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NREL Solar Radiation Resource Assessment Project: Status and Outlook

FY 1991 Annual Progress Report

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PREFACE

This report summarizes the activities and accomplishments of NREL's Solar Radiation Resource Assessment Project during fiscal year 1991. This project is part of the U.S. Department of Energy's Resource Assessment Program.

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Approved for the

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1.0 INTRODUCTION

The assessment of renewable energy resources, such as solar, wind, and biomass, is an essential factor in determining the degree to which renewable energy technologies can be used and in implementing these technologies. The Department of Energy's (DOE's) Resource Assessment Program has the responsibility of providing these assessments and the scientific documentation required to support these assessments. The legislation enabling this activity was passed by the 93rd Congress in 1974 as part of the Solar Energy Research, Development and Demonstration Act of 1974 (P.L. 93-473). Specifically, Section 5, titled Resource Determination and Assessment, states that a solar energy resource determination and assessment program shall be initiated "with the objective of making a regional and national appraisal of all solar energy resources. . . ." The legislation goes on to say that

> . . . the program shall emphasize identification of promising areas for commercial exploitation and development. The specific goals shall include:
>
> 1) the development of better methods for predicting the availability of all solar energy resources, over long time periods and by geographic location;
>
> 2) the development of advanced meteorological, oceanographic, and other instruments, methodology, and procedures necessary to measure the quality and quantity of all solar resources on periodic bases;
>
> 3) the development of activities, arrangements, and procedures for the collection, evaluation, and dissemination of information and data relating to solar energy resource assessment.

Since the early 1980s, the Resource Assessment Program, as it is now called, has been managed out of the Photovoltaics Branch of DOE's Office of Conservation and Renewable Energy. The program is currently focusing on solar radiation resources and is managed as the Solar Radiation Resource Assessment Project (SRRAP) at the National Renewable Energy Laboratory (NREL, formerly the Solar Energy Research Institute) in Golden, Colorado. This report describes the activities of the SRRAP during October 1, 1990 through September 30, 1991 (fiscal year 1991) and provides an outlook for future year activities.

The work described in this report was done in accordance with an annual operating plan [1] and other direct guidance from DOE during FY 1991. Previous years' activities and historical information pertinent to the FY 1990 work are documented in annual progress reports for 1987 to 1990 [2-5].

Section 2.0 of this report briefly reviews the overall objectives and priorities of the SRRAP and provides a summary of the scope of FY 1991 activities. Section 3.0 reviews the development and production of the 1961-1990 National Solar Radiation Resource Data Base, which will provide the basis for future assessment and analysis activities of the SRRAP. Section 4.0 reviews the SRRAP's educational activities that are under way and discusses mechanisms by which these activities can be focused to enhance the existing solar radiation monitoring activities in the United States. In Section 5.0, we summarize outreach activities, which represent the various mechanisms by which the technology developed within the SRRAP is transferred to user groups and the general public. Section 6.0 reviews international activities, and Section 7.0 summarizes activities under way at NREL's Solar Radiation Research Laboratory. Finally, this report concludes with pertinent information on program management (8.0), program outlook (9.0), and references (10.0).

2.0 SOLAR RADIATION RESOURCE ASSESSMENT PROJECT: OBJECTIVES AND PRIORITIES

2.1 Project Objectives

There are three broad objectives of the SRRAP: (1) to facilitate the implementation of renewable energy systems by providing accurate documentation of solar resource data and their uncertainties; (2) to foster the use of solar resource information by providing products that allow for valid end-use assessment of energy performance, including quantification of uncertainties associated with these assessments; and (3) to support the data and assessment products with technical and scientific peer-reviewed documentation. Within these three broad objectives lie the general theme and current priority of the SRRAP: to produce a credible, user-oriented solar radiation resource data base and associated data base products, which can support future multitechnology, multinational, and multidisciplinary research and assessments. This theme will be discussed in more detail in Section 9.0, Program Outlook.

2.2 Scope

Currently, the primary focus of the SRRAP is to produce a 1961-1990 National Solar Radiation Data Base, providing hourly values of global horizontal, diffuse, and direct normal solar radiation at approximately 250 sites around the United States. Because these solar radiation quantities have been measured intermittently at only about 50 of these sites, models were developed and applied to the majority of the stations to provide estimates of these parameters. Although approximately 93% of the data base consists of modeled data, this data base will represent a significant improvement over the SOLMET/ERSATZ 1952-1975 data base that has provided the main source of solar resource assessment information to date. The magnitude and importance of this activity are such that the majority of SRRAP human and financial resources were devoted to the data base development. However, in FY 1991 the SRRAP was involved in many other activities, which are reported here. These include the continued maintenance of a solar radiation monitoring network in the southeast United States at six Historically Black Colleges and Universities (HBCUs), the transfer of solar radiation resource assessment technology through a variety of activities, participation in international programs, and the maintenance and operation of NREL's Solar Radiation Research Laboratory.

3.0 NATIONAL SOLAR RADIATION DATA BASE PRODUCTION

3.1 Background on the 1961-1990 National Solar Radiation Data Base

3.1.1 Historical perspective

Solar radiation measurements have been traditionally obtained in this country by the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) since the late 1940s. Although this network has carried different names during the past 40 years, for the sake of clarity and consistency we will refer to this network as the SOLRAD (SOLar RADiation) network for all time periods. The primary measurement obtained in this network has been total (solar direct beam plus diffuse) radiation on a horizontal surface (or global horizontal radiation).[1] These measurements were made using broadband pyranometers whose characteristics have changed over the years.[2]

From 1952 to 1975, the SOLRAD network comprised about 60 stations. Some of these stations made continuous recordings on strip charts, while others recorded only the daily total energy (insolation) received. Much of these data were digitized at the station, using instructions that changed over the years, and were forwarded to regional centers (later centralized at the National Climatic Data Center, or NCDC), where they were subjected to varying degrees of quality control. These historical solar data suffered from neglect and contain serious errors resulting from a host of calibration and instrument problems. The data were also referenced to two different scales (the Smithsonian Scale of 1913 and the International Pyrheliometric Scale of 1956). When these data were evaluated for inclusion in the first national solar radiation data base (the SOLMET data), only 26 stations were deemed suitable for use (see the black dots in Figure 3-1). For this reason, a procedure was developed to estimate solar radiation at an additional 222 stations for which appropriate meteorological data were available. These estimates became known as ERSATZ data, and the combined 1952-1975 national data base is known as the SOLMET/ERSATZ data base [6].

During 1976, the SOLRAD network was essentially shut down while new equipment was purchased and installed at a reduced number of stations. From 1977 through 1980, data were collected at the 39 sites, identified with a triangle in Figure 3-1. Almost all of these stations recorded both global horizontal and direct normal radiation, and nine of the stations also recorded diffuse horizontal radiation. Furthermore, during the upgrade of the equipment at the stations, NOAA established a solar radiation calibration facility at Boulder, Colorado, where all of the pyranometers and pyrheliometers (used for measuring direct normal solar radiation) were periodically recalibrated. During this 4-year period, the operation of the network was funded jointly by DOE and NOAA. The quantity and quality of the data collected during these 4 years was affected favorably by adequate funding and improved instrumentation and calibration procedures.

After 1980, the plan was for DOE to end support of the network and for NOAA to obtain budget authority to support the entire network. However, beginning in 1981, the network budgets were reduced. As a result, from 1981 through October 1985, the network gradually decayed, and none of the data were processed. Thus, NOAA decided to close the network to make another equipment upgrade, and NWS did not collect solar radiation data from October 1985 through December 1987. In January 1988, the network started once again to collect global horizontal and direct normal radiation data at 27 stations.

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[1]"Irradiance" and "radiation" at the Earth's surface are used interchangeably in this report.

[2]These broadband pyranometers respond to a spectral range of about 0.3 to 3 μm.

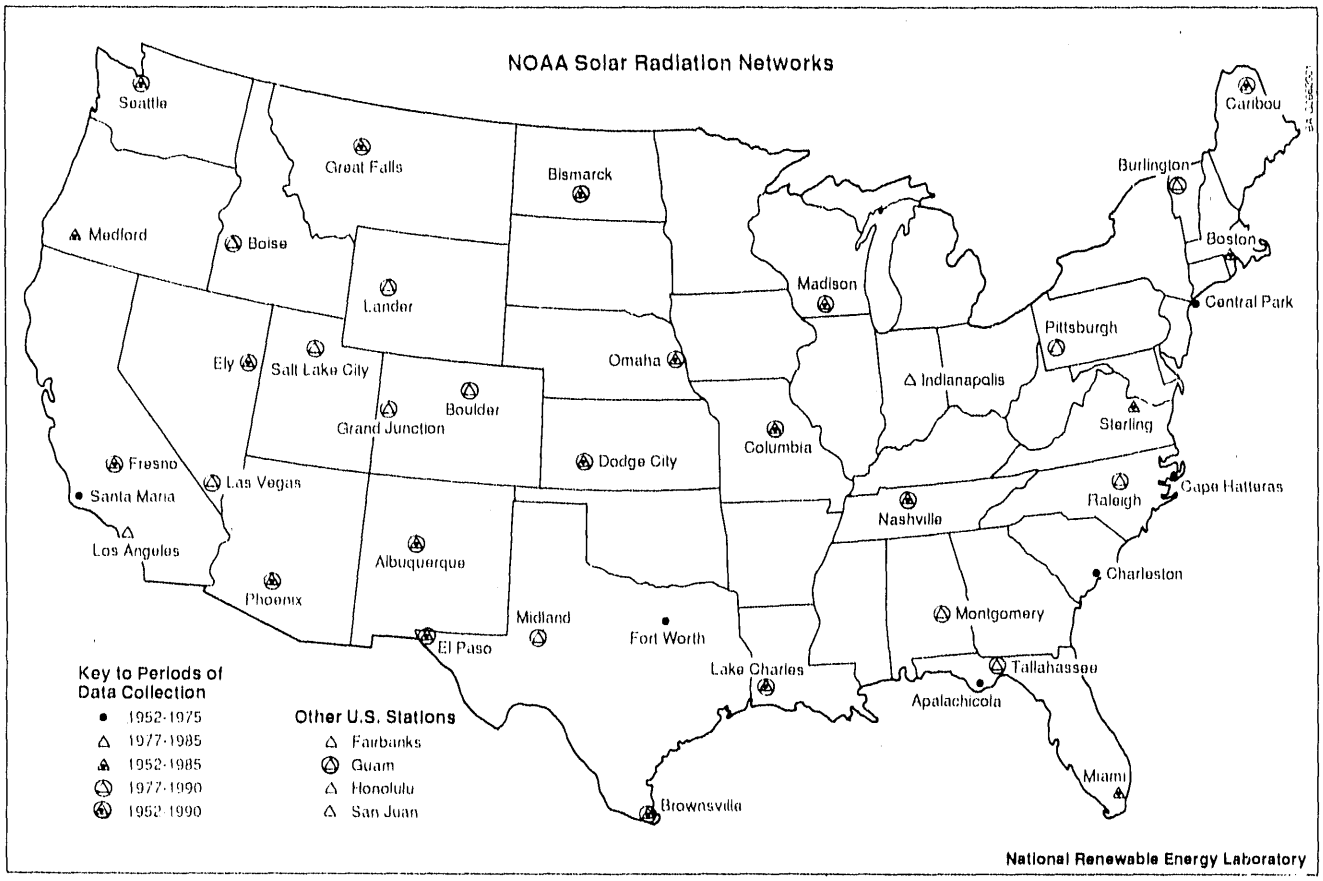


Figure 3-1. Station locations and periods of data collection for the SOLRAD network

In summary, as shown in Figure 3-1, 44 stations have participated in the SOLRAD network from 1952 through 1990. However, only 16 of these stations have been active during the entire time that the network was in an operational status. Those 16 stations are identified by the circle enclosing the triangle that encloses the black dot.

