460
4-19-79

MASTER

DR 2454

SERI/TR-36-110

December 1978

Insolation Models, Data and Algorithms

Annual Report FY78

Roland L. Hulstrom

Solar Energy Research Institute
A Division of Midwest Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

Operated for the
U.S. Department of Energy
under Contract No. EG-77-C-01-4042

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $6.00

NOTICE

SERI/TR-36-110
UC CATEGORY: 13,59,62,63A

INSOLATION MODELS, DATA AND ALGORITHMS

ANNUAL REPORT FY78

ROLAND L. HULSTROM

DECEMBER 1978

Solar Energy Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

FOREWORD

This annual report was performed in compliance with Contract Number EG-77-C-01-4042 for the Division of Solar Technology of the U.S. Department of Energy. The Report describes the research tasks of the Insolation Models, Data, and Algorithms Program (Task No. 3603) and was prepared by the staff of the Energy Resource Assessment Branch of the Solar Energy Research Institute, a Division of Midwest Research Institute.

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

Roland L. Hulstrom
Branch Chief
Energy Resource Assessment Branch
Research Division

J. Charles Grosskreutz
Assistant Director
Research Division

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

ABSTRACT

The FY78 objectives, descriptions, and results of insolation research tasks of the Solar Energy Research Institute's (SERI) Energy Resource Assessment Branch (ERAB) are presented. The purpose of ERAB is to provide state of the art and advanced state of the art data bases and physical models to ensure accurate design and analyses of solar energy conversion device performance. The tasks performed during FY78, the first year of operation for SERI/ERAB, addressed the resources of insolation ("sunshine") and wind. Described in this report is the insolation portion of the FY78 ERAB efforts, which resulted in operational computer models for the thermal (broadband) and spectral insolation, a data base (SOLMET) for the U.S. geographical distribution of thermal insolation, preliminary research measurements of the thermal insolation on tilted surfaces, and a complete design concept of advanced instrumentation to measure automatically the insolation on 37 tilted surfaces at various orientations.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 1.0

PROGRAM OBJECTIVES

This report describes the FY78 objectives, approach, and progress of SERI's Insolation Models, Data, and Algorithms Program (Task 3603). This program (Task 3603) is one of several being performed by the Energy Resource Assessment Branch (ERAB) of SERI's Research Division. The major efforts of ERAB are to:

- support and conduct joint studies with internal SERI branches concerning solar energy resource models, data, and data bases;
- aid industry in obtaining and using solar energy resource models and data bases;
- perform basic and applied research to evaluate existing models and to develop improved models, algorithms, and data bases for the solar energy resources; and
- provide direct support to DOE regarding solar energy resources and models.

Task 3603 supports ERAB's major efforts toward insolation research. Several subtasks were formulated that address the key technical problems and specific areas of technical support to DOE, SERI, industry, and the private sector. These subtasks are:

3603.1 - Relate Global and Direct Insolation to Insolation on Tilted Surfaces and into Various Apertures

3603.2 - Evaluation, Implementation, and Improvement of Insolation Algorithms and Models for Solar Applications

3603.3 - Implement SOLMET Data Base for SERI Use

3603.4 - Provide Support to SERI, DOE, Industry, and the Private Sector Regarding Insolation Data Bases and Models.

The major technical research effort is concentrated in Subtasks 3603.1 and 3603.2. Subtasks 3603.3 and 3603.4 are directed toward technical support and assistance to other SERI branches, DOE, industry, and the private sector.

THIS PAGE INTENTIONALLY LEFT BLANK

SECTION 2.0

PROGRAM SUBTASKS

2.1 INSOLATION ON TILTED SURFACES AND INTO VARIOUS APERTURES

The technical problems addressed by this Subtask (3603.1) are those of relating global (horizontal) insolation to total insolation on tilted surfaces and relating direct beam, normal incident, fixed aperture insolation to the direct beam into various apertures. These technical problems are created by the fact that historical and planned National Weather Service (NWS) Network insolation measurements are not directly applicable to solar energy applications. The specific problems are:

- The historical data--SOLMET--consist only of data pertaining to insolation on a horizontal surface; whereas, the solar application requires knowledge of insolation on tilted surfaces (flat plate collectors, usually pointed south).

- Little or no historical data exist for direct solar beam insolation as it relates to concentrating collectors (focusing devices).

- The new NWS network, which began operating in 1977, consists of 35 stations in the United States. Each station has a pyranometer for measuring horizontal insolation and a pyrheliometer for measuring direct solar beam insolation. Although this is a tremendous improvement over historical data, the problem of having only the horizontal insolation measurements remains, and the direct solar beam measurements are for a fixed aperture (5.7°). Solar concentrating collectors have varying apertures (concentration ratios).

- The historical and new NWS network insolation data are for the entire broadband (total) insolation required by the thermal conversion solar devices. Very little or no data exist or are planned to be taken for the spectral insolation required by solar photovoltaic conversion devices and spectrally selective surfaces.

To obtain data for the solar thermal energy conversion devices, techniques are needed to:

- translate historical and the new network horizontal (global) insolation data to tilted surfaces (solar thermal flat-plate collectors);

- translate historical horizontal (global) insolation data to direct beam insolation (solar thermal concentrating collectors); and

- translate the new network fixed aperture (5.7°) direct solar beam insolation data to solar beam insolation for various apertures (circumsolar radiation).

In addition, more extensive data and techniques are needed to define the spectral insolation on tilted surfaces and into various apertures for solar photovoltaic conversion devices. However, during FY78 subtask 3603.1 did not include spectral insolation.

The general approach of Subtask 3603.1 is to:

- review and compare existing techniques/algorithms; and,
- develop and operate an insolation research facility to collect data for evaluating and improving existing techniques and algorithms.

The review and comparison of existing techniques/algorithms is a necessary function in establishing the state of the art. This activity is relatively minor in terms of expended labor. It has been and will be complemented by similar efforts by Northrup Services, Inc., subcontracted to the University of Alabama, under DOE Contract No. EG-77-C-02-4494. Results of this effort will help to verify existing techniques/algorithms and to make a preliminary comparison among them.

The major effort of Task 3603.1 is the development and operation of an insolation research facility, the collection of research data, and use of the data to evaluate existing techniques/algorithms for translating horizontal insolation to tilted surfaces and fixed aperture direct beam insolation into apertures of varying sizes. Pending further feasibility and trade-off/cost studies, the specific research measurements of such a facility have been tentatively selected as:

Meteorological Measurements:

- temperature;
- dew point;
- wind speed and direction;
- pressure;
- precipitation;
- cloud cover;
- total ozone;
- NO_X, CO, O_3, SO_X;
- particulates--nephelometer; and
- precipitable H_2O vapor.

Solar Insolation Measurements:

- global-horizontal, broadband (WG 7 filter hemisphere), 0.285 to 2.80 μm;
- global-horizontal, near-infrared (RG 2 filter hemisphere), 0.630 to 2.8 μm;
- global-horizontal, visible (WG 7 - RG 2 filters), 0.285 to 0.630 μm;
- global-horizontal, ultraviolet, 0.295 to 0.385 μm;
- normal incident direct solar beam, fixed aperture (5.72°), broadband (quartz filter), 0.285 (as determined by atmospheric ozone absorption) to 2.75 μm;
- normal incident direct solar beam, fixed aperture (5.72°), near-infrared (RG 2 filter), 0.630 to 2.80 μm;
- normal incident direct solar beam, fixed aperture (5.72°), visible (quartz - RG 2 filters), 0.285 to 0.630 μm;
- normal incident direct solar beam, variable aperture (0.67°, 0.83°, 1°, 1.5°, 2.5°, 3°, 3.5°, 4°, 5° and 5.7°), broadband (quartz filter), 0.285 to 2.75 μm;
- global horizontal diffuse, broadband 0.285 to 2.8 μm, (global horizontal - fixed aperture direct horizontal);
- global horizontal diffuse, near-infrared RG-2 filter, 0.630 to 2.80 μm, (global horizontal - fixed aperture direct on horizontal);
- global horizontal diffuse, visible, 0.285 to 0.630 μm, (global horizontal - fixed aperture direct);
- global horizontal diffuse, broadband, 0.285 to 2.80 μm, (continuous shading disk method);
- total (direct solar beam and diffuse sky, ground reflections eliminated) on tilted surfaces, broadband, 0.285 to 2.80 μm; oriented north, south, east and west, tilted (inclination angle above horizon) at angles from 0° (horizontal) to 90° (vertical), with 10° increments (amounting to a total insolation measurement on 36 surfaces, 9 surfaces for each azimuth orientation of north, south, east, and west);
- total (direct, diffuse sky and ground reflected) spectral--0.280 to 0.630, 0.630 to 2.80 and 0.280 to 2.80 μm--insolation on tilted surfaces: oriented south, at tilt angles of 30°, 60°, and 90° with controlled and measured ground reflectance; and

- high resolution, approximately 0.020 μm, spectral, normal incident, fixed aperture (1°) direct beam, global horizontal, diffuse horizontal and total on tilted surfaces.†

Non-Standard Meteorological Measurements:

- percentage sunshine;
- atmospheric turbidity (photometer method);
- atmospheric total precipitable H_2O vapor (photometer method, and daily radiosondes); and
- visibility (nephelometer method).

The data listed above will be recorded on one-minute, one-hour, one-day, and one-month time scales. Synoptic and mesoscale characterizations of meteorological conditions will be made hourly and logged with the insolation and meteorological data.

The listed data and analyses will allow the various insolation translation algorithms/techniques to be evaluated and improved; it will also allow a determination of the relationships between the meteorological variables and the insolation properties. These empirically determined relationships can also be used to evaluate empirical and theoretical models that predict insolation properties for given meteorological conditions.

The specific approach to Subtask 3603.1 can be be described by considering the mathematical and physical relationships. The insolation on a horizontal surface, H_h, and that on a tilted surface, H_t, are mathematically related by:

$$H_t = I \cos \theta + \frac{D(1 + \cos \beta)}{2} + \frac{\rho H_h (1 - \cos \beta)}{2} \quad (1)$$

where: I = irradiance (solar radiant energy received per unit area per unit time) of the direct normal incident solar beam;

θ = angle of incidence of the direct beam to the tilted surface;

D = diffuse irradiance from the hemispherical sky;

ρ = ground reflectivity;

β = angle of tilt of the surface; and

H_h = insolation on a horizontal surface.

†To be added later in project

The assumption is made in Equation 1 that the diffuse sky irradiance and ground reflectivity are isotropic. The insolation on a horizontal surface can be given as:

$$H_h = I \cos \theta_o + D \quad (2)$$

where: θ_o = solar zenith angle.

A comparison of Equations (1) and (2) shows that the insolation on a tilted surface cannot be inferred directly from the horizontal insolation, because the direct and diffuse components cannot be deduced directly from a measurement of horizontal insolation; moreover, a knowledge of the ground reflectivity is not generally available. Additional problems arise because of the assumption that the diffuse and ground reflectance are isotropic. Certainly, partly cloudy skies (and even clear skies) deviate from isotropic conditions.

The algorithms required in converting horizontal to tilted insolation are shown in flow chart form in Figure 2-1.

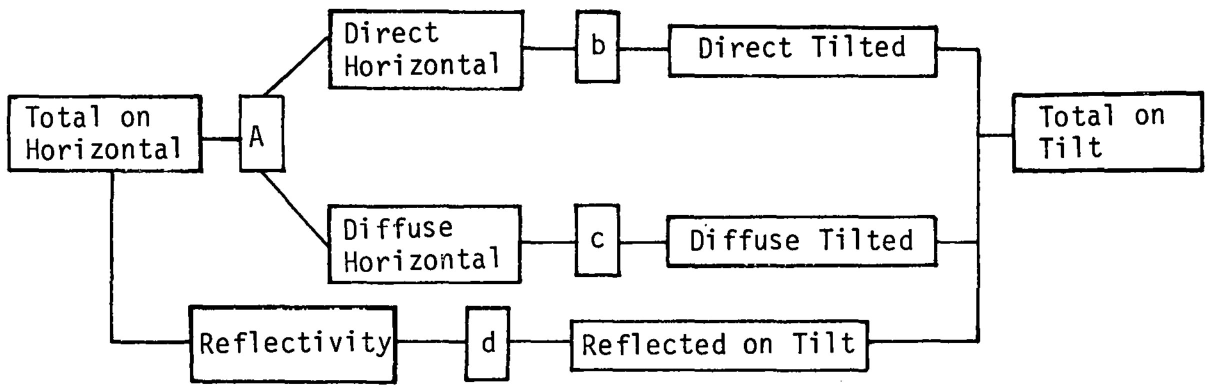


Figure 2-1. CONVERSION OF HORIZONTAL INSOLATION TO INSOLATION ON TILTED SURFACE

Items A, b, c, and d are the algorithms required. The major one, A, is needed to separate the horizontal insolation into the direct (on horizontal) and diffuse components. Algorithms b and c are required to convert the direct and diffuse horizontal insolation to that on a tilted surface. Algorithm d is used to convert the reflected irradiance to the tilted surface. The ground-reflected component, algorithm d, cannot be considered with, and in fact has to be eliminated from, a determination of algorithm c (shielding of tilted surface from the ground reflection). This is required because the diffuse sky and ground-reflected components of the insolation on a tilted surface [Equation (1)] cannot be separated by measuring the direct insolation on the surface and the total insolation. The surface must be shaded from the diffuse skylight or from the ground. Obviously, the former would also eliminate the direct beam and, therefore, require another (unshaded) sensor to measure the total insolation on the surface. Separate measurements of the reflected component and algorithm d will be described later in this report. The measurements will be used to deduce the ground-reflected component by subtracting the total measured on the tilted surface when it is shielded from the ground and from that when it is not shielded from the ground.

The list of insolation measurements given previously will be used to evaluate existing algorithms and to develop improved algorithms for A, b, c, and d. The specific measurements pertinent to each algorithm are:

- Algorithm A: conversion of horizontal insolation to direct beam insolation
  Measurements: global horizontal insolation and normal incident direct beam insolation

- Algorithm b: conversion of direct horizontal insolation to direct on tilted surface
  Measurements: normal incident direct beam insolation and global horizontal insolation

- Algorithm c: conversion of diffuse horizontal insolation to diffuse sky insolation on tilted surface
  Measurements: global horizontal insolation, normal incident direct beam insolation, and total insolation on tilted surfaces

- Algorithm d: conversion of total horizontal insolation to ground reflected insolation onto tilted surface
  Measurements: global horizontal insolation, total horizontal on tilted surface, shielded from ground, and not shielded from ground

The insolation measurements and analyses will consider three spectral regions: Broadband, 0.285 to 2.80 μm; visible, 0.285 to 0.630 μm; and the near-infrared, 0.630 to 2.80 μm. The broadband region represents the total thermal energy capable of being absorbed by solar thermal conversion devices. The visible and near-infrared regions are considered in order to separate the atmospheric effects on the algorithms of scattering (molecular and aerosol) in the visible wavelengths and attenuation due to water vapor in the near-infrared wavelengths. The meteorological measurements are intended to define the atmospheric conditions, their effects on the algorithms, and their relationship to mesoscale and synoptic weather. The atmospheric state parameters considered will be temperature, water vapor (surface and total precipitable), pressure, cloud cover, and aerosols (surface and total along solar beam path).

The conversion of fixed aperture beam, normal incident insolation to various apertures will be addressed by taking simultaneous measurements of the normal incident direct beam into apertures of the following sizes: 0.67°, 0.83°, 1°, 1.5°, 2.5°, 3°, 3.5°, 4°, 5° and 5.7°. The 5.7° aperture is commonly used by the instruments in the NWS network. The smallest aperture represents a reasonable lower limit that does not require very sophisticated or expensive tracking of the solar disk (0.53°). The magnitude of the direct solar beam will be plotted as a function of aperture size (0.67° to 5.7°). This represents the conversion algorithm from 5.7° to 0.67°. It represents physically the amount and angular distribution of the forward scattered beam insolation, known as circumsolar radiation. The algorithm function (direct beam insolation versus field of view) will be compared to atmospheric parameters that indicate the scattering and attenuation of insolation. These include:

- total precipitable H_2O vapor;
- turbidity--photometer;
- attenuation coefficients for the broadband, visible, and near infrared beam insolation;
- aerosols--nephelometer;
- amount of diffuse skylight--ratios of diffuse to total and diffuse to direct beam insolation in the broadband, visible, and near-infrared regions, also known as the cloudiness index K_t (Liu and Jordan); and
- cloud cover.

The major consideration in such comparisons will be to determine whether the common NWS meteorological and network insolation measurements can be used to define the variable aperture algorithm. Were this the case, the algorithm could be utilized to convert the fixed aperture NWS measurements to variable aperture insolation measurements.

The meteorological and insolation research will be performed at the SERI site near Golden, Colo., which is characterized by semiarid, high altitude, and clear atmospheric conditions. To expand the research measurements and analyses to other atmospheric conditions, the DOE Solar Energy Research and Training Sites will be used. These are eight sites in different regions of the United States where meteorological or insolation research is being conducted by selected universities: the University of California (Dr. K. L. Coulson), Davis, California; State University of New York (Dr. R. Stewart), Albany, New York; Georgia Institute of Technology (Dr. C. G. Justus), Atlanta, Georgia; Trinity University (Sr. E. Clark), San Antonio, Texas; Oregon State University (Dr. W. Hewson), Corvallis, Oregon; University of Michigan (Dr. D. Portman), Ann Arbor, Michigan; University of Alaska (Dr. G. Wendler,), Fairbanks, Alaska; and University of Hawaii (Dr. C. Ramage), Honolulu, Hawaii. These universities are establishing measurement sites and instrumentation similar to those described here so that their results can be utilized jointly in the conversion algorithm analyses.

2.2 INSOLATION MODELS FOR SOLAR ENERGY APPLICATIONS

Analytical models for determining performance and cost effectiveness of solar energy conversion systems usually require a subroutine for generating the amount of insolation at the collector for various weather conditions and geographical locations. Examples of such models are the SOLCOST and F-Chart routines. Such models can use actual or model-generated insolation parameters. The historical data--SOLMET--are for 26 locations throughout the

United States, while the NWS network covers 35 locations. However, this geographical coverage is not sufficient for all the widespread and dispersed applications of solar energy. The SOLCOST routine alone considers 124 U.S. cities. Therefore, insolation prediction techniques are required for sites where no data exist. There is also a need for such techniques for performance models that do not use actual data because of the labor and expense involved in reducing large amounts of data and in handling data tapes. Prediction models and techniques are especially needed for solar photovoltaics because very little data exist for the spectral insolation and its properties.

The wide variety of solar collection and conversion techniques, requires many insolation components. For example, flat plate thermal collector systems require a knowledge of the broadband insolation on a tilted surface whereas a concentrating solar photovoltaic system would require knowledge of the spectral, variable field-of-view (circumsolar), and direct solar beam insolation. Even more requirements are created by the various time scales and resolutions addressed by the solar collector design and performance models. Time scales range from almost instantaneous (minute) to monthly and yearly averages.

Subtask (3603.2/Insolation Models For Solar Energy Applications) considers the problem of providing suitable insolation prediction models to the wide variety of solar applications. The FY78 effort is limited to those relatively immediate requirements of the internal SERI research efforts. However, many of the requirements of DOE, industry, and the private sector are very similar to those of SERI and would consequently benefit from such models.

The approach used combines evaluation of existing models versus the specific solar application, implementation of the model, and (if required) improvement of the model. The evaluation process is preceded and continually updated by a thorough search and review of models listed in the literature. The typical criteria used for evaluation are:

- accuracy, validation;
- complexity, cost, ease of use;
- required meteorological inputs;
- availability of inputs;
- assumptions, methods used;
- time scale, resolution;
- spatial scale, geographical applicability;
- spectral range, resolution; and
- insolation outputs.

It must be realized that a solar energy system design or performance prediction can be only as accurate as the insolation assumed to be incident at the collector. Inaccuracies in the incident insolation will cause inaccuracies in design, performance prediction, and cost analyses. Therefore, accuracy is important in any insolation prediction model and it should be established by comparing directly the predicted insolation with measured values. If this has not been done adequately by the investigator(s) who developed a model, it will be established by utilizing available data from the NWS network, the SERI insolation research facility, and the Solar Energy Research and Training Sites. Another important criterion is the required meteorological inputs versus those that are available. If the required meteorological inputs are not easily and widely (goegraphically) available, then the model cannot be used easily nor would it be widely applicable. The complexity, cost, and ease of use criterion relates to the potential use of the model as a component subroutine in a system performance model and the accuracy of the model versus its complexity and cost. The goal, obviously, is to obtain the maximum (or acceptable) accuracy at minimum cost (labor and computer time).

Subtask 3603.2 is complemented by and utilizes somewhat related activities contracted by the DOE. These efforts are:

- "Estimation of Insolation at Selected Locations", National Oceanic and Atmospheric Administration (NOAA), Air Resources Laboratories, DOE Contract No. E(49-26)-1041 T015;

- Forecasting and Interpolation Analysis", Northrup Services, Inc., DOE Contract No. EG-77-C-02-4494;

- "A Study of the Distribution and Characteristics of Solar Radiation in the U.S. - A Program to Develop Material for a Solar Radiation Users Manual", Watt Engineering Ltd., DOE Contract No. E(49-18) - 2552; and

- "Effects of Aerosols and Clouds on Solar Radiation", NOAA, Wave Propagation Laboratory, DOE Contract No. E(49-26) - 1041 T012.

The insolation models determined to be acceptable for specific solar application are implemented on the SERI computer system (CDC-6000 series) for direct use by SERI investigators. They are also placed into the SERI Solar Energy Information Data Bank (SEIDB), for use by industry and the private sector.

2.3 ESTABLISH SOLMET DATA BASE

Subtask 3603.3 addresses the problem of providing SERI and other users with standardized insolation data bases for use in solar energy studies and development. Currently known as SOLMET, the standard data base merges all available (NWS) insolation and meteorological data into a single source. It contains hourly insolation data (for a horizontal surface) for 26 historical sites (rehabilitated from NWS measurements) and will be available for the new NWS network data (normal incident and horizontal insolation). SOLMET was intended to provide solar energy users with easy access to historical meteorological data and to data from the new NWS network and cooperators. The complete SOLMET data base (computer tapes) is available from the National Climatic Center (NCC).

The approach to Subtask 3603.3 is to obtain all available SOLMET data magnetic tapes from NCC and to implement them on the CDC computer system at SERI. The SOLMET data base would then also be available to solar energy data users directly though the SERI SEIDB. The effort represented by this subtask involves only obtaining and implementing the SOLMET tapes.

2.4 MONITOR SOLAR ENERGY RESEARCH METEOROLOGICAL SITES

The purpose of this Subtask 3603.4 is to provide management support to the DOE for administering the eight university meteorological and solar energy research sites described previously. This includes technical review of proposals, reports, and papers generated by the projects and recommendations concerning program progress, content, and direction. This effort is relatively minor, consisting of attending DOE reviews and responding to DOE requests for written reviews of the university program, proposals, papers, etc.

2.5 PROVIDE INFORMATION TO DOE, SERI, INDUSTRY, AND THE PRIVATE SECTOR REGARDING INSOLATION MODELS AND DATA BASES

The problem addressed by this Subtask 3603.5 is that of ensuring that standardized, proven models and data bases for insolation are used by solar system designers, evaluators, installers, etc. The typical problem encountered by potential users and evaluators of solar energy systems is that the various systems performance or design was based on different insolation models or data bases. Therefore, direct comparisons of system performance are not possible.

SERI ERAB will inform other SERI investigators, DOE, industry, and the private sector about the availability and use of standardized data bases and acceptable models for insolation properties. This is a relatively minor effort, consisting of answering inquiries and making presentations at meetings held by solar energy data users.

SECTION 3.0

SUMMARY OF PROGRESS

The major SERI ERAB FY78 effort on Task 3603 consisted of:

- obtaining measurements of insolation on tilted surfaces;
- review, comparison, and preliminary evaluation of algorithms for converting horizontal insolation to tilted surfaces;
- designing and developing an Insolation Research Facility (IRF) for making continuous research measurements of insolation on tilted surfaces, conventional insolation measurements, direct beam insolation into various apertures, and meteorological and atmospheric state definition measurements;
- providing broadband and spectral insolation models to other SERI investigators and branches;
- assisting DOE with startup of the university Solar Energy Research and Training Sites;
- obtaining and implementing the SOLMET data base and the Standard Meteorological Year tapes; and,
- assisting the private sector with insolation models and data bases.

The following sections summarize the FY78 progress. The same areas of effort will continue in FY79.

3.1 INSOLATION ON TILTED SURFACES AND INTO VARIOUS APERTURES

The FY78 efforts on Subtask 3603.1, relating global and direct insolation to insolation on tilted surfaces and into various apertures, consisted of:

- obtaining measurements of insolation on tilted surfaces;
- design and development of an Insolation Research Facility (IRF) to collect continuous insolation research data; and
- development of computerized techniques to review, compare, and evaluate horizontal to tilt insolation conversion algorithm using the IRF data.

Insolation on tilted surfaces were made from June to August 1978 on top of South Table Mountain near Golden, Colo. This site is the location of the future permanent facilities of SERI and is approximately 15 miles west of Denver. The site latitude is 39° 45' N, its longitude is 105° 10' W, and its altitude (above mean sea level) is 6000 ft. The climate is mild, sunny, and semiarid, typical of that over much of the Central Rocky Mountain region.

The tilted surfaces considered were at tilt angles relative to the horizon of 15°, 30°, 45°, 60°, 75°, and 90° (vertical). The azimuthal orientations of the surfaces considered were 0° (true north), 90° (east), 180° (south), and 270° (west). The instrumentation used included a Spectrolab-Spectrosun Model SR-75 thermopile pyranometer (see Figure 3-1); a Lambda Model LI-200S pyranometer; and a Model LI-190SE flat response (visible) sensor/pyranometer (see Figure 3-2). The purpose in using these three types of pyranometers is pertinent to the design and development of the Insolation Research Facility, to be discussed later. Data were collected for five selected days for approximately 4 hours each day, for approximately 20-minute intervals, for all tilt angles and for all azimuth directions. This resulted in approximately 1,000-1,200 data points. The horizontal insolation was measured during the same periods. The sky conditions ranged from completely clear to almost totally cloudy, with the greater portion of the data representing clear to slightly cloudy conditions.

The three types of pyranometers were mounted on a platform/tripod structure that allowed them to be tilted at the experimental angles--as measured by an inclinometer--and oriented toward the azimuths. (See Figures 3-3 and 3-4). With this arrangement the pyranometers were scanned through the different tilt angles for each azimuth orientation. The total time required to complete a set of measurements (all tilts and azimuths) was 12 minutes. The horizontal insolation was measured before and after each tilt scan, requiring about 3 minutes. This was done to monitor the uniformity of the incident insolation over the time periods.

