# Advances in Solar Energy

## An Annual Review of Research and Development

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# NOTICE



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# FOREWORD

The field of solar energy conversion has become an important discipline with a recognized potential to significantly contribute to the world supply of energy. It is diversified and encompasses a wide variety of disciplines — from mechanical engineering to physics, from biology to architecture, from ocean science to agriculture, from chemistry to atmospheric science, to name some of the major fields. It involves fields which have matured to the engineering aspects, such as the conversion of solar energy into heat or of wind into shaft work. It includes other fields in which more basic science research is necessary to unravel the micro-structures of nature, as, for example, for photovoltaic conversion or for certain bioengineering tasks.

Several of these fields have elements which have been common knowledge for centuries but sometimes forgotten at times of cheap energy supplies, while others have barely started with first studies. Most of the fields have seen during the last decade a substantial advance in sophistication, in theoretical understanding, in demonstrated feasibility, in developing hardware, in field testing, with some moving into a phase of initial commercialization.

As a field matures, need develops for a periodic, extensive survey on a larger sphere and level of completion than is usually covered in journals. These surveys are customarily the domain of "Advances in..." or other review volumes. Their aim is to assist the newcomer through a critical overview and a guide to who's who in the field. At the same time they assist the experienced researcher by providing a comprehensive and critical survey.

The state of development of solar energy conversion now demands such comprehensive reviews, and *Advances in Solar Energy* is designed to meet this need. The reviews will serve to bring together in a single document the results of years of work by many researchers in various locations, and also provide a comprehensive bibliography. There is sufficient knowledge in many facets of the field to warrant a detailed and comprehensive review, and to enlist the most qualified reviewer to present the material in a critical, yet not one-sided approach. We will proceed, therefore, according to the state of readiness of each of the topics, rather than along a sequential arrangement as is found in textbooks. Each of the topics shall be self-contained and may, in turn, reference not only original work but sub-topics reviewed in journals. As time progresses we will update reviews of subjects which, in the meantime, have advanced substantially.

Early volumes of this series will tend to emphasize more mature subjects. Later volumes may, in addition, start to treat areas that are not so mature, where the research is more current, and where implications of some results of the research may be more speculative.

The reader will find in the writings in this first volume of *Advances in Solar Energy* some variations in style and scope of the reviews. This is to be expected. Some of it will vanish as the field and this series mature; some of it will persist as we are serving a wide variety of readers.

To close this foreword, we express gratitude to the American Solar Energy Society for recognizing the timeliness and importance of this series and having offered to act as publisher, to Albert Henderson, as Director of the Publications Office, for having stimulated and encouraged the start-up, and to Barbara Bradley, as Publications Production Manager, for having put this volume together with patience and attention to the whole as well as to minute details.

Karl W. Böer
John A. Duffie
Co-Editors-in-Chief

# TABLE OF CONTENTS

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# RADIOMETRY—THE DATA

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**Abstract**
This chapter presents a summary of many of the important advances in the art and science of the use of solar radiation measurements. Emphasis is placed on those advances which will have the most impact in the utilization of solar energy. The work cited is mainly that done since 1977. The literature includes more comprehensive texts on solar radiation measurement,[1-3] a bibliography,[4] and a previous review of this field.[5]

## USES OF SOLAR RADIATION DATA

Today most people are aware that solar energy is potentially a major energy source for the world. Already there are significant applications where solar energy is replacing other energy sources in a cost-effective manner. The most common of these are:

- domestic water heating;
- space heating of buildings;
- electric power for remote installations; and
- electric power for spacecraft

A variety of other applications are possible for the future.

One of the major benefits of the solar energy resource is that it is generally available at the location where the energy is needed. Thus, transmission lines or transportation of fuel is unnecessary. However, since the availability of solar radiation does vary from place to place and time to time, a knowledge of the expected future availability is necessary for the design of solar systems. Solar system designers are the largest group of users of solar radiation data.

Another important use of solar radiation resource data is economic planning. Global and national energy resource planning is beginning to include solar radiation availability as a significant factor.

Solar radiation provides both desirable and undesirable energy contributions to buildings. Any designer of modern, high-rise buildings will analyze the projected solar energy gain of the building as part of the design process. Solar radiation data is a necessary input to this analysis.

Meteorologists and climatologists use solar radiation data in modeling the energy flows within the atmosphere. The energy input to this system is almost exclusively from the sun. Understanding the climate and weather requires a detailed knowledge of the solar radiation availability.

Agriculture is a major user of solar radiation data. Plants convert the available solar radiation by photosynthesis into chemical energy or biological energy. Models of agricultural productivity often include solar radiation measures. The irrigation requirements for crops are highly dependent upon evapotranspiration, which in turn is a function of solar radiation.[6] Brown et. al., state that forecasts of solar radiation availabilities are used for scheduling irrigation.[7] The

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forecasting is important because the magnitude of the irrigation system requires many days of advance planning.

Solar radiation is a major factor causing the weathering of materials. The precise measurement of solar radiation and knowledge of its distribution is important to testing of the durability of materials.[8]

Recently, it has been recognized that high levels of solar radiation, especially in the ultraviolet, may be an important factor in causing human skin cancer.

Statistics on use of solar radiation data show that in 1979 alone the Environmental Data Service of the National Climatic Center responded to 1,714 separate requests for solar radiation data. These are in addition to the over 300 regular recipients of published solar radiation data.[9] Many of these are institutions which then process the data and pass on the results in a different form to groups of users.