3.1.2 Rationale for a New National Solar Radiation Data Base

Because of considerable variability in the quality of the measured data used in the 1952-1975 SOLMET/ERSATZ data base (due to intermittent measurement periods, uncertainties in calibration procedures, use of outdated or poorly calibrated equipment, etc.), as well as the variability in the apparent quality of the ERSATZ data, there are significant uncertainties attached to these earlier data. This has left the designers of solar energy systems, as well as planners and analysts assessing the viability of renewable energy options, with a great many questions regarding the validity of these data. This has been further complicated because a large part of the renewable energy community was unaware of the uncertainties surrounding the data that they use to design and site solar energy systems. Furthermore, the SOLMET/ERSATZ data base does not incorporate any of the improved data collection procedures

implemented by NOAA in 1976.[3] As a result, a decision was made in 1989 to upgrade the SOLMET/ERSATZ data base to a 1961-1990 National Solar Radiation Data Base, using improved data and modeling techniques. Unlike short-term data bases with only a few years of solar radiation data, this national data base's 30 years of data will permit examining the inter-annual variability of the solar resource.

3.1.3 Composite Description of the New 1961-1990 National Solar Radiation Data Base

The goals for upgrading the solar radiation data base for the United States is to reduce the uncertainties associated with the SOLMET/ERSATZ data base, to account for any recent changes in climate, and to provide products that meet user needs. These goals are being met by addressing three primary objectives:

- To assess the quality of all measured data and attach source and quality flags to both measured and modeled data.[4]

- To estimate solar radiation using an improved parametric model incorporating readily available meteorological parameters and algorithms that reproduce the monthly statistical and stochastic characteristics of good quality measured data.

- To incorporate all three fundamental solar radiation elements (direct normal, diffuse horizontal, and global horizontal), using formats and media that will make the data base more user-friendly and by creating a statistical summary product to enhance the value of the data base.

The 1961-1990 National Solar Radiation Data Base will satisfy each of these objectives. The 30-year period has been chosen to be consistent with national and international meteorological and climatological practices.[5] The number of modeled stations (approximately 200) was limited by the selection of NWS stations that had nearly continuous collections of the required meteorological parameters from 1961 to 1990. These stations provide a sufficient number of locations to represent most regional solar radiation climates in the United States.

However, even with all the major changes and improvements that will go into the new national data base, it is not possible to incorporate all data collected by organizations other than the NWS or to incorporate all possible means of upgrading the data and still produce the data base in a timely fashion. Recognizing this, the version of the data base planned for release in the summer of 1992 will be named Version 1.0. As improved modeling techniques, quality assessment procedures, and data sources become available, the data base will be updated periodically, and the version number will be changed to reflect changed versions that enter the public domain. Documentation will also be revised accordingly. Minor changes, such as refinements to part of the data for existing stations, will result in the number following the decimal to change in the version nomenclature. Major changes, such as incorporation of many new data sets, use of an improved model, or changes in the period of time represented by the data base will be designated with new numbers preceding the decimal in the version nomenclature.

---

[3]Although the quantity of data varied greatly during 1976 to 1990, the quality of data that were collected is good due in large part to maintaining the solar radiation calibration facility in Boulder, Colorado.

[4]As with SOLMET/ERSATZ, the 1961-1990 National Solar Radiation Data Base will contain more than 90% modeled data.

[5]The latest update of climatological summaries of the National Weather Service will cover 1961 to 1990.

3.2 Data Base Production Methodologies for Solar Radiation Measurements

As indicated in Section 3.1, the new 1961-1990 National Solar Radiation Data Base is designed to make the following improvements on three major aspects of the SOLMET/ERSATZ data base: (1) to incorporate and quality assess more recent and improved solar radiation measurements; (2) to improve upon the techniques for estimating solar radiation; and (3) to provide a more user-friendly data format and statistical summaries pertinent to the solar energy industry. This section describes the data base production methodologies for the measured solar radiation data, along with key accomplishments during FY 1991.

3.2.1 Overview of Solar Radiation Data Issues

Figure 3-2 summarizes the periods of operation and status of the SOLRAD network. From this figure, it is evident that virtually none of the solar radiation data collected for the United States can be considered to be free of problems, and that a need exists to upgrade measurements for each of the four measurement periods indicated in the figure. The issues for each of these periods can be summarized as follows.

1952 to 1975. The so-called "light bulb" pyranometers used during this period exhibited temperature response and calibration problems, which were addressed during the creation of the SOLMET/ERSATZ data base. Furthermore, these pyranometers show a response to solar energy that varies with solar angle. These angular response characteristics were not considered, yet probably had a significant effect on the data and the methods used during the rehabilitation of these data, as noted by Flowers and Maxwell [7].

1977 to 1980. The data collected during this period have the least need for upgrading. Nevertheless, some data that violate physical relationships (e.g., situations in which the horizontal component of the direct beam is greater than the measured global horizontal) will be modified or replaced by model estimates. The data flagging scheme, reviewed in Section 3.5.3, will inform the user whenever this is done.

1981 to 1985. Data collected during this period were copied from cassette tapes to 9-track reels, with no examination or quality control. A large part of these data were unreadable using normal read commands. Some of the data have voltage offsets, and some have been displaced in time. Although the data have already been unscrambled (to the extent possible), other problems require further attention.

1988 to 1990. Data collected during this period should be similar in quality to data collected from 1977 to 1980. Examination of these data began during FY 1991 but will not be completed until FY 1992. We do know that more data are missing than during the 1977 to 1980 period.

3.2.2 Synthetic Calibrations (SYNCAL)

The data collected prior to 1976 required a procedure to establish or reestablish calibration factors. For the SOLMET/ERSATZ data base, this procedure was known as standard year irradiance/clear solar noon (SYI/CSN). SYI/CSN compared measured global horizontal radiation at clear solar noons with model estimates of the global radiation at noon. The ratio of the modeled standard year irradiance with the clear solar noon measured values provided a correction/calibration factor that was used for measured data at all hours and under all sky conditions. A new synthetic calibration was computed every time a clear solar noon occurred. The calibration factors for the periods between clear solar noons were obtained by linear interpolations from clear solar noon to clear solar noon. This procedure corrected the effects of seasonal changes in the solar declination angle and the angular response characteristics of the radiometers, but did not account for the effects of diurnal changes of azimuth and zenith angles. Furthermore, any variation in atmospheric turbidity or water vapor from solar noon to solar noon would have been interpreted as a change in the sensitivity of the instrument.

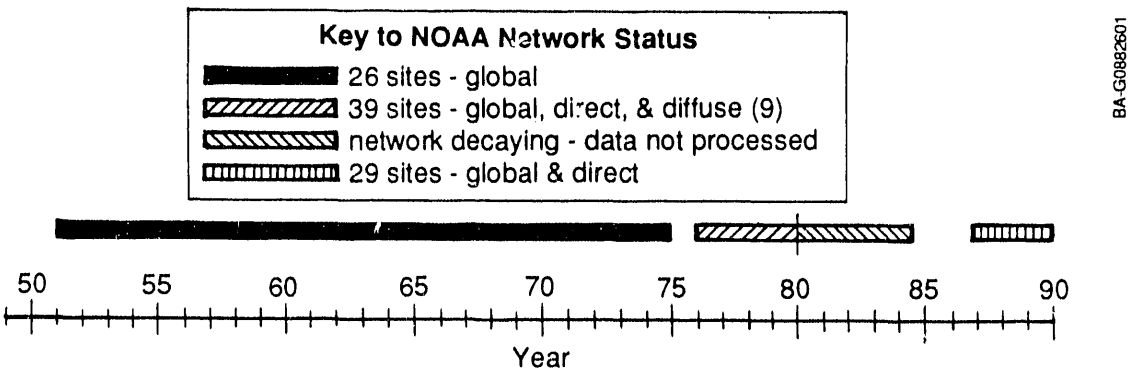


Figure 3-2. Periods of operation and status of the SOLRAD network

A new synthetic calibration procedure (SYNCAL) will be applied to pre-1976 data to correct for these deficiencies. SYNCAL will use hourly values of water vapor and daily values of aerosol optical depth in the new model algorithms, designed for Version 1.0, to calculate global horizontal radiation for most cloudless sky hours (not just solar noon) for all 26 SOLMET stations from 1952 to 1975. Comparisons of measured and calculated global horizontal values will be used to obtain synthetic calibration factors for each 10° x 10° azimuth-zenith angle cell for each pyranometer. This will produce synthetic calibration matrices that will significantly upgrade pre-1976 global horizontal measurements. The entire procedure will be validated using solar radiation data from the nine NOAA stations measuring all three components (global, direct, and diffuse) from 1977 through 1981. This method will not be applied to post-1976 data because modern pyranometers have improved angular response characteristics.

3.2.3 Data Quality Assessment

The SRRAP FY 1990 annual report [5] describes SERI QC, the software package used to assess the quality of measured data by comparing measured values with expected values. Reference 8 provides information on this procedure. This quality assessment of the measured data will be used to assign a two-digit quality flag to each measured value. A description of these quality flags is given in Section 3.5.3.

3.3 Simulation of Solar Radiation

The history of solar radiation measurements in the United States is such that a solar radiation model needs to estimate more than 90% of the data in the new 30-year national solar radiation data base. Because a multiyear data base will most often be used to create design- and typical-year subsets to establish normals, means, and extremes and to select and evaluate sites for large solar energy systems, the simulated data must accurately represent the following statistical and stochastic characteristics:

<u>Statistical</u>

- Monthly moments (mean, variance, skewness, kurtosis)
- Monthly cumulative frequency distributions

Stochastic

- Diurnal and seasonal patterns
- Hourly and daily autocorrelations
- Cross-correlations between components (global, diffuse, direct)
- Persistence.

A meteorological-statistical model (METSTAT) was developed to fulfill these requirements. Aspects of this model were reviewed in the FY 1990 annual report [5]. A brief overview of the current status of the model is provided here.

