cos(Z). \quad [\text{Eq 2}]$$

Figures 1 through 4 show the experimental data, giving the ratio B/BO plotted as a function of H/HO. Figure 1 is for the period from February 1 through March 5, while Figure 2 is for March 6 through April 6. Figure 3 is for August 3 through August 25, and Figure 4 combines the data from Figures 1 through 3.

Attempts to fit the data with a simple polynomial (of the form  $Y = A^0 + A_1X + A_2X^2 + A_3X^3 + \dots$ ) did not produce satisfactory results. A simple fit was made by computing the average value of B/BO for each 10 percent increment of H/HO. Table 1 provides the values found by this fit. Curves created by interpolation between these values are shown in Figures 1 through 4.

Table 1

Direct to Horizontal Correlations

H/H0	B/B0 for days (Julian dates)			Total
	32 - 64	65 - 96	215 - 237	
.05		.002		.002
.15	.014	.004	.006	.005
.25	.018	.010	.027	.017
.35	.056	.070	.057	.061
.45	.071	.125	.133	.100
.55	.170	.257	.287	.244
.65	.330	.440	.423	.403
.75	.533	.614	.589	.578
.85	.639	.744	.680	.656
.95	.739			.739

SOLAR RADIATION: DAYS 32 - 64

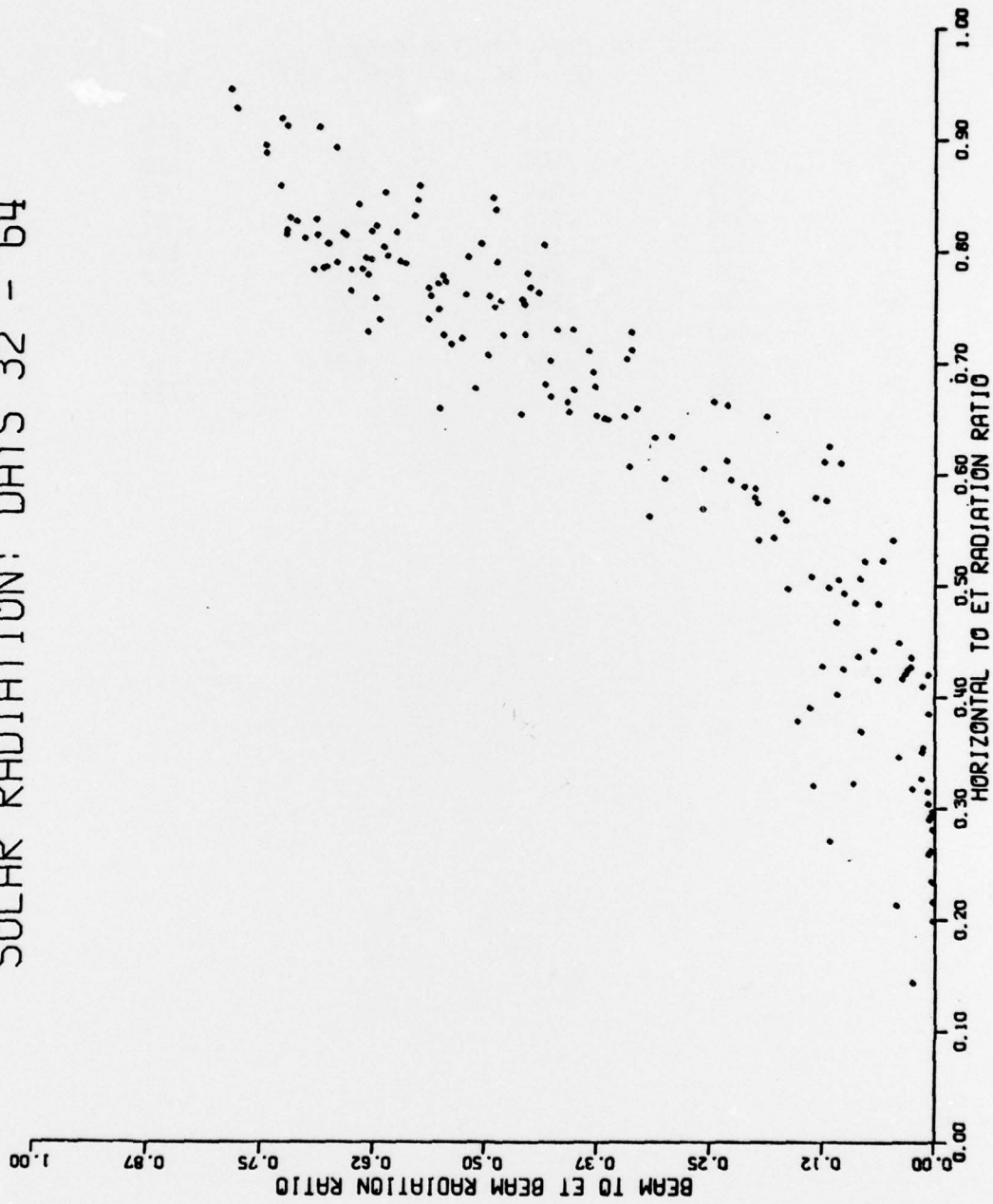


Figure 1. Solar radiation: days 32-64.

