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SERI Solar Radiation Resource Assessment Project: Fiscal Year 1990 Annual Progress Report

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SERI

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PREFACE

This report summarizes the activities and accomplishments of SERI's Solar Radiation Resource Assessment Project during fiscal year 1990. This project is part of the United States Department of Energy's (DOE) Resource Assessment Program.

Dr. Michael Pulscak is DOE's Resource Assessment program manager. Dr. Carol Riordan is the Solar Radiation Resource Assessment Project leader in SERI's Resource and Environmental Assessment Branch, Energy and Environmental Analysis Division. Questions and requests for information about the contents of this report and the project can be directed to Carol Riordan at (303) 231-1344 (FTS 327-1344).

ACKNOWLEDGMENTS

SERI would like to acknowledge the following individuals for their review of this report and good suggestions: Roland Hulstrom and Daryl Myers, SERI; Richard Perez, State University of New York at Albany; and Frank Vignola, University of Oregon.

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1.0 INTRODUCTION

The U.S. Department of Energy's (DOE) Resource Assessment Program produces scientific descriptions and assessments of the nation's renewable energy resources, such as solar energy. The program is currently focused on solar radiation resource assessment for the United States. DOE's lead center for solar radiation resource assessment is the Solar Energy Research Institute (SERI) in Golden, Colorado. Work is performed at SERI under the Solar Radiation Resource Assessment Project.

This annual progress report summarizes the activities and accomplishments of the Solar Radiation Resource Assessment Project at SERI for the period October 1, 1989, through September 30, 1990: fiscal year (FY) 1990. The work was performed in accordance with the project's annual operating plan [1] and other direct guidance from DOE during FY 1990. Previous years' activities and historical information pertinent to the FY 1990 work are documented in the FY 1987, FY 1988, and FY 1989 annual progress reports [2-4].

Section 2.0 of this report describes the project's purpose and priorities. Section 3.0 lists the FY 1990 key activities, and Sections 4.0 through 7.0 discuss the accomplishments for each key activity. Section 8.0 describes the laboratories' activities and technology transfer. Section 9.0 describes project management activities, and Section 10.0 discusses issues and initiativies.

2.0 SOLAR RADIATION RESOURCE ASSESSMENT PROJECT PURPOSE AND PRIORITIES

2.1 Purpose and Scope

The purpose of the Solar Radiation Resource Assessment Project is to help meet the needs of the public, government, industry, and utilities for solar radiation data, models, and assessments as required to develop, design, deploy, and operate solar energy conversion systems. The project scientists produce information on the spatial (geographic), temporal (hourly, daily, and seasonal), and spectral (wavelength distribution) variability of solar radiation at different locations in the United States.

Resources committed to the project in FY 1990 supported about four staff members, including part-time administrative support. With these resources, the staff must concentrate on solar radiation resource assessment in the United States; funds do not allow for significant efforts to respond to a common need for improved worldwide data.

2.2 Resource Assessment Needs

Needs for solar radiation resource information are evaluated by direct interaction with DOE, industry, utilities, and solar technology researchers. SERI also receives guidance from a Science and Technolgy Review Committee, with representatives from government, universities, and utilities. The broad categories of needs identified by the various sources are as follows:

- Long-term (30-year) data bases that facilitate system design by representing the natural variability of solar radiation
- Continuous, reliable measurements of solar radiation from a network of sites in the United States
- Solar radiation resource availability maps, data, and characterizations covering the United States for various types of solar collectors
- Spectral solar radiation models and data bases needed for the design and development of spectrally selective solar energy conversion systems
- Representative or typical solar radiation data sets (e.g., typical year) that can be used in economic comparisons of systems
- Methods for estimating site-specific solar radiaton that can be used to select optimum sites and site-specific designs and to predict the performance of various systems
- Models or algorithms that convert solar radiation data from one component to another (e.g., from total or global solar radiation on a horizontal surface to direct and diffuse solar radiation on a surface of any orientation)
- Quality assessment methods for evaluating measured data

- Instruments and methods that measure the solar radiation resource accurately and evaluate the performance of a solar energy conversion system reliably
- Worldwide solar radiation resource assessments that will help to evaluate market potentials for U.S. industries.