3.3.1 METSTAT: The Solar Radiation Simulation Model

METSTAT calculates solar radiation at the Earth's surface by simulating the effects of atmospheric processes on the known value of solar radiation at the top of the atmosphere (i.e., extraterrestrial radiation). For example, atmospheric water vapor acts to absorb solar radiation in certain wavelengths, while liquid water (in the form of clouds) absorbs and scatters radiation. Other atmospheric constituents (aerosols such as dust and natural and human-caused pollutants) also absorb and scatter solar radiation. Diffuse radiation associated with low cloud cover can be greatly enhanced when the ground albedo (percentage of incident solar radiation that is reflected back to the atmosphere) is increased significantly because of snowfall. All of these processes are incorporated into METSTAT by inputting meteorological data and exercising deterministic algorithms that account for physical processes.

A block diagram of METSTAT is shown in Figure 3-3. The diagram shows that hourly calculations are made using hourly total and opaque cloud cover, hourly precipitable water vapor, daily aerosol optical depth, and daily albedo input data. This is done to produce the representative diurnal and seasonal patterns, daily autocorrelations, and persistence. Statistical algorithms are placed between the input data and the deterministic algorithms to provide proper cross-correlations between the direct normal, diffuse horizontal, and global horizontal components.

The deterministic algorithms used in METSTAT calculate cloudless sky transmittance, cloudless sky scattering, cloud transmittance, cloud scattering, and ground-level reflectance. In addition, a procedure was developed to calculate seasonal values of aerosol optical depth at all sites.

The deterministic algorithms were designed to meet the objective of creating data sets with accurate monthly or seasonal means. The statistical algorithms will randomly vary input parameters (cloud cover and aerosol optical depth) such that monthly data sets exhibit representative statistical characteristics. However, since the effect of changing cloud positions, types, and thicknesses is represented by a random number generator and cumulative frequency distributions, it is possible the hourly autocorrelations will not be properly represented.

Although the choice of using only total and opaque cloud cover as inputs to the simulator might be expected to reduce the accuracy of each individual hourly simulation, it greatly simplifies the statistical algorithms that are essential to achieving data sets with representative statistical characteristics. Statistically varying hourly cloud type and cloud layer information are problematic, whereas randomly varying total and opaque values, to simulate the effect of changing cloud positions, proved to be straightforward. The development of parametric algorithms is best accomplished using post-1975 high-quality measured data to define the parametric relationships. This is accomplished using high-quality data obtained from the SOLRAD network. Hourly data from 29 stations, some measuring all three solar radiation components, were chosen to develop subsets of data that had limited ranges of air mass, cloud

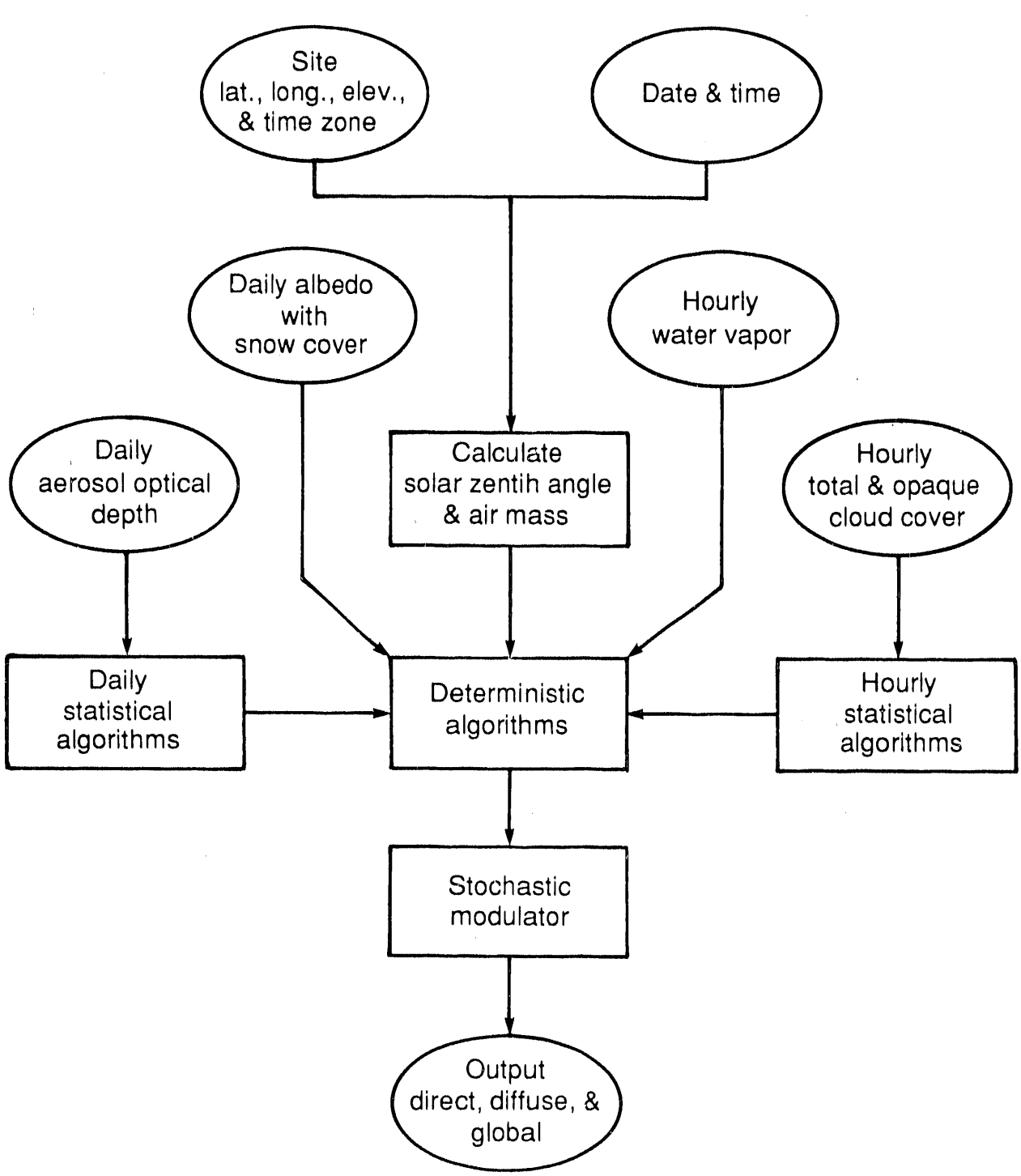


Figure 3-3. Block diagram of the METSTAT model developed for estimating solar radiation from meteorological parameters

cover, water vapor, aerosol optical depth, and albedo. This approach avoided regional and seasonal dependencies. These data subsets formed the basis for the development of deterministic and statistical algorithms used in METSTAT.

3.3.2 Processing and Incorporating Meteorological Data into METSTAT

Meteorological Data. The meteorological data required for METSTAT, as well as for the solar radiation data base, were obtained from the TD-3280 tape deck files, copies of which were provided by NCDC. These files contain data from the hourly surface observations made by the NWS at airport stations. The data that are read from these tapes include total and opaque sky cover, ceiling height, dry bulb and dew point temperature, relative humidity, atmospheric pressure, wind speed and direction, horizontal visibility, and present weather.

Precipitable Water Data. Precipitable water, an essential input parameter to the METSTAT model, is not generally available for individual radiosonde soundings, which are made twice daily (0000Z and 1200Z) at many NWS stations. Although monthly statistics are available and could have been used, the SRRAP team learned that a recalculation of precipitable water was being made for every sounding from 1948 through 1988 by Columbia University, under contract to DOE. In FY 1991, data for 73 stations were made available to NREL through the NCDC, which was performing the calculations under subcontract to Columbia University. During FY 1991, NREL issued a contract to the NCDC to complete the calculations for 1989 and 1990 and to perform calculations for some stations not included in the Columbia University activity. These calculations will be completed in early FY 1992. However, initial evaluation of the radiosonde data indicate:

- Autocorrelations of total precipitable water yield values between 0.9 and 0.6 for lags of 12 and 24 hours. This indicates that linear interpolations between soundings can be used to obtain hourly values of precipitable water for input to METSTAT.

- Cross-correlations between stations show a well-behaved reduction in the correlation coefficients with increasing distance between stations. This indicates that simple spatial interpolations can be used to estimate precipitable water for stations up to 400 km apart that do not have radiosonde data. This method is applicable throughout the United States.

Broadband Aerosol Optical Depth Data. Aerosol optical depth is and will probably continue to be the most difficult input parameter to obtain for models such as METSTAT. Although measurements have been made at selected wavelengths using sun photometers, these data are considered to have large uncertainties that become larger when extrapolated to a broadband value for the entire solar spectrum [9, 10, 11]. Furthermore, such data are only available for a limited number of locations for limited periods. Consequently, calculations of aerosol optical depth are linked to the METSTAT model by using the calculations of direct normal transmittances for ozone absorption (T_O), Rayleigh scattering (T_R), absorption of uniformly mixed gases (T_{UM}), and water vapor absorption (T_W). These are combined to obtain a value for molecular transmittance, T_M:

$$T_M = T_O T_R T_{UM} T_W \tag{3-1}$$

Aerosol transmittance can then be calculated as

$$T_A = I_N / I_0 T_M \tag{3-2}$$

where I_N is the measured direct normal radiation and I_0 is the extraterrestrial direct normal radiation. Finally, Beer's law is used to compute broadband aerosol optical depth,

$$\tau = -ln(T_A/m) \tag{3-3}$$

where m is the relative air mass. The procedure for calculating monthly mean aerosol optical depths begins with selecting quality assessed measurements of direct normal radiation under cloudless skies. These measurements are obtained with an instrument that was calibrated by comparison with an absolute cavity pyrheliometer. Then Beer's law is used to calculate broadband aerosol optical depth and aerosol transmittance. These data are used to establish seasonal patterns, which are extrapolated to other locations.

Albedo. The effect of ground-to-cloud reflections have a significant effect on diffuse radiation when surfaces are strongly reflecting (high albedo). Snow cover information (depth and number of days since the last snowfall), modified by vegetation cover and terrain factors, are used to infer higher albedo conditions.

Ozone. Published summaries of ozone data are used to obtain long-term monthly means as a function of climate and latitude zones within the United States. These are essentially the same data used in the SOLMET/ERSATZ data base.

3.4 Production Management and Documentation

Many of the details associated with producing Version 1.0 of the 1961-1990 National Solar Radiation Data Base are described in the FY 1990 annual report [5] and are not repeated here. This section will focus on the current schedule and the production procedures and documentation requirements that evolved during FY 1991.