SOLAR RADIATION: DAYS 65 - 96

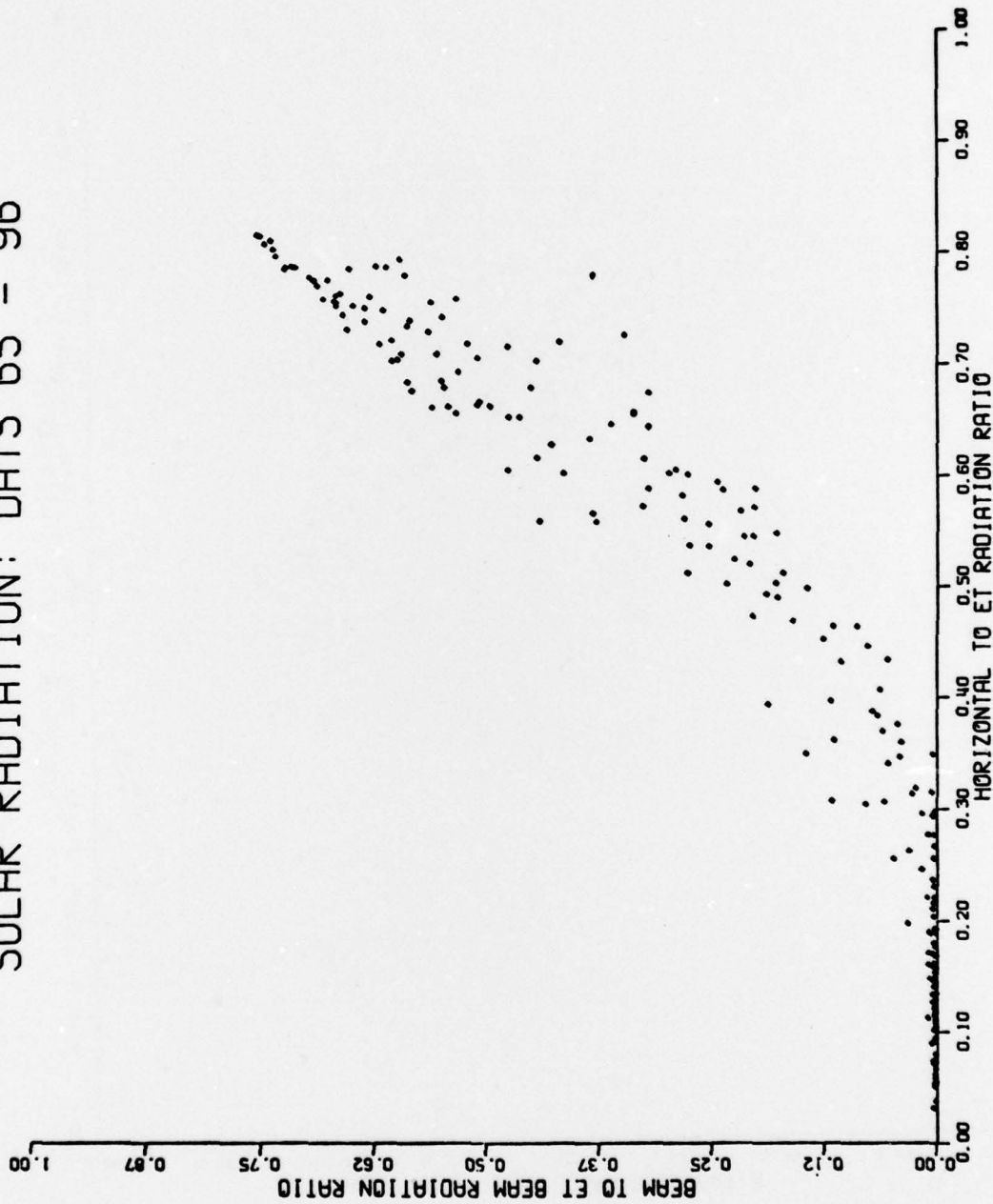


Figure 2. Solar radiation: days 65-96.