## TRENDS IN DATA COLLECTION AND USE

Today there is a strong trend toward improved data collection methods and instrumentation, resulting in more accurate, more meaningful, and more useful data. The major elements causing this trend are:

- much greater use of the data by a wider population of users;
- increasing availability of higher quality sensors;
- increased use of high quality sensors;
- improved data recording devices;
- more accurate calibration methods and more widespread knowledge about their use;
- increased use of digital computers and availability of solar radiation data in computerized form; and
- better data processing methods, including better methods for detecting and correcting errors.

Solar radiation has been measured regularly at many locations since the early 1900s. The earliest measures were attempts to determine the value of the "solar constant"* and its possible variation by careful measures of the direct solar beam radiation at a variety of locations. Later measures were directed more toward the understanding of the energy available for the growth of crops and the energy inputs for weather phenomena. The most recent interest in the measurement of solar radiation has been for a better understanding of the energy impacts of climate on buildings and the development of solar energy systems.

Historically, solar radiation data have been summarized and published in the form of daily or monthly averages. However, the increased use of electronic digital computers has caused the use of detailed simulation models to be developed, and the demand for solar radiation data on an hourly basis has increased. Many researchers have demanded actual measures of hourly data in order to investigate the dynamic performance of systems in a realistic environment. Within the past year (1981), hourly solar radiation data have even become available for microcomputers on a floppy diskette.[10]

The basic instruments for the measurement of solar radiation are pyranometers, which measure the radiation incident on a horizontal surface, and pyrheliometers, which measure the beam radiation in a plane normal to that beam. Historically, a variety of other names have been applied to these instruments, but the type of measurement has been typically one of these two. Recent improvements, such as temperature compensation, have made these instruments more accurate and easier to use.

The best quality pyranometers are thermopile instruments. The stability of the calibration of instruments is very important, and has been a major problem for both manufacturers and users. The Precision Spectral Pyranometer (PSP) of the Eppley Laboratory is widely accepted as the best quality, commercially available instrument because of its demonstrated stability and other inherent characteristics. A new instrument was announced in 1981 by Kipp & Zonen, which is similar to the PSP, except that the manufacturer uses thick-film, mass-production techniques for the thermopile. If this instrument proves to be sufficiently stable, then it is likely it will be adopted widely if it maintains a lower cost.

Until the mid 1970s, few long-term, continuous measurements were made of the direct-beam solar radiation. The major problem had been the design of an instrument which would reliably track the diurnal and annual motions of the sun. The Eppley Tracker, which tracks the diurnal motion, has made beam measurements

*The solar constant is the flux of solar radiant energy across a unit area oriented normal to the solar beam at the mean earth-sun distance.

practical in some climates, but a number of problems still remain. These are:

- the difficulty in aligning the tracker axis parallel with the earth's polar axis to the necessary precision;
- the need for once or twice weekly manual adjustment of the tracker to account for the change of declination of the sun; and
- the inability to set or align the tracker when the sun is obscured by clouds.

New trackers have now been developed which alleviate the last two of these problems. These trackers are controlled by microprocessors and follow both the diurnal and annual motions of the sun. A problem with these trackers is that they are expensive.

Data collection, in the past, has been treated one parameter at a time. Temperature was recorded by one instrument, the data were processed in one way at one time, archived in one place, and published in one document. Wind was treated separately. Solar radiation data were still different. The data user had to search in different places for different parameters covering the same time period at the same location. It was up to the user to fill in missing data or to find complete data sets for matching time periods. Solar data were integrated over one time period related to solar time, and temperature data were integrated over another, related to local standard time. The result was that people relied heavily on statistically developed, representative-of-average data sets for design purposes.

Today, the data are beginning to be collected by one data recording system using standard times for all parameters and recording all the data on one computer-readable medium. Combined data sets prepared for specific purposes are beginning to emerge. The SOLMET data available for the U.S. is an example. These data provide a much improved dynamic picture of the environment for building and solar system designers.

Along with the coordinated data collection systems, better data processing methods are developing. Models are being used to check the reasonableness of the measured data. Two basic types of checks are used: the first is a check to see if the values are reasonable for the date of recording, and the second is the comparison of related measures by using a model which predicts one from the other. When these checks are applied during, or soon after, the measurement itself, problems with the instruments or recording system can often be detected before many data are lost.

Much of the need for measures of solar radiation is for the availability on surfaces which are nonhorizontal. The most convenient and generally adequate method for obtaining these data is by the use of models. The reason for this is that a significant portion of the solar energy available on nonhorizontal surfaces is reflected from the ground and other surroundings, and the reflectivity of these surroundings changes drastically even over very short distances. Thus, nonhorizontal measures of the energy incident on surfaces at one point are not necessarily representative of those at another point, even a short distance away. Models are used to transform the measures of the solar radiation incident on a horizontal surface to those on a nonhorizontal surface. The improved measurements mentioned in the foregoing paragraphs, and specialized measures of solar radiation on nonhorizontal surfaces where the reflectivity is known, are promoting the development of better models.

Another use of specialized measures of solar radiation is the use of "reference cells" for the testing of photovoltaic devices. A reference cell is a photovoltaic cell, usually from the same production process as those to be tested, which has been calibrated by a testing laboratory. The use of a reference cell is necessary because other instruments for measuring solar radiation do not have the same spectral response as the photovoltaic devices to be tested. The choice of a cell from the same production process is intended to minimize the effect of the natural spectral variations in solar radiation on the test results.