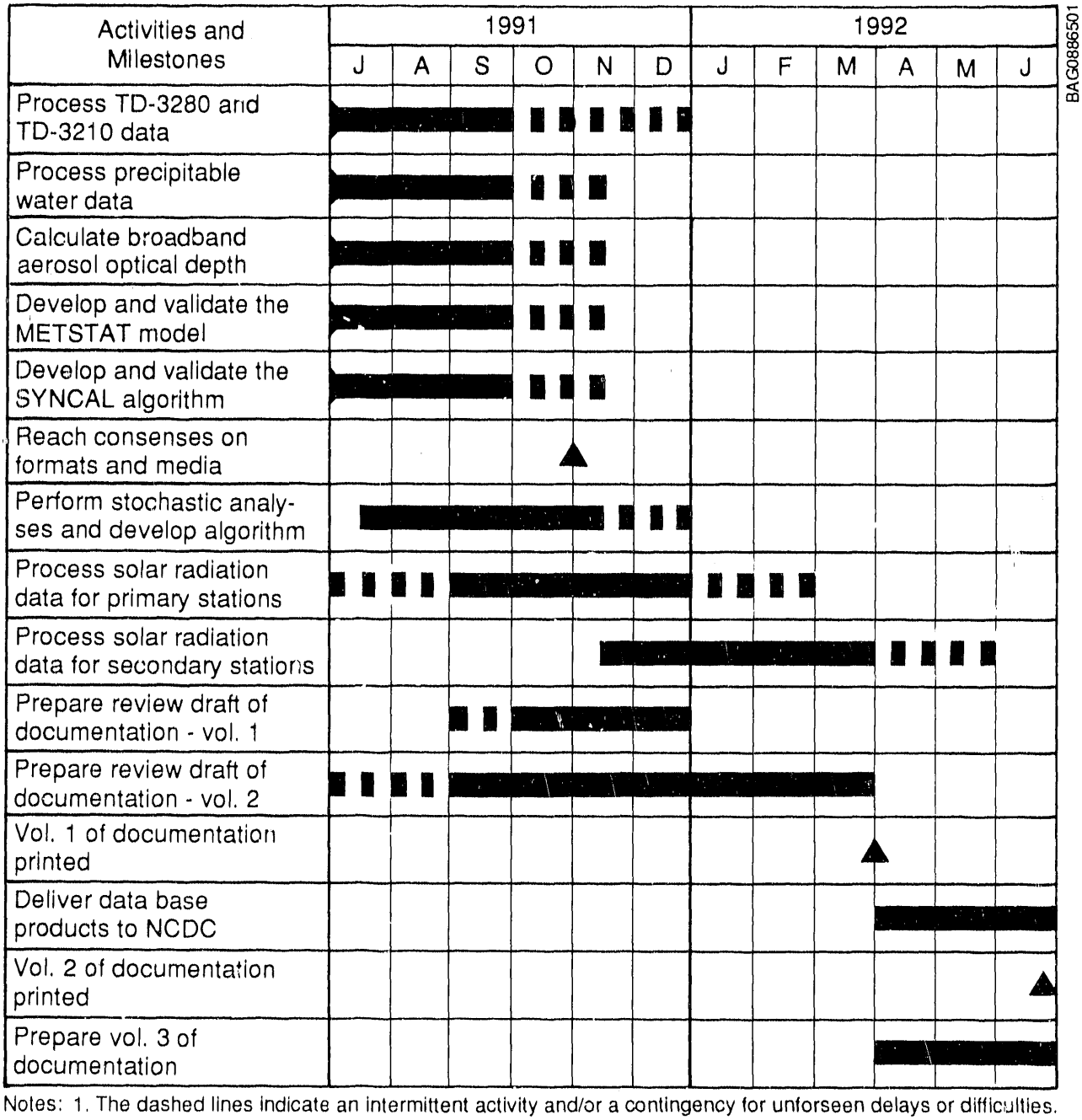
3.4.1 Schedule

In June 1991, an internal planning document titled *Update on the 1961-1990 Solar Radiation Data Base for the United States* was prepared by NREL staff and reviewed by selected external reviewers. The purpose of this document was to describe procedures and present a schedule for completing the 1961-1990 National Solar Radiation Data Base, a task that was begun during FY 1989. In this document, a production schedule was included, which shows the tasks that must be completed to finalize Version 1.0 by June 30, 1992. This schedule is reproduced in Figure 3-4.

The schedule shown in Figure 3-4 has some similarities to the one published in the FY 1990 annual report [5], but the schedule also has some notable differences. Besides the obvious differences of not including those tasks that were already completed by the end of FY 1990, Figure 3-4 does not include the task called "conduct shakedown cruise" that was discussed in the FY 1990 annual report. This task was intended to test software and hardware to be used in producing the data base. The purpose of this testing was to identify problems in both hardware and software and correct them before embarking on the full-scale data base production. This task was not formally implemented in FY 1991, partly because of serious delays in acquiring some of the computer hardware upgrades required to process all the solar radiation and meteorological data. Furthermore, a rigorous "verification and validation" procedure was applied to all software, which addresses some of the issues intended to be identified in a "shakedown cruise."

3.4.2 Production Procedures

Because of the large volume of data involved in the data base production (up to 10^{10} pieces of information for 250 stations), a pair of optical disk drives was purchased for the project. Each of these devices can



Notes: 1. The dashed lines indicate an intermittent activity and/or a contingency for unforseen delays or difficulties.

2. ▬ Indicates an activity already under way on July 1, 1991.

Figure 3-4. Production schedule for the 1961–1990 National Solar Radiation Data Base, Version 1.0

write 600 megabytes per removable disk (300 megabytes per side) and can transfer data much faster than traditional magnetic tape. After a 9-month delay, this optical disk system became available to the project in late FY 1991. Two VAX computers are used for the processing: a MicroVAX II and a VAXstation 3100.

The delay in receiving the optical disks required development of a procedure to speed processing and reduce the amount of storage space. This was accomplished by creating a compressed data structure to be stored in a binary file. This required the development of a suite of library routines that could read and write the binary files and translate the compressed data into the variables used in the production process. Once the production process is completed, the binary files will be converted back to ASCII before being sent to the NCDC.

A significant portion of software development time is devoted to software testing. Two fundamental concepts are employed: verification and validation. Verification determines if the software meets specifications, and validation determines if the specifications are correct. Much of this strategy employs conventional techniques, such as functional testing and logic analysis. For example, during functional testing, verification is accomplished by comparing program output with that predicted from the input.

The large volume of data involved in the data base production requires a stringent control and monitoring process. This is accomplished through three tracking facilities: (1) the Process Status Log, which defines the number of hours that each variable exists in any number of predefined production states (for example, missing or interpolated values); (2) the Production Status Data Base, developed from the Process Status Log, which contains information about the status of each site/year/variable (this helps in tracking the progress of production); and (3) the File Status Log, which provides information about which processes have been applied to which files and where the files are located.

3.4.3 Documentation

The NCDC will be the primary distributor of the data base. NREL will prepare complete documentation to go along with the data base so that when individuals receive data products they will have all the essential information on using the data base and understanding what it comprises. NREL will prepare this three-volume set during FY 1992. Volume 1 will be a user's manual and an overview of the data base, including pertinent station statistics. This volume will be available from NCDC at the same time as the data base (early summer 1992). Volume 2 will constitute the final technical report of the data base development activity and will include all significant research results. This volume will be available by the end of FY 1992. Volume 3 will include a complete listing of all computer codes used in processing the data and will provide a comprehensive record of all processes performed. Volume 3 will be a permanent archive from which all intermediate and output products can be reconstructed. This volume will not be available until FY 1993 and will be distributed by NCDC or NREL by special request.

3.5 Data Base Output Products

The two basic products coming out of the development of the Version 1.0 data base are the data base itself and the monthly and annual statistics associated with the data base. A number of options are still being considered relative to these products and are briefly discussed here.

3.5.1 Formats and Media

Although the file structure and formats to be used for the data base were not finalized in FY 1991, discussions with NCDC, the primary archiver and distributor for the data base, have taken place regarding this. Based on these discussions, NCDC will receive the data base in a special TD-3280 format on

9-track tape. This format will likely be designated as TD-3282, because the original SOLRAD network data are designated TD-3281. NREL and/or NCDC will then develop software for converting data from TD-3282 to major user formats such as SOLMET and TMY.

NCDC is also equipped to produce data products on CD-ROM, which may be an activity for FY 1993. Compact disk (CD) drives are inexpensive and readily available for personal computers and offer the advantages of greatly reduced storage space, more permanent storage, random access to the files, and greatly reduced costs. Furthermore, a number of commercial services are available to incorporate software on the disk for display and analytical purposes.

3.5.2 Monthly and Annual Statistics

Monthly and annual statistics for each year and for the entire 30-year period will be produced for each solar radiation and meteorological variable contained in the data base. Statistics for daily totals as well as hourly averages will be produced as appropriate. This product will be entirely separate from the data base itself and will first be available on personal computer diskettes and later on CD-ROMs.

In addition to their intrinsic value for many applications, such as maps and data manuals, the monthly and annual statistics will also be of value for producing typical- and design-year data sets. A typical year is defined as a data set in which normals and means are similar to the normals and means of the 30-year reference data base. Typical data sets, therefore, can be used to evaluate the normal performance of a solar energy system year after year. Design years, on the other hand, are data sets that contain conditions representative of long-term *extremes* that can be used by a system designer to ensure proper performance of a system under the extreme conditions that may occur during the lifetime of the system. Thus, generally, typical-year data sets can probably be successfully applied to a large number of systems and applications. Design-year data sets, on the other hand, may require the use of different criteria for selecting the data to be included. A design-year data set for a building heating and cooling system would probably be based on different criteria than a design-year data set for a photovoltaic power plant.

3.5.3 Quality Flags

A two-digit quality flag will be attached to each hourly solar radiation element and some (but not all) meteorological elements. These quality flags will allow users to select only data that meet their criteria of acceptability.

Solar Radiation Elements. NREL will define and assign the quality flags for the solar radiation data elements. The first digit provides information about the source of each hourly value for each element, including the methods and input data used to derive model estimates. For example, a high-quality source of information would be represented by direct measurements of global, direct, and diffuse radiation, while a relatively lower quality is assigned to modeled information. The second digit designates the uncertainty attached to each hourly value.

Meteorological Elements. Although NCDC assigned flags for meteorological data to the TD-3280 tapes, many of them are specific to an individual meteorological element and, in some instances, are specific to data from a particular period of time. As a result, users would often have difficulty in interpreting these flags for their own use. Furthermore, no flags are available for precipitable water and aerosol optical depth. Thus, NREL has adopted a two-digit flag system for most meteorological data. The first digit represents source flags such as "data as received from NCDC," or "derived," or "estimated" values. Uncertainty flags represent a range of uncertainty percentages or represent unknown or undefinable uncertainty. The uncertainties for meteorological elements will be less rigorous than those for solar

radiation elements because they will be estimated from limited information. In some cases, the uncertainty will be estimated from the original NCDC flags.

3.6 Plans for FY 1992

Version 1.0 of the data base and statistical summary products will be completed, with documentation, during FY 1992. Several activities are planned to inform the solar community of this accomplishment. Foremost among these will be a national seminar/workshop tentatively scheduled for the second week of November 1992. The seminar will inform users about the data base and other recent developments in solar radiation resource assessment activities.