SOLAR RADIATION: DAYS 215 - 237

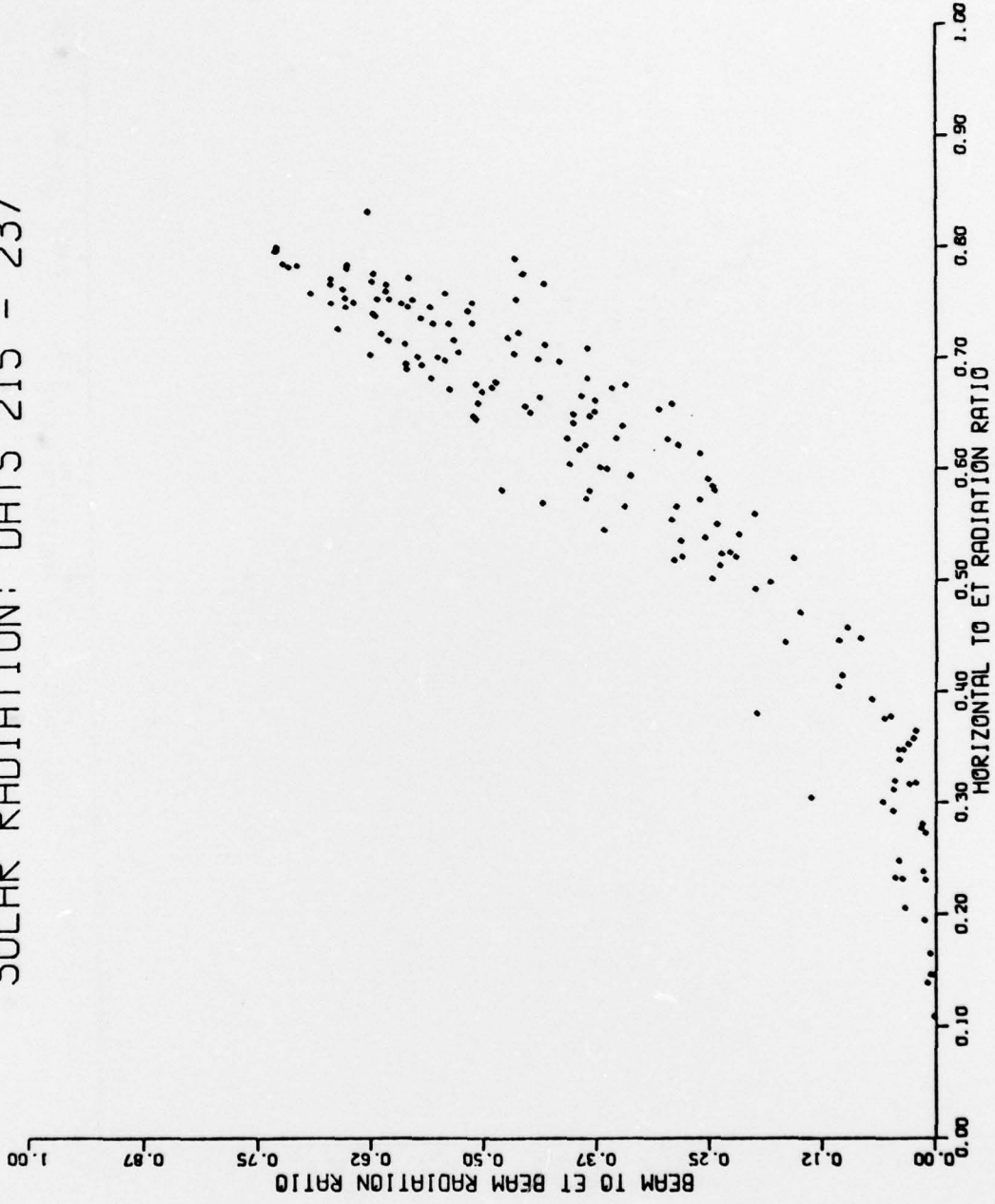


Figure 3. Solar radiation: days 215-237.