There has been an increased awareness of the importance of measurements of the spectral distribution of solar radiation. The need to estimate the solar radiation resource availability for photovoltaic devices has caused many persons to look for data which show the impact of the spectral characteristics of atmospheric absorption on the solar radiation resource availability for photovoltaic devices. There are a number of factors which must be considered. These are:

- most measures of solar radiation availability are made with instruments having equal sensitivity to the all parts of the solar spectrum;
- photovoltaic devices are sensitive to only a restricted part of the solar spectrum;

- different photovoltaic devices have different spectral sensitivities;
- the spectral transmission of the atmosphere varies with the varying climatic conditions, the major effects being absorption by water vapor, and absorption and scattering by atmospheric dust and gaseous molecules;

and

- some of the energy scattered from the solar beam reappears as diffuse solar radiation. This scattering is strongly dependent on the wavelength, and has its most rapid change in the region of the spectrum where the photovoltaic sensitivity is the greatest.

The resulting problems are:

- the accuracy of the resource estimates for flat-plate photovoltaics using the traditional measures will depend upon the atmospheric conditions at the time of use; and
- the accuracy of the resource estimates for concentrating photovoltaic systems will be even poorer than those for flat plate systems. Additional measures of the atmospheric characteristics are needed to improve the accuracy of the knowledge of the resource for these concentrating systems.

The increased development, testing, and application of mathematical models of the spectral characteristics of atmospheric transmission are due to the more widespread availability of computers and the decreasing cost of their use. These improved models are also showing us where improved instrumentation is needed and assisting in the definition of new instruments and measures.

Another trend is the decreasing use of the bimetallic strip type of solar radiation sensors. The general reason here is that these instruments tend to have poor accuracy.

## EDUCATION, TRAINING, AND DISSEMINATION OF KNOWLEDGE

The recent interest in solar energy has created a much greater demand for solar radiation data than previously existed. More people are measuring solar radiation, more people are using the data, and there is a demand for more and better quality data.

The methods of measurement and the problems in using solar radiation data are not immediately obvious to the untrained user. A number of recent publications and workshops have helped eliminate the gap in that knowledge. Representative of these are:

(a) *The California Solar Data Manual.*[11] This publication provides general solar radiation data for the state of California, along with general formulas and other appropriate information for design of solar systems.

(b) *Radiation Measurement.*[12] This booklet describes instruments, their installation, calibration, and use. It is intended for the scientist or engineer who wants to set up a sophisticated solar radiation measuring station.

(c) *An Introduction to Meteorological Measurements and Data Handling for Solar Energy Applications.*[13] A compendium of chapters by many authors which serves as an introduction to solar radiation measurement.

(d) *Listing of Solar Radiation Measuring Equipment and Glossary.*[14] A listing of manufacturers as of 1976.

(e) *On the Nature and Distribution of Solar Radiation.*[15] An introduction to solar radiation and its atmospheric interaction.

(f) *Solar and Terrestrial Radiation.*[3] A text with emphasis on radiation instrumentation.

(g) Numerous solar radiation workshops have been held in the U.S. These have been sponsored by the U.S. Department of Energy, and most have been organized by one or more of the eight University Meteorological Research and Training sites.[16]

(h) There have been periodic review meetings of the U.S. Department of Energy contractors in the field of solar radiation resource assessment. These meetings have provided a center for information exchange and researcher interaction in the U.S. since 1975.

## RESEARCH FACILITIES

A number of research facilities have recently been established in the U.S. which have provided, and will continue to provide, advances in the knowledge about solar radiation and its interaction with the atmosphere. Four of these are:

(1) The Solar Energy Research Institute (SERI), which has one entire division dedicated to solar radiation and solar energy resource evaluation. SERI is located in Golden, Colo., and was established in 1976.

(2) The eight University Meteorological Research and Training sites, which were established in 1977.[16] These are located at universities with atmospheric science units, as follows:

(a) The University of California at Davis
(b) The State University of New York at Albany
(c) The Georgia Institute of Technology at Atlanta
(d) The Solar Data Center, Trinity University at Antonio
(e) Oregon State University at Corvallis
(f) The University of Michigan at Ann Arbor
(g) The University of Alaska at Fairbanks
(h) The University of Hawaii at Honolulu

(3) The Solar Radiation Facility of NOAA Environmental Research Laboratory which was established at Boulder, Colo., in 1975. The primary purpose of this facility is to maintain standards and calibrate solar radiation measuring instruments for the U.S. government. Much of the current knowledge about the performance of solar radiation measuring instruments has come from research and calibration tests done there.[17]

(4) The DSET Laboratories at New River, Ariz., has recently established facilities for international solar radiation measuring instrument intercomparisons and calibration.[8]

## PROCESSING, ARCHIVING, AND PUBLICATION

Solar radiation measurements for resource assessment are usually summed over hourly or daily time intervals, and then archived. The resource data customarily have been published as average monthly values. Some processing of the data is obviously needed between measurement and publication.

Undetected errors can contaminate large data bases, making them of poor quality or even unusable. Sometimes errors can be detected and partially corrected, even many years after they occur. The best time to detect measurement errors, however, is during or as soon after measurement as possible. An excellent example of a system to detect errors is given by Wendler et. al.[18]

The following sections illustrate some of the problems in processing, archiving, and publication. Corrective procedures are noted and procedures for the publication of the data in one specific format are identified. The methods developed, while solving problems, were applied to provide additional data sets generated by regression models. These sections provide good examples of potential problems and possible solutions.

## REHABILITATION OF THE U.S. SOLAR RADIATION DATA BASE

This section describes a major effort to correct historical errors in the U.S. solar data base. The U.S. experience is not the first, nor will it be the last, of this type. This author has seen many other data bases with similar problems. Unfortunately, errors are often detected only when it is too late, and the usual solution is to discard the data. The rehabilitation methods are described here because important methods were developed for detecting and for correcting errors in solar radiation data.