The seminar will also be a forum to obtain input on user needs for future products to be developed from the data base and other sources such as satellite data. The completion of the 1961-1990 data base is an important milestone that should be viewed as the establishment of a tool from which resource assessment products will be developed. Creation of the data base will be a major first step toward significant improvements in our ability to assess solar radiation resources for renewable energy developments.

4.0 EDUCATIONAL ACTIVITIES

4.1 HBCU Solar Monitoring Network

NREL continues to fund and oversee the Historically Black Colleges and Universities (HBCU) Solar Monitoring Network, which has been in operation at six locations in the southeastern and eastern United States since 1985. The network is shown in Figure 4-1, and the following colleges and universities participate in this network:

- Bethune-Cookman College, Daytona Beach, Florida
- Bluefield State College, Bluefield, West Virginia
- Elizabeth City State University, Elizabeth City, North Carolina
- Mississippi Valley State University, Itta Bena, Mississippi
- South Carolina State College, Orangeburg, South Carolina
- Savannah State College, Savannah, Georgia.

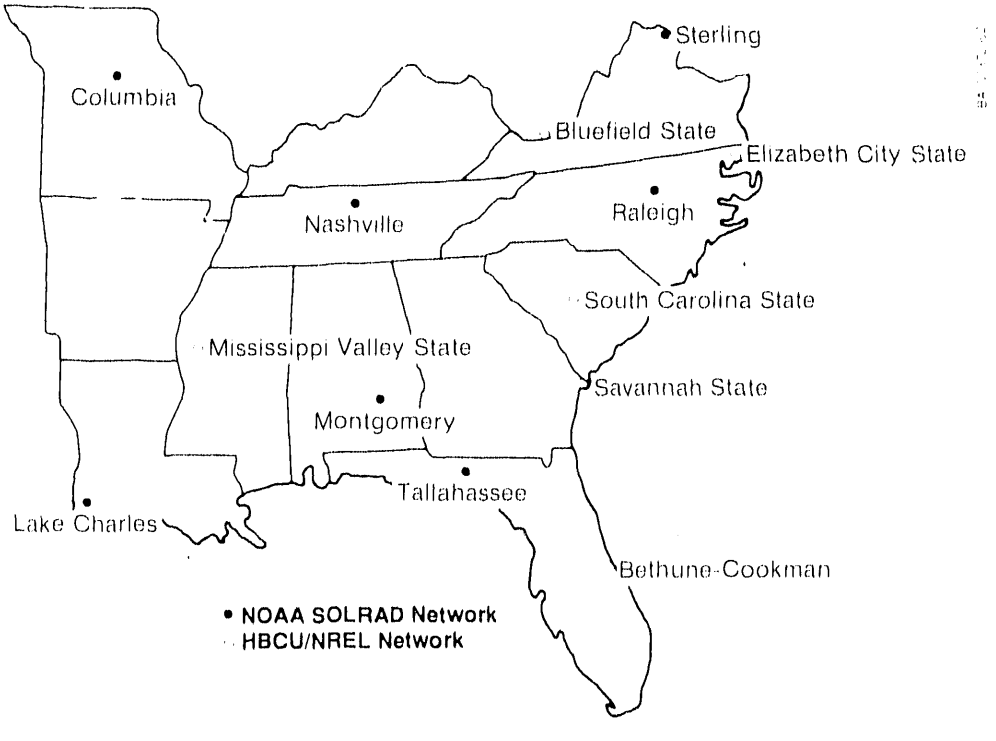


Figure 4-1. The HBCU and SOLRAD monitoring stations in the southeastern United States

The objectives of the network continue to be realized:

- To significantly improve the assessment of solar radiation resources in the Southeast
- To encourage the development of academic and research programs in solar energy at HBCUs
- To encourage the distribution of solar radiation resource information and the development of solar energy applications in the Southeast.

Each station is equipped with a thermopile-type pyranometer for measuring global horizontal solar radiation, a shadowband stand with another pyranometer for measuring the diffuse horizontal solar radiation, and a battery-powered microprocessor-based data acquisition system for recording 5-minute and hourly averages of 10-second samples. The stations at Bluefield State College and Elizabeth City State University also have a pyrheliometer mounted in a battery-powered automatic sun-following tracker for measuring the direct normal solar radiation, as shown in Figure 4-2.

The data acquisition system records the data on audiocassette tapes that are sent monthly to NREL for processing. Listings of the data for 5-minute, hourly, and daily periods are also produced at the station as an immediate display that may be used to check station operations. A maintenance inspection of the station equipment and a brief meteorological observation are made at least once a day, Monday through Friday.

NREL processes the data monthly, producing archived data in the NREL standard broadband format [12], printed monthly tabular reports with hourly averages and daily totals, and time-series plots. The 5-minute data are quality assessed using NREL software developed for this project. The quality assessment methodology involves comparisons with physical limits and internal consistency tests using the two or three solar radiation elements.

Data collection for the six-station network remains excellent. From October 1990 through September 1991, more than 90% of the possible 5-minute averaged data were recovered and passed NREL's data quality assurance testing. Other accomplishments during FY 1991 included a substantial funding increase for the operation and maintenance of each station; continued off-site data storage for safeguarding the network archives of digital media; continued funding for a part-time student to assist with data processing; and production of monthly newsletters providing helpful feedback about data collection and developments in renewable energy research and development. We also continued to provide telephone support for addressing operational problems at each station.

The open communications with each station are vital for the collection of high-quality data. We feel data quality *control* can only be undertaken at the time the data are collected. By keeping open the channels of communication with each station, those responsible for data collection know as soon as possible when and how corrective action must be taken.

4.2 Educational Initiative Plan

During the summer of 1991, two high school teachers, M. Stone and J. Beasley, worked with the SRRAP to help prepare a plan for using educational institutions to expand solar radiation network measurements in the United States. This plan was presented as a proposal titled *Crisis: Planet Earth, A National Renewable Energy Resource Assessment Network Serving Science and Education.* This plan represents a 5-year strategy to develop a national renewable energy resource data base through a partnership with the public education system of the United States. The plan envisions a network of stations measuring nine climatic parameters (global, diffuse and direct radiation, wind speed and direction, precipitation, relative humidity, temperature, and barometric pressure). One or two stations per state will be installed; seven regional centers throughout the United States will manage this network. A core support team will

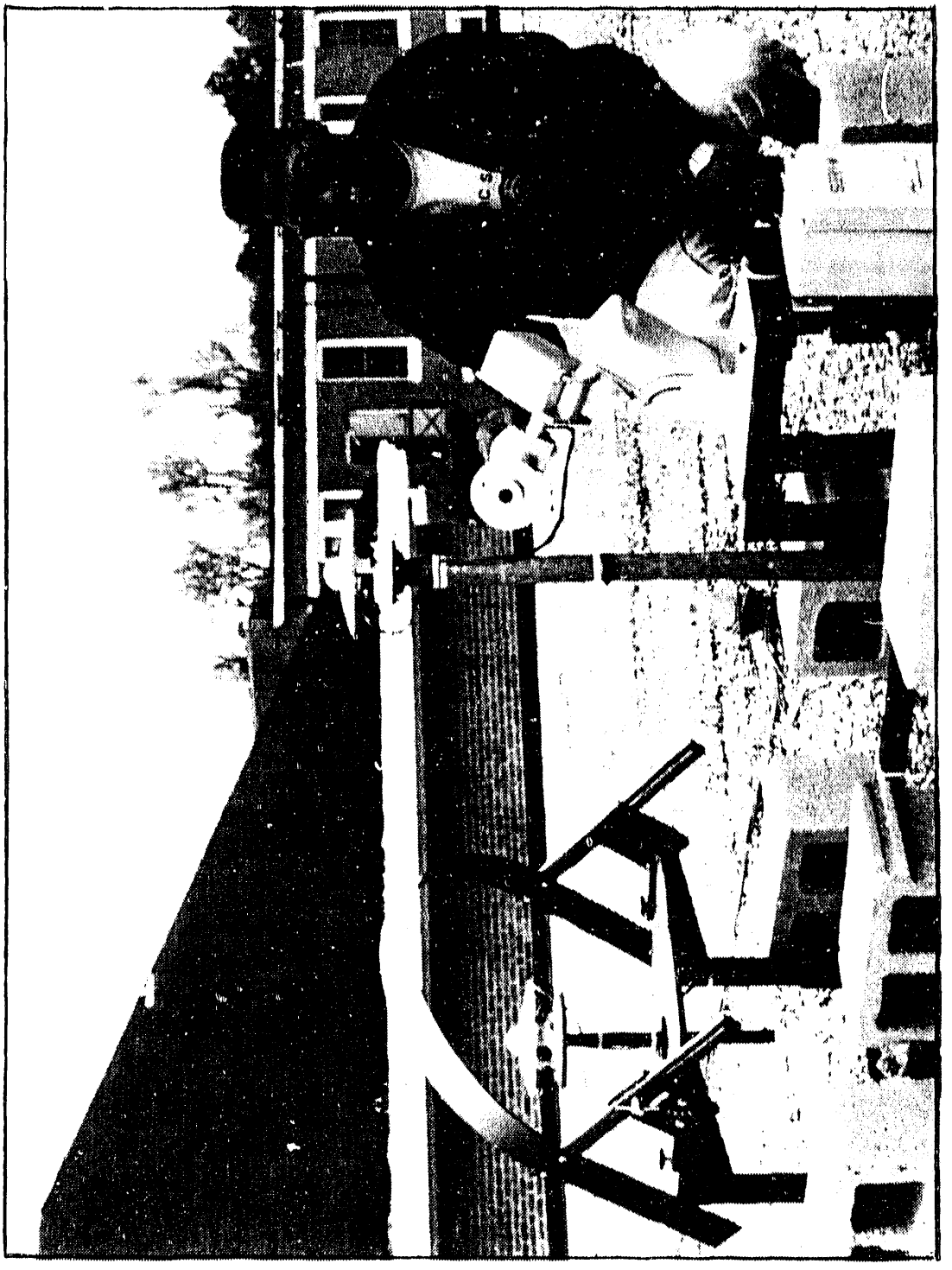


Figure 4-2. Student Eddie Vinson examines the NREL-designed instrumentation fixture at Elizabeth City State University. The instruments measure (left to right) diffuse, global, and direct solar radiation elements.

comprise regional college and university faculties from the seven regions. They will train 10 to 20 local site teachers how to operate the equipment package, collect and transmit data, and foster the development of new instructional programs and hands-on activities in energy- and environmental-related areas. Besides these data collection activities, the program includes plans for dissemination of data products, models, and reports. This proposal helps form the basis for an educational initiative plan to be developed during FY 1992.