SOLAR RADIATION: DAYS 32 - 237

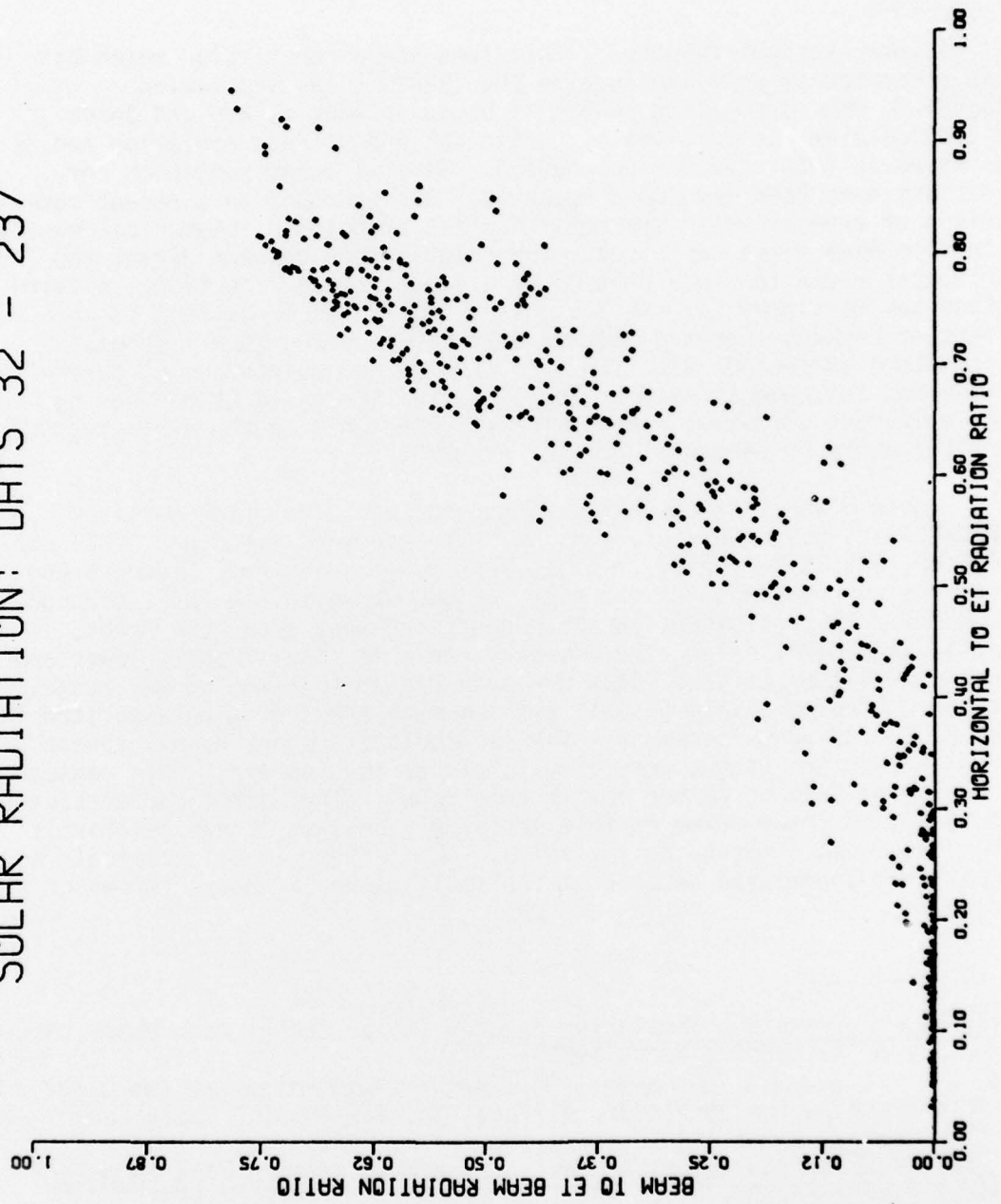


Figure 4. Solar radiation: days 32-237.

## 4 ANALYSIS

### Comparisons

Several current computer simulations use a correlation which has been presented in equation form in the TRNSYS solar simulation program.<sup>1</sup> The correlation, which is based on work by Liu and Jordan,<sup>2</sup> is predicted on daily values of horizontal and diffuse radiation and is expressed as a third-order polynomial. Several other radiation correlations have been developed recently. One was used in a recent comparison of several solar system simulation programs.<sup>3</sup> Historical hourly data from many sites were used. The relationship between direct and horizontal radiation is expressed by a simple linear function. A third method was developed for the National Climatic Center as part of an effort to produce standard weather data tapes called SOLMET tapes.<sup>4</sup> This method collected data from more than 20,000 points, using carefully calibrated instruments at four locations in the United States having very different climates. The SOLMET correlation uses the averaging process for every 10 percent increment of H/H<sub>0</sub>.

Figure 5 shows three correlations and the correlation obtained during this study. This study is in best agreement with the SOLMET correlation, but it generally predicts less beam radiation. Figure 6 compares the correlations for the time periods shown in Figures 1 through 3 to SOLMET. This illustration shows good agreement among the March, August, and SOLMET data. The February curve is significantly lower and shows some values of H/H<sub>0</sub> which are much higher than the normal range. Figures 1 through 3 show a small problem with the averaging algorithm in the .80 to .90 H/H<sub>0</sub> increment. The data points are not evenly spread across the entire range, occurring mostly at the low end. This causes the value of B/B<sub>0</sub> to be too low in this range. The SOLMET correlation shows an even lower value in this increment, because it had relatively fewer data points above the .82 value. This effect is not critical in annual energy analysis because of the small number of hours for which it applies.