The millivolt outputs of each pyranometer were measured with a precision digital voltmeter and converted to absolute irradiance units by multiplying by the reciprocal of their respective calibration constants:

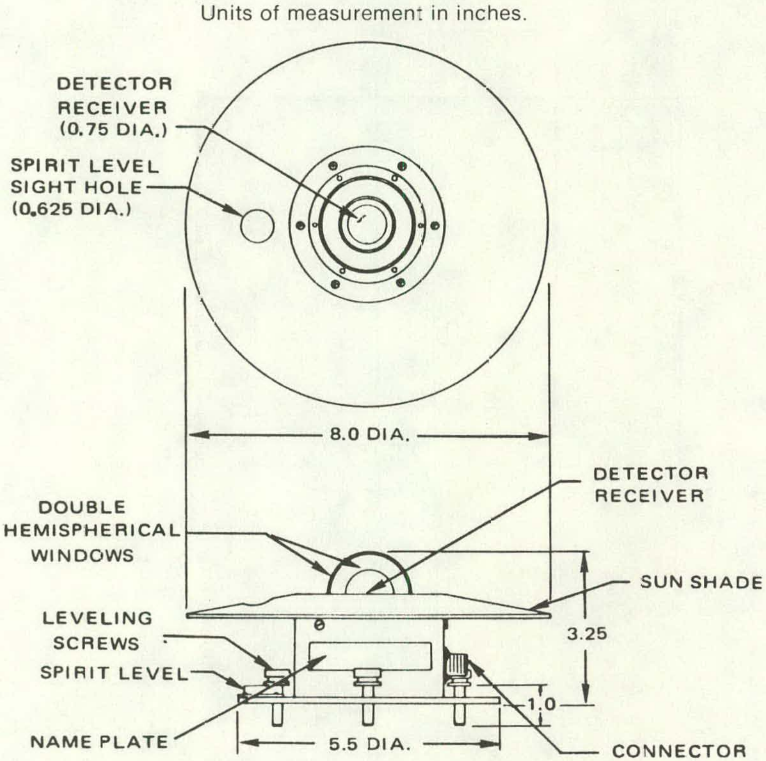
SR-75 No. 73-23, 9.47 μ V/Wm^{-2},

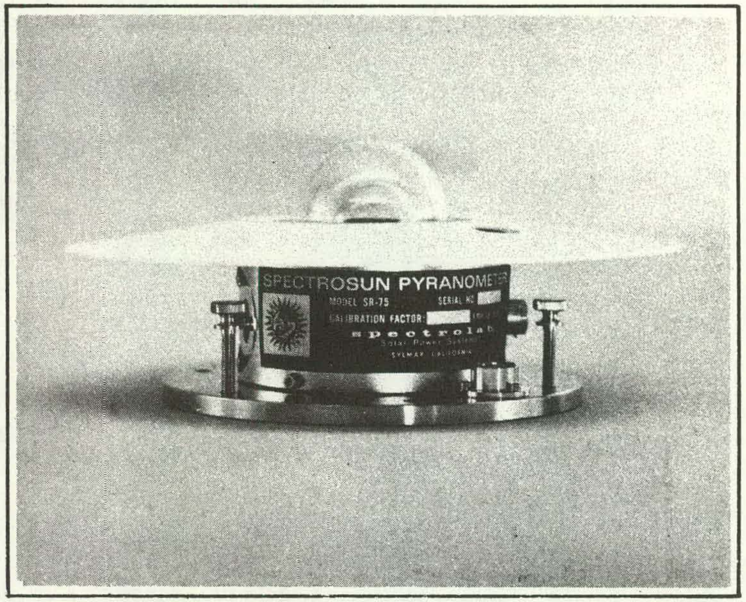
LI-200S No. PY 1245-7806, 8.54 μ V/Wm^{-2}, and

LI-190SE No. SE 102-7806, 20.64 μ V/Wm^{-2}.

The SR-75 and the LI-200S both measure the absolute insolation in the 0.30 to 3.0 μm thermal region and their measurements are comparable. The calibration constant for the SR-75 was supplied by the NOAA Calibration Facility (Boulder, Colo.), and the constants for the Lambda instruments were supplied by the factory. The absolute quantities of the LI-190SE are for only the visible (0.4 to 0.7 μm) portion of the spectrum and are therefore not directly comparable to the SR-75 and LI-200S measurements.

An example of the absolute insolation on tilted surfaces for the azimuth orientations for a specific day and time (solar elevation and azimuth), and for typical clear sky conditions, is shown in Figure 3-5 (a, b, c, and d). The specific sky conditions were characterized by less than one tenth cloud cover of fair weather cumulus clouds located over the mountains to the west and not exceeding an elevation angle of 10° above the horizon. As can be seen in Figure 3-5, the absolute amount of insolation is highly dependent upon

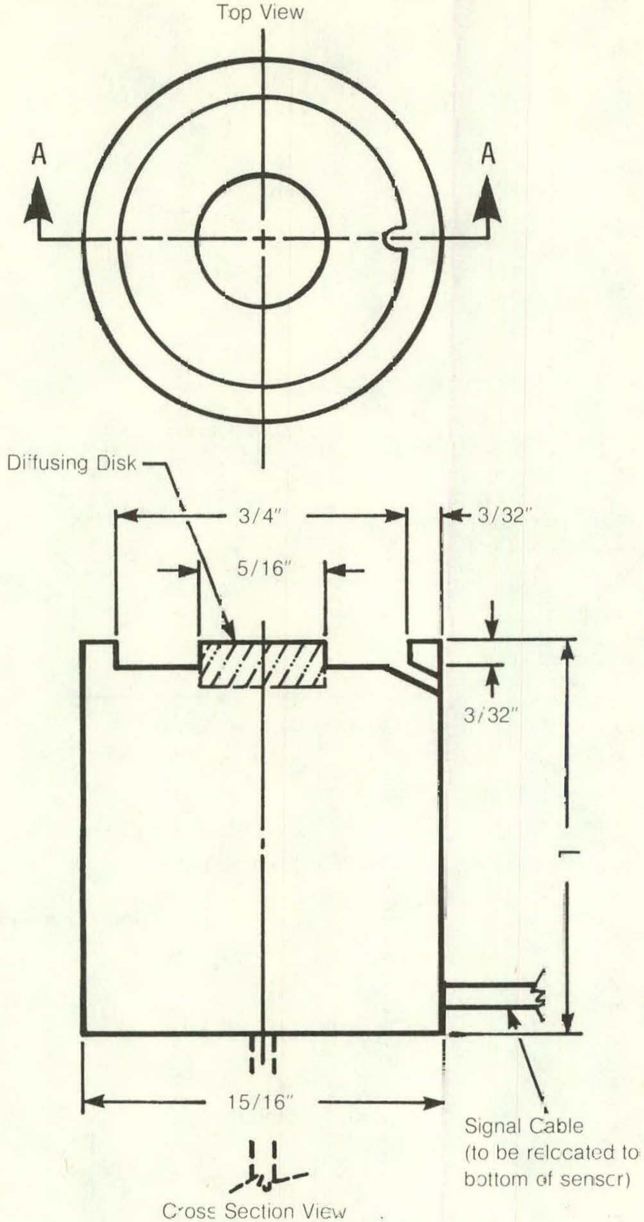




SPECIFICATIONS

Calibration	Intercompared with standard instruments at the NOAA Calibration Facility, Boulder, CO
Sensitivity	5 mV/Langley/min (nominal)
Linearity	Useful range 0 to 4 Langleys/min
Stability	Not specified
Response Time	1.6 sec for 63% point
Temperature Dependence	±1% from -20° to +40°C; ±2% from -20°C to -40°C
Cosine Correction	±3% from 0° to 70° and ±7% from 70° to 80°
Azimuth Error	3% from 0° to 360°

Figure 3-1. DESCRIPTION AND SPECIFICATIONS SPECTROSUN MODEL SR-75 PYRANOMETER.



SPECIFICATIONS

Calibration	Calibrated against an Eppley Pyranometer under natural daylight, clear conditions; absolute accuracy under these conditions is ± 5%; all sensors calibrated to within 1%
Sensitivity	Typically 50μ A/1000 Wm^{-2} or 5 mV/1000 Wm^{-2} when used with a 2200S Millivolt Adapter
Linearity	Maximum deviation of 1% up to 3000 Wm^{-2}
Stability	Less than 2% change in 1 year
Response Time (10-90%)	10 μ sec
Temperature Dependence	±15%/°C Maximum
Cosine Correction	Cos corrected up to 82° angle of incidence; a maximum error of +1% from 0° to 60° and -3% from 60° to 80°
Azimuth Error	Less than 1% over 360° at 45° elevation
LI-190SE Pyranometer Sensor	Similar to LI-200S except wavelength response is limited to 0.4 to 0.7μm, uniform response

Figure 3-2. DESCRIPTION AND SPECIFICATIONS OF THE LAMBDA MODELS LI-200S AND LI-190SE PYRANOMETER

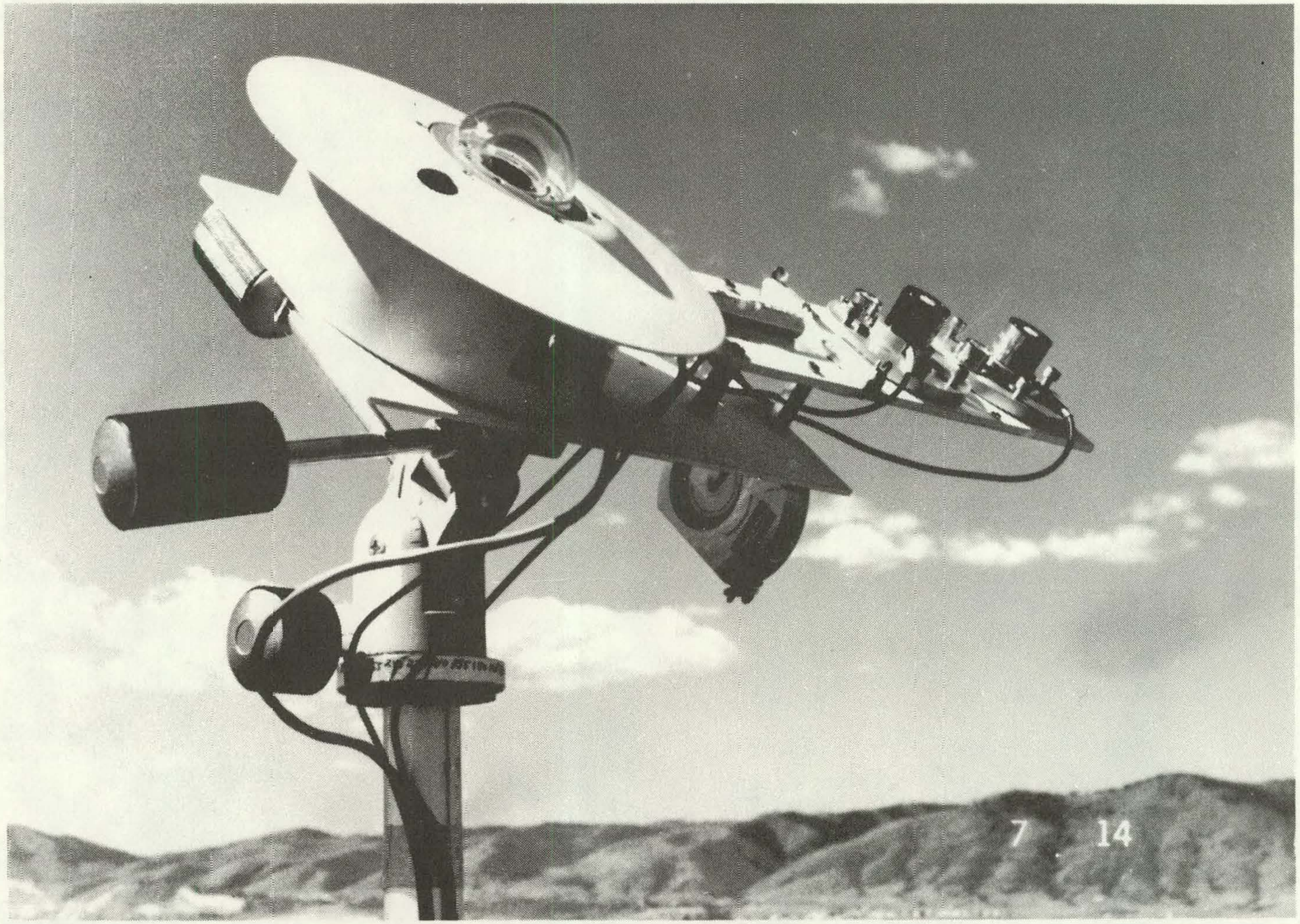


Figure 3-3. PHOTO OF PYRANOMETER AND TILT/AZIMUTH ARRANGEMENT

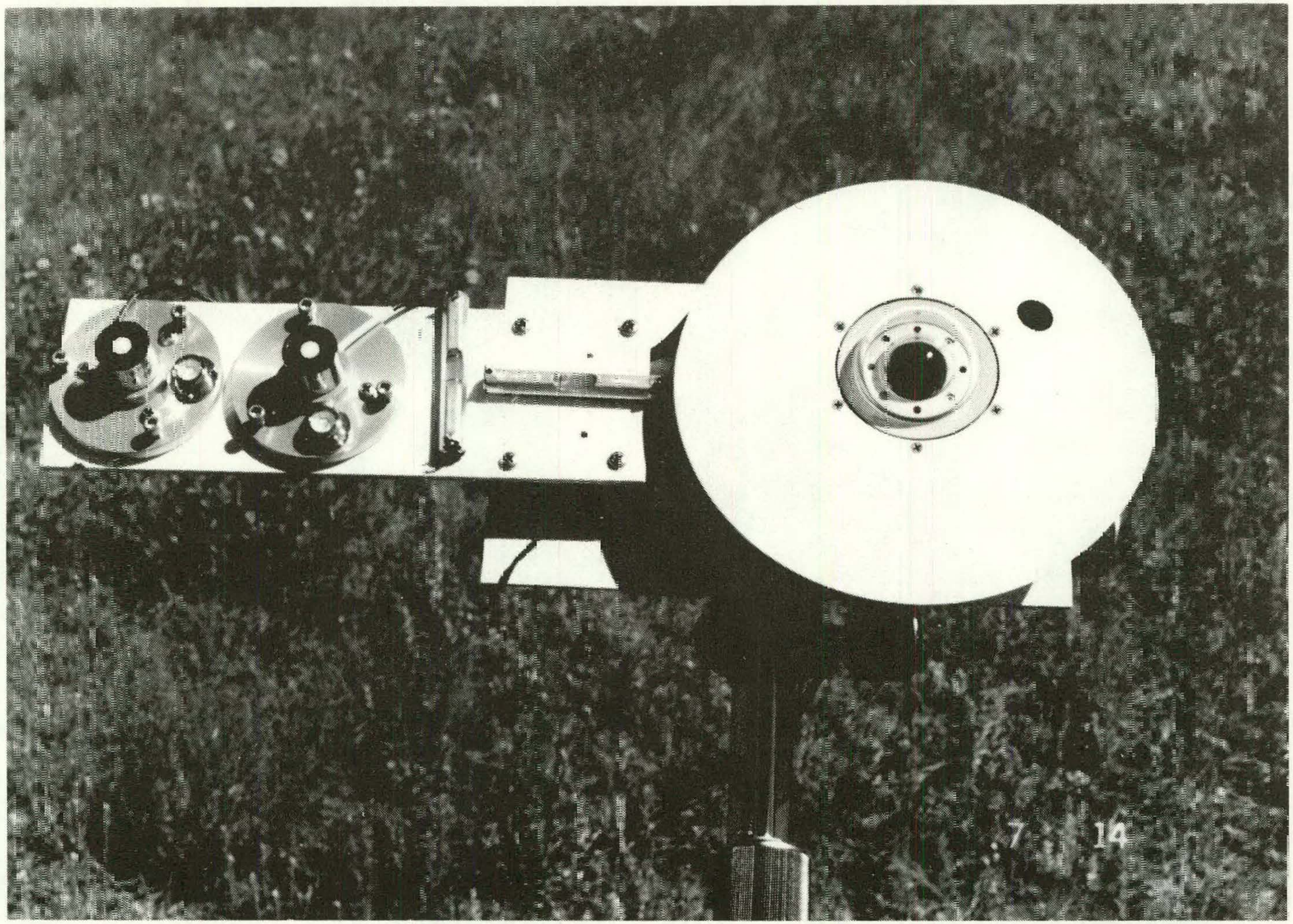


Figure 3-4. CLOSE-UP OF PYRANOMETER MOUNTED ON TILT/AZIMUTH PLATFORM

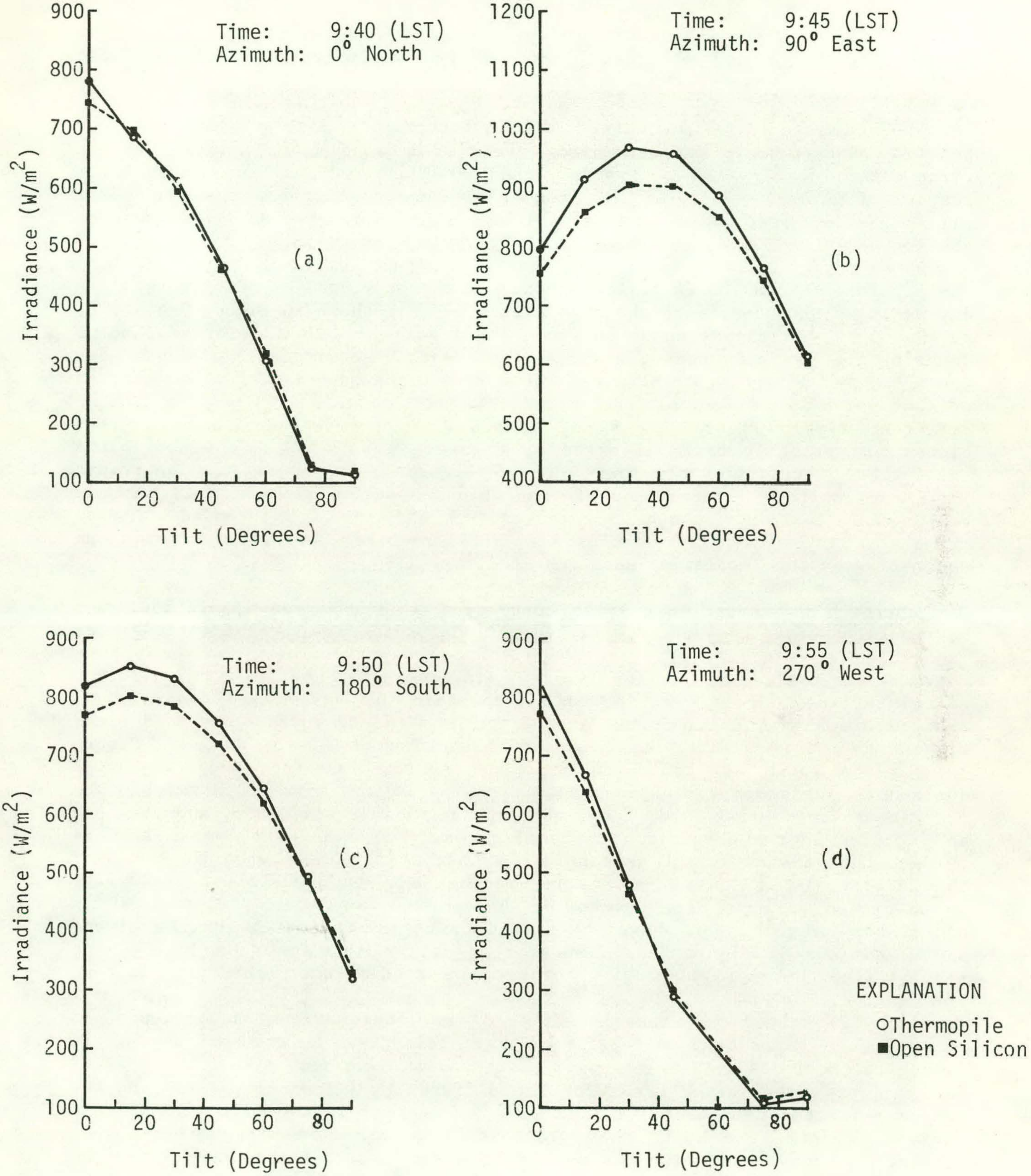


Figure 3-5. ABSOLUTE INSOLATION ON VARIOUS TILTED SURFACES AND ORIENTATIONS, CLEAR SKY CONDITIONS, JULY 13, 1978

surface tilt angle and azimuth orientation. It should be noted that the pyranometers were not shielded from the ground, which had an estimated reflectivity of about 20-25%.

The measurements shown in Figure 3-5 also indicate fairly good agreement between the thermopile broadband pyranometer and the silicon sensor pyranometer, which has a typical open (nonfiltered) silicon wavelength response from 0.4 to 1.0 μm. Any lack of agreement varies depending on sensor tilt angle and orientation. This will be discussed in more detail in a later section.

The absolute insolation on tilted surfaces for cloudy conditions, for the same day as the clear conditions shown in Figure 3-5, is shown in Figure 3-6 (a, b, c, and d). The cloudy conditions consisted of four tenths towering cumulus covering the sky area near the sun and one tenth high cirrus cloud cover near the sun. The direct solar beam was intermittently shaded by the clouds, as is evident in examination of the horizontal (0° tilt angle) insolation at different times (Figure 3-7 a, b, c, and d). The attenuating effects of clouds are probably best exhibited by Figure 3-6 d in which the horizontal insolation is significantly lower than in Figures 3-6a, b, and c. The result is a more uniform distribution of insolation versus tilt angle. It must be noted that the data shown in Figures 3-5 and 3-6 are intended only as examples; any definite conclusions will require long-term, continuous monitoring by the Insolation Research Facility (IRF).

One approach to investigating the conversion algorithm for insolation on a horizontal surface to that on a tilted surface is to evaluate the ratio of the insolation at a given tilt (angle) to that on a horizontal. Obviously this ratio represents the conversion algorithm for the horizontal insolation to the tilted surfaces. If this ratio and the absolute insolation on the horizontal surface are known, the absolute insolation on a tilted surface can be derived without having to predict directly the absolute quantities. Shown in Figure 3-7 is the ratio of insolation on tilted surfaces to the insolation on a horizontal surface for the same conditions as Figure 3-5. Because absolute quantities are not involved, the flat response visible silicon pyranometer can be included in the comparison. When Figures 3-5 and 3-7 are compared it is evident that the different sensors are in better agreement when the ratio of the insolations is considered instead of the absolute quantities. This will be discussed in more detail when the design and development of the IRF is addressed. Figure 3-8 shows the tilted to horizontal ratio for the cloudy sky conditions of Figure 3-6. The scatter of the data shown for Figure 3-6d results from the rapidly changing insolation caused by the clouds.

Equation (1) showed that the insolation on a tilted surface should depend on the cos θ (θ = incident angle of the direct solar beam to the surface). This is due to the I cos θ (I = intensity of the normal incident direct solar beam) term and the view factor terms for the diffuse sky $[(1 + \cos\beta)/2]$ and the ground reflected component $[(1 - \cos\beta)/2]$ where β is the tilt angle of the surface. Figure 3-9 shows the relationship between the tilt to horizontal insolation ratio versus the cosine of the direct beam incident angle for the clear sky conditions described previously. The ratio (conversion algorithm) is markedly linear with respect to the cosine of the incident angle; however, the slopes and magnitudes versus cos θ are dependent upon the azimuth orientation,

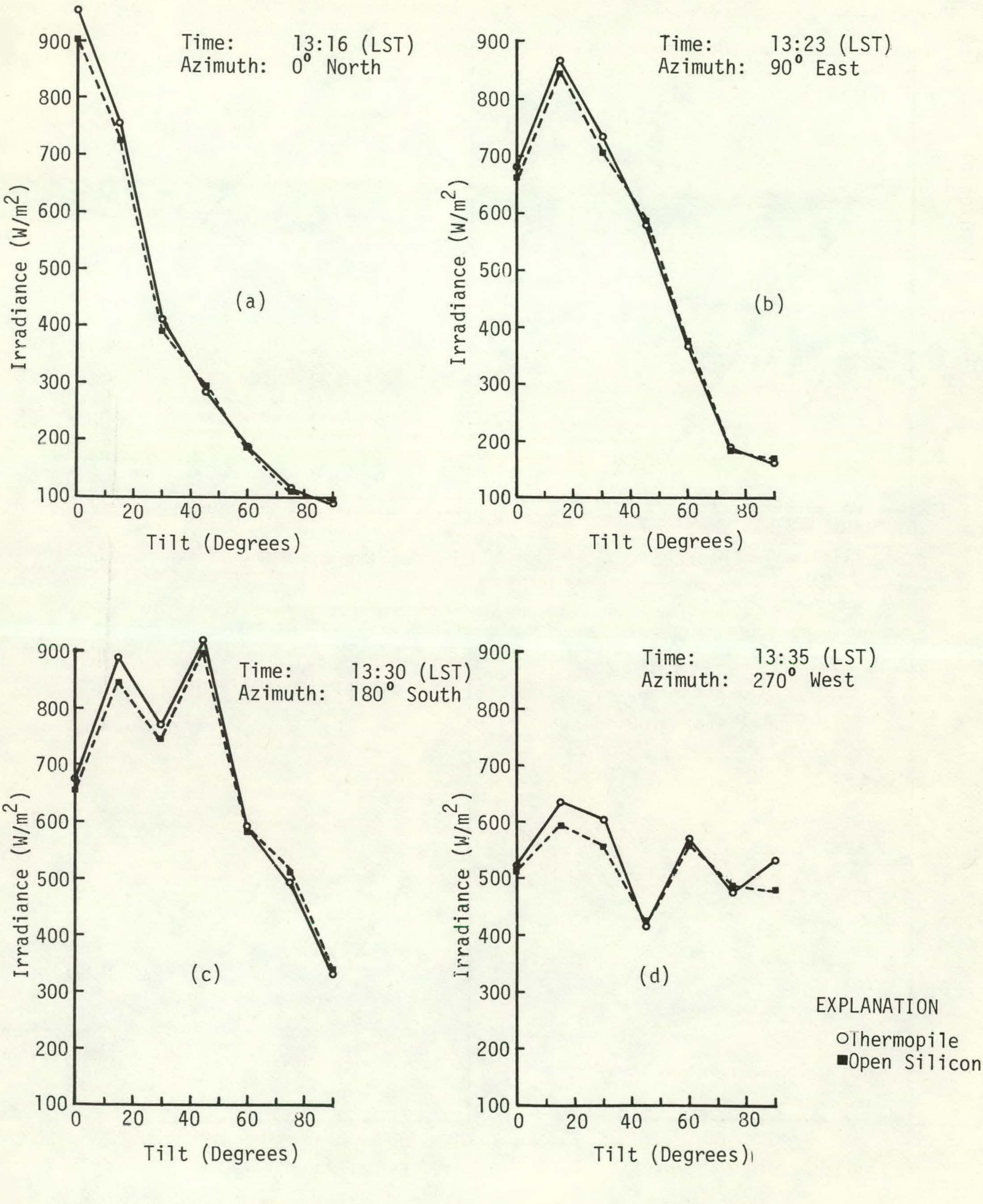


Figure 3-6. ABSOLUTE INSOLATION ON VARIOUS TILTED SURFACES AND ORIENTATIONS, FOR CLOUDY SKY CONDITIONS, JULY 13, 1978.