5.0 OUTREACH

5.1 American Society of Heating, Refrigerating, and Air-Conditioning Engineers

SRRAP personnel actively participate in the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). More than 50,000 members are in ASHRAE, representing engineers and architects who could benefit from renewable energy technologies. The society in turn offers the SRRAP the opportunity to stay informed about user needs. In FY 1991, SRRAP staff members attended the annual and winter meetings of the society, participated as a member (secretary) of the Technical Committee 4.2, Weather Information, provided technical reviews for society publications and presentations, and served on the Rocky Mountain Regional Chapter of ASHRAE.

5.2 Weather Year for Energy Calculations

As part of this participation in ASHRAE, SRRAP staff members are producing a revised meteorological data set called WYEC2. This second version of ASHRAE's Weather Year for Energy Calculations (WYEC) will be an expansion of the original data set and includes data from the TMY data set prepared for NOAA. Hourly WYEC2 data will be available for 59 cities in the United States and Canada, shown in Table 5-1. The surface meteorological data have been retained and combined with solar radiation estimates using the latest modeling techniques. In addition to revised estimates of the direct normal and diffuse solar radiation, the WYEC2 data format includes fields of illuminance and luminance estimates. The WYEC2 data will be distributed with a software "Toolkit" for providing easy access to the data on a personal computer. The WYEC2 data will be available from ASHRAE.

5.3 American Association of State Climatologists

The SRRAP Science and Technology Review Committee (this committee is discussed in Section 8.0) recommended that a member of the staff participate in meetings of the American Association of State Climatologists. In addition to the individual state climatologists, the association provides the opportunity to interact with federal and state agencies such as the NOAA, U.S. Department of Agriculture, U.S. Forest Service, U.S. Geological Survey, California Office of Hydrology, Oklahoma Water Survey, and others. A SRRAP staff member presented a briefing on "Low-Cost Solar Monitoring" at the annual meeting.

5.4 Meeting of the International Solar Energy Society

All of the SRRAP staff attended selected sessions of the International Solar Energy Society's (ISES) 1991 Solar World Congress held in Denver, Colo., in August; and two of the staff members chaired sessions on solar radiation. Four papers authored by the project staff were presented during the Congress, and two papers co-authored by the staff were presented. Titles of these papers are included in Appendix A of this report. In addition, the project staff participated in the annual meeting of the American Solar Energy Society Resource Assessment Division, which was held during the ISES Congress.

5.5 Other Technology Transfer Activities

The transfer of technical information from SRRAP to users is an increasingly important part of our activities. We receive requests for information about all aspects of solar resource assessment and use a standard form to maintain a record of most requests. A total of 136 documented requests for technical information are on file for FY 1991. We responded to requests from the following sectors:

- Private industry (engineering, architecture, life sciences, environmental sciences, etc.)
- Education (primary and secondary schools, colleges and universities)
- Government (local, state, and federal agencies)
- Research and development (including other NREL elements).

Sample requests in FY 1991 include world maps of solar radiation resources for the National Geographic Society, resource assessment overviews for electric utilities and others, detailed 5-minute data from the Solar Radiation Research Laboratory (SRRL) for an NREL solar detoxification project, international sources of solar radiation for various photovoltaic applications, spectral radiation data and descriptions of instrumentation for the Oak Ridge National Laboratory, radiometer calibration techniques and data for the Electric Power Research Institute, and tours of the SRRL for many U.S. and foreign visitors.

Table 5-1. Inventory of the 77 WYEC2 Data Files (By City)

City	State	Station Number	Data Source
Albuquerque	New Mexico	23050	(T)
Albuquerque	New Mexico	23050	(W)
Amarillo	Texas	23047	(W)
Apalachicola	Florida	12832	(T)
Atlanta	Georgia	13874	(W)
Birmingham	Alabama	13876	(W)
Bismarck	North Dakota	24011	(T)
Bismarck	North Dakota	24011	(W)
Boise	Idaho	24131	(W)
Boston	Massachusetts	94701	(T)
Boston	Massachusetts	14739	(W)
Brownsville	Texas	12919	(T)
Brownsville	Texas	12919	(W)
Cape Hatteras	North Carolina	93729	(T)
Caribou	Maine	14607	(T)
Charleston	South Carolina	13880	(T)
Charleston	South Carolina	13880	(W)
Cheyenne	Wyoming	24018	(W)
Chicago	Illinois	14819	(W)
Cleveland	Ohio	14820	(W)
Columbia	Missouri	03945	(T)
Dallas/Ft. Worth	Texas	03927	(T)
Dallas/Ft. Worth	Texas	03927	(W)
Dayton	Ohio	93815	(W)
Denver	Colorado	23062	(W)
Des Moines	Iowa	14933	(W)
Detroit	Michigan	94847	(W)
Dodge City	Kansas	13985	(T)

Table 5-1. Inventory of the 77 WYEC2 Data Files (By City) (continued)

City	State	Station Number	Data Source
Dodge City	Kansas	13985	(W)
Edmonton	Alberta	25145	(W)
El Paso	Texas	23044	(T)
El Paso	Texas	23044	(W)
Ely	Nevada	23154	(T)
Fresno	California	93193	(T)
Great Falls	Montana	24143	(T)
Great Falls	Montana	24143	(W)
Indianapolis	Indiana	93819	(W)
Kansas City (Municipal)	Missouri	13988	(W)
Lake Charles	Louisiana	03937	(T)
Lake Charles	Louisiana	03937	(W)
Las Vegas	Nevada	23169	(W)
Little Rock	Arkansas	13963	(W)
Los Angeles	California	23174	(W)
Madison	Wisconsin	14837	(T)
Madison	Wisconsin	14837	(W)
Medford	Oregon	24225	(T)
Medford	Oregon	24225	(W)
Miami	Florida	12839	(T)
Miami	Florida	12839	(W)
Minneapolis/St. Paul	Minnesota	14922	(W)
Montreal	Quebec	94792	(W)
Nashville	Tennessee	13897	(T)
Nashville	Tennessee	13897	(W)
New York City (LaGuardia)	New York	94278	(T)
New York City (LaGuardia)	New York	14732	(W)
North Omaha	Nebraska	94918	(T)
North Omaha	Nebraska	94918	(W)
Oklahoma City	Oklahoma	13967	(W)
Phoenix	Arizona	23183	(T)
Phoenix	Arizona	23183	(W)
Pittsburgh	Pennsylvania	94823	(W)
Portland	Maine	14764	(W)
Portland	Oregon	24229	(W)
Raleigh/Durham	North Carolina	13722	(W)
Salt Lake City	Utah	24127	(W)

Table 5-1. Inventory of the 77 WYEC2 Data Files (By City) (concluded)

City	State	Station Number	Data Source
San Antonio	Texas	12921	(W)
Santa Maria	California	23273	(T)
Seattle/Tacoma	Washington	24233	(T)
Seattle/Tacoma	Washington	24233	(W)
St. Louis	Missouri	13994	(W)
Tallahassee	Florida	93805	(W)
Tampa	Florida	12842	(W)
Toronto	Ontario	94791	(W)
Vancouver	British Columbia	24287	(W)
Washington/Sterling	District of Columbia	93734	(T)
Washington/Sterling	District of Columbia	93734	(W)
Winnipeg	Manitoba	14996	(W)

Note: (T) = Data source is typical meteorological year (26 cities)
(W) = Data source is weather year for energy calculations (51 cities)

The station numbers for the five Canadian cities have been assigned currently accepted WBAN values:

City	Province	Station Number WYEC	Station Number WYEC2/WBAN
Edmonton	Alberta	32205	25145
Montreal	Quebec	75250	94792
Toronto	Ontario	68655	94791
Vancouver	British Columbia	18447	24287
Winnipeg	Manitoba	53222	14996

6.0 INTERNATIONAL ACTIVITIES

6.1 International Energy Agency, Solar Heating and Cooling Programme

6.1.1 International Energy Agency (IEA) Task 9

The IEA Solar Heating and Cooling Program (Task 9) was initiated in October 1982 to advance the state of the art in the measurement and estimation of solar radiation. The initial three subtasks were completed in 1987, and three new subtasks were begun at that time. The schedule for completion is June 1991. E. Maxwell attended the final meeting of Task 9, held in Toronto on April 22–25, 1991. Final technical results were presented for each of the subtasks.

Subtask 9D: Techniques for Supplementing Network Data for Solar Applications. The objective of this task was to evaluate techniques for estimating solar radiation resources at locations between measurement stations. The techniques evaluated included several methods of geostatistical interpolation (e.g., "nearest neighbor," "gravity weighted averaging," and "Kriging"), satellite estimates, cluster analysis using topographical data, and cloud-based models. Primarily, the United States participated in this subtask to provide three 1-year data sets (one each from the Pacific Northwest, the Southwest, and the Northeast) and to analyze cloud-based models and satellite techniques.

The final conclusions of this subtask are that some combination of modeling, satellite data, and geostatistical interpolation will be needed for most locations. No single technique is likely to produce satisfactory results. In addition, the time and cost of Kriging are not justified by the small improvements over the simple gravity method of interpolation.

Subtask 9E: Representative Design Years for Solar Energy Applications. This subtask produced a valuable overview of the statistical characteristics of solar radiation data, surveyed the meteorological elements that should be included in design-year subsets, and studied methods for creating synthetic data sets. The United States participated to provide meteorological and solar radiation data sets for climates dissimilar from those found in Europe.

The final results of this subtask will include recommendations for producing design-year subsets, a report on solar radiation statistical characteristics, and sample design-year subsets for several European countries.

Subtask 9F: Irradiance Measurements for Solar Collector Testing. This subtask undertook extensive evaluations of the characteristics of solar radiometers, the development of instructions for using pyranometers in tests of solar energy converters, and the development and testing of a single tracker reference global radiometer. The United States participated to evaluate the aging of pyranometers.

The final results from this subtask will include several reports on pyranometer characteristics. Each of the existing pyranometer types showed shortcomings that should be addressed in the near future. Single tracker reference global radiometers were developed and tested by Canada, Germany, and Sweden. Their measurements of global horizontal radiation generally agreed within 1%. Instructions for the use of pyranometers in testing the performance of solar systems were prepared and tested by engineers from institutions that perform such testing. These instructions will be published and made available to all potential users.

Publication of Final Reports. The lead country for each subtask is responsible for publishing the final reports from Task 9. Although the task formally ended June 30, 1991, the publication of reports will not be completed until 1992. NREL will provide final editing for the Subtask 9D final report during FY 1992.

6.1.2 IEA Task 17

During 1991, the IEA Solar Heating and Cooling Programme initiated a new Task 17 on Measuring and Modeling Spectral Radiation Affecting Solar Systems and Buildings. The objective of this task is to improve the quantity and quality of spectral radiation data, both broadband and narrow band, needed for the design and analysis of solar systems and buildings. As of September 1991, the task consisted of five subtasks: Subtask A—narrow-band spectral and broadband infrared radiometry; Subtask B was deleted by consensus of the task participants in September; Subtask C—narrrow-band spectral radiation data acquisition and analysis; Subtask D—narrow-band spectral radiation modeling; Subtask E—broadband visible radiation data acquisition and analysis; and Subtask F—broadband infrared radiation data acquisition and analysis. The Task 17 operating agent, F. Kasten (Deutscher Wetterdienst, Meteorologisches Observatorium Hamburg, Germany), requested that C. Riordan (NREL) lead Subtask D, and NREL was asked to participate in subtasks A, C, and D. R. Perez (State University of New York-Albany), the only other U.S. participant, was asked to be the leader of Subtask E.