The cause of the errors in the U.S. data base was two-fold. First, the lack of interest in the measurement program caused a situation where there was little support, and the training of those managing the program was inadequate. Second, a change in the manufacturing process for the instruments used created a situation where the calibration of some instruments changed with time. The most comprehensive description of this effort is given in Ref. 19. The following is excerpted from that reference. The long-term errors are described as:

(a) instrument sensitivity changes;
(b) improper calibration;
(c) wrong units used;
(d) changes in sensor environment or location;
(e) undocumented instrument changes;
(f) temperature sensitivity of calibration factor.

Besides these shortcomings, the solar radiation data were also referenced to two different international scales.

The rehabilitation process was divided into three phases:

(a) clean up and reformating;
(b) correction and quality control; and
(c) modeling and completion.

The clean-up and reformating phase consisted of:

(a) organizing the data and cataloging it;
(b) identifying and labeling any missing values;
(c) converting the entire solar data set to one time scale; and
(d) converting the data to metric units.

At the end of this phase, meteorological data were merged with the solar radiation data and temperature corrections were applied to the solar data to compensate for the temperature coefficient of the older instruments.

The correction and quality control phase consisted of:

(a) reasonableness checks on the data. The following situations were flagged as potential errors and checked individually:

- solar radiation > 0 during night;
- temperature > 51.7°C
- dew point > dry bulb, and so on.

(b) Engineering corrections, including:

- calibration changes;
- solar radiation scale differences;
- midscale recorder chart setting;
- Parson's black paint degradation;
- so-called crossmatch problem;
- temperature response.

These engineering corrections were all based on the historical records of the instrument, station, or recorder, and were based on documented effects which could be defined and quantified. Figure 1 gives an idea of the data prior to the engineering corrections.

(c) Standard Year Irradiance (SYI) Corrections. A standard year irradiance model was developed by Hanson and Hoyt which calculated the irradiance on a clear day at solar noon.[19, 20] This model was used to finally adjust the solar radiation values to account for all errors which could not be indentified or corrected by other methods. The correction was applied to all of the data.

The modeling and completion phase consisted of the following steps:

(a) The filling of missing solar radiation values with values estimated from a regression model using sunshine and cloud cover data *

(b) The addition of direct beam values generated from a model developed by Randall and Whitson.[22] Users should note that all the direct-beam values in the SOLMET data base are model-generated, not measured. This model is described elsewhere in this chapter.

The rehabilitated data base, termed SOLMET data, is now available from the U.S. National Climatic Center on computer magnetic tape. It is described in Ref. 23. The rehabilitation process and models are described in Refs. 19 and 22.

## SOLAR RADIATION DATA FROM THE REGRESSION MODEL

The regression model developed for filling the gaps in the rehabilitation process was very successful. There existed about 222 sites where sunshine data or cloud cover observations had been made, but where no solar radiation measurements had been made. It was decided to apply the regression model to these 222 sites using the regression constants from nearby solar radiation measurement locations to obtain synthetic or regression modeled solar radiation data for these locations. These data are now available in the SOLMET format. They are sometimes termed "ersatz," or Regression Modeled Data, to differentiate them from the measured data of the same format.

## THE NEW 38-STATION U.S. SOLAR RADIATION MEASURING NETWORK

Many lessons were learned from the rehabilitation process and the examination of the network operation. A decision was made to revise the entire solar radiation measuring network, to install new instrumentation, to modernize the data recording and processing methods using computer technology, and to publish the data on a periodic basis.

The new solar radiation measuring network included:

(a) new instrumentation:

- pyranometers—measuring total global;
- pyrheliometers (at some locations)—measuring direct beam; and
- pyranometers with shadow bands (at some locations)—measuring diffuse.

(b) New data logging equipment with the following characteristics:

- data recorded directly on digital magnetic tape cassettes;
- measurements at one-minute intervals;
- clock contained in the datalogging system and;
- hourly integrated values printed by the datalogging system as the measurements were made.

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* There is currently some indication that the version of the model used underestimated the solar radiation values for locations at the higher latitudes during cloudy days with snow on the ground. This is due to the lack of accounting for the increased albedo of the surface.[21]