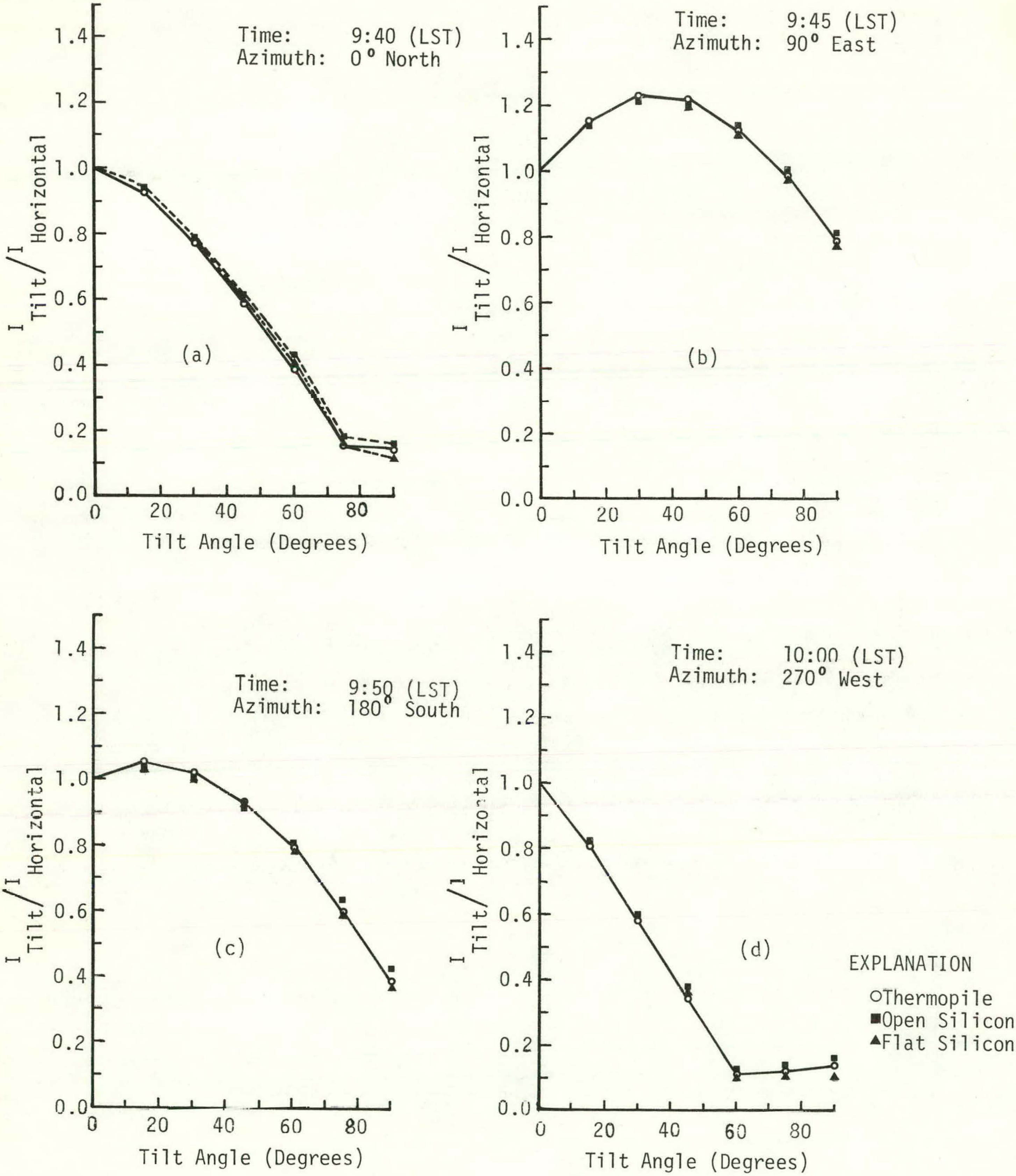


Figure 3-7. RATIO (CONVERSION ALGORITHM) OF INSOLATION ON A TILTED SURFACE TO HORIZONTAL SURFACE, FOR CLEAR SKY CONDITIONS, JULY 13, 1978.

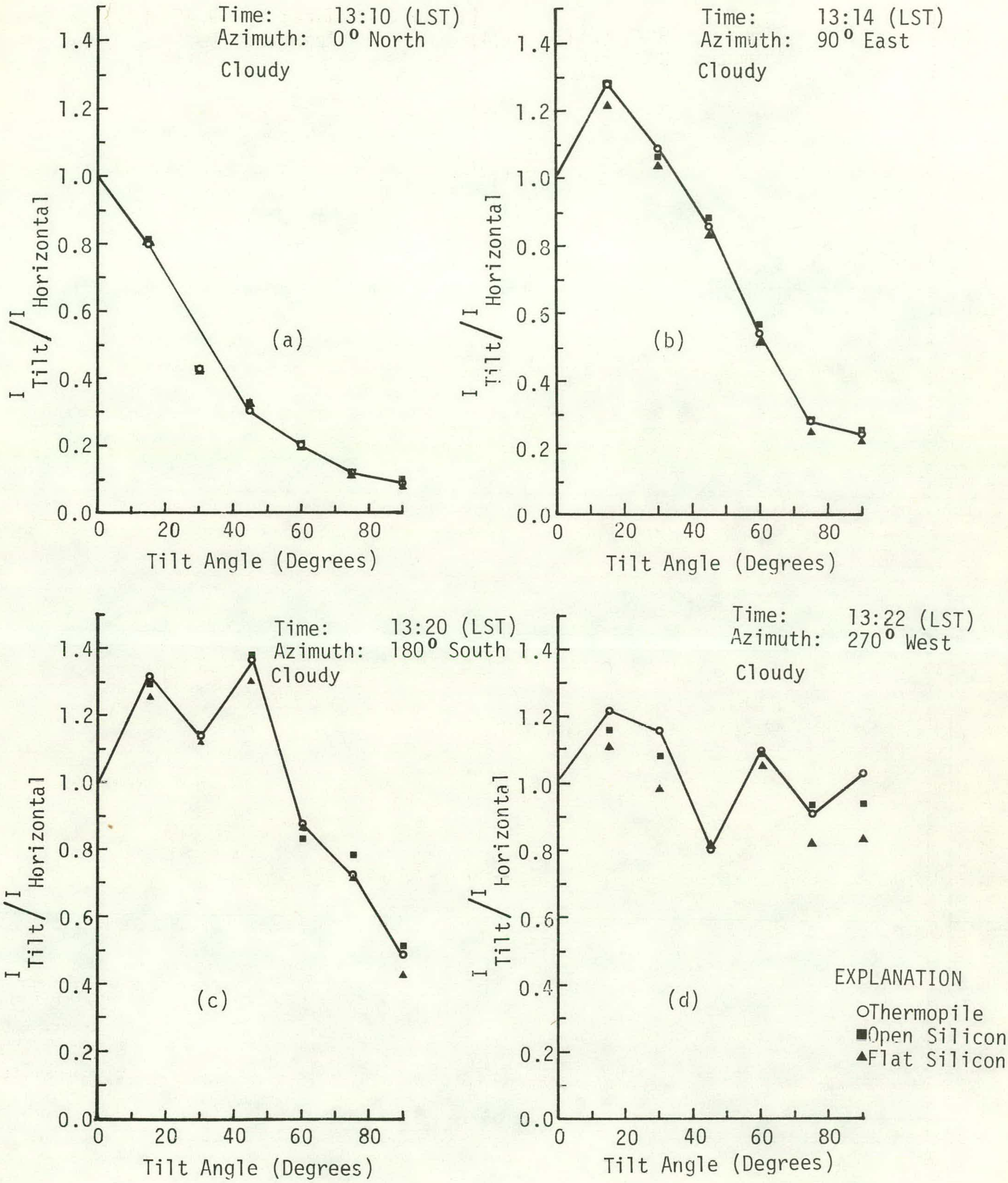


Figure 3-8. RATIO (CONVERSION ALGORITHM) OF INSOLATION ON A TILTED SURFACE TO HORIZONTAL SURFACE, FOR CLOUDY SKY CONDITIONS, JULY 13, 1978

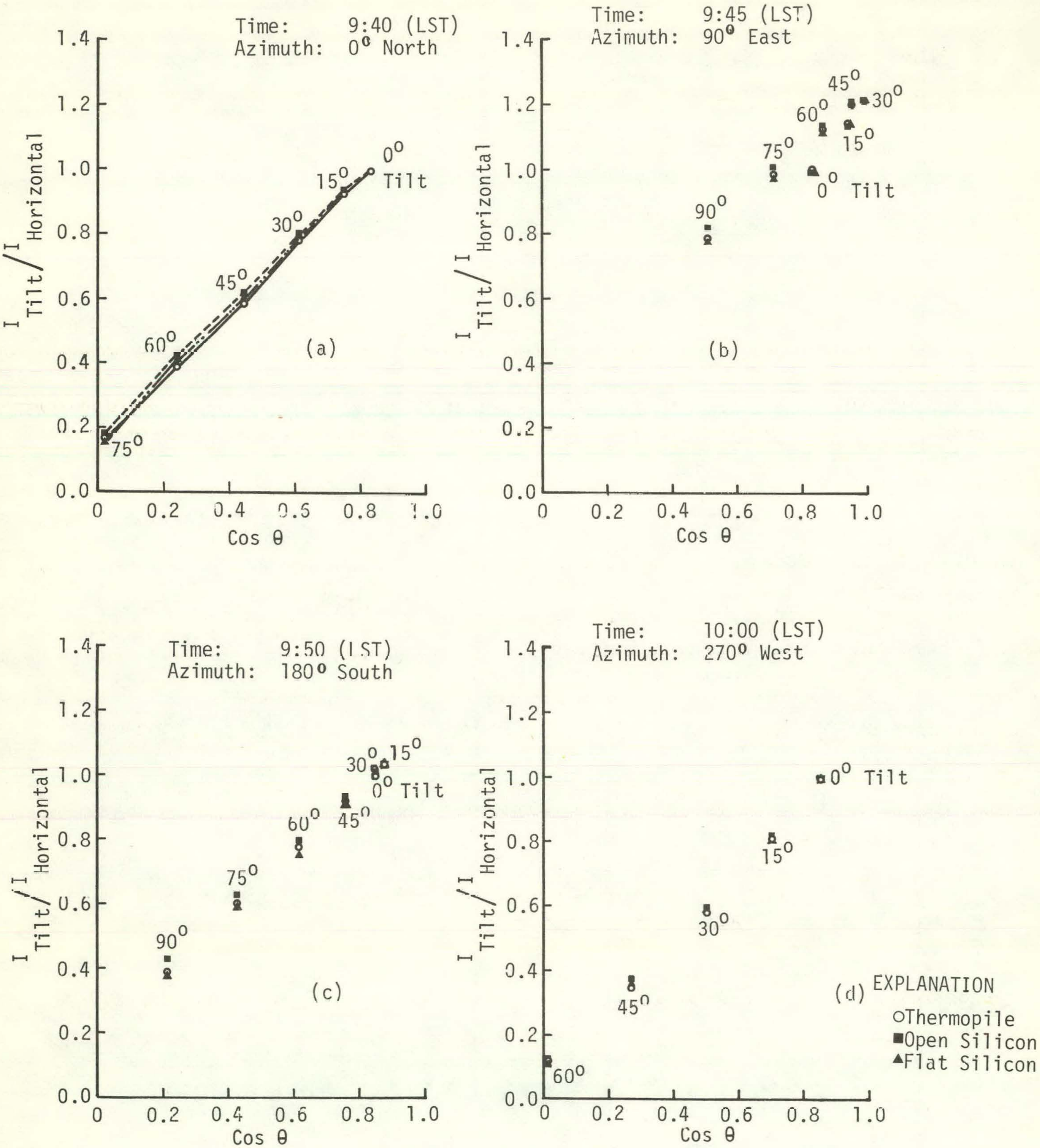


Figure 3-9. DEPENDENCE OF INSOLATION ON TILTED SURFACE TO INSOLATION ON HORIZONTAL SURFACE, ON THE DIRECT SOLAR BEAM INCIDENCE ANGLE, FOR CLEAR SKY CONDITIONS, JULY 13, 1978

as shown in Figure 3-10. The greatest difference is that between the east and west azimuth orientations. This azimuth dependence is partly caused by the fact that for a given cos θ, the tilt angle of the various surfaces (at the various azimuths) are not the same (see Figure 3-9). Therefore, the magnitude and nature of the diffuse insolation--from sky and ground--would be different because of the different sky and ground view factors (see equation 1) of each tilted surface. The difference in the sky and ground insolation components is also due to the nonisotropic properties of the sky-light and ground reflectance. For the particular solar-tilted surface geometry (solar zenith and azimuth angles--position of the sun with respect to the tilted surfaces) represented in Figure 3-10, these differences are significant. Considering a cos θ = 0.800, which implies that the direct solar beam component is equal on all tilted surfaces, the east-oriented surface receives 32% greater sky and ground insolation than the west-oriented surface. This example is, of course, specific to the limited data represented; however, it indicates the importance of the sky and ground components of insolation on tilted surfaces, even for clear conditions. The IRF will investigate such relationships and the conversion algorithm on a general and long-term basis.

The major program effort for Task 3603 was spent in the design and development of the Insolation Research Facility (IRF). Because of its intended use and impact, the IRF has to be as well-designed as possible and yield high quality data. The data and analyses produced must meet the requirements of and directly benefit a wide range of solar applications and analyses.

The solar technologies and applications are:

- solar flat-plate thermal conversion;
- solar concentrator thermal conversion;
- solar flat-plate photovoltaic conversion;
- solar concentrator photovoltaic conversion; and
- solar passive heating and cooling.

The different solar applications and technologies create a wide range of requirements for research data and analyses which will be met by the IRF. In order to design and develop the IRF such requirements had to be specified or at least estimated:

- absolute broadband-thermal (0.3 to 3.0 μm) and spectral (photovoltaic region, typically 0.4 to 1.1 μm) insolation on tilted surfaces oriented at various azimuths;
- absolute broadband-thermal (0.3 to 3.0 μm) and spectral (photovoltaic region, typically 0.4 to 1.1 μm) normal incident direct solar insolation into apertures of different size;
- atmospheric state definition and meteorological conditions that would likely affect the solar broadband or spectral insolation; and

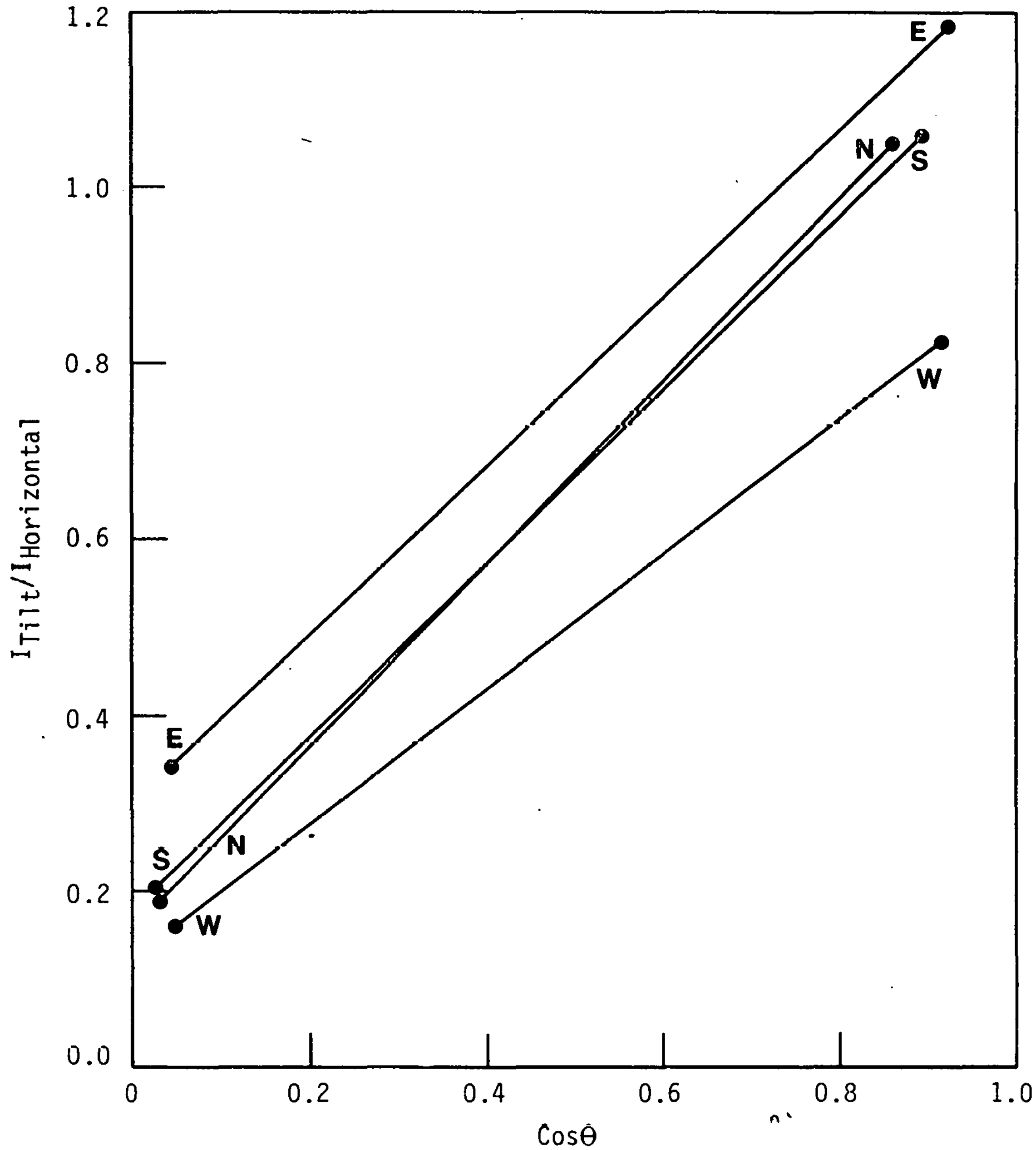


Figure 3-10. COMPARISON OF INSOLATION ON TILTED SURFACE TO HORIZONTAL SURFACE VS. DIRECT BEAM INCIDENT ANGLE, FOR VARIOUS AZIMUTH ORIENTATIONS

- conventional, NWS insolation and meteorological measurements in order to translate such widespread determinations to the specific solar applications and technologies.

The first set of requirements relates directly to insolation characteristics pertinent to flat plate, tilted, oriented solar thermal and photovoltaic conversion systems. The second set of requirements relates directly to insolation characteristics pertinent to concentrating aperture, solar thermal, and photovoltaic conversion devices. The third set of requirements is directed at quantifying the effects of the atmospheric state and meteorological variables on the insolation characteristics to predict those characteristics wherever insolation measurements are not available. The fourth set of requirements is directed at determining and quantifying the relationships between the conventional NWS network insolation and meteorological measurements and the insolation characteristics specific to solar energy.

The time and sampling intervals of the insolation and meteorological measurements depend on the temporal variability of the atmospheric parameters and upon the requirements of solar energy conversion systems. The sampling intervals for the IRF were established through discussion with DOE and the University Solar Energy Research and Training Sites' principal investigators. The agreed-upon sampling interval was one minute (average). The one minute data will be used to determine hourly, daily, and monthly values.

The sequence of the IRF insolation instrumentation design and development effort was established as:

(1) broadband, visible and near-infrared insolation on horizontal surface, fixed aperture (5.72°) normal incident direct beam, and horizontal diffuse skylight;

(2) broadband insolation on tilted surfaces at varying azimuths;

(3) broadband normal incident direct beam into different apertures;

(4) spectral (0.4 to 1.1 μm), aperture (1°), normal incident direct beam, horizontal, and diffuse skylight on horizontal;

(5) spectral (0.4 to 1.1 μm) insolation on tilted surfaces at varying azimuths; and

(6) spectral (0.4 to 1.1 μm) normal incident direct beam onto different apertures.

The meteorological and data logging instrumentation systems were addressed in parallel with the insolation instrumentation systems, with the data logging system receiving highest priority.

The effort to date has included mainly items (1), (2), and (3) and the data logging and analysis system. Item (2), insolation on tilted surfaces, has required the major effort to date. The meteorological system is considered a minor problem, requiring only standard off-the-shelf components.

Off-the-shelf instrumentation is required for item (1)--broadband, visible, and near-infrared insolation. The normal incident, fixed aperture, direct solar beam will be measured with two pyrheliometers mounted on a solar tracker (equatorial mount). One pyrheliometer will be equipped with a quartz window that allows the broadband (0.285 to 2.80 μm) insolation to be measured. The other pyrheliometer will be equipped with an RG 2 filter that allows the near-infrared (0.630 to 2.80 μm) insolation to be measured. By subtracting the measured near-infrared insolation from the broadband insolation, the visible (0.285 to 0.630 μm), region is determined. This will be done by computer software routines. The total insolation on a horizontal surface will be measured in a similar fashion using off-the-shelf pyranometers. The diffuse sky insolation on a horizontal surface--for the broadband, visible, and near-infrared regions--will be determined by using the measured normal incident direct beam insolation, I, and the measured total horizontal insolation, H_h. The diffuse horizontal sky insolation, D_h, is determined by:

$$D_h = H_h - I \cos\theta_o \quad (3)$$

where θ_o is the solar zenith angle. The computer software will be used to perform these functions. For purposes of comparison the broadband diffuse insolation on a horizontal surface will also be measured with a continuously tracking disk, where the direct solar beam is continuously shaded by a small disk. This allows the pyranometer to measure the diffuse insolation directly. The broadband diffuse insolation on a horizontal surface will also be measured by the shadow band method, where a shadow band is positioned so as to continuously shade the direct solar beam. The three methods will be compared to determine the agreement among them. This is required in order to translate historical and current diffuse measurements.

As mentioned previously, the major effort has been devoted to designing and developing an instrumentation system to measure insolation on tilted surfaces oriented at different azimuths. The preliminary measurements of insolation on tilted surfaces, shown in Figures 3-5 through 3-9, were made to aid in design. The requirements of such an instrumentation system are somewhat difficult to establish because of the wide range and complexity of the intended applications of the measurements and because of lack of insolation data on tilted surfaces. In addition, no off-the-shelf system, standard technique, or instrument for making such measurements exists.

The most critical requirements were those of the number and orientation of the tilted surfaces. This requirement directly determines the instrumentation used, its cost, number of data channels, the cost of the data logging system, and the cost of data processing. In general, solar flat plate thermal and photovoltaic collectors address the entire range of tilts and azimuths. Therefore, evaluations of existing conversion algorithms should address the entire range of tilts and azimuths, to determine such characteristics as the nonisotropic nature of the diffuse skylight. In addition, the passive solar heating and cooling technology also addresses the entire range of tilts and azimuths.

The azimuths selected were north, south, east, and west. This allows various regions of the sky to be viewed and relates to the common orientation references for solar energy collectors.

The number of tilted surfaces was determined by model simulations and the field measurements shown in Figures 3-5, 3-6, 3-7 and 3-8 which revealed that the amount of insolation is markedly dependent upon tilt angle for all azimuths. The model simulations also indicate this marked variation (Figures 3-11 and 3-12). The insolation model and techniques were used to generate plots comparable to Figures 3-5 and 3-6. The model results differed somewhat in magnitude but the curves were similar. Based on the dependence of the insolation on tilt angle, a tilt angle increment of 10° was selected. An increment of 15° appears too coarse, and an increment of 5° appears too rigorous, especially considering the effect of the number of tilts on cost and feasibility.

The specifications to be used in measuring insolation on tilted surfaces are:

- surface azimuths of north, south, east, west;
- surface tilt angle increments of 10°;
- surfaces shielded from ground-reflected sunlight;
- surfaces able to view entire sky without unwanted obstructions (buildings, etc.);
- measurement of the broadband (0.285 to 2.80 μm) insolation;
- a temporal resolution of 1 minute; and
- continuous monitoring on daily, monthly, and yearly basis.

With these requirements established, design concepts and instruments were investigated. This activity did not include detailed engineering trade-off studies of multiple concepts.

The most basic design questions in light of the requirements are:

- Should the measurements made at the various tilts be performed by a single sensor operating in a tilt and azimuth scanning mode?
- Should the tilt measurements be made with sensors fixed at each position?
- What sensor should be used?
- How should the sensor be shielded from the ground-reflected radiation?

Making measurements at the tilts and azimuth positions with a scanning sensor device has the following advantages and disadvantages.

<u>Advantage:</u> The measurement is made with only one sensor.