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<sup>1</sup> TRNSYS - A Transient Simulation Program (Solar Energy Laboratory, University of Wisconsin, March 1975).

<sup>2</sup> B. Y. H. Liu and R. C. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation," Solar Energy, Vol 4 (1960), pp 1-19.

<sup>3</sup> A Test Problem and Solutions for Solar Heating and Cooling Computer Simulation Programs, Draft (U.S. Department of Energy, 1978).

<sup>4</sup> C. M. Randall and M. E. Whitson, Jr., Hourly Insolation and Meteorological Data Bases Including Improved Direct Insolation Estimates, Aerospace Report ATR-78 (7592)-1 (The Aerospace Corporation, 1977).

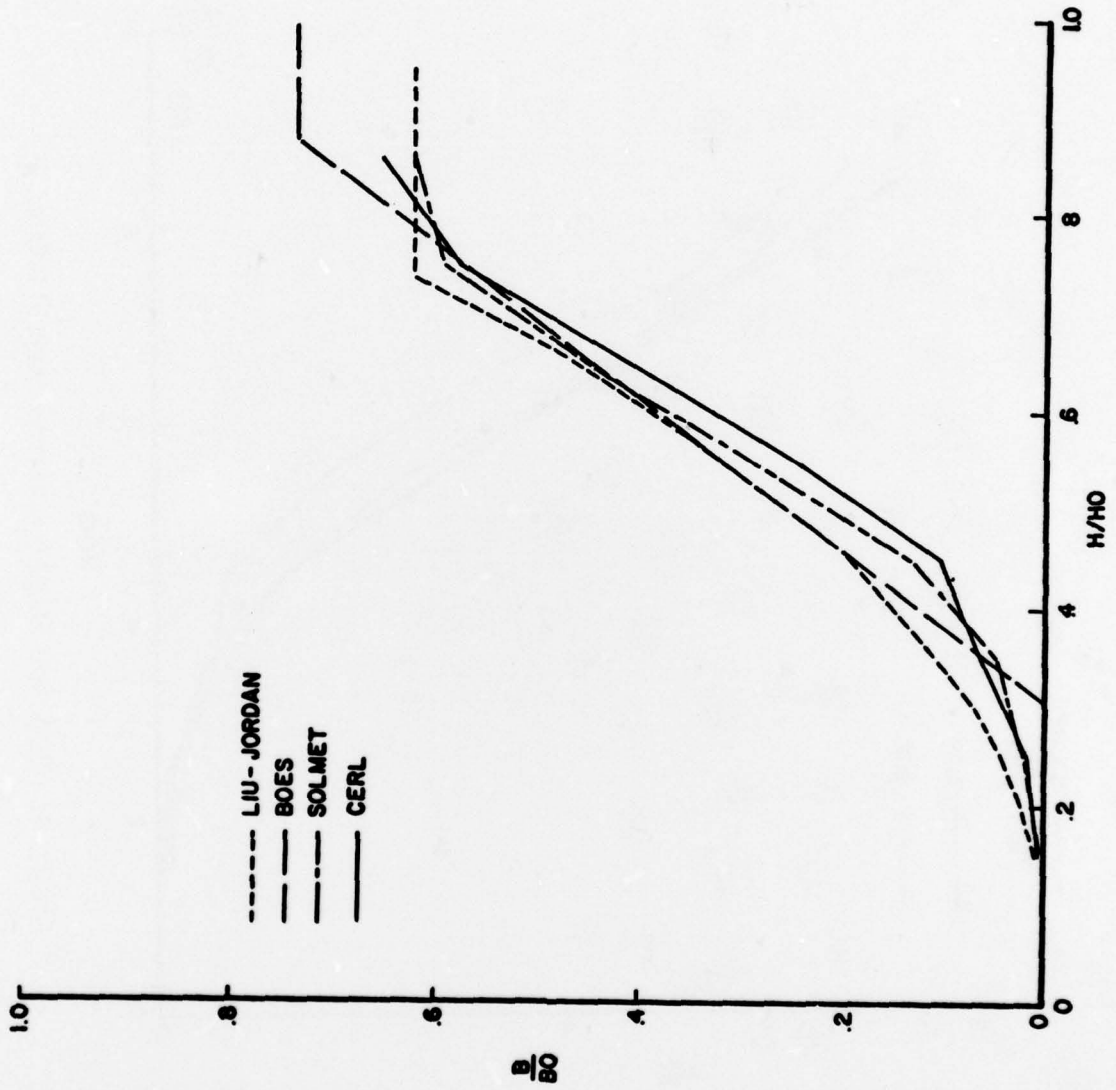


Figure 5. Four radiation correlations.