NREL hosted the Task 17 Project Definition Workshop in Golden, Colorado, in February 1991. The first Experts' Meeting was held in Freiburg, Germany, in September 1991, hosted by the Institute for Solar Energy Systems (ISE). C. Riordan attended this meeting and acted as subtask leader for Subtask D; however, her participation was in an unofficial capacity because DOE approval for participation in Task 17 is still under consideration. NREL also funded R. Perez to participate in Task 17 in an unofficial capacity to enhance U.S. participation and to establish a DOE tie to the International Daylight Measurement Program through Subtask E of Task 17.

A detailed trip report for the Freiburg meeting was submitted to DOE in October 1991. Briefly, the report describes a tour of ISE and the proposed Task 17 structure, participants, and action items for each subtask. The Task 17 documents are being reviewed for approval by the IEA Executive Committee.

C. Riordan continues to act as the Subtask D leader while DOE approval for participation in Task 17 is under review. Continued NREL support for R. Perez is under consideration pending DOE approval. The Task 17 work closely parallels planned and needed work in the DOE Resource Assessment and Buildings programs. With a small investment in coordination time, NREL can participate in a task that increases, by at least 15, the U.S. staff working on spectral solar radiation modeling, measurements, and data sets. The task work will provide information on spectral solar radiation needed to design and evaluate the performance of spectrally selective solar conversion technologies such as photovoltaics and specially designed windows for daylighting and energy management in buildings. By participating in Task 17, NREL's input about the direction of the research can be beneficial to the DOE programs and the U.S. solar energy industry.

6.2 Saudi Arabian Solar Resource Assessment

In early FY 1990, E. Maxwell traveled to Saudi Arabia as part of a four-person DOE team to explore opportunities for joint Saudi Arabian/U.S. renewable energy projects. Following that visit, plans were prepared for a joint effort involving the King Abulaziz City for Science and Technology (KACST) and NREL to upgrade the assessment of solar radiation resources in Saudi Arabia.

During FY 1991, three scientists from KACST visited NREL to discuss three options, proposed by NREL, for carrying out this work. Based on these discussions, a detailed statement of work and budgets were prepared for a 4-year project. These plans, which were submitted to KACST for their review at the start of FY 1992, call for the use of a small part of the SRRAP funds to partially support these activities that will, in turn, be synergistic with research planned for this same period. Most of the funding will be provided by the government of Saudi Arabia.

Two of the activities planned for this project will particularly benefit the long-term SRRAP objectives. The first involves the detailed characterization of the bimetallic actinographs used to collect most of the historical solar radiation data in Saudi Arabia. These instruments have been used in many countries because they do not require any external power source for their operation. The characterization of these instruments under the joint KACST/NREL project will provide valuable information regarding the quality of the data collected in Saudi Arabia and in all other countries where they have been used. Furthermore, the characterization will likely support the upgrade of historical, current, and future data collected with these instruments.

Of even greater potential benefit to SRRAP activities will be the development of techniques to combine surface measurements of solar radiation and meteorological data with satellite radiometer measurements to produce a uniform grid of solar radiation data across all of Saudi Arabia. Although the satellite data for Saudi Arabia will come from the European Meteosat satellite, the methods developed and the improved scientific knowledge will directly benefit similar efforts planned for the United States using the Geostationary Observational Earth Satellite (GOES) and NOAA polar orbiter satellites. Because both U.S. and Saudi Arabian efforts will take place during the next several years, both countries will accrue benefits from this joint project.

7.0 SOLAR RADIATION RESEARCH LABORATORY ACTIVITIES

7.1 Background

The Solar Radiation Research Laboratory (SRRL) is located on South Table Mountain in Golden, Colorado, near the NREL offices (Figure 7-1). SRRL provides the outdoor research measurement capabilities needed by the project and supports other programs at NREL. Since 1979, the development and operation of the laboratory have focused on the following objectives:

- Building a research data base that characterizes solar radiation and meteorological conditions for the various solar technologies
- Providing a world-class facility for outdoor calibrations of radiometers traceable to international standards
- Accommodating the varying research needs associated with the development and testing of improved solar radiation instruments, atmospheric models, and solar energy conversion devices
- Establishing a long-term solar radiation and meteorological and climatological data base for South Table Mountain near Golden, Colorado.

The Baseline Monitoring System (BMS) at SRRL collects the 17 data elements listed in Table 7-1. We use a battery-powered data acquisition system for sampling the channels every 10 seconds. Five-minute averages are stored on cassette tape for all but the wind speed and wind direction data, which are instantaneous samples on a 5-minute interval. The cassette tapes are processed weekly, using a system of personal and mini computers in the Solar Radiation Data Processing Laboratory. With assistance from staff members at the NREL Metrology Laboratory, we performed daily maintenance checks on the BMS through June in conjunction with a special project funded by the Photovoltaics Program (see Section 7.2). Beginning in July, maintenance reverted to weekdays only. Maintenance records are written on a standard log form as part of our quality assurance efforts. More than 95% of the possible 5-minute data values were recovered during FY 1991.

7.2 Radiometer Calibrations

More than 90 radiometers were calibrated outdoors at SRRL during FY 1991. We continue to refine our Broadband Outdoor Radiometer CALibration (BORCAL) procedures. Pyrheliometers are calibrated by comparing the voltage signals from the radiometer being tested with the reference direct normal solar radiation as measured with an electrically self-calibrating absolute cavity radiometer. Typically, the average of more than 500 such 1-minute comparisons over at least three cloud-free days are used in determining the mean calibration factor (in μV per W/m^2). Pyranometers are calibrated by summing measurements of the reference direct normal solar component, as measured with an absolute cavity, and the diffuse horizontal component, as measured with a thermopile-based pyranometer under a tracking disk. The reference global solar radiation is calculated from these two measurements and the corresponding computed solar zenith angle. We compare the reference radiation with the voltage signal from each pyranometer tested to determine the calibration factor (in μV per W/m^2).

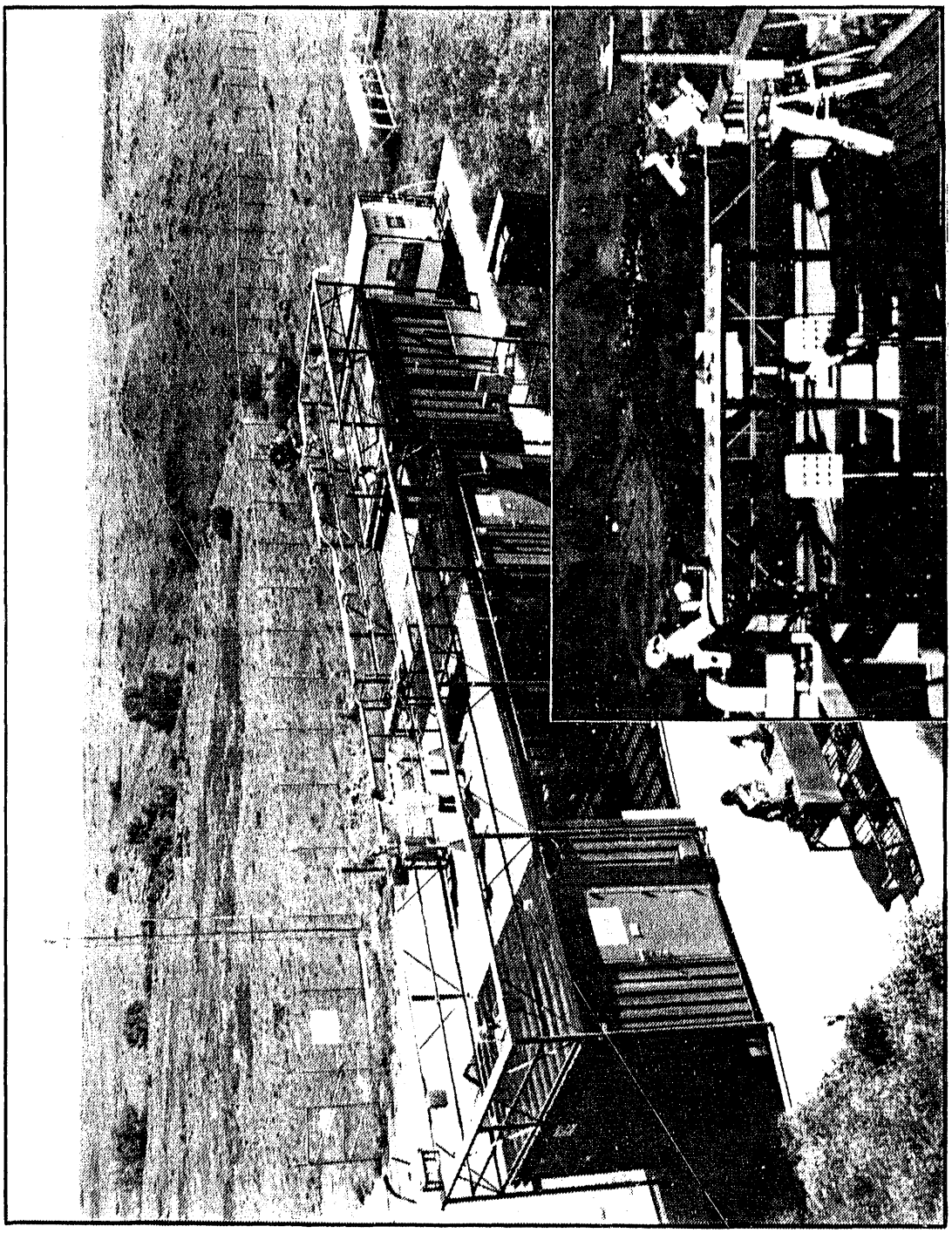


Figure 7-1. The Solar Radiation Research Laboratory (SRRL) located on South Table Mountain near Golden, Colorado

Table 7-1. SRRL Baseline Monitoring System Data Channels

No.	Measurement Parameter	Instrument*
1	Global horizontal irradiance	PSP
2	Diffuse horizontal irradiance	PSP
3	Direct normal irradiance	NIP
4	Global irradiance on 40° south-facing tilt	PSP
5	Global normal irradiance on two-axis tracking surface	PSP
6	Global irradiance on one-axis tracking surface (horizontal, north-south axis)	CM-11
7	Global horizontal irradiance (780 - 3000 nm)	PSP
8	Direct normal irradiance (780 - 3000 nm)	NIP
9	Total-horizontal ultraviolet irradiance (295 - 385 nm)	TUVR
10	Ground-reflected irradiance	PSP
11	Direct normal irradiance (500 nm)	LCSP
12	Wind speed, 10 m above ground level	TGT
13	Wind direction, 10 m above ground level	TGT
14	Dry bulb temperature	CSI
15	Relative humidity	CSI
16	Barometric pressure	YSI
17	Direct normal ultraviolet irradiance (295 - 385 nm)	TUVR

*Instrument abbreviations:

CM-11 = Kipp & Zonen Pyranometer, model CM-11
CSI = Campbell Scientific, Inc., model 207 Probe
LSCP = NREL-designed low-cost sun photometer (T. Cannon)
NIP = Eppley Laboratory Pyrheliometer, model NIP
PSP = Eppley Laboratory Pyranometer, model PSP
TGT = Teledyne-Geotech Wind System
TUVR = Eppley Laboratory Photometer, model TUVR
YSI = Yellow Springs Instrument Company

During FY 1991, we developed and tested a system for calibrating pyranometers on an inclined surface such as those used for plane of array measurements. We confirmed that the tilt effects of the Eppley Laboratory's model PSP are less than our measurement uncertainty established for our calibration methods.