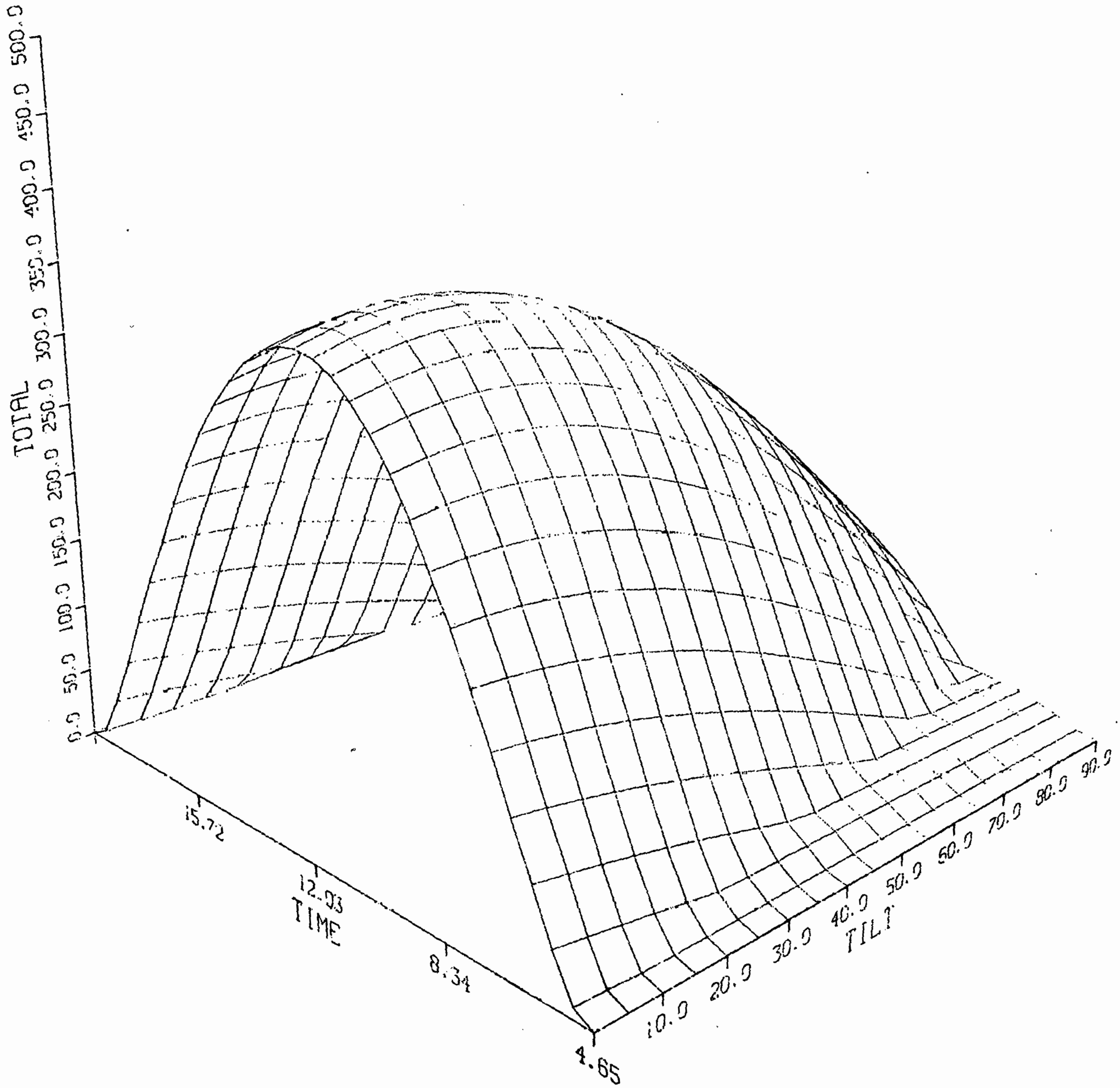


Figure 3-11(a). SIM MODEL PREDICTIONS OF TOTAL (Btu/Ft^2 Hr) INSOLATION AVAILABLE ON VARIOUS TILTED SURFACES, POINTED SOUTH, JUNE 21, 1978, DENVER, COLORADO, CLEAR SKY CONDITIONS

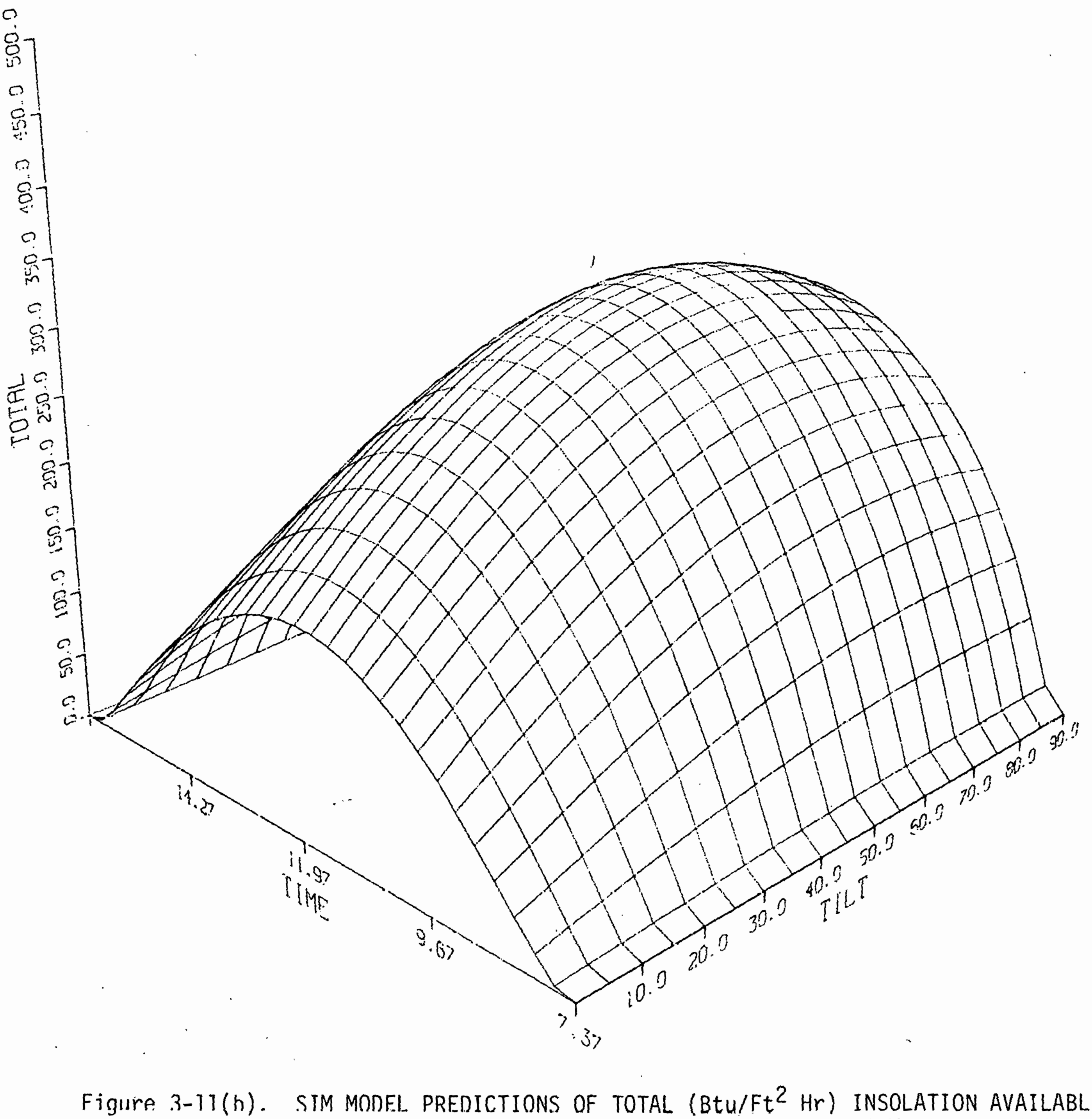


Figure 3-11(b). SIM MODEL PREDICTIONS OF TOTAL (Btu/Ft^2 Hr) INSOLATION AVAILABLE ON VARIOUS TILTED SURFACES, POINTED SOUTH, DECEMBER 21, 1978, DENVER, COLORADO, CLEAR SKY CONDITIONS

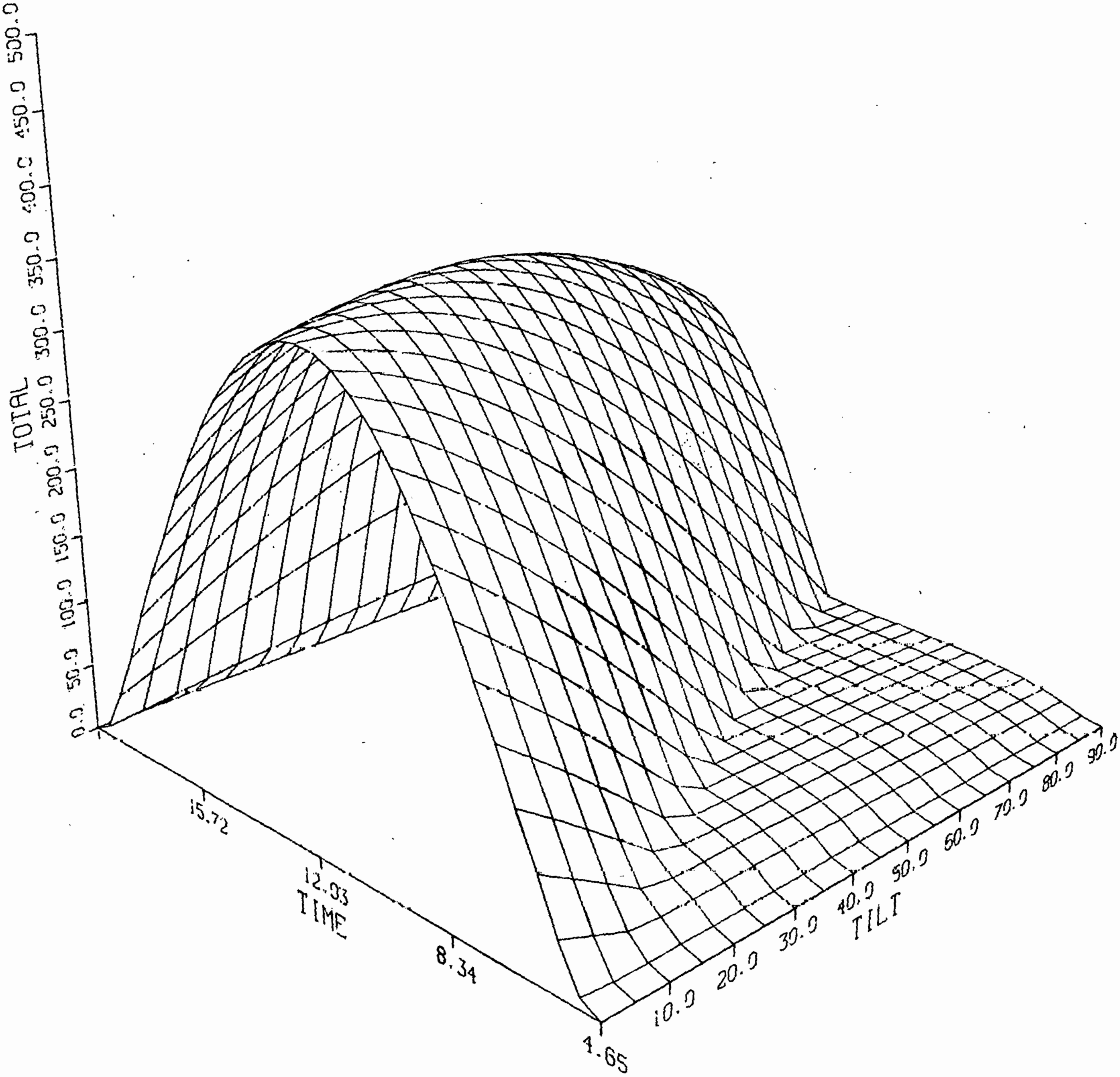


Figure 3-12(a). SIM MODEL PREDICTIONS OF TOTAL (Btu/Ft^2 Hr) INSOLATION ON VARIOUS TILTED SURFACES, POINTED WEST, JUNE 21, 1978, DENVER, COLORADO, CLEAR SKY CONDITIONS

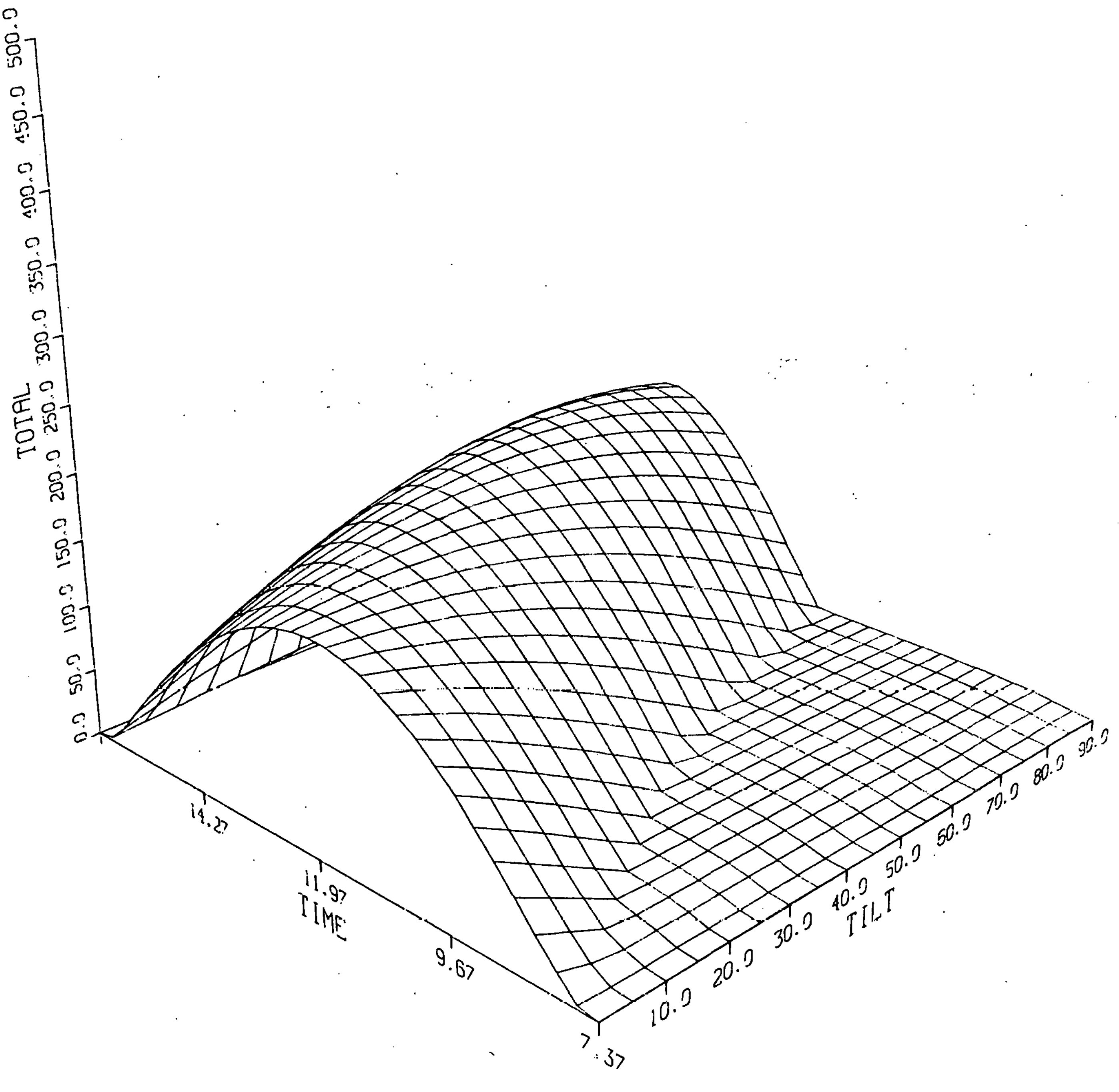


Figure 3-12(b). SIM MODEL PREDICTIONS OF TOTAL (Btu/Ft^2 Hr) INSOLATION ON VARIOUS TILTED SURFACES, POINTED WEST, DECEMBER 21, 1978, DENVER, COLORADO, CLEAR SKY CONDITIONS

Disadvantages:

- The method requires a scanning and pointing system which is likely to fail. This system, which is not readily available, would probably be expensive.
- The measurements on the various tilts are not taken simultaneously because of the time lag required by the scanning mechanism.
- Some sort of positioning determination system would be required to record accurately and report the tilts and azimuths.
- The nature of the scanning mechanism may make it difficult to eliminate ground reflections.

Making the measurements at the various tilts and azimuths with the multiple fixed sensor technique has the following advantages and disadvantages.

Advantages:

- Measurements are made nearly simultaneously on all tilts.
- No moving parts are required.
- Each tilt and azimuth surface is precisely known and oriented.
- Data logging is done for each tilt/azimuth surface.
- Because the sensors are fixed they can probably be shielded from the ground.

Disadvantage: The measurements are made with several sensors which require precise intercomparisons and calibrations.

The advantages and disadvantages of the two methods were interpreted as favoring the multiple, fixed sensor system for measuring insolation on measured surfaces.

The next design step was selecting a sensor. The requirements for measuring insolation on tilted surfaces were:

- measures broadband (0.3 to 3.0 μm) insolation;
- good cosine response that can be calibrated and is reasonably consistent for several sensors;
- fast time response;
- temperature corrected;
- 180° field of view;

- not affected by tilt;
- an absolute accuracy comparable to the conventional thermopile pyranometer (± 3-5%);
- not sensitive to azimuth orientation; and
- inexpensive.

Shielding the tilted sensors from the ground-reflected radiation and the number of tilt angles and surfaces restrict sensor size. The measurements of insolation on tilted surfaces at the four azimuth orientations require that the sensors be positioned along a circular arc from south to north and along another circular arc from east to west, as shown in Figure 3-13. The nonreflective surface has to be large enough to shield the sensors from the ground-reflected radiation. This shielding factor is determined geometrically by the height of the sensor above the shield and the radius of the shield. A small computer routine was formulated to calculate this view factor. The tilt angle most susceptible to the ground-reflected radiation is the one on the vertical (90° tilt). View factor calculations revealed that a shield having a radius of ten times the height of the top sensor (see Figure 3-13) would yield a ground view factor of less than 1.10 (10%) for the vertical sensor. This ratio (10 to 1) of shield radius to height of the top sensor was taken to be a minimum; i.e., a maximum ground view factor of 10% or less. The height of the top sensor is determined by the number and size of the sensors used along the circular arc from vertical to horizontal (see Figure 3-13). To measure the insolation on the vertical and at each 10° tilt increment requires nine sensors. The length of the arc along which the sensors are placed is equal to 9d (assuming sensors are placed tightly against each other), where d is the diameter of one sensor. From simple geometry, the height of the top sensor above the shield, h (Figure 3-13), is given by $18d/\pi$. The radius of the shield to give a ground view factor of 10% would be 57.3d. Thus the sensor should be kept as small as possible in order to keep the size of the shield manageable.

The commonly available and widely used thermopile pyranometer, such as the one shown in Figure 3-1, has a diameter of nearly 8 in. This dictates a ground shield radius of slightly greater than 38 ft, or a total diameter of 76 ft. The height of the top sensor would be almost 4.4 ft. Such a large shield and structure are undesirable because of expense, wind loading, snow loading, etc. In addition, the cost of such thermopile sensors is approximately $1,000. On the basis of size and cost, the thermopile sensors were judged to be undesirable.

The photovoltaic (silicon cell) sensor pyranometer shown in Figures 3-2, 3-3, and 3-4 are much smaller and more suitable for the multiple, fixed sensor system in Figure 3-13. The diameter of the LI-200S is 15/16 in, which would make the radius of the ground shield about 53 in (4.42 ft). The photovoltaic sensor pyranometer is also attractive (see Figure 3-2) because of its extremely fast response (10 μsec), stability, cosine response, and uniformity with respect to azimuth. The major uncertainties concerning the photovoltaic sensor are its wavelength-dependent response and its limited wavelength sensitivity (0.4 to 1.1 μm). Normally the LI-200S is calibrated against an

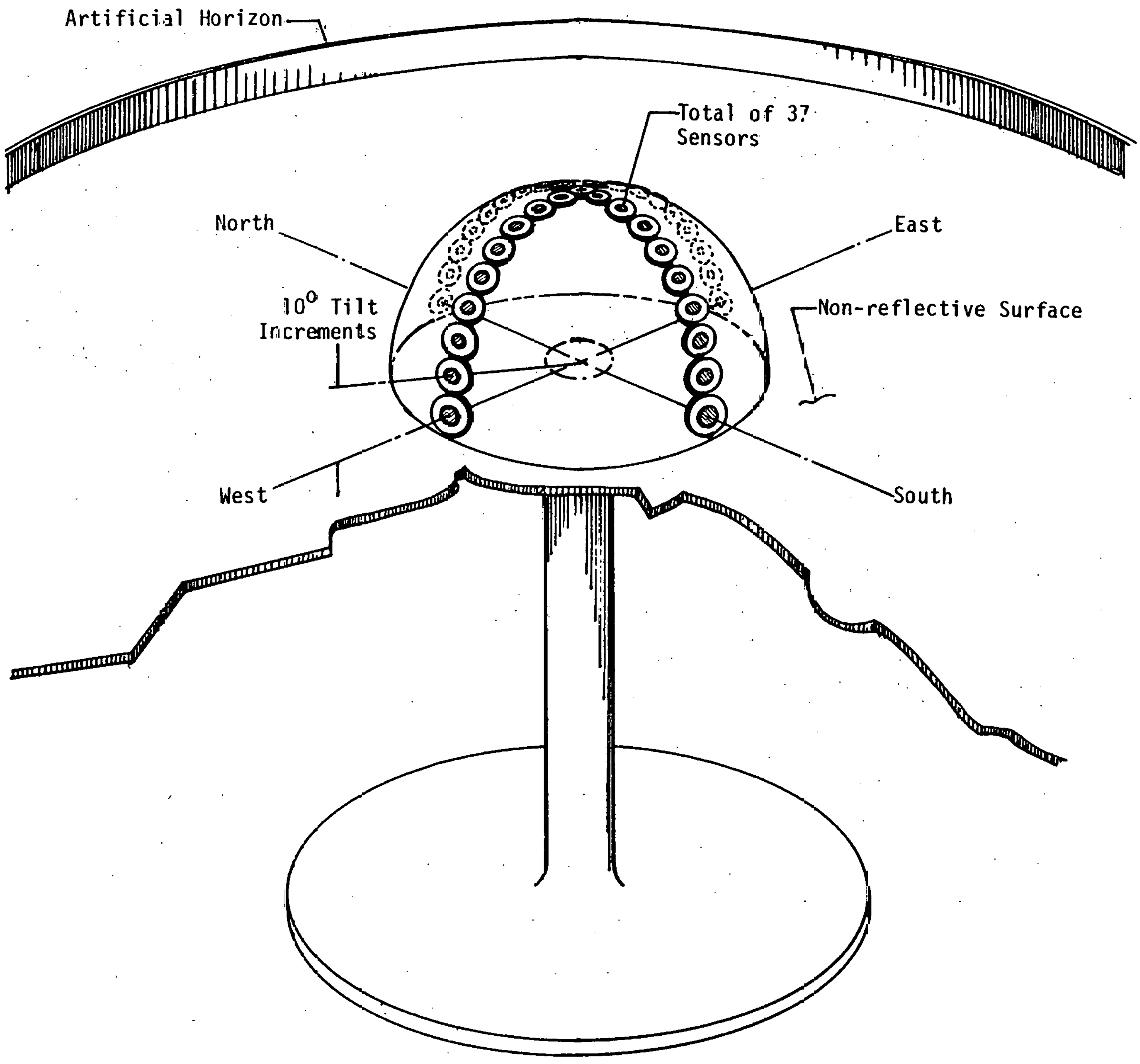


Figure 3-13. INSOLATION RESEARCH FACILITY TILT ARRAY

Eppley thermopile pyranometer in the horizontal position and under "natural daylight clear conditions". It has not been tested or calibrated for absolute insolation measurements on tilted surfaces or under various daylight conditions. The greatest uncertainty would arise when the photovoltaic sensor viewed only the blue skylight (shaded from the direct beam), because of the spectral distribution. Any effects due to the actual tilting of the LI-200S should be insignificant.

In order to investigate any differences between the photovoltaic pyranometer and the thermopile pyranometer for tilted surface insolation measurements field experiments were performed using the thermopile pyranometer, an open response (typical silicon response from 0.4 to 1.1 μm) silicon pyranometer (LS-200S), and a visible, flat response silicon pryanometer (LI-190SE)--Figures 3-1, 3-2, 3-3, and 3-4. The LI-190SE sensor was included because of its flat spectral response from about 0.4 to 0.7 μm, as compared to the LI-200S typical silicon response (peaking at 0.900 μm) from 0.4 to 1.1 μm. If the changes in the spectral distribution of insolation as a function of tilt angle are significant, they should be evident when the three types of sensors are compared. Of course, the other source of any differences would be those in cosine response of the sensors.

The comparison of the absolute insolation on the horizontal and tilted surfaces for clear and cloudy conditions are shown in Figures 3-5 and 3-6. Figure 3-5 shows that differences exist, but they seem to be dependent on tilt angle and azimuth orientation. As Figure 3-5 also shows, the two types of pyranometer have a basic difference at the horizontal position. This difference could probably be reduced significantly if the specific thermopile pyranometer were used to calibrate the silicon pyranometer, as is done at the factory. The maximum differences observed were about 5-8%, as shown in Figure 3-5-b. This was encouraging, especially when the measurements of diffuse conditions seemed to be in good agreement, as shown in Figures 3-5-a and 3-5-d--tilt angles greater than 75°. The measurements under cloudy sky conditions also seem to be in good agreement.

In order to eliminate differences due to the absolute calibration constant of the sensors, the individual sensor determinations of the ratio of the insolation on tilted surfaces to that on a horizontal were compared, as shown in Figures 3-7 and 3-8. A marked improvement in agreement is evident when such a ratio is addressed as compared to absolute quantities. Also evident is the good agreement of the flat response silicon sensor with the open response silicon sensor. Shown in Figure 3-9 is the measured ratio of tilted to horizontal insolation as a function of the cosine of the direct solar beam incident angle. Again, good agreement is evident over a wide range of incident angles and for the different azimuth orientations. These results suggest using the silicon pyranometer to measure the ratio of tilted to horizontal insolation in conjunction with a thermopile pyranometer to measure the absolute horizontal insolation.

The silicon pyranometer ratios of tilted insolation to horizontal insolation were used in the manner just described to deduce the absolute insolation on a tilted surface. Shown in Figure 3-14 are the actual silicon-pyranometer measured absolute insolation (using its factory calibrations constant) and the silicon pyranometer-measured ratio of tilted to horizontal insolation. Both

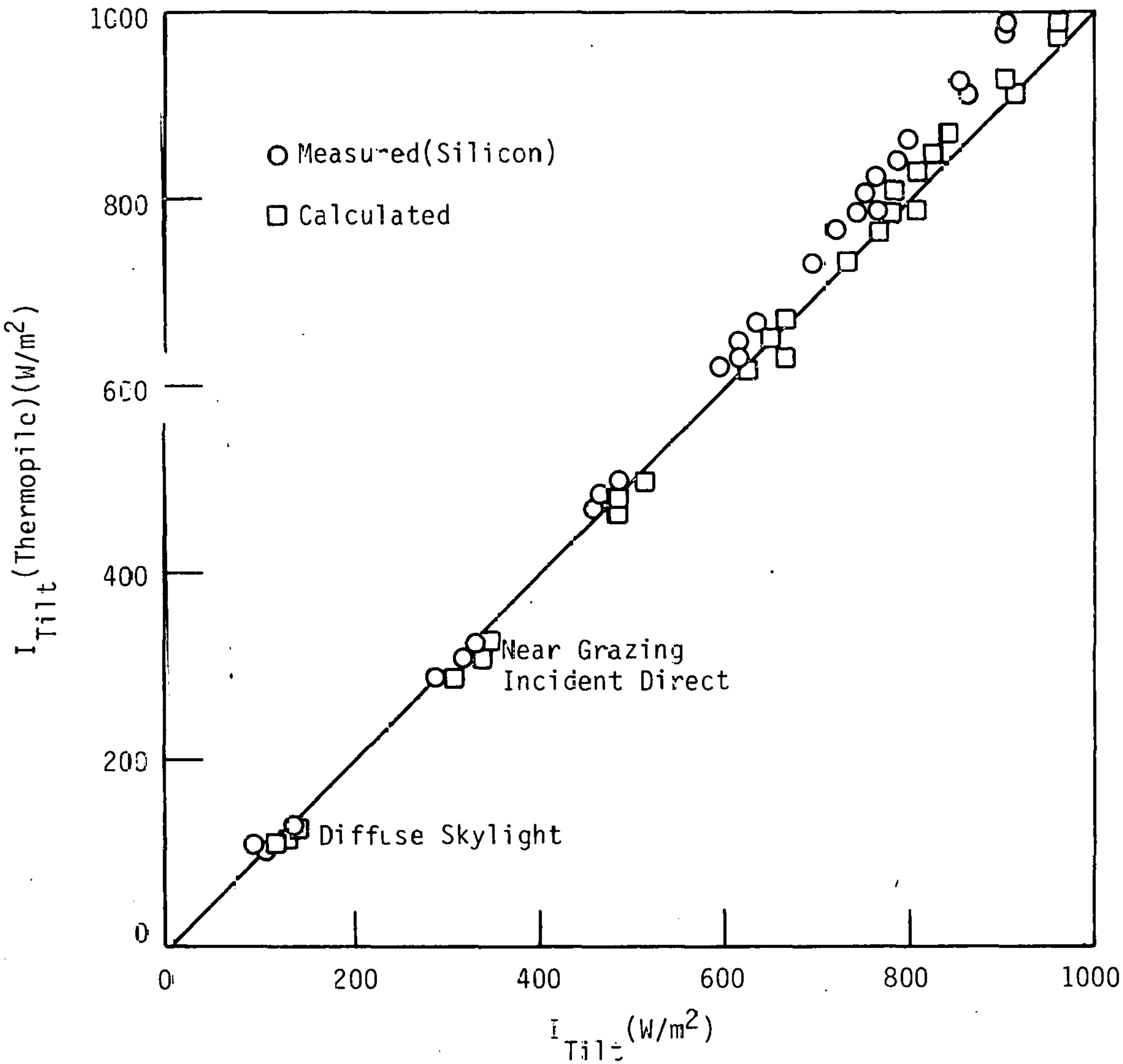


Figure 3-14. COMPARISON OF ABSOLUTE MEASUREMENTS OF TILTED SURFACE INSOLATION, BETWEEN THERMOPILE AND SILICON SENSOR PYRANOMETERS.

of these quantities are compared to the absolute insolation on all tilted surfaces, over all azimuths, and over all incident angles as measured by the SR75 thermopile pyranometer. The silicon pyranometer values appear to be in good agreement with the SR75 thermopile measurements over the lower values of insolation. These lower values are characteristic of low direct beam incident angles and totally diffuse conditions on clear days. Toward the higher insolation level, the silicon pyranometer measurements gradually become less than the thermopile measurements. The calculated insolation agrees quite well over the entire range. This indicates that the ratio technique greatly reduces the disagreement among the different types of sensors.