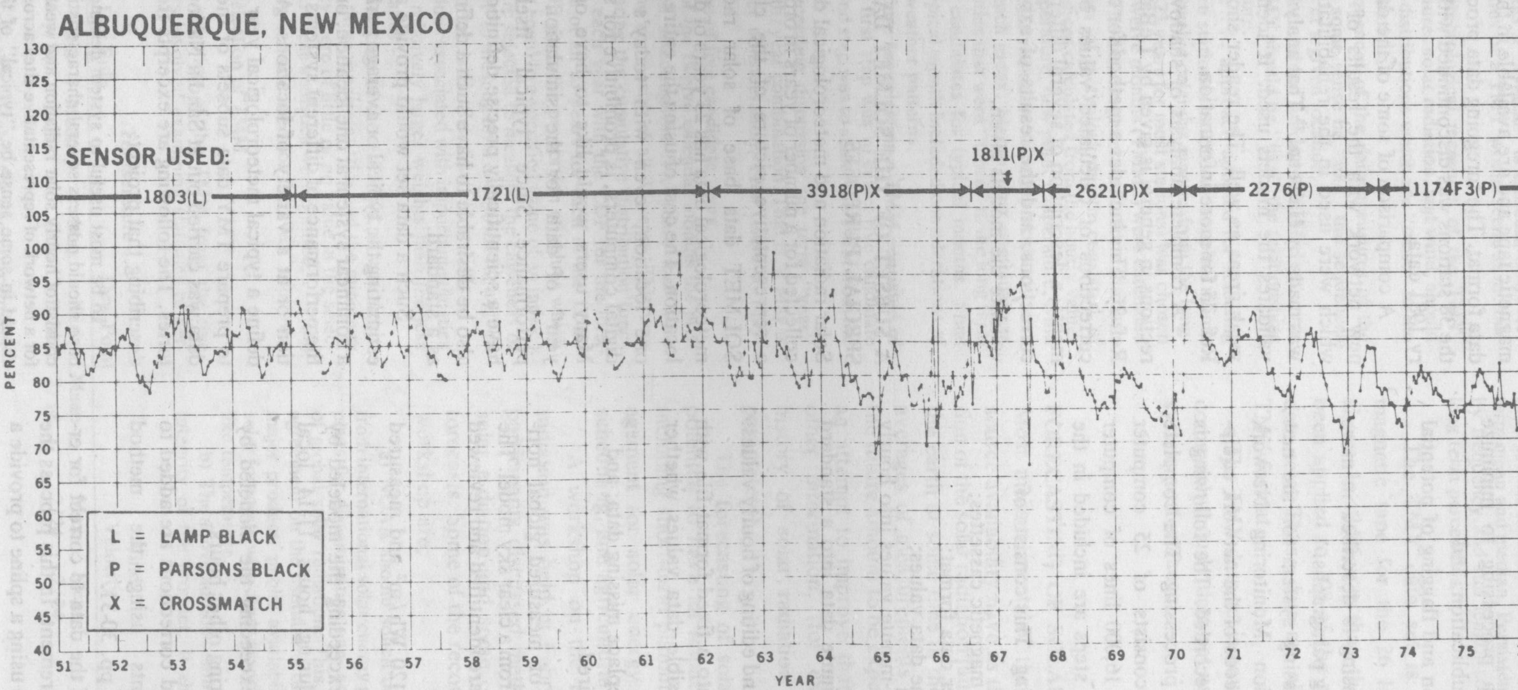


Fig. 1. Example of the solar radiation data from one station in the U.S. network prior to the Engineering corrections. Each point represents the average of approximately two weeks of solar noon measurements. The vertical axis is percent of extraterrestrial solar radiation.[19]

(c) A data processing system with the following characteristics:

- computerized data processing to minimize cost and time to publication; and
- automatic detection and flagging of potential errors.

The data processing is described in more detail in the following paragraphs.

The data processing system for the new U.S. Solar Radiation Monitoring Network evolved to suit the needs of the network equipment and the data recorded. The following is an overview of the processing. The complete processing system consists of 25 computer programs and over 16,000 lines of computer code. The following steps are included in the processing:[24]

(a) cassette editing. This consists of:

- reading the digital magnetic cassettes;
- checking for proper data format;
- range checks on the data values;
- combining the one-minute values into hourly sums; and
- writing the one-minute data into a standard microfiche report.

(b) Formatting and editing of hourly values:

- placing the data into a fixed format file with spaces for all possible data values whether they exist or not;
- adding values to replace missing data; and
- other edits as required.

(c) Comparison of measured global horizontal data with that from a clear sky model. The following conditions are identified and reviewed individually:

- modeled value < 120 Wh/m² and measured > 180 Wh/m²;
- measured values exceeding the modeled by more than 5% during hours 11-14 local standard time; and
- measured values exceeding the modeled by more than 10% during other hours.

(d) Shadow band corrections are added to diffuse measurements using the method described in Ref. 12, pp. 30-31.

(e) Time shift of the data to correct for errors in time of measurement. In this process the data are fit to a curve using a spline to provide a smooth curve.

The data, through December of 1980, from the new network are archived on computer magnetic tape and are available in the SOLMET data format. The foregoing data processing from the 38 stations was discontinued with the January 1981 data.

A comparison of some of the data from the new network with the results of the models which were used in the rehabilitation process was made by Hall et al.[25] That analysis generally validates the models used. It identifies some weak areas as well. The reader should refer to Ref. 25 for more information.

A complete analysis of shadow band corrections in general is given by LeBaron et al. in Ref. 26. This includes a method for checking the corrections of calculated values by measurements, a description of several different types of corrections, and the results of experiments to validate the models given.

## A SUBSET OF THE SOLMET DATA FOR SPECIAL PURPOSES

Solar radiation and meteorological data must be collected for a number of years in order to obtain a representative picture of the climate. The SOLMET data base of solar radiation and meteorological data has 23 years of data for each location. The cost of using the entire data set for one location, even with today's high-speed digital computers, is prohibitive for some users. Many users would like to have one "typical year" of data for the simulation of system performance. Since "typical" itself does not have a scientifically precise definition, it would also be desirable to have such a definition to use as a standard.

Such a data set would provide a means for estimating the typical or average performance of a nonlinear system at one location, or comparing the performance of different systems at one location or at a variety of locations. A project to define a typical meteorological year (TMY) and to prepare TMY data subsets of the SOLMET data was carried out at Sandia National Laboratories. The following are excerpts from Ref. 27, describing that project:

> To be most useful to system designers, this data base should possess several characteristics. It should consist of hourly solar radiation and weather readings for a network of representative sites across the U.S. It should in some sense be "typical" of the long term data base and it should be of a year's duration. For a

given site this data base could be reasonably called a "typical meteorological year" (TMY).