Also during FY 1991, we received the results of the International Pyrheliometer Comparisons held in September and October 1990. We operated two electrically self-calibrating absolute cavity radiometers during the intercomparisons at the World Radiation Center in Davos, Switzerland. Our traceability to the World Radiometric Reference (WRR) for each of the absolute cavity radiometers is achieved by adjusting the radiation values by the multipliers resulting from the intercomparison.

7.3 Testing Rotating Shadowband Radiometers

The Solar Radiation Resource Assessment Project cooperated with the NREL Photovoltaics Program and the Electric Power Research Institute (EPRI) to compare several solar radiation measurement systems as options for performing solar radiation assessments in a utility's service territory [13]. EPRI acquired instruments called rotating shadowband radiometers (RSR) from two manufacturers, and NREL installed them at SRRL for a 6-month comparison with SRRL radiometers. The RSRs [14, 15, 16] use a commercially available silicon-detector pyranometer to measure global horizontal radiation as well as diffuse radiation when the rotating band blocks the direct radiation during the band's rotation. Direct normal radiation is calculated by subtracting diffuse from global, and by calculating the sun's position from the location, time, and day of the year. Thus, one instrument is used to obtain values for global, direct, and diffuse radiation. Data from the RSRs were compared with data from the baseline measurement system at SRRL, which includes a pyranometer for measuring global horizontal radiation, a pyranometer with a manually adjusted shadowband measuring diffuse horizontal, and a pyrheliometer mounted in a solar tracker measuring direct normal radiation. On selected clear-sky days, reference radiation was measured with a cavity radiometer (direct normal) and a pyranometer with a tracking shading disk (diffuse).

Data from the various instruments were compared for 6-months, from January through June 1991. Comparisons of daily total radiation from the RSRs and SRRL instruments gave coefficients of determination greater than 0.98 for global, direct, and diffuse radiation measurements. The structure of the daily profiles of 5-minute averaged radiation was similar for all instruments. Further analysis will be performed to compare the systems on several time scales (1-minute, 5-minute, 15-minute, and hourly) and to make comparisons with the highest accuracy reference systems. In general, preliminary evaluation of the data indicated that all instruments in the comparison can be considered as options for solar radiation resource assessment. However, we must recognize that the RSRs are still under development, and there is limited field experience to date. Details of the comparison will be available in a test report being prepared by NREL and EPRI, with expected completion in early 1992.

8.0 PROGRAM MANAGEMENT

Routine program management activities in FY 1991 included technical and management interactions with DOE, national laboratories, and other federal agencies; production of monthly reports, 6-month self-performance self-assessments, and program review meetings; preparation of field work proposals and annual operating plans; and continual management of budgets, schedules, and milestones. In addition, a number of special activities took place in FY 1991 and are summarized here.

Several NREL projects, including the SRRAP, supported the participation of staff members of NREL's Solar Radiation Research and Metrology Branch in a cavity radiometer intercomparison at Davos, Switzerland, during September 24 through October 12, 1990. These intercomparisons allow for calibration of radiometers at the Solar Radiation Research Laboratory to be traceable to world standards.

A meeting of the SRRAP Science and Technology Review Committee was held on December 3-4, 1990. This group meets approximately annually to provide external review of SRRAP research and development plans. Presentations from SRRAP staff members were made to the committee, which provided feedback during the meeting. The committee also submitted a letter report summarizing its review and offering suggestions to the NREL director, D. Sunderman.

Special reports prepared or completed during FY 1992 include a *Resource Assessment 5-Year Plan*, a resource assessment overview brochure, and the *SERI Solar Radiation Resource Assessment Project: Fiscal Year 1990 Annual Progress Report*. An internal planning document updating the plans for completing the 1961-1990 National Solar Radiation Data Base was developed and sent to a number of reviewers for comment. A special lecture on spectral solar radiation modeling was presented to representatives of Oak Ridge National Laboratory involved in the development of a spectroradiometer for DOE's Atmospheric Radiation Measurement (ARM) Program. Staff members participated in numerous conferences, workshops, and intergovernmental meetings such as SOLTECH '91 in San Francisco, California, the Air Force Geophysics Directorate's annual meeting on atmospheric transmission models in Boston, Massachusetts, and the meeting of the International Solar Energy Society (ISES) in Denver, Colorado.

Extensive preparations were made for the environment, safety, and health (ES&H) Tiger Team that visited NREL in July 1991. The training and review of safe operating procedures in the laboratory greatly enhanced the awareness of ES&H policies and procedures among NREL staff, including the SRRAP.

SRRAP staff members contributed to several planning documents. One document in particular for which staff members provided review was the DOE Office of Solar Conversion SOLAR 2000 plan.

In September 1991, two new staff members were added to the SRRAP team. D. Renné joined NREL to manage the SRRAP because C. Riordan was moved into a branch manager position. B. Marion joined the staff to develop documents and other products resulting from the data base development activities.

9.0 PROGRAM OUTLOOK

By the end of FY 1991, the SRRAP was approaching a point of significant transition in the scope of its activities. With the data base production well under way, and the release of the data base scheduled for early summer 1992, it becomes appropriate to view the direction in which SRRAP should proceed. The ultimate objective of the SRRAP is to provide assessment products and tools to the user and planning community that reduce the uncertainties in evaluating the feasibility of employing solar energy technologies at any given location. Their use of these products and tools, in turn, provide guidance to the SRRAP for research to further reduce the uncertainties in solar resource information. This interactive process is exemplified in Figure 9-1. Thus, the data base is the foundation of these assessments, which are expected to take a variety of forms. For example, an updated atlas of solar energy resources for the United States is necessary; the data base, along with the uncertainty flags attached to the data, will provide the basis for this atlas, which will strive to present our best knowledge of the spatial variability of solar resources.

Various interpolation techniques need to be applied to the data base so that solar radiation resource estimates, along with a statement of their uncertainty, can be developed for any point within the United States. These interpolation schemes must be based on physical processes. Satellite data offer a promising method for estimating solar radiation over large geographic regions to fill in data gaps between surface measuring stations. Understanding cloud and fog formation processes, particularly in large regions of complex terrain where few measurement stations exist, is crucial to the interpolation techniques.

Among the most important products to be developed will be the typical year data set, which provides a standard for evaluating energy production from any form of solar energy technology at any of the sites incorporated in the data base. However, resource data also need to be interpreted in ways that allow for understanding the interannual variability of solar resources. In this way, guidance can be provided to industries that often must rely on short-term measurements or typical year data sets for making decisions relating to the long-term performance of a technology. Included in this interpretation is a "design-year" data set, so that manufacturers and users of renewable technologies can be aware of the extreme conditions that may occur at a site.

Another important activity to be addressed upon completion of Version 1.0 of the data base will be methods for maintaining and archiving the data. Although Version 1.0 will be well documented and publicly available through NCDC, it is likely that NREL will continually be made aware of new data sets that can be incorporated into Version 1.0 and new refinements that can be incorporated into the models used to produce data for the secondary stations in Version 1.0. Although a schedule of future revisions to the data base cannot be established at this time, some form of data management activity will exist on a continuing basis at NREL.

Another major turning point in the program will coincide with the possible termination of routine solar radiation monitoring by NOAA. This provides an opportunity for NREL to pursue the re-establishment of a research-quality solar radiation monitoring program, probably through some form of educational initiative. This activity will require multiagency support. As discussed in Section 4.2, an educational program focused on radiation measurements and monitoring will be designed in FY 1992, with possible preliminary implementation of this program by the end of the year. This activity would be expected to continue through at least the end of the decade.

NREL's involvement with the IEA in Task 17, with the objective of developing methods for producing a spectrally resolved data base to augment the existing broadband data base, is likely to continue for the next several years.

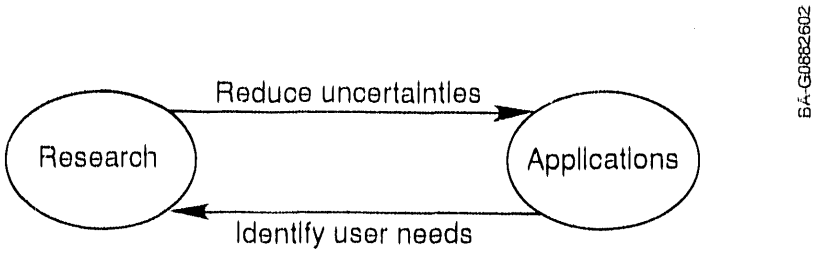


Figure 9-1. The interrelationship between the development and use of solar resource assessment products

The scope of SRRAP activities is also expected to expand through collaboration with other programs. For example, DOE's Atmospheric Radiation Measurement (ARM) Program [17] will be establishing long-term facilities at up to five locations around the world to observe clouds and radiation. These facilities will provide comprehensive observational data on the ways in which clouds affect solar radiation at the Earth's surface and can represent an important way for testing and improving the parametric algorithms used in models such as METSTAT. As another example, NREL will continue to explore ways to collaborate on programs with EPRI, such as the testing of the rotating shadowband radiometers (described in Section 7.3), so that objectives mutual to both organizations can be met more efficiently.

Over the next several years, NREL will work toward incorporating the National Solar Radiation Data Base into a geographic information system (GIS), along with other key renewable energy resource data bases, such as wind and biomass, and certain geophysical data. These other data bases would come from the organizations in which they were developed. This comprehensive data set will allow for planners, system designers, and independent users of renewable energy systems to perform comparative evaluations of various technologies at any given location, knowing what the resource base and its inherent uncertainties are for each technology. This GIS-based system can be particularly valuable when producing large-scale energy assessments such as those associated with the development of the National Energy Strategy. NREL also plans to expand the solar data base into an international data base, incorporating, to the extent possible, information derived from other countries. By producing a worldwide resource data base in a common format, comparative assessments of solar technologies for different regions around the world can be performed. An international data base will provide strategic guidance for U.S. solar technology companies to evaluate international markets.

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APPENDIX A

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