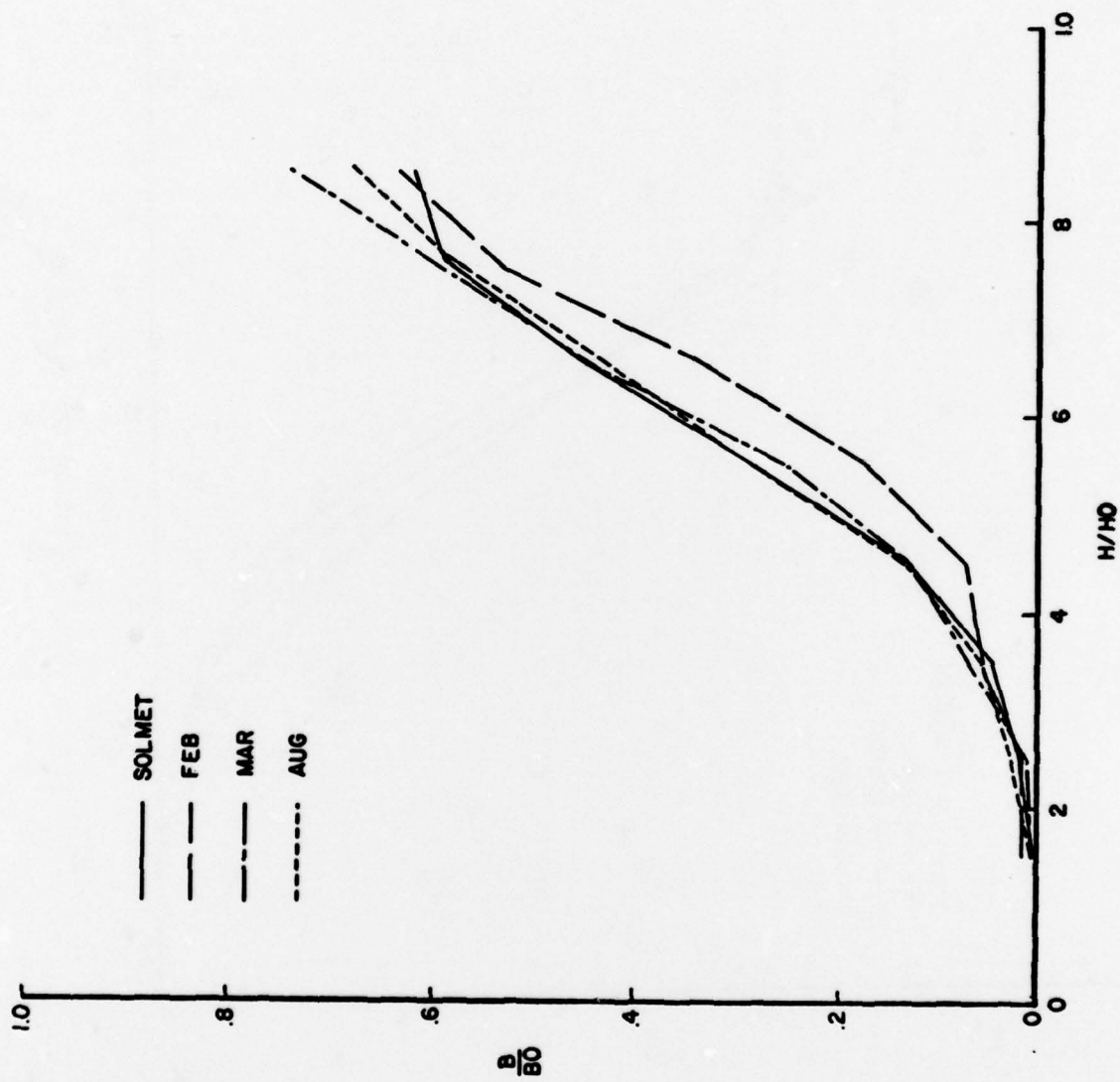


Figure 6. CERL and SOLMET radiation correlations.

### Time of Day Factors

Figures 7 and 8 show August radiation data separated by morning and afternoon observations. The  $H/H_0$  ratio is typically higher in the morning, which is caused by a common summer weather condition in Illinois. Mornings start clear, but small cumulus clouds then form and grow larger in size and number throughout the day. This pattern does not occur in March and is not observed in the data. This condition can be significant for summer applications of beam solar radiation and will affect the orientation of the solar collector.