2.3 Multiyear Goals

The project's multiyear goals are developed with DOE by reviewing the common needs and choosing activities that address a large number of users, with the assumption that the level of project funding will remain the same or increase. The multiyear goals, as given in DOE's Resource Assessment 5-year (FY 1991 to FY 1995) Plan [5], are as follows:

- To produce a 30-year (1961–1990) solar radiation data base for the United States to replace the 1952–1975 data base, followed by the development of products (design/typical year data sets, maps, data summaries, etc.) and methods for site-specific solar radiation estimates
- To support the collection of high-quality solar radiation data for the United States through cooperation with the National Oceanic and Atmospheric Administration (NOAA), which operates the national solar radiation (SOLRAD) network, with DOE's solar radiation network sites at selected Historically Black Colleges and Universities (HBCU), and with other regional networks as resources permit
- To produce a limited, research-quality spectral solar radiation data base and spectral simulation model for various climate conditions, as needed for the development of spectrally selective solar energy conversion technologies
- To disseminate products and research results and maintain laboratory expertise as the nation's lead center for solar radiation resource assessment.

3.0 FISCAL YEAR 1990 KEY ACTIVITIES

DOE and SERI agreed on FY 1990 priorities and key activities to help achieve the multiyear goals. To provide effective research management and direction, the key activities were grouped technically under two research tasks. The following tasks, key activities, and allocation of the total budget (%) were developed.

1. Broadband Solar Radiation Data Bases and Models (75%)
   E. Maxwell, Task Leader

   Activities

   - National 30-year data base development, including model development
   - Support of national monitoring networks
   - Site-specific solar radiation estimation methods

2. Spectral Solar Radiation Data Bases and Models (25%)
   C. Riordan, Task Leader

   Activities

   - Spectral solar radiation models
   - Spectral solar radiation data bases

Funding for the project was reduced by about 9% in April 1990 and was accommodated mostly by reducing the activity on Task 2.

The project activities and accomplishments related to these two tasks are described in Sections 4.0 through 7.0.

4.0 NATIONAL SOLAR RADIATION DATA BASE DEVELOPMENT

4.1 Background

From the early 1950s, the National Weather Service (NWS), a part of the NOAA, has measured solar radiation at a network of more than 30 locations across the United States. The number of stations in the network, the location of these stations, and the instruments used for measuring solar radiation have changed from time to time during this 40-year period. The map shown in Figure 4-1 identifies the locations that have been used in the development of the existing national solar radiation data bases. The 26 stations identified from 1952 to 1975 represent less than half of those actually in operation for at least part of this time. As indicated on Figure 4-2, only global-horizontal solar radiation was routinely measured at the network sites during this period of time.

From January 1952 through December 1975, the 26 stations collected approximately 6,000 station-months of global-horizontal solar radiation data (see Figure 4-3). This estimate of 6,000 station-months reflects extensive periods of time when the solar radiation instrumentation was either not installed or not operating. This estimate does not account for short periods of time (hours or days) when the equipment may have failed, been shut down for maintenance, or produced erroneous data caused by factors outside the control of the station operators.

When interest in these data increased during the oil embargo of the early 1970s, DOE and NOAA cooperated to produce a national solar radiation resource data base from the historical solar radiation data. This became a major rehabilitation project when missing calibration records and other problems made it difficult to verify the data accuracy.

This rehabilitation employed engineering corrections and the best models available, and it resulted in the SOLMET (SOLar-METeorological) data base, covering the period from 1952 through 1975. Of the 248 stations included in this data base, only the 26 SOLMET stations contained measured data from the original NWS network. The data for the other 222 ERSATZ (synthetic) stations were derived from regression models. All of the direct-beam data (radiation from the solar disc) were derived from models. This SOLMET/ERSATZ data base was ultimately used to create other products, such as the typical meteorological year (TMY) [6] data sets and the Solar Radiation Energy Resource Atlas of the United States [7]. These products remain the primary source of national solar radiation data for the United States.