Defining the characteristics of a meteorological year which makes it "typical" is difficult; however, sensible properties of a TMY would seem to include the following:

(a) The meteorological measures of the TMY, that is, temperature, solar radiation, and wind, should have frequency distributions which are "close" to the long-term distributions.

(b) The sequences of the daily measures of the TMY should in some sense be "like" the sequences often registered at a given location.

(c) The relationships among the different measures for the TMY should be "like" the relationships observed in nature.

Briefly, the . . . approach adopted for selecting TMYs for a given station is as follows: a typical month for each of the twelve calendar months from the long-term data base (23 years for most stations) was chosen and then these twelve months (TMMS) were catenated to form TMYs. The data set generated to form the basis for the selection of a typical month consisted of thirteen daily indices calculated from the hourly values of dry bulb temperature, dew point temperature, wind velocity, and solar radiation. Monthly statistics were calculated for each index. Month/year combinations which had statistics that were "close" to the long term statistics were candidates for typical months. Final selection of a typical month included considerations of persistence of weather patterns.

The procedure for selecting a TMM consisted of two steps. The first step was to select five candidate years. The second step was to select the TMM from the candidate years.

In the succeeding discussion the term "year" refers to a month/year combination. That is, if May is the month under consideration, 1966 refers to May, 1966.

a) Selection of five candidate years

For each of the twelve calendar months the procedure involved selecting the five years that were "closest" to the composite of all 23 years. This was done by comparing the cumulative distribution function (CDF) for each year with the CDF for the long term composite of all 23 years for each of the 13 indices. (The CDF gives the proportion of values which are less than or equal to a specified value of an index.) . . . The statistic selected to measure the closeness of each year's CDF to the long term composite for a given index was the Finkelstein-Schafer (FS) statistic.

The FS values associated with important statistics would receive relatively larger weights than the less important statistics.

In the generation of these TMYs, it was determined that the three range statistics and the minimum of wind velocity were of little or no value in the selection process, so these statistics were omitted, . . . The actual weighting scheme used for the TMY's follows:

b) Final selection of TMM

The final selection of the TMM from the five candidate years involved examining statistics of persistence structure associated with mean daily dry bulb temperature and daily global solar radiation. The statistics examined were the FS statistic and the deviations for the monthly mean and median from the long term mean and median. Persistence was characterized by frequency and run length above and below fixed long term percentiles.

The TMY data set is now available on magnetic tape for the 26 locations described above. In addition to that, the same process has been applied to 208 of the regression modeled data sets. Those data are also available in the TMY format.

The TMY data set is now probably the most commonly hourly data set used for modeling of system performance.

## FORECASTING OF SOLAR RADIATION

Most measurements of the solar radiation resource availability have as their goal the prediction of the solar radiation falling on some point of the earth at some time in the future. Long term averages of measurements give an estimate of the future amount to be expected. Forecasting is an attempt to improve that estimate by using other information, (for example, the recent history of solar radiation and other related parameters).

The forecasting of solar radiation has the potential to have an impact on several areas, including short-term planning of and load management for solar energy systems, irrigation scheduling, and agricultural management.

A workshop on the forecasting of solar radiation was held in February of 1981.[28] The participants discussed methods for forecasting solar radiation and some of the uses of these forecasts. Some of the recommendations of that workshop are:

a) NOAA should solicit outside advice, perhaps from international solar energy groups, to formulate its plans for disseminating one- and two-day predictions of global solar radiation. This review should include agreement on the usefulness of the forecasts, format, major product, public availability and association of solar forecasts with other associated weather elements like temperature.

b) The above ad-hoc committee should ensure the integrity of the product. It should especially try to

| | Temperature | | | | | | Wind | | Solar |
|---|---|---|---|---|---|---|---|---|---|
| | Dry Bulb | | | Dew Point | | | Velocity | | Radiation |
| | Max | Min | Mean | Max | Min | Mean | Max | Mean | |
| Wi: | 1/24 | 1/24 | 2/24 | 1/24 | 1/24 | 2/14 | 2/24 | 2/24 | 12/24" |

where the Wi are the weights for each parameter.

make the nature of the forecast as useful to users as is possible, (e.g. mean values, probabilities, etc.)

c) In particular, and if possible during the heating periods, the solar forecasts should be given together with a measure of heating needs, e.g. degree-days, and during cooling periods together with cooling needs.

Partly as a result of that workshop, a program of daily forecasts of solar radiation availability was initiated late in 1981 by the National Weather Service. These forecasts are available on the National Digital Facsimile Network as a map of the continental U.S. twice daily, giving forecasts twice daily for 24 and 48 hours ahead.[29] An example of one of these maps is shown in Fig. 2.

## CIRCUMSOLAR RADIATION

The recent interest in highly concentrating solar energy systems, and the lack of detailed knowledge about the effects of the atmosphere on the energy available from within the solar aureole, were the major stimuli for a program of investigation of circumsolar radiation. The primary focus of the program, thus far, has been the development of design data for highly concentrating solar energy systems. However, there is considerable potential for using these data to develop a better understanding of the atmospheric optical phenomena.