The differences between the silicon and thermopile measurements were suspected to result from their cosine response differences. This is indicated by the agreement at low insolation values (low incident angles) and divergence at high insolation values (high incident angles). The ratio of the absolute insolation on a tilted surface as measured by the silicon pyranometer to that measured by the thermopile pyranometer, versus the cosine of the direct beam incident angle, was investigated and is shown in Figure 3-15. A systematic cosine response difference is quite apparent, demonstrating that the silicon pyranometer has a lower response at higher incident angles. The two responses gradually approach each other at lower cosines (incident angles). The range of difference extends from 0.92 (8%) at near normal incidence (cosine = 1.0) to 1.02 at grazing incidence (cosine = 0.2). A similar comparison, but using the ratio technique, is shown in Figure 3-16. As can be seen, the ratio technique improved the comparison at the higher cosines (higher insolation values) and somewhat degraded the comparison at grazing incidence. The general comparison (Figure 3-16), shows a better than 3% agreement from incident angles from 0° to 44° and a 5% agreement from 44 to 80°.

With the data and comparison just discussed, it is difficult to choose the pyranometer with true cosine response. The factory specifications (Figure 3-1 and 3-2) would favor the silicon sensor. Discussions with the factory engineers revealed that each sensor is calibrated for cosine response in the laboratory and each meets the specifications shown in Figure 3-2. The thermopile pyranometer may be sensitive to orientation and tilt; however, this has not been quantified. Most important is the fact that the differences between the silicon pyranometer measurements on tilted sufaces and the thermopile measurements appear to be due to a systematic difference in cosine response. Such a difference could be eliminated with proper calibration procedures.

In view of these results and the advantages of the silicon pyranometer listed previously, the silicon pyranometer will be used for the Insolation Research Facility tilted surface array shown in Figure 3-13. The detailed design of the array is shown in Figure 3-17. The total of 37 sensors, with tilt increments of 10° in each of four azimuths, is approximately 6 in. in height.

Detailed ground and sky view factors for each tilted surface were calculated to determine the radius of the ground shield (nonreflective surface, Figure 3-13) and height of the artificial horizon. The geometry of the array and ground is shown in Figure 3-18. The results of the sky and ground view factor calculations, shown in Figures 3-19 and 3-20, were used to design the ground shield and artificial horizon of the tilted surface array. The results for the system shown in Figure 3-17 are:

Surface Tilt Angle	% of Sky Viewed	% of Ground Shielded
10°	100	99.2
20°	100	98.8
30°	100	98.0
40°	100	98.0
50°	100	98.0
60°	100	98.6
70°	100	99.5
80°	99.5	100
90°	98.2	100

The design allows nearly unobstructed viewing of the sky and almost total shielding of the ground.

The resulting Insolation Research Facility tilted array system will allow nearly simultaneous measurements of broadband, total (direct solar beam plus sky diffuse) insolation on the tilted surfaces. The approximate costs are:

Sensors (37)	\$4,000
Structure	\$5,000 (estimated)
Total	\$9,000

Thus, the multiple, high-tilt resolution (10°), tilted surface array has been achieved at a relatively low cost of \$9,000. The cost using conventional thermopile sensors would be about \$42,000.

The individual silicon pyranometer sensors used in the tilted surface array will be calibrated precisely for cosine response as well as absolute calibration constant both at the factory and on-site. The factory will calibrate each sensor's cosine response in a laboratory. Sensors will then be selected that have as close to identical responses as possible. These 37 sensors will then be compared rigorously, with each other and with two thermopile pyranometers (Eppley PSP Model 2), on-site (SERI, Golden, Colo.). The Eppley thermopile pyranometers will be calibrated for cosine response at the factory. The intercomparisons and calibrations will be performed over clear and cloudy conditions and over a wide range (0.1 to 1.0) of cosines (0° to 85° incident angles). Each sensor will then be assigned a calibration constant as a function of cosine angle for both absolute insolation on a tilted surface and the ratio of tilted to horizontal insolation. All of the pyranometers will be calibrated independently for absolute cosine response by the shading method. In this technique the tilted pyranometer is shaded from the direct solar beam to measure the diffuse insolation on the tilted surface while the absolute direct solar beam insolation is measured with a standard pyrheliometer. The sum of the diffuse and direct solar insolation is compared to the total insolation measured by the pyranometer. This is a commonly accepted technique for calibrating pyranometers on the horizontal that will be

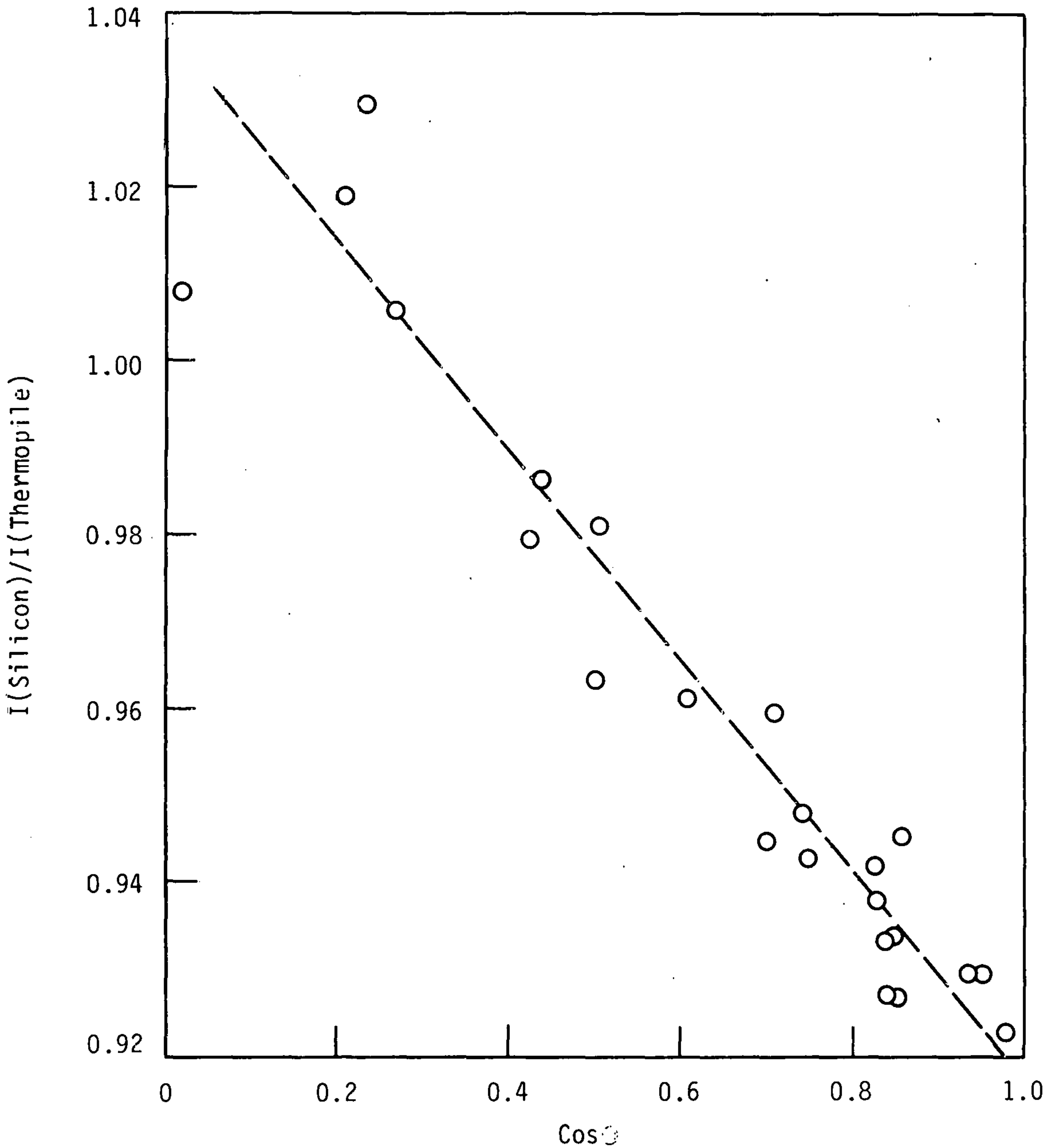


Figure 3-15. COMPARISON OF COSINE RESPONSE OF THERMOPILE AND SILICON SENSOR PYRANOMETERS

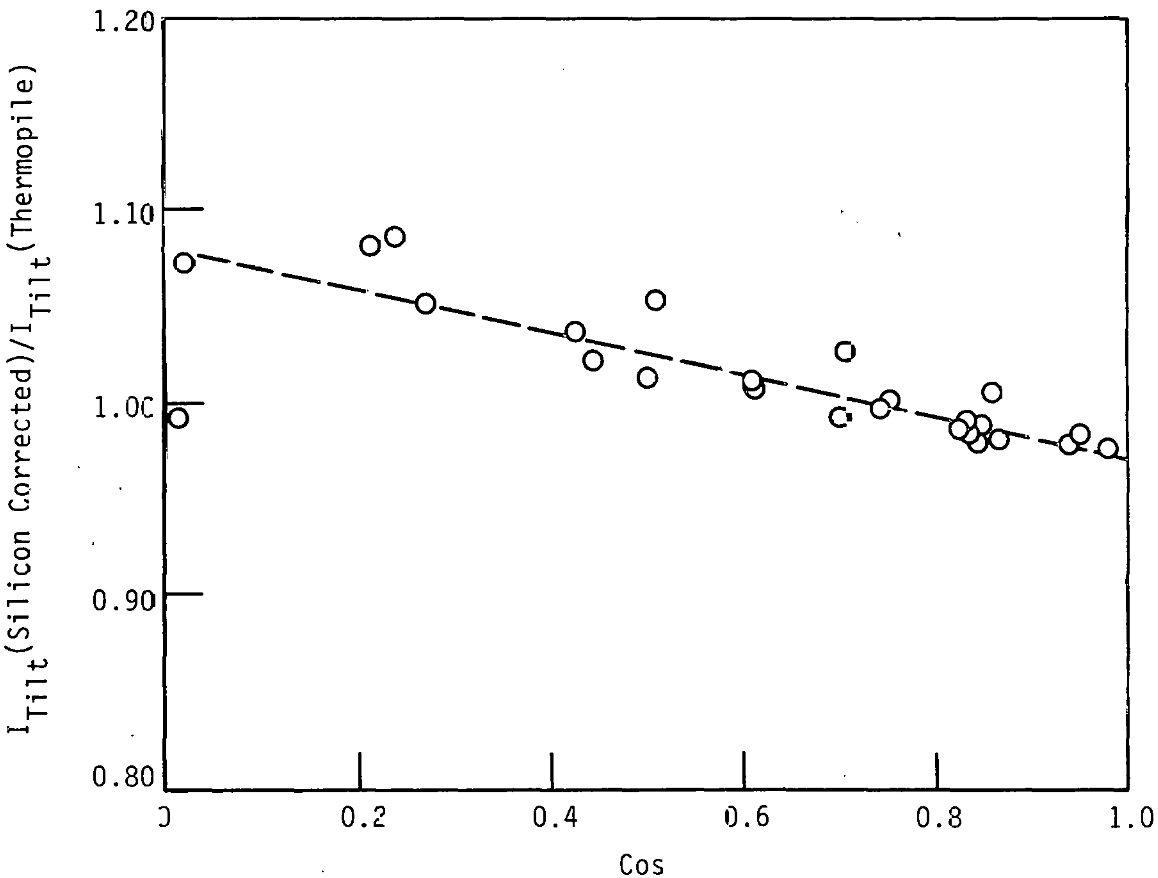


Figure 3-16. COMPARISON OF RATIO CORRECTED COSINE RESPONSE OF THERMOPILE AND SILICON SENSOR PYRANOMETERS

IRF ARTIFICIAL HORIZON GEOMETERY

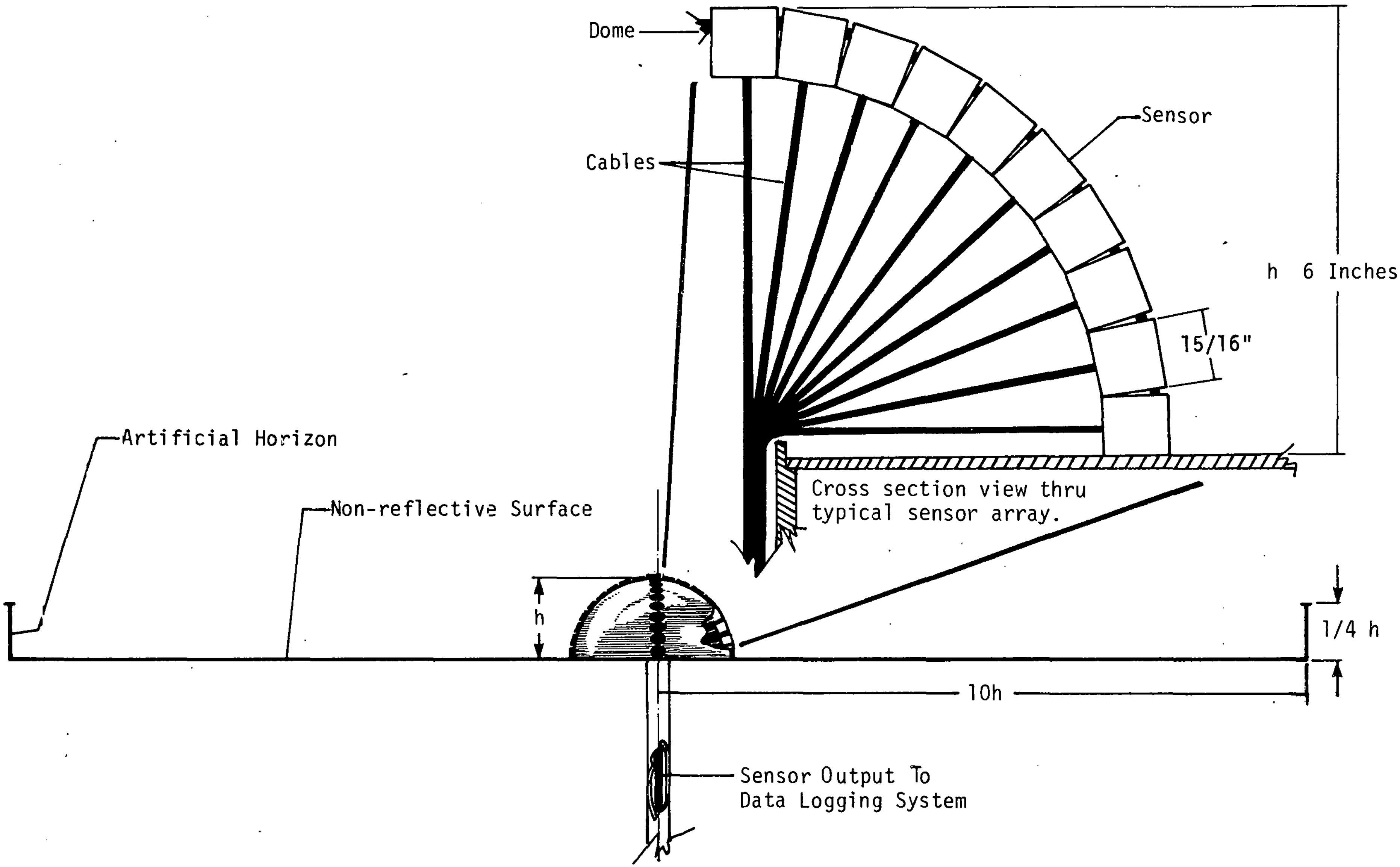


Figure 3-17. CROSS SECTION VIEW OF TILTED SENSOR ARRAY DESIGN

$$\tan \Psi = \frac{h + r \cos \beta - H}{d - r \sin \beta}$$

r = radius of tilt array

h = height of tilt array above ground

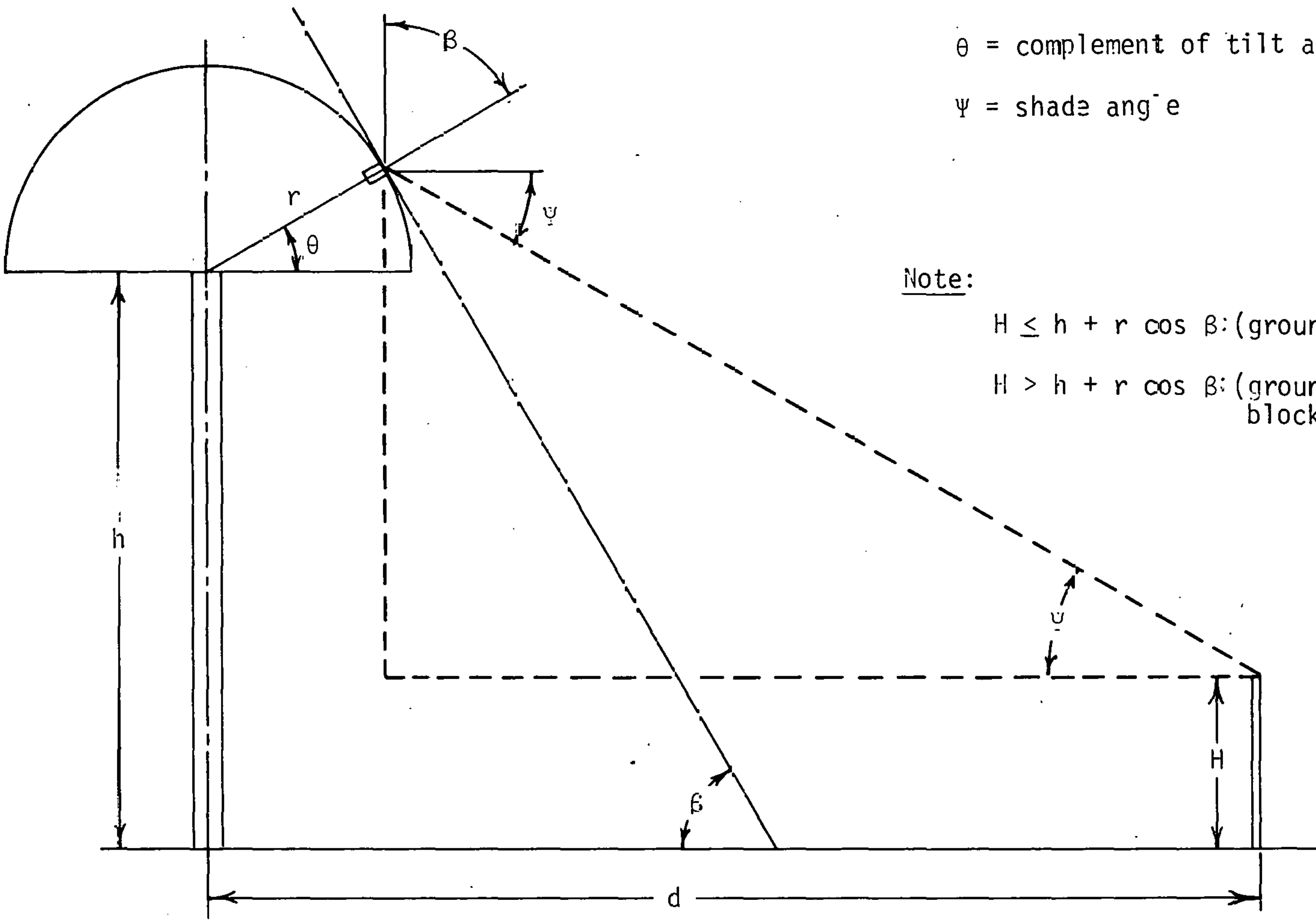
d = distance to artificial horizon

H = height of artificial horizon

β = tilt angle

θ = complement of tilt angle

Ψ = shade angle



<u>Note</u>:

$H \leq h + r \cos \beta$: (ground blocking)

$H > h + r \cos \beta$: (ground + sky blocking)

Figure 3-13. SKY AND GROUND VIEW FACTOR GEOMETRY

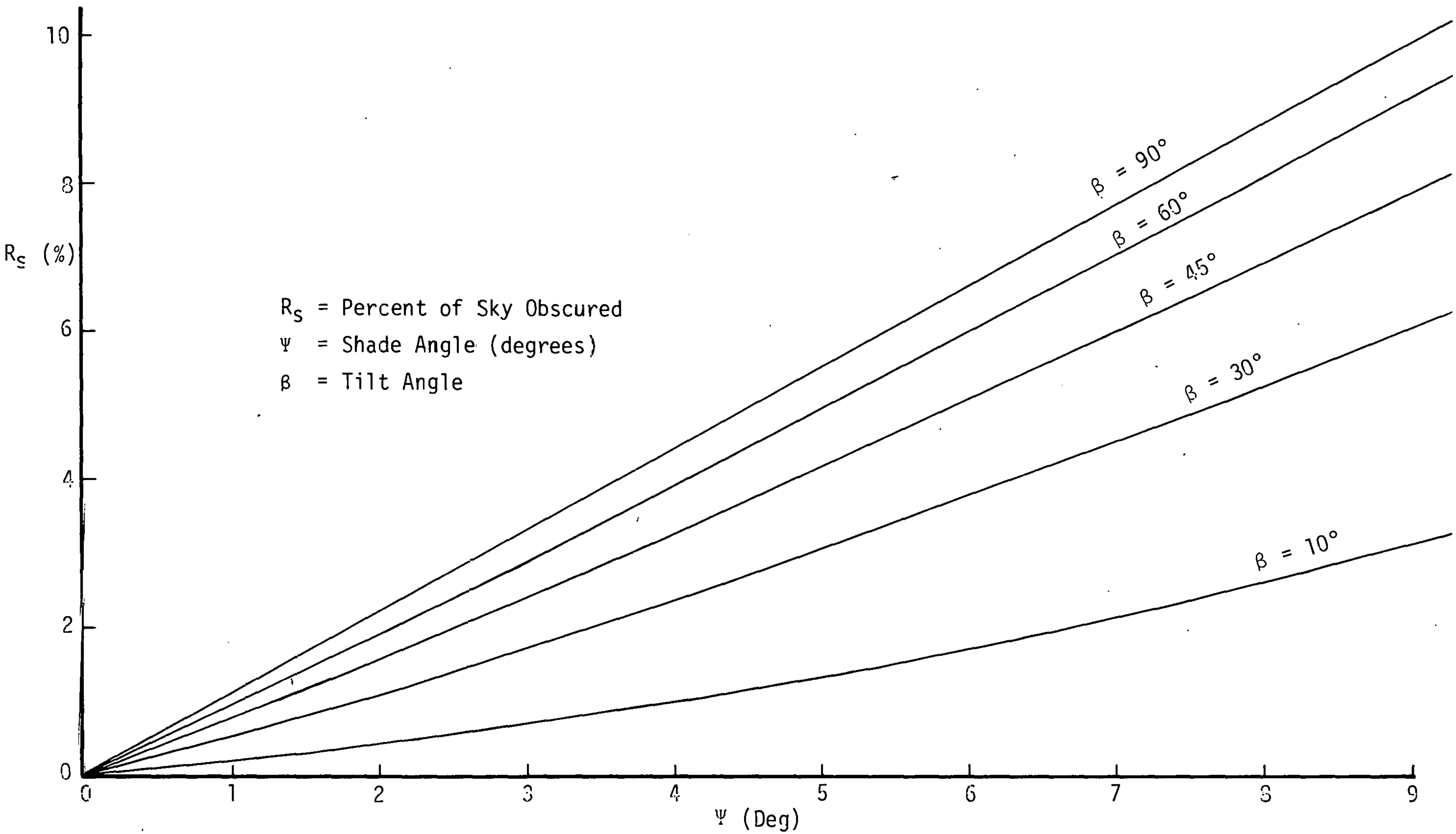


Figure 3-19. PERCENT OF SKY OBSCURED, R_S, BY TILTED SURFACE ARRAY ARTIFICIAL HORIZON, FOR VARIOUS TILTED SURFACES

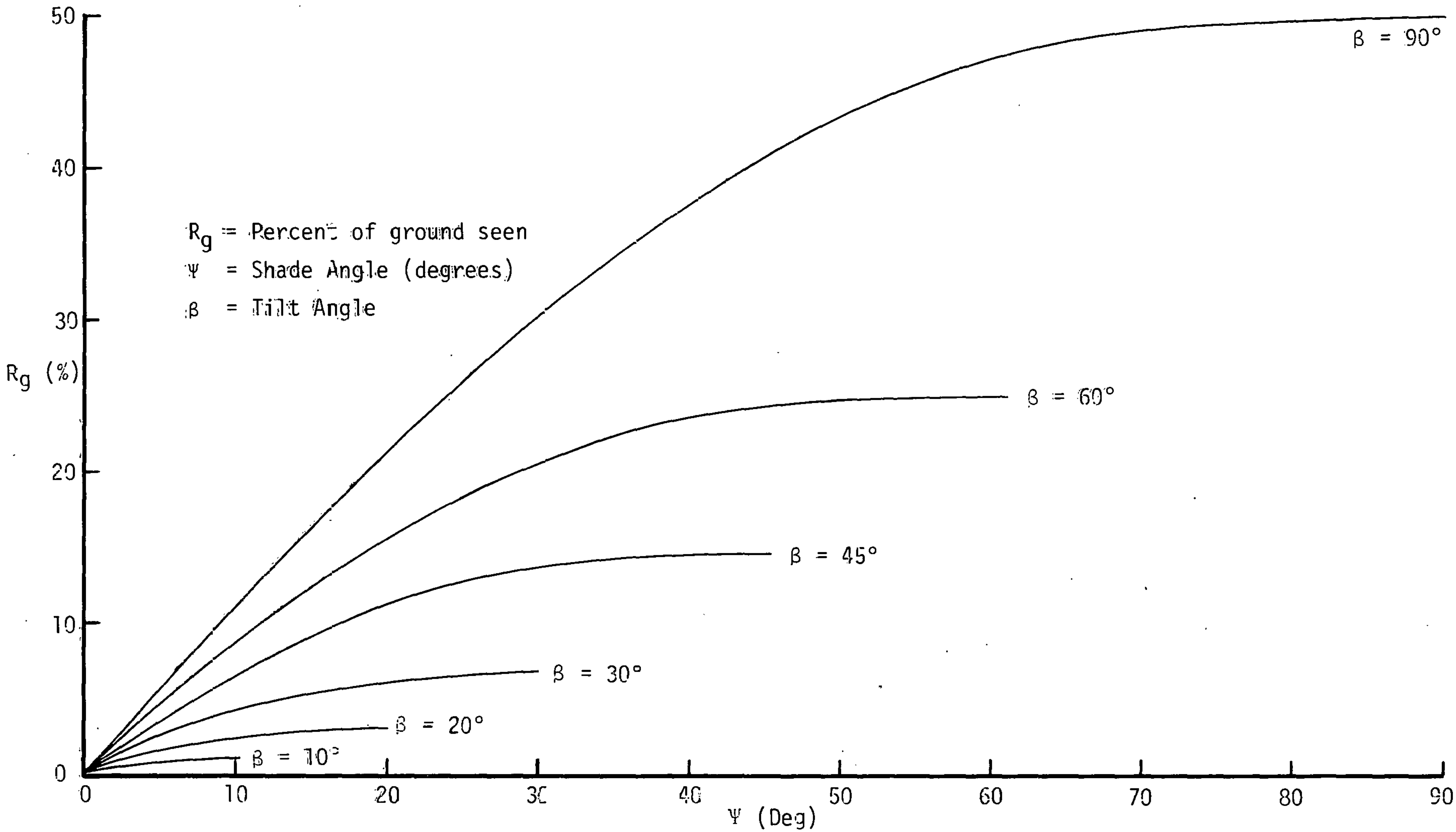


Figure 3-20. PERCENT OF GROUND SEEN, R_g, BY TILTED SURFACES, AS DETERMINED BY TILTED SURFACE ARRAY GROUND SHIELD GEOMETRY

used here on a tilted surface. Because both the direct solar beam insolation and the direct beam incident angle will be measured accurately, the cosine response of the sensors will be determined as accurately as possible. The on-site absolute measurements of the calibration constants and cosine responses will then be compared with those determined independently at the factory. Each sensor will have a cosine response and absolute calibration constant that will be used to derive absolute insolation on a tilted surface.