### Sources of Error

The severe weather in February affected the data quality. Long periods of cloudy weather prevented proper alignment of the shadow band for subsequent clear days, especially on weekends when no one was present to adjust the band as soon as its shadow could be seen. Occasionally, the snow made it too hazardous for researchers to adjust the shadow band on the roof.

The shadow band weathered unexpectedly, becoming somewhat reflective instead of retaining its original flat black color. As a result, it now reflects radiation from the ground, especially from snow, back onto the diffuse measuring pyranometer.

MORNING RADIATION: DAYS 215 - 237

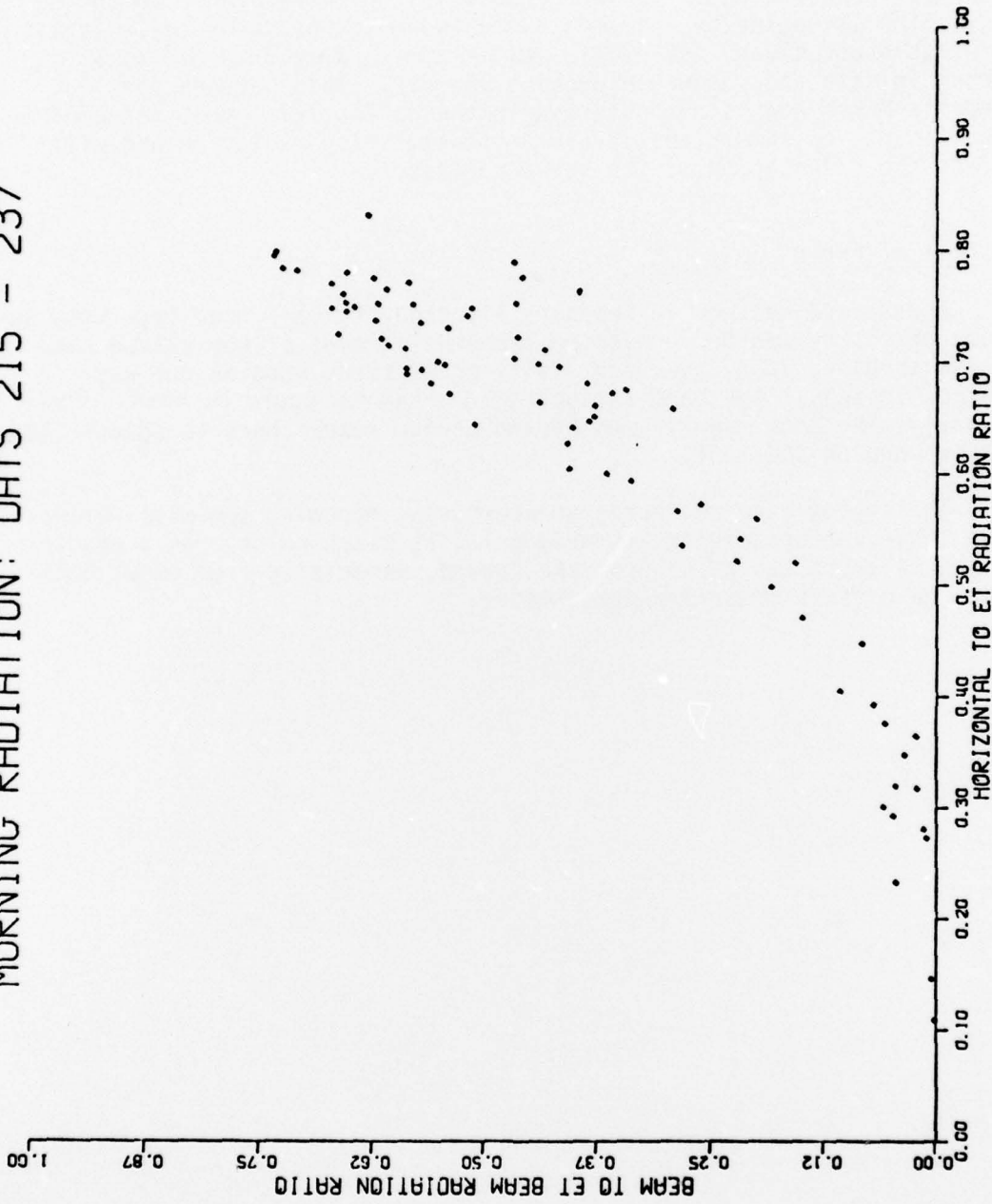


Figure 7. Morning radiation: days 215-237.