The design of the instruments and data collection has been performed by the Lawrence Berkeley Laboratory of the University of California, Energy and Environment Division (LBL). Descriptions of this project are given in a number of reports from LBL,[30-34] from which the following are excerpts:

> The purpose of this project is to provide measurements and analyses of the solar and circumsolar radiation for application to solar energy systems that employ lenses or mirrors to concentrate the incident sunlight. Circumsolar radiation results from the scattering of direct sunlight through small angles by atmospheric aerosols (e.g., dust, water droplets or ice crystals in thin clouds).
>
> Concentrating solar energy systems will typically collect all of the direct solar radiation (that originating from the disk of the sun) plus some fraction of the circumsolar radiation. The exact fraction depends upon many factors, but primarily upon the angular size (field-of-view) of the receiver. A knowledge of the circumsolar radiation is then one factor in predicting or evaluating the performance of concentrating systems.
>
> The project employs unique instrument systems (called Circumsolar Telescopes) that were designed and fabricated at LBL. The basic measurements are:
>
> 1) the "circumsolar scan," the brightness of the sun and circumsolar region as a function of angular distance from the center of the sun and
>
> 2) the usual "normal incidence" measurement of a pyrheliometer.
>
> Both measurements are made for the entire solar

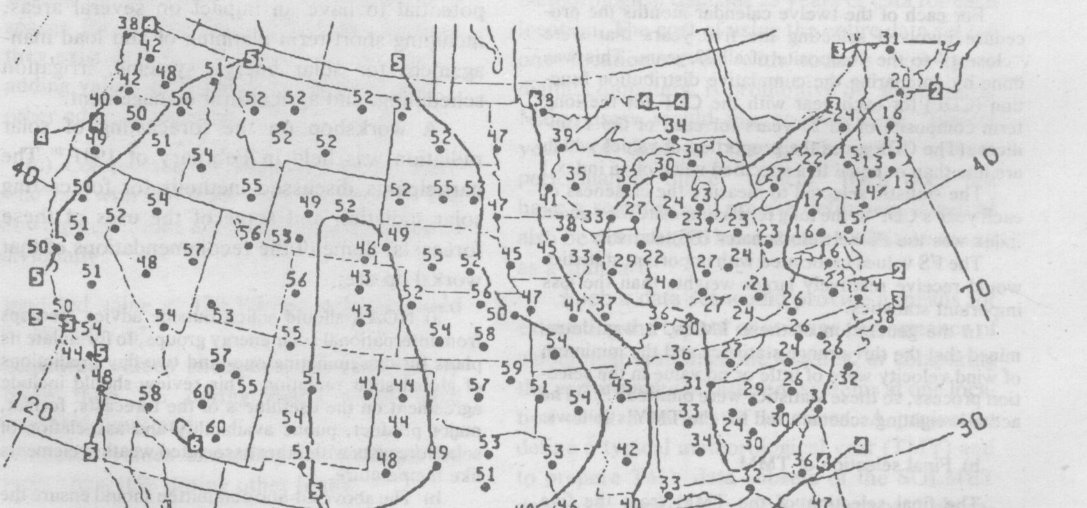


Fig. 2. An example of the NOAA solar radiation forecast maps.[29] The units are tenths of kWh/m², (divide by 10 to get kWh/m²).

spectrum, and (via colored filters) for eight essentially contiguous wavelength bands. Thus the measurements are applicable to systems in which the receiver is essentially wavelength-insensitive (e.g., central receiver) and to wavelength-sensitive systems (e.g., concentrating photovoltaics).

A secondary purpose of the project is to relate the data to the atmospheric processes that attenuate the solar radiation available to terrestrial solar energy systems.[32]

Data have been collected at different times at a number of different locations. These locations represent a variety of different climates. The locations, all within the U.S. include:

- Boardman, Oreg.
- Coalstrip, Mont.
- Atlanta, Ga.
- Albuquerque, N.M.
- Ft. Hood, Tex.
- Argonne, Ill.
- Berkeley, Calif.
- Edwards, Calif.
- Barstow, Calif.

Some of the important conclusions from this project are:

1) A pyrheliometer of usual design (6 degree field-of-view) will yield an overestimate of the direct solar radiation (originating from the disk of the sun).

2) This overestimate is, on the average, a few percent of the total energy in the beam.

3) Data from nondesert areas have a generally higher fraction of the energy in the aureole than do the desert areas.

4) For sky conditions such as haze and cirrus clouds, a measure of the circumsolar radiation is necessary to understand the performance of an operating, highly concentrating system.[34]

An analysis of some of these circumsolar data and the development of a model to estimate the circumsolar radiation from solar and meteorological data was performed by Watt.[35] This report also includes data from the circumsolar telescope and a description of the atmospheric components causing the circumsolar radiation.

A method of expressing the distribution of circumsolar radiation intensity as a function of Gaussian distributions has been developed by C. N. Vittoe and F. Biggs, using the data from the circumsolar telescope.[36] This method provides a computationally simple analytic description of the intensity profile of the circumsolar radiation.

## THE SOLAR CONSTANT MEASUREMENTS

The sun has a constant energy output, at least we treat the measurements of solar radiation at the surface of the earth as though it were constant. Historically, a major problem in solar radiation measurement has been establishing the value of the solar constant and defining a scale for the measurement.[8] Recently, however, measurements of the extraterrestrial solar radiation from earth-orbital spacecraft have refined this measurement and established a new value for the solar constant. The satellite measurements show some variability in the "solar constant" with time.

Two experiments are currently (1982) providing measurements of the solar constant. These are the Nimbus 7 spacecraft, Hickey[37] and the Solar Maximum Mission spacecraft, Willson.[38] Their respective values for the solar constant, 1372.6[37] and 1368.31[38] $W/m^2$, differ by only about 0.3%. Both experiments show that there are variations, over periods of the order of days, about the mean value, which exceed 0.2% of the mean value. Both also indicate that there currently appears to be a downward trend of the solar constant which is greater than 0.015% per year. However, since only two to three years of these measures are available, it is not yet possible to show how long such a trend might be expected to continue. One illustration of these data is shown in Fig. 3.[39]

These experiments are important because the research is now beginning to link solar variability with impacts on the climate at the earth's surface.[40,41] Measurements of this type may ultimately be a major source of information for forecasters of solar radiation at the surface of the earth, and for other weather forecasters.