The silicon sensor tilted surface array measurements will be complemented by Eppley PSP Model 2 thermopile pyranometer measurements of spectral, total (direct plus sky plus ground) insolation on tilted surfaces of 30°, 60° and 90°, oriented south. The spectral regions considered will be the visible (0.285 to 0.630 μm), near-infrared (0.630 to 2.85 μm), and broadband (0.285 to 2.80 μm) regions. This is achieved by equipping one pyranometer with a clear WG 7 (transmittance of 0.285 to 2.80 μm) hemisphere and one pyranometer with an RG 2 (transmittance of 0.630 to 2.80 μm) hemisphere. The visible region is measured by subtracting the RG 2 from the WG 7 measurement. These measurements will include the ground reflected component so that its influence on the total insolation on a tilted surface can be investigated, along with evaluation of algorithms for calculating the reflected component. By addressing the spectral regions, the spectral dependence of the insolation components can be investigated. To compare silicon pyranometers with thermopile pyranometers, a silicon (model LI-200S) pyranometer will be mounted beside each of the Eppley pyranometers.

The total spectral insolation on the 30°, 60°, and 90° south facing tilted surfaces will be made by mounting the Eppley and silicon pyranometers on platforms attached to the south side of the Insolation Research Facility building. This building will be approximately 10 ft wide by 10 ft high by 16 ft long with a reinforced roof for mounting the sensors and tilted surface array. The building will be mounted on a 20 to 30 ft base and will house computer data logging equipment.

The south-facing, tilted-surface Eppley pyranometers will view the ground surface to the immediate south of the building. To evaluate the contribution of the reflected component [Equation (1)] the reflectance/albedo of the ground needs to be measured; it should be uniform over the entire area viewed by the tilted surface. The dimensions of the building and tilt angles (30°, 60°, and 90°) were used, along with the previously described view factor calculations, to determine the area "seen" by each pyranometer. The lowest tilt angle (30°) receives over 90% of the total available reflected irradiance from an area contained within an 88-ft radius of the building. This area will be covered with a uniform material of moderate (20-30%) reflectivity, such as crushed lava rock. Two Eppley pyranometers (WG 7 and RG 2 filters) will be positioned looking downward, approximately 3 ft above the center of this control area, to measure the reflected insolation, 95% of which comes from (view factor) a 30-ft diameter ground area. This measurement, along with the measurement of total horizontal insolation, will then determine the instantaneous (minute) reflectivity of the controlled area. The reflectivity of the controlled area will be that of the uniform lava rock, but it will vary depending on the amount of rain (moisture) and certainly snow cover. This natural variation of the reflective surface will be of experimental benefit because it will represent the real conditions viewed by a flat-plate collector.

The measurements of the broadband, normal incident, direct solar beam insolation into various apertures will be made by a variable field of view, absolute capacity pyrheliometer. The fields of view have been tentatively established as 0.67°, 0.83°, 1.0°, 1.50°, 2.5°, 3.0°, 3.5°, 4.0°, 5.0°, and 5.7°. As discussed previously, the smallest field of view represents a trade-off between the ideal smallest field of view (0.53°, solar disk) and the cost of a tracking system. Tracking systems for the 0.53° field of view would have to be very accurate and thus expensive. The 5.7° value is the standard, fixed aperture field of view of the pyrheliometers used in the National Weather Service insolation network. The variable field of view pyrheliometer and tracker system will be a modified, standard cavity radiometer that is available commercially. A special variable aperture disk will be installed to allow the apertures to be viewed in sequence, with the variable aperture automatically driven and stopped. The final design and instrumentation including the tracker system will be procured from a vendor.

The data logging and analysis systems designed for the Insolation Research Facility will allow data logging of all channels on a minute time scale. The system is a dedicated small general-purpose minicomputer based on the Digital Equipment Corporation LSI-11 microprogrammed central processor. The complete system has the following components:

- central processor, memory, and real-time clock;
- magnetic tape subsystem;
- video terminal;
- line printer;
- standard interfaces; and
- software system.

The central processor is a DEC LSI-11/2 with a 16-bit work length and the PDP-11 series instruction set. (Note: Through the years a vast amount of software has been developed for the PDP-11 series computers; this software is compatible with the LSI-11.) The memory is 64K byte semiconductor random access (RAM). The real-time clock allows the computer to coordinate its activities with the external physical world.

The magnetic disc subsystem provides random access of bulk storage. The disc drive provides 5M bytes of storage in one removable front-loading cartridge disc (RK05, IBM 2315) and one fixed disc. The disc subsystem is used for software development and storage and for temporary data storage.

The magnetic tape subsystem provides sequential access of bulk storage. The tape drive is a 9-track unit with dual-density format capability (800 CPI-NRZI/1600 CPI-PE). The drive is capable of using 10-1/2 in. 2400-ft tape reel size. The magnetic tape subsystem is used mainly for data archiving and is compatible with most 9-track tape drives.

The video terminal provides interaction between man and computer. The terminal displays alphanumeric characters on a raster scan CRT and has a typewriter-like keyboard.

The line printer provides hardcopy alphanumeric output. The printer is a microprocessor controlled bidirectional matrix printer with a 180 character per minute printing rate. Printing is done on standard computer fan-fold paper at 132 columns per line. The line printer is used mainly for software development and data output.

Standard interfaces are included for expansion capability: an IEEE-488 bus interface and three RS-232-C (RS-422 and RS-423) asynchronous interfaces. In addition, slots are available in the backplane of the LSI-11 (Q-bus) for interface expansion.

The software system provides the environment for program generation and execution and has three components: (1) operating system with utilities, (2) FORTRAN subsystem, and (3) BASIC subsystem. The operating system is a single user real-time disc. Interactive program development and real-time tasks are supported under both single job and foreground/background modes of processing. System and program development utilities include test editor, assembler, librarian, linker, and file maintenance utilities. The FORTRAN subsystem conforms to NASI X3.9-1966 and includes the compiler and object time system. The BASIC subsystem is a single-user incremental version.

The Subtask 3603.1 FY78 effort regarding the review, comparison, and evaluation of algorithms for converting horizontal insolation to tilted surfaces was a relatively minor effort. Extensive literature searching to identify such conversion techniques is being conducted by Northrop Services Inc. and the University of Alabama (DOE Contract No. EG-77-C-02-4494). This contract also involves some experimental evaluation and measurements on a tilted surface but is limited to just one azimuth orientation and one tilt angle. During FY79, when the SERI Insolation Research Facility is completely operational, a major effort will utilize the extensive multiple-orientation, multiple tilt angle, and spectral data generated to compare and evaluate the conversion methods identified by Northrop. In addition, the review of horizontal to tilted surface insolation conversion methods will continue to identify new methods developed by other investigators.

The Subtask 3603.1 FY78 effort concerning existing horizontal to tilted surface algorithms consisted of developing computerized techniques for directly comparing and evaluating the many existing algorithms with the IRF data. The result is shown in Figure 3-21. The IRF raw field data will be recorded and permanently archived on 9-track, 1600 BPI, phase-encoded magnetic tape that will then be put on a CDC 6000 series computer to perform the following functions:

- convert sensor signals to absolute insolation units;
- calculate solar geometry;

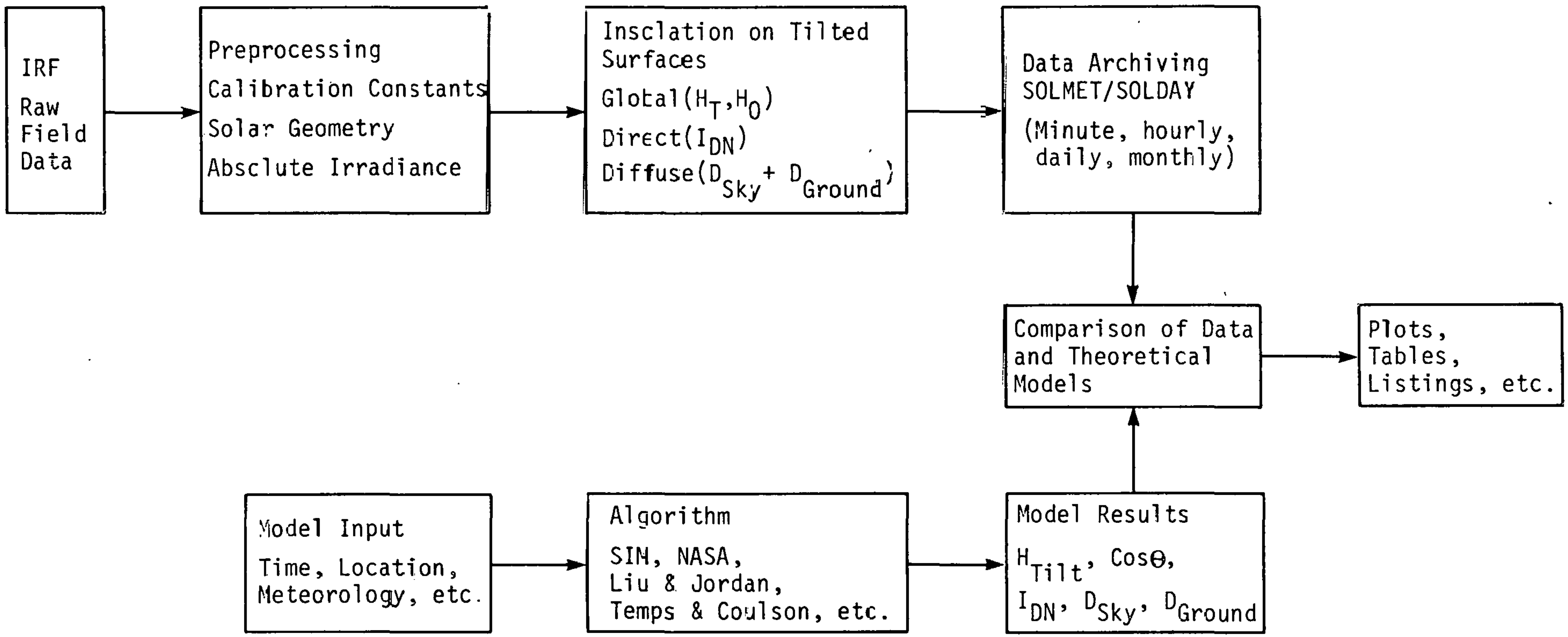


Figure 3-21. ANALYSIS AND REDUCTION OF FIELD DATA AND COMPARISON WITH MODELS-ALGORITHMS.

- determine absolute insolation of all tilted surfaces, direct beam, horizontal diffuse, etc;
- develop and produce fully reduced data tapes in the SOLMET and SOLDAY format archive tapes and send to the NCC;
- generate predicted insolation on tilted surfaces, direct solar beam, horizontal diffuse, etc., from several models and conversion algorithms;
- compare models, algorithms and data; and
- develop improved models and algorithms.

3.2 INSOLATION MODELS FOR SOLAR ENERGY APPLICATIONS

The task addresses the evaluation, implementation, and improvement of insolation models for solar applications. Its purpose is to provide such models to internal SERI investigators, DOE, industry, and the private sector. The FY78 effort was limited to providing insolation models for the immediate SERI needs.

One of the most immediate needs during FY78 was the SERI Photovoltaics Branch research requirement for a model of the detailed spectral insolation incident on a photovoltaic device. The incident spectral insolation and the photovoltaics device characteristics are then used to determine the efficiency of the device. The spectral insolation model should be capable of generating the incident spectral insolation as a function of relative air mass (slant path through the atmosphere) and atmospheric conditions, so that the device efficiency can be determined over a range of relative air masses and atmospheric conditions.

The existing models for the incident spectral insolation commonly used by photovoltaic device investigators were developed by Moon [1], Gates [2], and Thekaekara [3]. The more recent work of Thekaekara and Gates is quite commonly used to predict the spectral incident insolation. All such models must use a "solar constant" for the spectral distribution outside the earth's atmosphere and then modify this spectrum by calculating the spectral transmittance of the intervening atmosphere.

The work of Moon (1940) was probably the first attempt to model the insolation spectrum over the entire solar spectrum--0.3 to 3.0μm. Moon used a value of the total, broadband, solar constant of 1322 Watts/m^2, a value derived by the Smithsonian Institute (from 1920 to 1934). For the solar constant spectral distribution, Moon used values obtained by several investigators for various spectral regions by extrapolating ground-based measurements to the extraterrestrial values. Moon used atmospheric spectral transmittance models developed by other investigators for specific regions of the spectrum, for the specific attenuation process of Rayleigh (molecular) scattering, the scattering effect of water vapor, the scattering effect of dust particles, absorption by ozone, and absorption by water vapor.

For the Rayleigh scattering effect of water vapor and water vapor absorption, Moon used data and techniques derived by Fowle [4]. Fowle derived the Rayleigh scattering attenuation function empirically from measurements of the direct solar beam at Mount Wilson (elevation 3,250 ft). Moon used Fowle's data to derive empirically an equation for the attenuation due to water vapor scattering, again for the atmosphere above Mount Wilson. The same data and Washington D.C. data were used to derive an empirical attenuation function for atmospheric dust. Moon also relied on Fowle's data to derive an empirical attenuation function for water vapor absorption.

Although a detailed discussion of the Moon techniques for calculating spectral insolation is not within the scope of this report, the following are shortcomings of the Moon spectral insolation calculations:

- they are ground-based, empirically derived functions based on site specific data (Mt. Wilson and Washington D.C.);
- the solar constant used is obviously outdated;
- the simple Bouguer formula (exponential law of attenuation) assumed for the water vapor absorption is now known to be in error; and
- the experimental data used were limited by the use of old (1920's) instrumentation.

Thekaekara used an approach similar to Moon's. Employing the data and analyses of various investigators for the different regions of the spectrum, he determined the spectral insolation for the total spectrum.

For Rayleigh and aerosol attenuation functions of the atmosphere, Thekaekara used the Bouguer/Beer's law of exponential decay:

$$I_\lambda = I_{o\lambda} e^{-\tau_\lambda m} \quad (4)$$

where: I_λ = spectral (λ = wavelength) normal incident direct beam intensity at the ground

$I_{o\lambda}$ = extraterrestrial intensity

τ_λ = atmospheric attenuation coefficient

m = relative air mass (relative to the verical path length.

Whereas Moon used empirical techniques to establish the Rayleigh, ozone, and aerosol attenuation components of τ_λ , Thekaekara utilized Rayleigh and ozone attenuation coefficients calculated by Elterman [5]. For the aerosol attenuation component Thekaekara utilized the Angstrom [6] formulation:

$$\tau_a = \beta / \lambda^\alpha \quad (5)$$

where α and β are constants related to the size distribution and density of the aerosols. The transmittance of water to vapor was calculated by Thekaekara from the empirically derived functions of Gates and Harrop [7, 8]:

$$T_{\lambda_1} = e^{-C_4\sqrt{wm}} \quad (6)$$

$$T_{\lambda_2} = e^{-C_5\sqrt{wm}} \quad (7)$$

$$T_{\lambda_3} = (1 - C_6\sqrt{m}) \quad (8)$$

Where: w = amount of precipitable water vapor

m = relative air mass

C_4, C_5, C_6 = empirical constants

The appropriate water vapor attenuation equation (6, 7, and 8) is chosen depending on the absorption band. Equation (6) is for the strong absorption bands, Equation (7) for the weak bands, and Equation (8) for regions where water vapor absorption is negligible.

For extraterrestrial insolation Thekaekara used a NASA-derived distribution [9] having a total integrated value of 1353 Watts/m^2. A typical extraterrestrial and terrestrial spectrum obtained by Thekaekara techniques (and somewhat the work of Gates) is shown in Figure 3-22. The anomalous (strong) absorption feature in the region from 0.80 to 1.0 μm should be noted. It is well known (R.M. Goody [10]) that the water vapor absorption bands in this spectral region are identified as the ρ, σ, and λ features. The σ band is at 0.940 μm and is fairly strong, but all three absorptions are confined to the 0.870 to 0.990 μm region. The only strong absorption feature is the band from 0.920 to 0.968 μm. The spectral region between 0.80 to 1.0 μm, where the anomalously strong attenuation of the Thekaekara-Gates techniques occurs, is particularly significant to photovoltaic devices. Since the 0.80 to 1.0 μm region is the region of peak response of the silicon photovoltaic conversion devices, strong attenuation in this region would have significant effects on calculations of photovoltaic device efficiencies.

The Gates' [2] formulations and model of the incident spectral insolation used were similar to those of Thekaekara. The Beer's law exponential formulation for Rayleigh, aerosol, and ozone attenuation was used, as were the formulations for water vapor absorption [Equations (6), (7), and (8)]. For the Rayleigh attenuation coefficients Gates used values calculated by Penndorf [11] applied to the U.S. 1962 Standard Atmosphere molecular densities. For ozone and aerosol attenuation he used the work of Elterman [5]. The resultant spectral insolation is similar in spectral shape to the Thekaekara curve shown in Figure 3-22. The anomalously strong absorption characteristic between 0.80 to 1.0 μm is also apparent in the Gates' spectral curves [2]. This same feature can be found in numerous technical publications that used the Gates' water vapor absorption calculation technique.

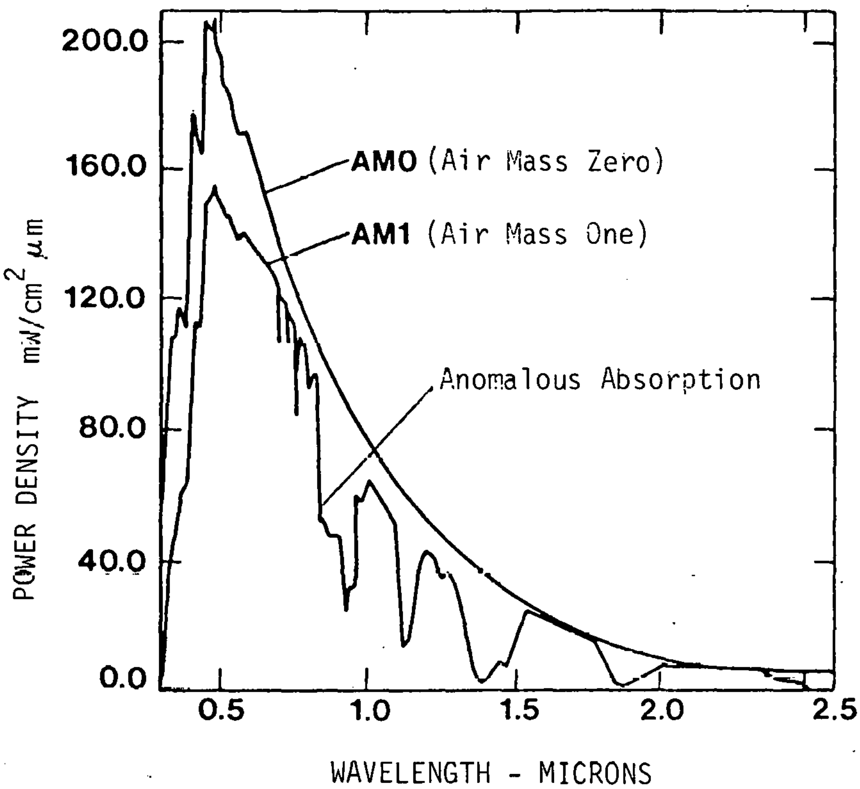


Figure 3-22. TYPICAL SOLAR EXTRATERRESTRIAL (AMO) AND TERRESTRIAL (AM1) SPECTRUM, BY THEKAEKARA, FOR THE U.S. STANDARD ATMOSPHERE, 20 mm H_2O VAPOR, 3.4 mm OZONE

The anomalous water vapor absorption feature can be traced to the results reported by Gates in 1960 [7], in which he noted high spectral resolution measurements of the direct solar beam between 0.872 to 2.537 μm. The measurements were made for one day, Oct. 15, 1954, in the Boulder-Denver, Colo., area. Gates performed an analysis of 59 wavelength positions from 0.872 to 2.537 μm to determine the quantity, C_4, shown in Equation (6). On page 1303 of that publication, the absorption constant is shown as a function of wavelength, and the region from 0.800 to 1.00 μm clearly reflects the shape of the spectral curve shown in Figure 3-22. Gates [8] repeated the experiment in January of 1955 in Denver, Colo., but did not show results for wavelengths shorter than 1.0 μm.

The techniques for calculating the spectral incident insolation developed by Moon, Gates, and Thekaekara have two common characteristics:

- they were derived by empirical analysis of ground-based spectral data;
- the ground-based data were limited to specific sites and atmospheric conditions.

Probably the most uncertain feature of these techniques is the calculation of attenuation due to water vapor absorption. For example, it is known that the amount of absorption depends on the concentration of the absorber, temperature, pressure, path length, and concentration and composition of other gases. However, equations such as (6), (7), and (8) consider only concentration and path length. The concentration of water vapor is handled as the total precipitable water vapor in the entire column of atmosphere. Obviously, the altitude profile of the water vapor concentration, temperature profile, and to a lesser extent pressure profile, can be quite variable. Thus it is possible for the total precipitable water vapor to remain fairly constant while the conditions that determine absorption--concentration, pressure, and temperature--can be quite variable.

Recently an effort has been made to develop rigorous methods for calculating the detailed transmittance of the atmosphere. J.E. Selby and R.A. McClatchey [12] of the Air Force Geophysics Laboratories have developed a computer model (LOWTRAN) for this purpose based on recent laboratory transmittance measurements and theoretical molecular line constants in line-by-line transmittance calculations [13]. The atmosphere is treated as several layers, each having a specific temperature, pressure, water vapor concentration, gaseous mixture, etc. The transmittance over each layer is then calculated to a resolution of 20 cm^{-1} using methods based on the best available laboratory measurements of the absorption characteristics and theoretical molecular line constants. In addition, the path length through the layer is calculated, taking into account atmospheric refraction. This method allows the detailed structure and altitude profile of the atmosphere to be treated, and the calculation technique(s) are based on laboratory measurements of the absorption characteristics under controlled conditions. For these reasons, the LOWTRAN program represents a significant improvement over the Moon, Gates, and Thekaekara models.

The current version of LOWTRAN is the LOWTRAN 4 computer code [14], which is identical to LOWTRAN 3B except for the addition of a radiance calculation routine. The LOWTRAN 3B computer code is quite versatile in terms of atmospheric conditions. A total of six standard atmospheres can be addressed:

- tropical model atmosphere;
- midlatitude summer;
- midlatitude winter;
- subarctic summer;
- subarctic winter; and
- U.S. 1962 Standard.

Each atmosphere has a specific pressure, temperature, density, water vapor, and ozone altitude profile (1-km resolution). However, a very important feature of LOWTRAN is its capability of using a measured altitude profile.

The LOWTRAN 3B program also treats atmospheric aerosols and their attenuation. Four different aerosol types can be considered:

- rural (continental);
- urban (35% soot);
- maritime (95% sea spray); and
- tropospheric (very clear conditions).

The altitude variation of the aerosol concentrations are the same as those measured by Elterman [5]. The amount of aerosol is specified by the meteorological range (visibility). Each aerosol model has a specific wavelength variation of the extinction/attenuation coefficient.

LOWTRAN 3B also allows any surface altitude to be considered. However, the altitude profile of the atmospheric constituents and physical state is not changed from that at sea level.

The LOWTRAN computer code represents a significant amount of scientific effort and the current methods for calculating atmospheric transmittance properties. In addition, the Air Force Geophysics Lab is continually updating LOWTRAN. For these reasons it was selected for use for the direct beam, incident spectral insolation properties.

The LOWTRAN computer code supplies the wavelength dependent transmittance of the atmosphere but it does not supply the incident spectral insolation. In order to do this, the LOWTRAN calculation procedures were combined with the Thekaekara [9] extraterrestrial solar spectrum. Currently, the extraterrestrial spectrum of Labs and Neckel is also being considered. This allows the spectral distribution of the direct solar beam (excluding circumsolar radiation) to be calculated as a function of relative air mass (including refraction) and a wide range of atmospheric conditions. The resultant computer code, called SOLTRAN, is available on the CDC 6000 series system.

An example of SOLTRAN spectral distribution is shown in Figure 3-23. The SOLTRAN program was also used to calculate the transmittance of water vapor in the 0.80 to 1.0 μm region and to compare it with the Gates and Thekaekara calculations (Figure 3-24). The SOLTRAN/LOWTRAN 0.80 to 1.0 μm, transmittance displays the well-known ρ and σ absorption bands but does not show the weak band because of the low resolution (200 cm^{-1}). As can be seen, the Gates-Thekaekara transmittance in the region from 0.85 to 0.90 μm is only about 0.55, whereas the SOLTRAN/LOWTRAN transmittance is nearly 1.00. The anomalously low transmittance calculated for water vapor by the Gates-Thekaekara model accounts for the sharp decrease in solar intensity shown in Figure 3-22.