As the historical data were being rehabilitated, NOAA and DOE were launching an upgrade of the SOLRAD network. The new 38-station SOLRAD network began collecting data in 1977 and was equipped with improved pyranometers to measure the global-horizontal solar radiation and included tracking pyrheliometers to measure the direct-normal solar radiation from the solar disc. Nine of the stations also measured the diffuse radiation from the sky. A radiometer calibration facility, set up by NOAA in Boulder, Colorado, helped ensure the accuracy of data.

Only 16 of the 44 stations operating at one time or another from 1952 to 1990 have been used continuously for data collection during the entire 38-year period. An additional 11 stations were operated from 1977 to 1990. During the three years from 1976 through 1978, radiometers, solar trackers, and data recording systems were purchased and eventually installed at 38 NWS stations.

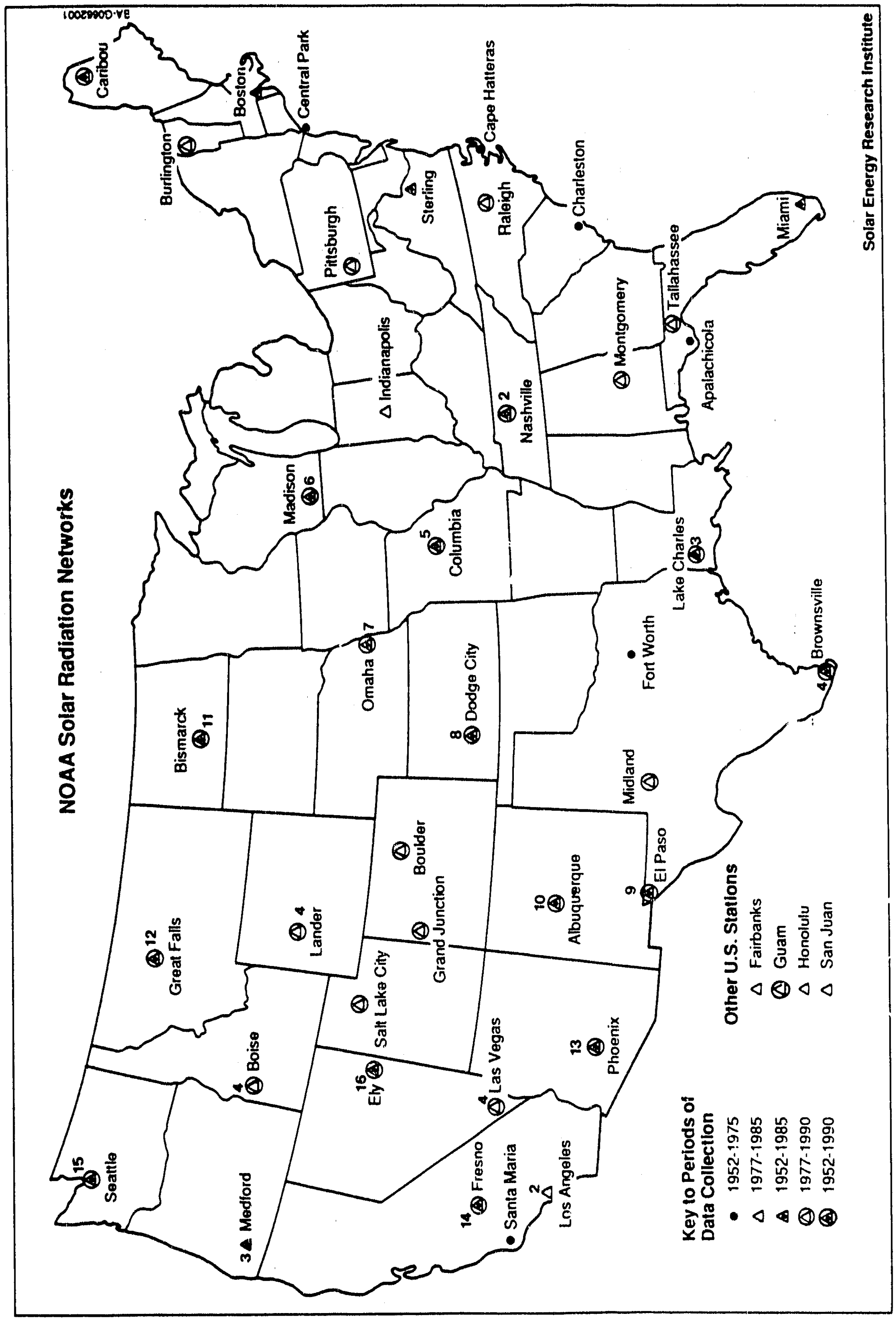

Figure 4-1. NOAA Solar Radiation Network

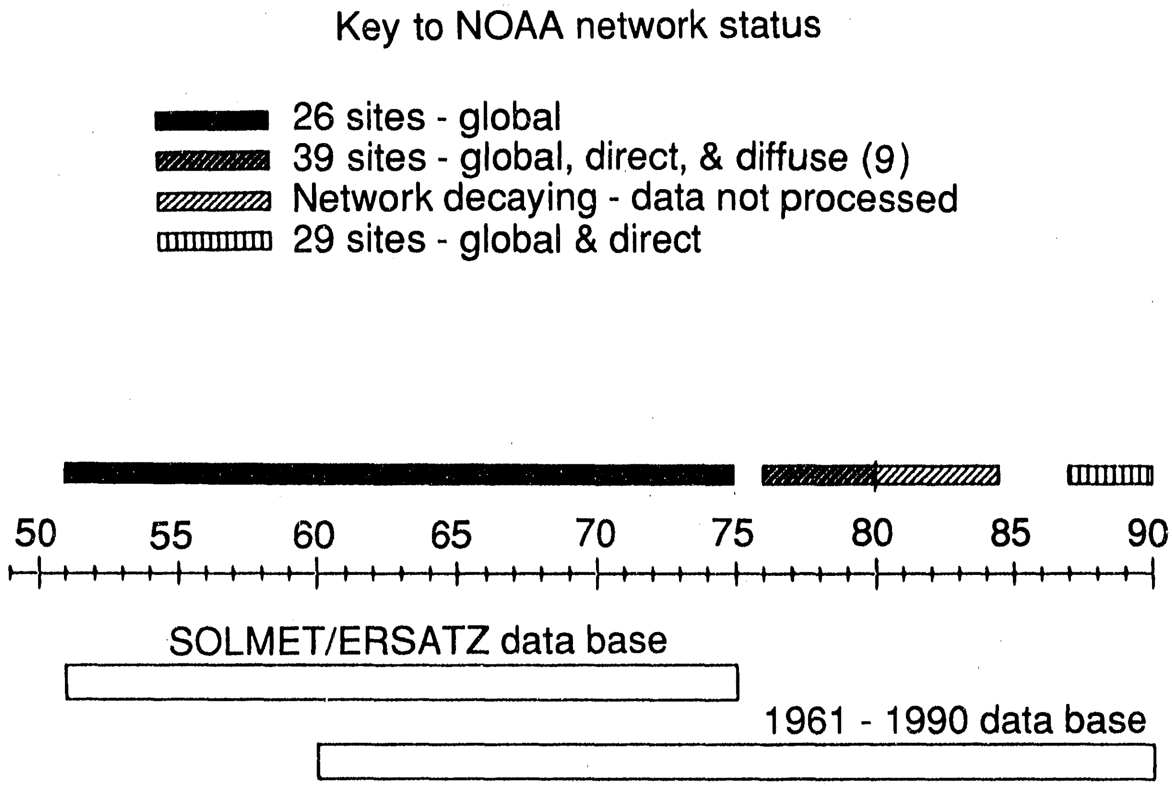

Figure 4-2. NOAA Solar Radiation Network Status Relative to the Historical and New Data Bases

From 1977 through 1980, the network was funded by a combination of NOAA and DOE funds. During these four years, the network was well maintained, the data were continuously processed and quality controlled, and a reasonable collection of good-quality data was accumulated. Data were collected, quality controlled, and archived at the National Climatic Data Center (NCDC), a NOAA facility in Asheville, North Carolina. At the start of 1981, however, the funding for the network was severely reduced. DOE was no longer able to provide any funds for the network, and NOAA budgets were also cut back. For this reason, during the next five years the data cassettes received from the field were copied to computer tapes and shipped to SERI without any processing or quality control. At SERI the tapes were put in a tape vault without making any attempt to read and extract the data they contained because other high priority activities took precedence.