## DIRECT, DIFFUSE, TOTAL SOLAR RADIATION AND THEIR INTERRELATIONSHIP

The most commonly measured solar radiation parameter is the total global radiation on a horizontal surface. The parameters most needed for energy design and analysis are the total global solar radiation on a tilted surface and the direct-beam solar radiation. Because of the lack of data in the latter forms, many people have worked on methods for estimating one from the other. These relationships are normally needed on an hourly, daily, and monthly average basis.

The most commonly used method was pub-

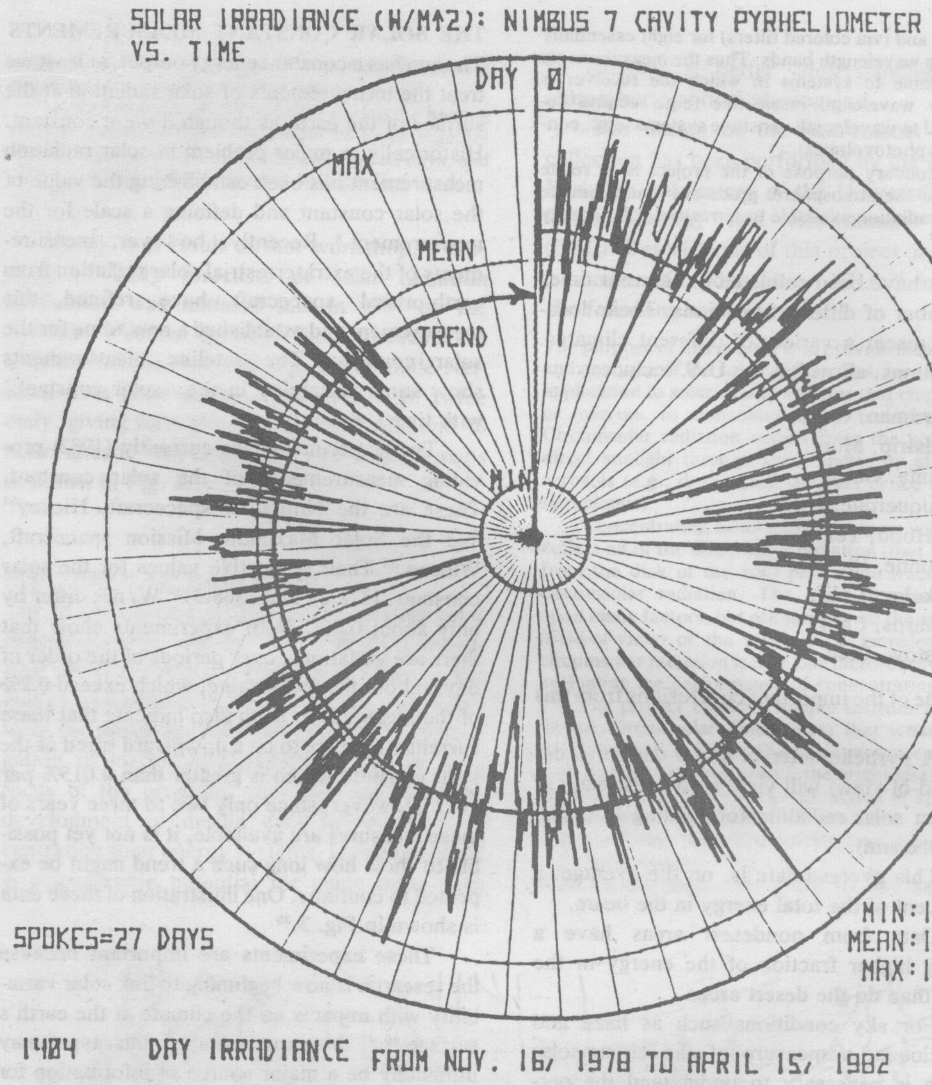


Fig. 3. Illustration of Solar Irradiance Measurements from the Nimbus 7 Spacecraft. Time begins at day 0 (vertical) and increases clockwise. The data for 1247 days are plotted. Each spoke represents 27 days, (1404 days for 360 degrees). Intensity is expressed as increasing radius, with a suppressed zero. The center of the circle represents 1368 W/m$^2$, the outer circle is 1376 W/m$^2$. This is engineering level data and subject to revision. This plot compliments of John R. Hickey, Eppley Laboratory, NASA and NOAA/NESS: NASA/GSFC data, April 1982.[39]

lished originally by Liu and Jordan in 1960.[42] Since that time, the basic method has been:

a) applied to daily and hourly relationships,[22,43-45]

b) extended to surfaces not facing toward the equator,[46]

c) revised with new data,[45,47,48] and

d) compared to models of atmospheric transmission.[49]

The above references are not a complete list of all the work on this topic, but rather will give an idea of its extent.

The primary value in the Liu and Jordan technique is that it allows the estimation of other parameters from just the total horizontal global radiation. While most of the work relating to this method has established its validity and usefulness for many purposes, a comprehensive analysis of the potential errors inherent in it has not been published. An approach to such an analysis was suggested in Ref. 49.

Engles et. al.,[50] suggest the use of a new parameter $Z = I_{th}/I_{th}^*$ instead of the more traditional $K_t$. The difference is that $I_{th}^*$ is based on the transmission by a standard atmosphere, rather than on the extraterrestrial solar radia-