AFTERNOON RADIATION: DAYS 215 - 237

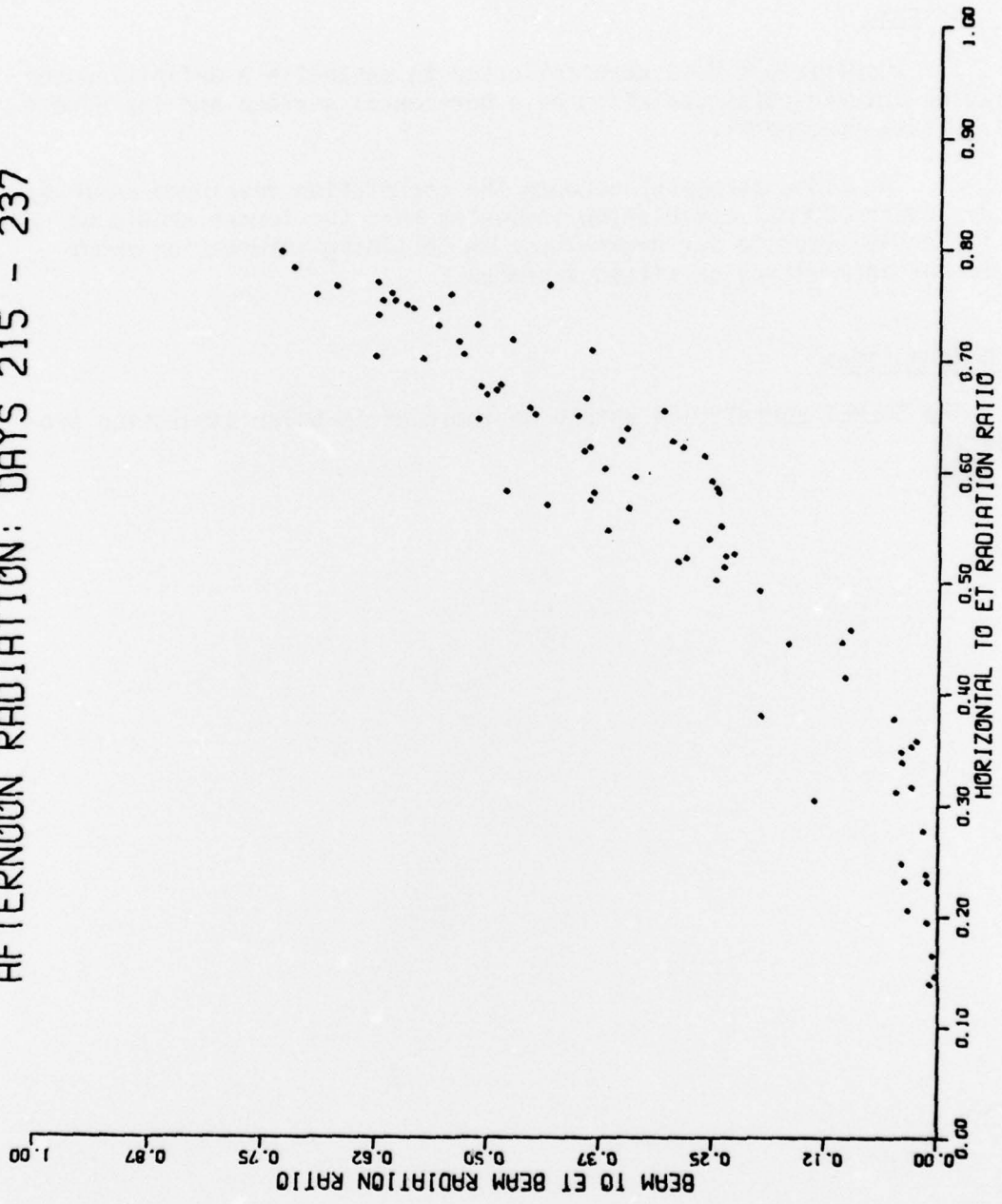


Figure 8. Afternoon radiation: days 215-237.

## 5 CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

1. Insufficient data were collected to establish a definitive correlation between total radiation on a horizontal surface and its direct and diffuse components.

2. The close agreement between the correlation developed in this study and the SOLMET correlation indicates that the former should be sufficiently accurate for general use in obtaining information about radiation intensities on tilted surfaces.

### Recommendations

The SOLMET correlation should be included in solar simulation programs.

## REFERENCES

- A Test Problem and Solutions for Solar Heating and Cooling Computer Simulation Programs, Draft (U.S. Department of Energy, 1978).
- Liu, B. Y. H., and R. C. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation," Solar Energy, Vol 4 (1960), pp 1-19.
- Randall, C. M., and M. E. Whitson, Jr., Hourly Insolation and Meteorological Data Bases Including Improved Direct Insolation Estimates, Aerospace Report ATR-78 (7592)-1 (The Aerospace Corporation, 1977).
- TRNSYS - A Transient Simulation Program (Solar Energy Laboratory, University of Wisconsin, March 1975).

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