When SERI began processing these data, it was found that very little of the data could be read using standard formats. Figure 4-4 is a line-by-line print of the one-minute data on these tapes in the prescribed format. Figure 4-5 is a typical printout of the data as it appeared on a major part of the 200 tapes.

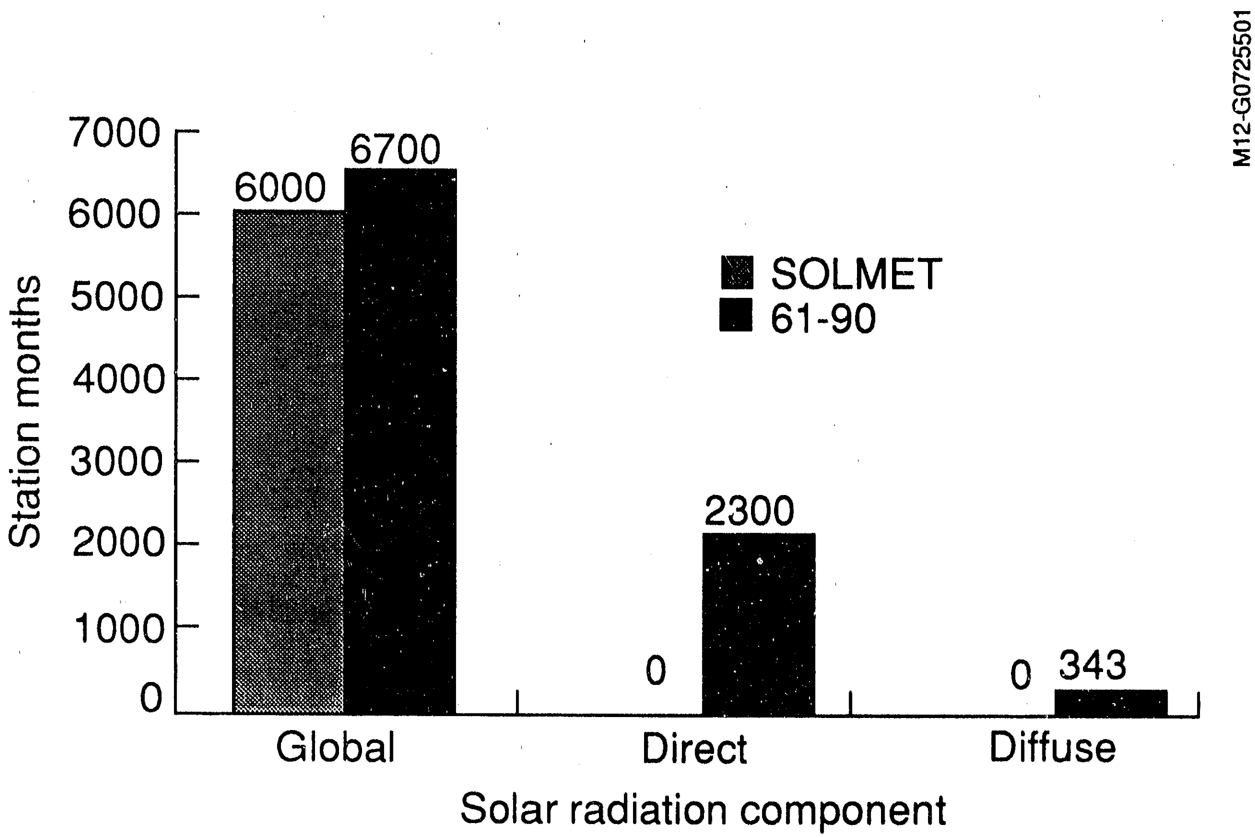

Figure 4-3. NOAA Solar Radiation Network Data Collection from January 1952 through December 1975

SERI found several processing problems:

- The data fell out of synchronization with the format
- Spurious or illegal characters were present
- Data were not organized either chronologically or by site
- Unknown site codes were present.