SOLTRAN was used during FY78 routinely by the SERI Photovoltaics Branch to calculate the efficiency and performance characteristics of photovoltaic devices under varying conditions. The SOLTRAN computer code is now being distributed by the Photovoltaics Branch to other investigators.

Future effort regarding spectral insolation models and measurements will be to:

- add routines to SOLTRAN to calculate the spectral circumsolar radiation;
- conduct high resolution spectral measurements of the direct beam and compare them with SOLTRAN predictions;
- review, evaluate, and implement models for calculating spectral insolation on horizontal and tilted surfaces; and
- conduct high resolution spectral measurements of the insolation on horizontal and tilted surfaces.

The spectral measurements are important because the limited amount of existing data prevents any thorough determination of the accuracy and limitations of models such as SOLTRAN. One key question is the extent to which a model's accuracy and applicability depend on specific meteorological inputs. For example, SOLTRAN requires an estimate of the meteorological range (visibility) in order to select an aerosol concentration; however, measurements of meteorological range are not widely available. Visibilities reported at NWS stations are only observer estimates that should not be used as quantitative measures of aerosol and dust concentrations.

Models or techniques for estimating the broadband incident insolation from meteorological conditions have been investigated since the turn of the century [Kimball, 15]. Davies and Hay [16] have given a fairly thorough review of the historical development and the existing models for predicting insolation. This review discusses numerous formulations for calculating insolation components given certain meteorological inputs. The investigator who is

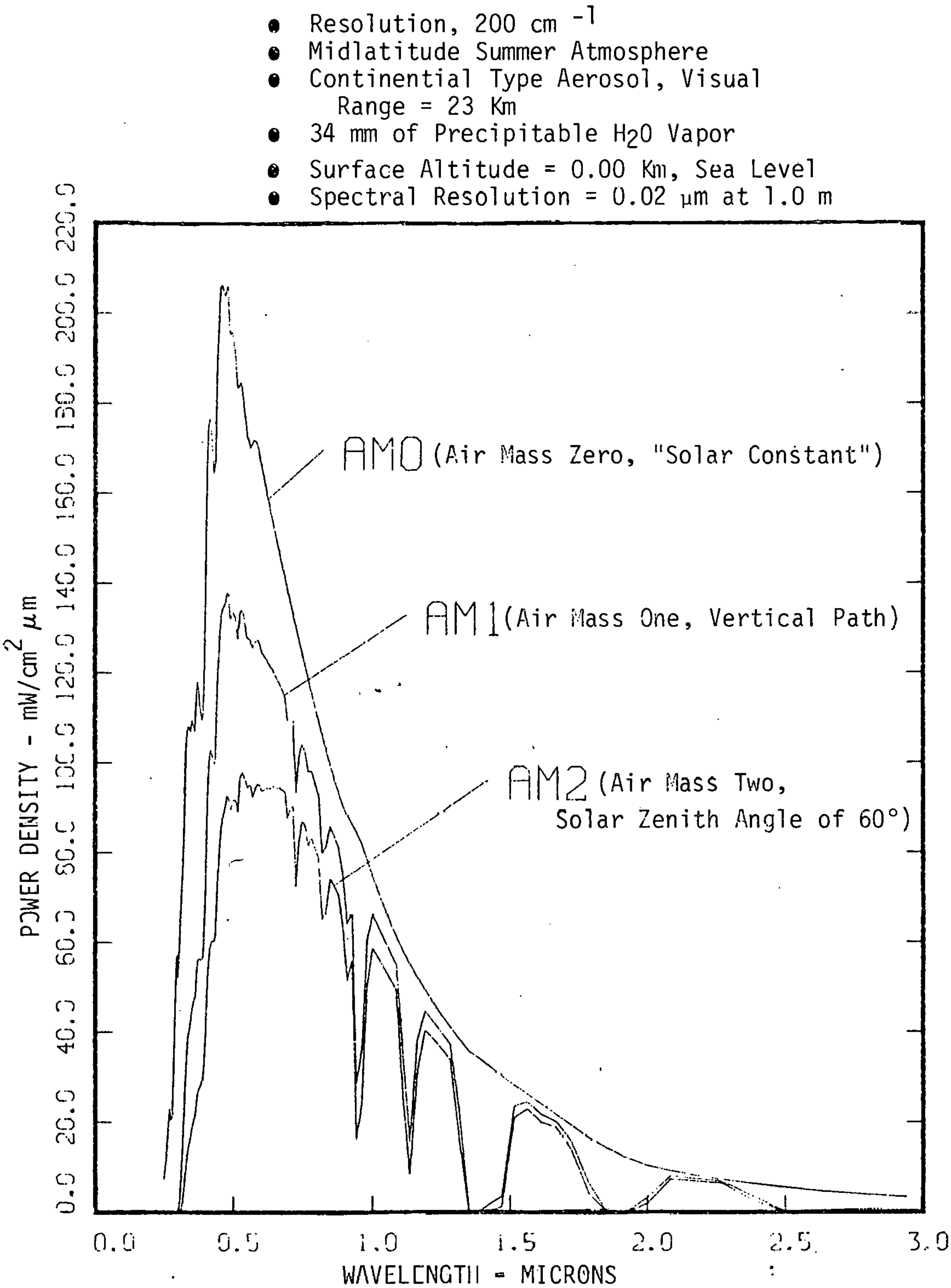


Figure 3-23. SOLTRAN COMPUTED TERRESTRIAL, DIRECT BEAM (EXCLUDING CIRCUMSOLAR RADIATI INSOLATION SPECTRUM (NOTE: THE OXYGEN ABSORPTION LINE AT 0.762 μm IS NOT SHOWN BECAUSE OF THE LOW RESOLUTION, 200 cm^{-1}).

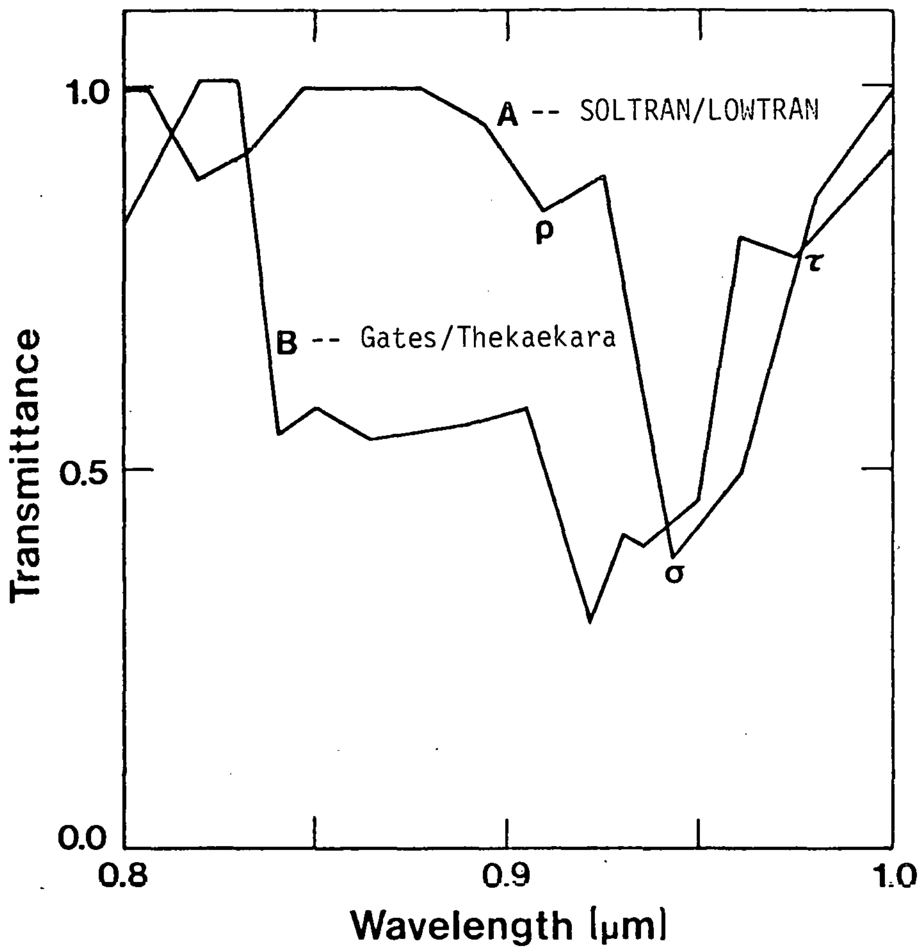


Figure 3-24. COMPARISON OF SOLTRAN (LOWTRAN 3B) CALCULATIONS OF WATER VAPOR TRANSMITTANCE (FOR ONE AIR MASS), WITH CALCULATIONS USING GATES/THEKAEKARA MODELS

interested in such models must select formulations suitable to his application.

Theoretical calculations of the broadband insolation have been performed using the theory of radiative transfer [17], but they require an extremely long computer time--as much as 20 hours [16]. In addition, they require meteorological inputs that simply are not available, including detailed characterization of the atmospheric aerosols such as the concentration, size distribution, complex index of refraction, altitide profile, etc. The lack of such data creates uncertainties in the atmospheric optical properties, which introduce uncertainties in the theoretical calculations. Because of this problem the great expense in computer time in using the "exact" theoretical calculations is not justified [18]. The rigorous theoretical models are useful for determining the exact nature of the radiative transfer through the atmosphere and for defining key parameters that control the radiative transfer processes.

Because of the difficulty, expense, and uncertainties of the theoretical calculation of broadband insolation, various simplified empirical and semi-empirical models have become the alternative. In general, empirical relationships have been derived between the insolation components (total horizontal, direct beam, and diffuse sky) and meteorological conditions such as cloud cover, percentage sunshine, water vapor, visibility, etc. As early as 1919, Kimball [15] derived and used such relationships to establish the amount of total horizontal solar energy in the U.S.

Since the pioneering work of Kimball, many investigators have derived empirical and semiempirical insolation prediction formulations [16]. The scope of the Task 3603.2 effort during FY1978 did not allow a detailed evaluation or even review of all of them. However, on a long-term basis the SERI ERAB intends to establish the evolution and accuracy of insolation prediction models.

The goal of the FY78 effort was to implement a simple, fairly accurate model for predicting the broadband insolation at different geographical locations. The model was to be simple in its calculation techniques (computer time) and meteorological inputs. The broadband insolation was to consist of the normal incident direct beam (for solar thermal concentrators), the total horizontal insolation (for comparison with historical data), and the total insolation of tilted surfaces (solar thermal flat plate collectors).

With a similar goal, the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (Operations Planning and Analysis Branch) recently reviewed and compared insolation algorithms and models [19] using the rehabilitated SOLMET data base for 26 stations throughout the United States. The insolation component considered was the mean daily total horizontal insolation for each month of the year. The models investigated were:

- ASHRAE Cloud Cover Model--Insolation values calculated from theoretical clear day values modified by a cloud cover factor.

$$H_{cloudy} = H_{clear} * CCF$$

where H_{clear} is the horizontal insolation for "clear" day conditions, H_{cloudy} is the total horizontal insolation under cloudy conditions, and CCF is the cloud cover modifier [20].

- ASHRAE Percentage Sunshine Model--Insolation Values calculated from ASHRAE theoretical clear day values modified by percentage of possible sunshine [21].

$$H_{cloudy} = H_{clear} * \% \text{ Sunshine}$$

- SIM (Solar Insolation Model)--Hourly insolation values calculated from the model developed by Hulstrom [22]. This model uses a combination of the percentage sunshine and ASHRAE cloud cover methods.

The results of the comparison are shown in Table 3-1. Also included in the comparison was the well-known F-CHART data base. As can be seen, SIM is nearly twice as accurate as the ASHRAE techniques, and it is as accurate as the actual F-CHART data base. In addition, SIM is extremely simple to use, requiring input data readily available from the National Climatic Atlas and the standard ASHRAE manuals. For these reasons SIM was implemented on the SERI CDC-6000 series computer system and, at least initially, will be used as an insolation model predictor. Other models will be reviewed on a continuous basis to identify improved techniques.

A description of SIM is given in reference 21 and in even more detail in reference 22. Only the basic principles of SIM will be given here. SIM uses a combination of the basic ASHRAE percentage sunshine and cloud cover calculation techniques.

The total instantaneous horizontal insolation is calculated by:

$$H_h = I \cos \theta_o + D \qquad (2)$$

Where: H_h = horizontal insolation
I = normal incident direct beam insolation
θ_o = solar zenith angle
D = diffuse sky irradiance

SIM calculates H_h and D for clear sky conditions and for cloudy conditions (total overcast).

For clear sky conditions, the direct solar beam insolation is calculated by:

$$I = I_o \times R \times CN \times e^{-\tau_a \sec \theta_o} \qquad (9)$$

Where: I_o = solar constant (428 Btu/Ft^2 hr)
R = Earth-sun distance correction to the solar constant (see Ref. 22)
CN = atmospheric clearness number

Table 3-1: COMPARISON OF SIM, ASHRAE, F-CHART, AND SOLMET (STANDARD)

	Station	ASHRAE % Sun	ASHRAE Cloud Cover	F-CHART	SIM
1.	Alb, NM	21.1	8.9	5.7	7.1
2.	Apa, FL	9.8	9.8	13.7	7.3
3.	Bis, NM	25.4	16.4	11.9	5.5
4.	Bos, MA	12.7	25.9	3.9	12.0
5.	Bro, TX	17.5	14.8	4.6	13.4
6.	Hat, NC	--	12.4	20.5	4.1
7.	Car, ME	--	26.7	12.3	8.2
8.	Cha, SC	13.2	29.0	22.6	16.6
9.	Col, MO	20.5	9.4	9.4	11.7
10.	DCt. KS	16.3	11.7	8.0	5.0
11.	EIP, TX	18.4	10.5	3.4	8.2
12.	Ely, NY	25.1	13.7	4.1	9.4
13.	FtW, TX	11.0	14.6	10.8	4.5
14.	Fre, CA	12.1	10.5	5.9	12.1
15.	GrF, MT	27.4	16.7	8.6	8.2
16.	LCh, LA	12.2	21.7	13.3	7.0
17.	Mad, WI	23.4	18.4	7.0	8.0
18.	Med, OR	38.8	7.0	6.0	15.8
19.	Mia, FL	9.1	6.0	10.7	7.2
20.	Nas, TN	11.6	15.9	8.8	4.3
21.	NwY, NY	5.5	22.7	2.6	16.6
22.	Omh, NE	16.4	23.7	7.9	6.0
23.	Pho, AZ	11.1	9.6	4.8	6.0
24.	SMa, CA	13.2	11.3	10.4	8.2
25.	Sea, WA	31.1	14.8	9.5	7.4
26.	Was, DC	13.3	13.6	6.3	6.3
	MEAN ERROR (b)	17.3	15.2	9.0	8.7
	MEAN ERROR (c)	16.1	15.3	---	8.1

(a) Mean monthly percentage absolute error for monthly average total daily insolation on a horizontal surface, using SOLMET data as standard.

(b) Using data tapes with gaps

(c) Using data tapes with gaps filled with model

τ_a = apparent optical attenuation coefficient of the atmosphere
$\sec_o$ = relative air mass (path length)

The product of I_o and R is the extraterrestrial insolation for a given day of the year. SIM differs somewhat from the standard ASHRAE techniques in this calculation. ASHRAE [23], using the techniques of Stephenson [24], calculates the clear day direct beam insolation by:

$$I = I_a e^{-\tau_a \sec\theta_o} \qquad (10)$$

where I_a is the apparent extraterrestrial insolation. Evidently Stephenson used the results of Threlkeld [25] to determine I_a and τ_a. Threlkeld calculated the broadband (0.3 to 3.0 μm) normal incident direct beam insolation by performing detailed calculations using the techniques developed by Moon [1] for the spectral direct beam insolation; then he integrated the spectral insolation to obtain the broadband insolation. All of this was necessary because Equation (10) (Beer's Law) applies only to monochromatic radiation. It cannot be used directly to calculate the direct beam broadband insolation because of the deviation caused by attenuation due to water vapor absorption [Equations (6), (7) and (8)]. In an attempt to eliminate the need for the detailed spectral attenuation calculations, Stephenson used Threlkeld's results to derive what is called the "apparent" (or "effective") extraterrestrial insolation and the "apparent" optical attenuation coefficient. Stephenson derived these terms by plotting ln I (broadband) versus $\sec\theta_o$, where I was calculated by Threlkeld for various latitudes, months, and times of day for what he called his "standard" atmosphere. The resulting plot was a straight line whose y-intercept (zero air mass) was I_a and whose slope was τ_a. Stephenson did this on a monthly basis, yielding monthly values of I_a and τ_a, as commonly listed in the ASHRAE manuals.

Threlkeld's "standard" atmosphere was that at sea level, characterized by 2.5 mm of precipitable ozone, 200 dust particles per cc, and a varying amount of precipitable water vapor. Threlkeld determined the variable amount of water vapor on a monthly basis by a semiempirical technique. He used measurements of the broadband direct beam insolation (at Blue Hill, Mass.; Lincoln, Neb.; and Madison, Wis.), in conjunction with the Moon calculation routine, to derive indirectly the corresponding amount of precipitable water vapor. In other words, he derived the amount of water vapor simply by determining the value that made Moon's predictions agree with the measurements. He then took the mean of the values for each month and defined this water vapor monthly concentration as the "standard" atmosphere values. The monthly values given by Stephenson/ASHRAE are thus indicative of the monthly changes in atmospheric transmittance due to the changes in Threlkeld's "standard" atmosphere water vapor concentration.

The Clearness Number, CN, is a sort of atmospheric clarity adjustment to the Threlkeld "standard" atmoshere. He recognized the fact that the atmospheric transmittance of insolation will vary throughout the United States. To handle this, he defined the Clearness Number as:

$$CN = \frac{I\ (\text{measured})}{I\ (\text{standard, calculated})} \qquad (11)$$

Where: I (measured) = measured broadband normal incident solar insolation

I (standard, calculated) = calculated for the Threlkeld "standard" atmosphere

Hence, if I (measured) is greater than I (standard, calculated), the CN would be greater than 1.00, indicating a clearness or transmittance greater than the "standard" atmosphere. Because no measurements of the direct solar beam were available to Threlkeld for different locations in the United States, he calculated a CN based on measurements of precipitable water vapor and the Moon prediction model. This calculated clearness number is:

$$CN_c = \frac{I\text{ (calculated, actual } H_2O \text{ vapor)}}{I\text{ (calculated, standard atmosphere)}} \tag{12}$$

He then used Weather Bureau data [26] for water vapor at several locations in the United States to calculate the Clearness Number for these locations and to produce the well-known Clearness Number contour map of the United States used by ASHRAE [23].

The SIM model utilizes the same technique as ASHRAE for calculating clear day direct beam insolation [Equations (9) and (10)], except for a slight difference in the extraterrestrial insolation. ASHRAE uses the "apparent solar constant" I_a where SIM uses the following:

$$I_a \simeq (I_o)(R)(0.90) \tag{13}$$

where the factor of 0.90 was determined by Hulstrom [22] from experimental data to give a correlation between the actual and "apparent" solar constant. [See Ref. 27; Stephenson, From analysis of actual measurements, also proposed an "apparent" or effective solar constant of 385 Btu/ft^2 hr, or (428)(0.9).] Considering an average for twelve months, the comparison between the ASHRAE "apparent" solar constant and the one using Equation (13) is 4.6% whereas the comparison using Equation (13) is higher than the ASHRAE value. This is not considered a significant difference. The advantage in using Equation (13) is that the known variation of the extraterrestrial insolation with the earth-sun distance (the factor R) is preserved in the calculations. The factor 0.90, then, represents the average ratio of the extrapolated extraterrestrial insolation (ln I vs. sec θ_o, at secθ_o = 0 air mass) to the actual value; i.e., it is a correction to Beer's Law, Equation (5), for water vapor absorption over the entire broadband region.

SIM calculates the amount of diffuse sky irradiance on clear days by:

$$D_{cs} = (CI)/CN^2 \tag{14}$$

where C is the diffuse sky factor. This is the ASHRAE technique, taken from the work of Threlkeld [27] and Stephenson [24]. Stephenson derived the empirical term, C, from measurements by Threlkeld [27] that included 44 clear days in 1958 and 1959 at Minneapolis. Similar empirical correlations have also been made by Kimball [15].

For total overcast, no direct beam, SIM calculates the amount of diffuse sky irradiance by using a modification of the cloud cover factor technique derived by Kimura and Stephenson [20] and also used by ASHRAE. By analysis of total horizontal insolation on clear days, H_{clear}, and that on cloudy days, H_{cloudy}, Kimura and Stephenson derived the Cloud Cover Factor (CCF) as:

$$H_{cloudy} = H_{clear} * CCF \tag{15}$$

and

$$CCF = \frac{H_{cloudy}}{H_{clear}} \tag{16}$$

and

$$CCF = P + Q \cdot CC + R(CC)^2 \tag{17}$$

where P, Q, and R are empirical correlation coefficients and CC is the cloud cover (given in tenths). P, Q, and R were determined for four months (March, June, September, and December) corresponding to ranges of the solar elevation angles. P ranged from 0.95 (September) to 1.14 (December); Q ranged from 0.033 (June) to 0.003 (December) to -0.0108 (September). For simplicity SIM utilizes a yearly average of the three coefficients. The Cloud Cover is defined as the recorded total amount of cloud minus half of the amounts of cirrus, cirrostratus, and cirrocumulus. The CC formulation is then:

$$CC = TCA = 0.5(X) \tag{18}$$

where TCA is the Total Cloud Amount and X is the amount of cirrus clouds. For total overcast as addressed by SIM, TCA = 10.0; the amount of cirrus clouds is approximated by 0.25 TCA, giving a CC for total overcast conditions of 0.875 TCA or 8.75. Kimura and Stephenson give the diffuse sky insolation on a horizontal surface for cloudy conditions as:

$$D_{cd} = H_{clear} \left[CCF - K\left(1 - \frac{cc}{10}\right)\right] \tag{19}$$

where K is given by:

$$K = \frac{\sin \beta}{C + \sin \beta} + \frac{P - 1}{1 - Y} \tag{20}$$

and Y is given by:

$$Y = 0.309 - 0.137 \sin \beta + 0.394 \sin^2 \beta \tag{21}$$

where β is the solar elevation angle.

The final SIM formulation for the diffuse sky irradiance under cloudy conditions is:

$$D_{cd} = H_{clear} (CCF - 0.125K) \tag{22}$$

where CCF is given by Equation (17) and K is given by Equation (20).

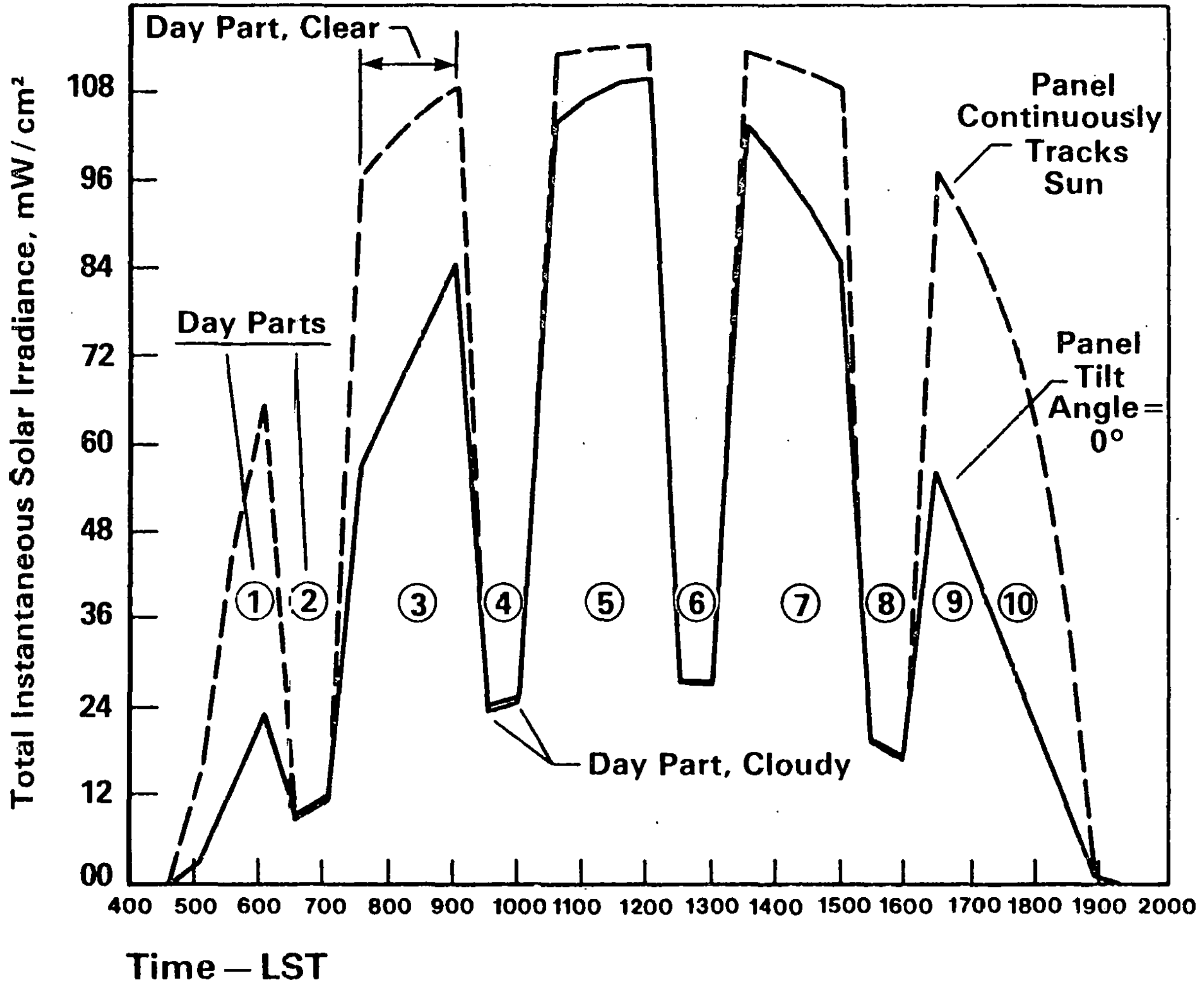
In order to eliminate the need for detailed observations of cloud cover, SIM utilizes the percentage sunshine. The specific site percentage sunshine is used to determine the portion of a day calculated according to the clear day formulations and the portion calculated according to the cloudy day (total diffuse, no direct beam) conditions. To do this, a Day Definition Matrix was developed as follows:

Table 3-2. DAY DEFINITION MATRIX[a]

Day Part	1	2	3	4	5	6	7	8	9	10	SUM
Day Fraction	0.12	0.08	0.12	0.08	0.12	0.08	0.12	0.08	0.12	.08	1.00
CC	0	10	0	10	0	10	0	10	0	10	
Clear	X		X		X		X		X		0.60
Cloudy		X		X		X		X		X	0.40

a Percentage sunshine = 60% monthly average
b Cloud cover in tenths
c Total cloud cover; no direct beam

Thirty-one calculations of insolation are made on an instantaneous basis for one day. One day is divided into 10 day parts. For each day part, a day fraction is assigned that specifies its length. For example, as shown above, a day fraction of 0.12 is equivalent to 0.12 times the total number of minutes (seconds) in that day. The day part is also designated as clear or cloudy. If it is clear, the clear day formulations are used to calculate the insolation (direct + diffuse); if it is cloudy (CC = 10), the cloudy day formulations are used. The lengths of the day fractions designated clear or cloudy are determined by the percentage sunshine. For example, if the site's percentage sunshine is 60% and the number of clear day parts is 5, the length of the day fraction is 0.60/5, or 0.12. The remaining time would be cloudy, 40%, and the day fraction is 0.08. The user can specify any order of clear and cloudy day parts or any number of day parts from 2 to 10. In normal operation, SIM takes the percentage sunshine and distributes it in five clear day parts and five cloudy day parts in an alternating sequence; i.e., clear - cloudy - clear - cloudy. An example of a SIM calculation of a total day of insolation is shown in Figure 3-25. The daily total insolation is determined by integrating over the daily profile of instantaneous insolation. Monthly or yearly amounts of insolation are then determined by summing the individual daily totals.



Solar Irradiance Model

Denver-Solar — Jun 15, 1976

Lat = 39.73 Long = 104.98

Figure 3-25. EXAMPLE OF SIM CALCULATIONS OF INSTANTANEOUS INSOLATION -- DAILY PROFILE

SIM also calculates the insolation on tilted surfaces by the formulation

$$H_{tilt} = I \cos \theta + D\frac{(1 + \cos \beta)}{2} + \rho H_h \frac{(1 - \cos \beta)}{2} \quad (1)$$

on the assumptions that diffuse skylight is isotropic, $\frac{(1 + \cos\beta)}{2}$ and the reflected radiation is isotropic, $\frac{(1 - \cos \beta)}{2}$. The user inserts values for the ground reflectance ρ.

The required inputs to SIM and user-selected variables are:

- site location (latitude, longitude);
- site percentage sunshine;
- site Clearness Number;
- collector tilt angle;
- collector orientation-azimuth; and
- ground reflectance.

The site percentage sunshine can be obtained for some 190 sites from the National Climatic Center, Asheville, N.C., Comparative Climatic Data. The site Clearness Number can be obtained from the U.S. contour maps in standard ASHRAE manuals.

Examples of the products of SIM are shown in Figures 3-11-a and b and 3-12-a and b which show that the variation in insolation is a function of time of day (for clear days only), collector tilt angle, and collector orientation. Simple three-dimensional plots such as these can be utilized by design engineers, architects, or collector installers to select the optimum tilt angle of the collector and to determine the maximum expected level of insolation. An insolation plot for every day throughout the year is shown in Figure 3-26. When the daily total insolation throughout the year (including the seasonal variation of percentage sunshine and Clearness Number) is considered as a function of collector tilt angle, the collector tilt angle receiving maximum insolation for the heating or cooling season is readily apparent. Simple plots such as Figure 3-26 could become inexpensive design tools for architects, installers, and the private sector. Because of the simplicity and low cost of the SIM program, such plots could be generated for numerous cities and geographical regions in the United States, an activity which is being considered by the SERI Commercialization and Information Systems Divisions.

The agreement of the SIM predictions with actual SOLMET data (Table 3-1) is encouraging. Certainly SIM is as accurate or more accurate than the ASHRAE techniques for predicting the mean daily total horizontal insolation, whereas solar flat plate thermal collectors require the total insolation on a tilted surface. Predicting the latter, as was pointed out in Section 2.1, is quite different from predicting total horizontal insolation. The major problem in

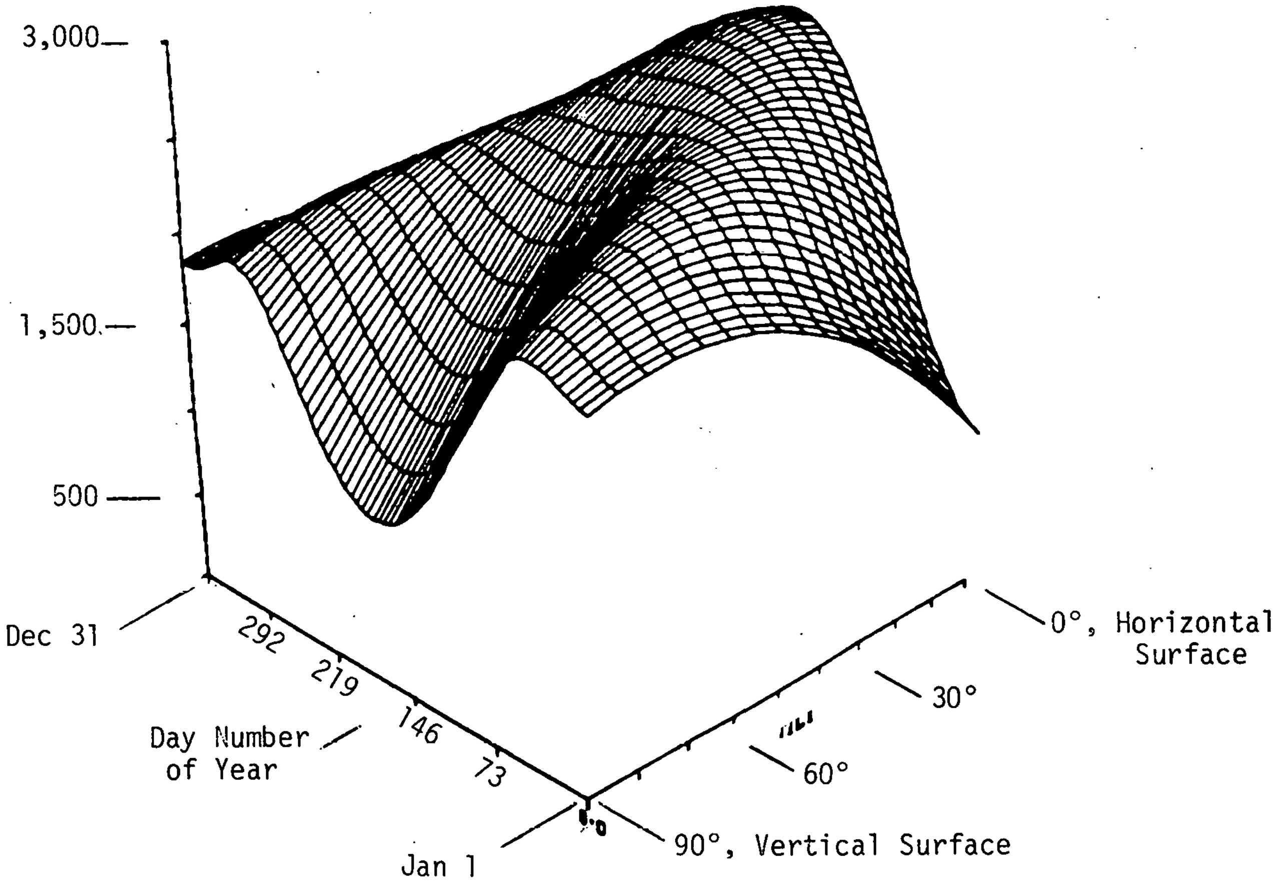


Figure 3-26. TOTAL (Btu/Ft^2 DAY) DAILY INSOLATION ON VARIOUS TILTED SURFACES, POINTED SOUTH, FOR ONE YEAR PERIOD, DENVER, COLORADO, CLEAR SKY CONDITIONS

predicting total insolation on a tilted surface is that if accurately predicting the direct beam insolation, the diffuse sky insolation on the tilted surface, and the reflected ground radiation. The comparisons shown in Table 3-1 are for the total horizontal insolation, the sum of direct and diffuse components. Thus, the comparison of total horizontal insolation does not uniquely determine the accuracy of the direct and diffuse sky irradiance predictions which would determine the accuracy of the predictions of insolation on tilted surfaces.

Future efforts involving the SIM program will compare the predictions of the direct, diffuse, and tilted-surface insolation with actual data. The data generated by the IRF facility can certainly be used for such comparisons along with similar data generated by the university research stations and measurements from the new NWS insolation network.

Future efforts involving the SIM program will also include the improvement of insolation calculation techniques, mainly in calculating the direct solar beam insolation. The Clearness Numbers used by SIM and ASHRAE can be improved substantially by using new models such as SOLTRAN and more recent data for water vapor at the geographical sites. It will be recalled that Threlkeld used the outdated Moon model for the atmospheric spectral transmittance, limited water vapor data for the United States, and assumed that the dust content of the atmosphere was constant throughout the United States. He considered only "clear" rural atmospheres, not real urban atmospheres. The data from the IRF facility, the university research stations, and the new NWS network can also be used to measure the Clearness Number and compare measured values with the Threlkeld predictions and SOLTRAN.

The methods by which SIM and ASHRAE techniques utilize percentage sunshine require further review and investigation. These techniques basically assume that the percentage sunshine values represent completely clear "bright" conditions of the direct beam. It is known that the percentage sunshine instruments could register sunshine while thin clouds are in front of the sun, thereby resulting in much lower values for the direct beam. Watt [28] has compared predictions of the direct solar beam using the Moon techniques and percentage sunshine (for monthly average values) to actual measurements at three sites. Watt contends that the actual direct beam insolation is only 85% of that predicted by the percentage sunshine-atmospheric transmittance technique. However, transmittance comparisons were done for only two sites--Albuquerque, N.M., and Maynard, Mass. Only the Albuquerque site had actual percentage sunshine spatially coincident with the direct beam data. For the Maynard, Mass., site, estimated values used sky cover data from Blue Hill, Mass., 25 miles away, and percentage sunshine data from Boston, Mass., 25 miles away. The ratio of the actual to predicted values of the direct solar beam is most likely site dependent because it is determined by the specific cloud and atmospheric conditions such as haze. Further investigations are required to understand this problem, so that SIM and ASHRAE sunshine-based models can be improved. One model that would benefit from such studies would be the SOLCOST model.

The SIM program will be improved through improved empirical determinations of such parameters as the "apparent" atmospheric optical attenuation coefficient, the "apparent" solar constant, the diffuse sky factor, and the Cloud Cover

Factor or similar empirical cloud cover modifiers. For example, Sadler [29] has found an apparent optical attenuation coefficient and diffuse sky factor are similar to those derived by Stephenson/ASHRAE, his apparent solar constant is significantly lower than the ASHRAE and SIM values. Studies such as this will be reviewed for possible incorporation in SIM.

3.3 ESTABLISH SOLMET DATA BASE

This Subtask (3603.3) is a nontechnical effort directed at establishing the SOLMET data base for SERI use. The task effort consisted of simply implementing the SOLMET tapes available from the National Climatic Center on the SERI computer system. The SOLMET rehabilitated data sites are shown in Figure 3-27. The currently available tapes are for the hourly solar radiation data; the data for daily solar irradiation, termed SOLDAY, will be available in the near future. The detailed information content and format of SOLMET data tape are shown in Figure 3-28. Data from the new NWS network will be in this format and available in the near future.

3.4 MONITOR SOLAR ENERGY RESEARCH METEOROLOGICAL SITES

This Subtask (3603.4) is designed to aid DOE in monitoring the eight university Solar Energy Meteorological Research Sites (SEMRS) program.

The SEMRS program began on November 9, 1977, with a meeting of the university principal investigators, the DOE Environmental and Resource Assessment Branch, NOAA Air Resources Lab, and SERI. The major purpose of this meeting was to review each university program and to identify specific research measurements, instrumentation, data recording intervals, and data recording techniques.

Specific SERI ERAB contributions included the following:

- formulation and delivery to DOE of a detailed matrix of specific research measurements, instrumentation to be used, procedure, sampling, and comments;
- coordination of the purchasing of instrumentation, by which a 10 to 15% cost saving on the instrumentation to be purchased by the universities was negotiated;
- coordination of the design and development of a tracking disk shading mechanism for pyranometers;
- direct aid to the universities concerning the UV and IR tracking standards; and
- review of the university technical programs for the first year.

On May 16 and 17, 1978, the first Quarterly Management Review of the Solar Energy Meteorological Research Sites Program was held at DOE. The SERI ERAB attended and participated in the review.

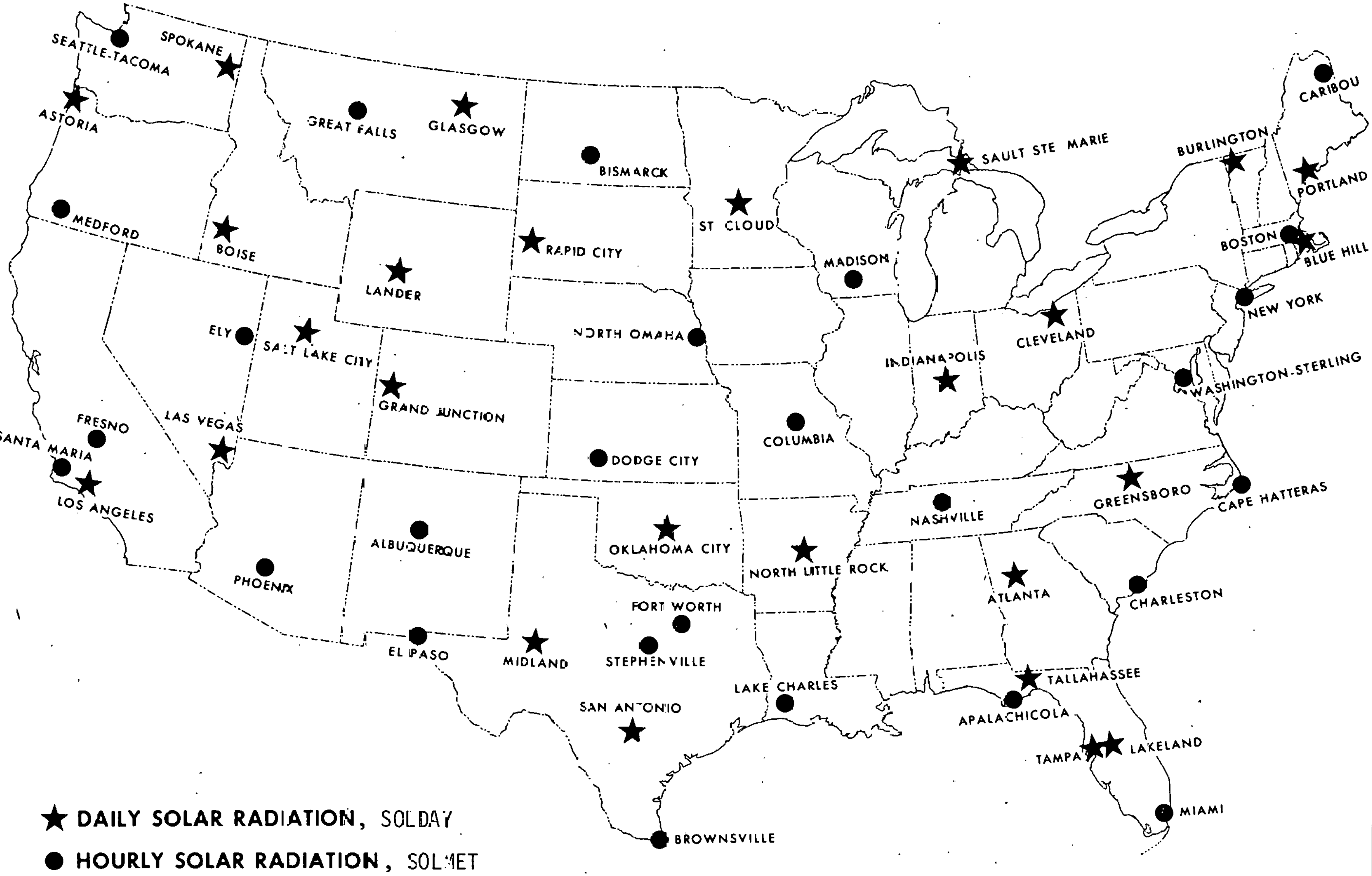


Figure 3-27. SOLMET AND SOLDAY SITES HAVING REHABILITATED INSOLATION AND METEOROLOGICAL DATA BASE

IDENTIFICATION							SOLAR RADIATION OBSERVATION										
TAPE DECK #	WBAN STN #	SOLAR TIME				LST TIME	ETR KJ/m²	RADIATION VALUES KJ/m²									SUNSHINE MIN
								DIRECT	DIFFUSE	NET	TILTED	GLOBAL			A	B	
		YR	MO	DY	HRMN							OBS	ENG COR	STD YR COR			
9724	XXXXX	XX	XX	XX	XXXX	XXXX	XXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	XX
FIELD NUMBER 001	002	003				004	101	102	103	104	105	106	107	108	109	110	111

SURFACE METEOROLOGICAL OBSERVATION																											
OBS. TIME LST	CEILING dam	SKY COND	VSBY hm	WEATHER	PRESSURE kPa		TEMP °C		WIND		CLOUDS																SNOW COVER
											TOTAL	LOWEST			SECOND				THIRD				FOURTH			OPAQUE	
					SEA LEVEL	STATION	DRY BULB	DEW-PT.	DIR deg	SPD m/s		AMOUNT	TYPE	HEIGHT dam	AMOUNT	TYPE	HEIGHT dam	SUM AMT	AMOUNT	TYPE	HEIGHT dam	SUM AMT	AMOUNT	TYPE	HEIGHT dam		
XX	XXXX	iXXXX	XXXX	XXXXXXXX	XXXXX	XXXXX	XXXX	XXXX	XXX	XXXX	XX	XX	XX	XXXX	XX	XX	XXXX	XX	XX	XX	XXXX	XX	XX	XX	XXXX	XX	X
201	202	203	204	205	206		207		208		209																210

TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT
001	001 - 004	TAPE DECK NUMBER
002	005 - 009	WBAN STATION NUMBER
003	010 - 019	SOLAR TIME (YR, MO, DAY, HOUR, MINUTE)
004	020 - 023	LOCAL STANDARD TIME (HR AND MINUTE)
101	024 - 027	EXTRATERRESTRIAL RADIATION
102	028 - 032	DIRECT RADIATION
103	033 - 037	DIFFUSE RADIATION
104	038 - 042	NET RADIATION
105	043 - 047	GLOBAL RADIATION ON A TILTED SURFACE
106	048 - 052	GLOBAL RADIATION ON A HORIZONTAL SURFACE - OBSERVED DATA
107	053 - 057	GLOBAL RADIATION ON A HORIZONTAL SURFACE - ENGINEERING CORRECTED DATA
108	058 - 062	GLOBAL RADIATION ON A HORIZONTAL SURFACE - STANDARD YEAR CORRECTED DATA
109, 110	063 - 072	ADDITIONAL RADIATION MEASUREMENTS
111	073 - 074	MINUTES OF SUNSHINE
201	075 - 076	TIME OF COLLATERAL SURFACE OBSERVATION (LST)
202	077 - 080	CEILING HEIGHT (DEKAMETERS)
203	081 - 085	SKY CONDITION
204	086 - 089	VISIBILITY (HECTOMETERS)
205	090 - 097	WEATHER
206	098 - 107	PRESSURE (KILOPASCALS)
207	108 - 115	TEMPERATURE (DEGREES CELSIUS TO TENTHS)
208	116 - 122	WIND (SPEED IN METERS PER SECOND)
209	123 - 162	CLOUDS
210	163	SNOW COVER INDICATOR

7/77

Figure 3-28. SOLMET DATA TAPE CONTENT AND FORMAT

3.5 PROVIDE INFORMATION TO DOE, SERI, INDUSTRY, AND THE PRIVATE SECTOR REGARDING INSOLATION MODELS AND DATA BASES

The FY78 effort on this Subtask (3603.5) consisted of general support and advice to other SERI branches, DOE, industry, and the private sector.

Other SERI branches were provided with insolation models and data bases for incorporation into their investigations:

- the SOLMET data base, conversion algorithms, and the SIM model for use in the SERI Thermal Conversion Branch study of industrial process heat;
- the SOLTRAN program to the SERI Photovoltaics Branch for use in determining photovoltaics device efficiency;
- the SOLMET data base to the SERI Systems Analysis Branch for use in study of wind/solar power systems; and
- providing consultation and aiding the SERI Commercial Readiness Branch concerning insolation models and data products for the building and architectural industries.

The SIM model was also provided to the Electric Power Research Insititute (EPRI) for their evaluation. By assisting EPRI in their requirements for insolation models, conversion algorithms, and data bases, SERI ERAB will communicate its developments directly to the utility industry. The communications between EPRI and the SERI ERAB have been frequent and beneficial.

The SERI ERAB receives numerous phone calls and letters from private industry and the private sector concerning insolation models and data bases. A mailing list is being compiled so that SERI ERAB results can be applied directly to the private sector.

REFERENCES

1. Moon, P., 1940. "Proposed Standard Solar Radiation Curves for Engineering Use", Journal of the Franklin Institute, Vol. 20, p. 583.

2. Gates, D. M., 1966. "Spectral Distribution of Solar Radiation at the Earth's Surface", Science, 4 Feb. 1960, Vol. 141, No. 3710.

3. Thekaekara, M. P., 1976. "Experimental and Theoretical Studies on Solar Energy for Energy Conversion", Volume 1, International & U.S. Programs Solar Flux, Sharing the Sun, Solar Technology in the Seventies, Joint Conference of the American Section ISES and Solar Energy Society of Canada, Inc., Aug. 15-20, 1976.

4. Fowle, F. E., 1918. "The Atmospheric Scattering of Light", Smithsonian Misc. Coll., Vol. 69, No. 3, 1918.

5. Elterman, L., 1968. "UV Visible, and IR Attenuation for Altitudes to 50 Km", AFCRL-68-0153.

6. Angstrom, A., 1929. "On the Atmospheric Transmission of Sun Radiation and on Dust in the Atomsphere", Geograph, Ann. 11, p 156-166.

7. Gates, D. M., 1960, "Near Infrared Atmospheric Tranmissions to Solar Radiation", Journal of the Optical Society of America. Vol. 50, No. 12.

8. Gates, D. M., and W. J. Harrop, 1963. "Infrared Transmission of the Atmospheric to Solar Radiation", Applied Optics, Vol. 2, No. 9.

9. Thekaekara, M. P., 1965. "The Solar Constant and Spectral Distribution of Solar Radiant Flux", Solar Energy, Vol. 9, No. 1, January 1965, page 7.

10. Goody, R. M., Atmospheric Radiation, Clarendon Press, Oxford, England, 1964.

11. Penndorf, R. J., Journal of the Optical Society of America, 47, 176, 1957.

12. Selby, J. E. A. and R. A. McClatchey, 1975. "Atmospheric Transmittance from 0.25 to 28.5 Microns: Computer Code LOWTRAN 3", Air Force Cambridge Research Labs, AFCRL-TR-75-0255, AD-A017 734.

13. McClatchey, R. A., R. W. Fenn, J. E. A. Selby, F. E. Volz and J. S. Goring, 1972. Optical Properties of the Atmosphere (Third Edition), AFCRL-72-0497.

14. Selby, J. E. A., F. Y. Kneizys, J. H. Chetwynd Jr., and R. A. McClatchey, 1978. Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 4 , AFGL-TR-78-0053.

15. Kimball, H. H., 1919. "Variations in the Total and Luminous Solar Radiation with Geographical Position in the United States", Monthly Weather Review, Vol, 47, No. 11, W. B. No. 699, pages 769-793.

16. Davies, J. A. and J. E. Hay, 1978. "Calculation of the Solar Radiation Incident on a Horizontal Surface", Proceedings, First Canadian Solar Radiation Data Workshop, April 17-19, 1978, to be published by the Canadian Atmospheric Environment Service.

17. Braslau, N. and J. V. Dave, 1973. "Effect of Aerosols on the Transfer of Solar Energy Through Realistic Model Atmospheres; Part 1: Nonabsorbing Aerosols", Journal of Applied Meterology, 21, pages 601-615.

18. Louis, A. A., and J. E. Hansen, 1974. "A Parameterization for the Absorption of Solar Radiation in the Earth's Atmosphere", Journal of Atmospheric Science, 31, pp 118-133.

19. Schlagheck, R. A., 1977. "Solar Insolation Algorithm Model Comparison Using SOLMET Data", presented at the DOE-sponsored Solar Heating and Cooling System Simulation and Economics Analysis Working Group Meeting, Nov. 14, 1977, Golden, Colorado.

20. Kimura, K. and D. G. Stephenson, 1969. ASHRAE Transactions, paper 2106, pages 227-233; and Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations, ASHRAE, 1975.

21. ASHRAE Fundamentals Handbook, Chapter 22; and ASHRAE Transactions, paper 2110, pages 34-42, 1969.

22. Hulstrom, R. L., 1977. "An Accurate, Economical, Solar Insolation Computer Model for the United States", Proceedings of the 1977 Annual Meeting of the American Section of the International Solar Energy Society, Volume One, Sections 14-25, pages 14-11.

23. Applications of Solar Energy for Heating and Cooling Buildings, ASHRAE GRP 170, 1977, Edited by R. C. Jordan and B. Y. H. Lin, Chapter IV.

24. Stephenson, D. G., 1967. "Tables of Solar Altitude and Azimuth, Intensity and Solar Heat Gain Tables", Tech. Paper No. 243, Division of Building Research, National Research Council of Canada, Ottawa, April 1967.

25. Threlkeld , J. L., 1958. ASHRAE Transactions, Vol. 64, pages 45-68.

26. "Mean Precipitable Water in the United States", U.S. Weather Bureau Technical Paper No. 10, April 1949.

27. Threlkeld, J. L., 1963. "Solar Irradiation of Surfaces on Clear Days", ASHRAE Transactions, Vol. 69, 1963, p. 24.

28. Watt, D., 1978. "On the Nature and Distribution of Solar Radiation", DOE Contract No. EX-76-C-01-2552. Report No. HCP/T2552-01.

29. Sadler, G. W., 1970. "Measurement of Apparent Solar Constant and Apparent Extinction Coefficient at Edmonton (Alberta) Canada", Solar Energy, Vol. 3, pages 35-41.

No. of Copies	Distribution
	Department of Energy
	DOE, SERI Site Officer Contracting Officer Attn: Charles M. Skinner
1	Chicago Operations Office Interim Program Division Attn: M. E. Jackson
1	Division of Solar Technology Office of Asst. Director for Administration Attn: R. H. Annan
2	Office of Asst. Secretary for Conservation & Solar Applications Attn: R. Scott
1	Office of Solar, Geothermal Electric & Storage Programs Attn: H. H. Marvin
2	Division of Energy Technology Administration Attn: S. Hansen
1	Division of Distributed Solar Technology Office of the Director Attn: R. San Martin
1	Division of Central Solar Technology Office of the Director Attn: H. Coleman
1	Division of Energy Storage Systems Office of the Director Attn: G. Pesdirtz
1	Division of Planning & Energy Transfer Office of the Director Attn: M. Adams

☆ U.S. Government Printing Office: 1979—O-677-083/5