More information on these problems and the computer processing that was required to find and extract useful data are described in a report in preparation [8], which will be sent to NCDC along with the processed and quality assessed data.

```
57208810000534  0756010004  0000020015  0011030025  0021040034  0031050046  0043
        060056  0054070066  0064080076  0072090084  0079100094  0089110106  0100
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        180174  0160190184  0169200195  0180210206  0191220217  0201230228  0212
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        300309  0288310319  0295320329  0301330336  0302340343  0303350351  0307
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```

Figure 4-4. Sample NOAA Data in the Correct Format

```
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        451307  1272  1362461323  1292  137748|:17214471339  1307  1393481505  1
03  1408201523111733111423011511111759111439921455111755111454831449111701111469
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111111117911601111301111603011551111551111756111111111111111190321274  1277  1205
```


Figure 4-5. Sample of Unreadable NOAA Data

The network gradually decayed and was shut down in October 1985. Fortunately, the radiometer calibration facility in Boulder, Colorado, continued to perform its vital function. At the same time that the network was being shut down, NOAA was undertaking a second upgrade. New solar trackers (Eppley Model SMT-3) and a new data acquisition system were installed to correct technical problems that had caused the network shutdown. A 31-station SOLRAD network was reactivated in January 1988, but funding limitations prevented its full operation. Figures 4-2 and 4-3 show the network operations during this period.

4.2 New 1961–1990 National Solar Radiation Data Base

An effort to upgrade and update the SOLMET/ERSATZ solar radiation data base for the United States was begun at SERI in FY 1989. During FY 1990, SERI's Solar Radiation Resource Assessment Project devoted a major part of its resources to this work. The new data base will cover the period from 1961 to 1990, which will correspond to the 30-year period to be used by NOAA to calculate new climatological normals, means, and extremes.

Figure 4-6 shows actual and scheduled activities that have been or will be undertaken during the three-and-one-half years from FY 1989 to the middle of FY 1992. At the end of FY 1990, SERI researchers completed SERI QC, a software package for performing quality assessment of solar radiation data. It has been distributed for peer review and will be given wider distribution during FY 1991. SERI QC was developed specifically to assess the quality of data collected by SERI and NOAA. The NOAA data, in particular, forms the mainstay of data used to develop the 1961–1990 solar radiation data base for the United States. SERI QC was used to quality assess all of the NOAA data collected from 1977 through 1985. This work was completed during the fourth quarter of FY 1990. The 1981–1985 NOAA data are some of the best solar radiation records for the United States. As soon as a report describing the processing of the data is peer reviewed and printed, these data will be sent to NCDC for distribution.

The upgrading of SERI's DISC model [9] for converting global-horizontal solar radiation data to direct-normal solar radiation data was completed under a subcontract to the State University of New York at Albany. This model can be used to estimate direct-normal and diffuse components of solar radiation from measured global-horizontal data.

Progress was made during FY 1990 on the development of a meteorological model for simulating solar radiation data at locations where no measurements are available. A meteorological model uses readily available meteorological data (e.g., cloud cover) to estimate solar irradiance at the earth's surface. Researchers completed most of the deterministic algorithms for the model by the end of FY 1990 and laid a foundation for the statistical algorithms to be developed during FY 1991.

Researchers began upgrading the rehabilitation tools needed for the pre-1976 data; they also began acquiring meteorological data needed for simulating data at nonmeasurement locations. Plans for developing production software were also developed, and some production software was written, specifically software required to extract data from the NCDC meteorological data tapes.

During the fourth quarter of FY 1990, researchers began selecting all sites to be included in the data base; the selection should be completed by the middle of FY 1991. Generally, the sites will be

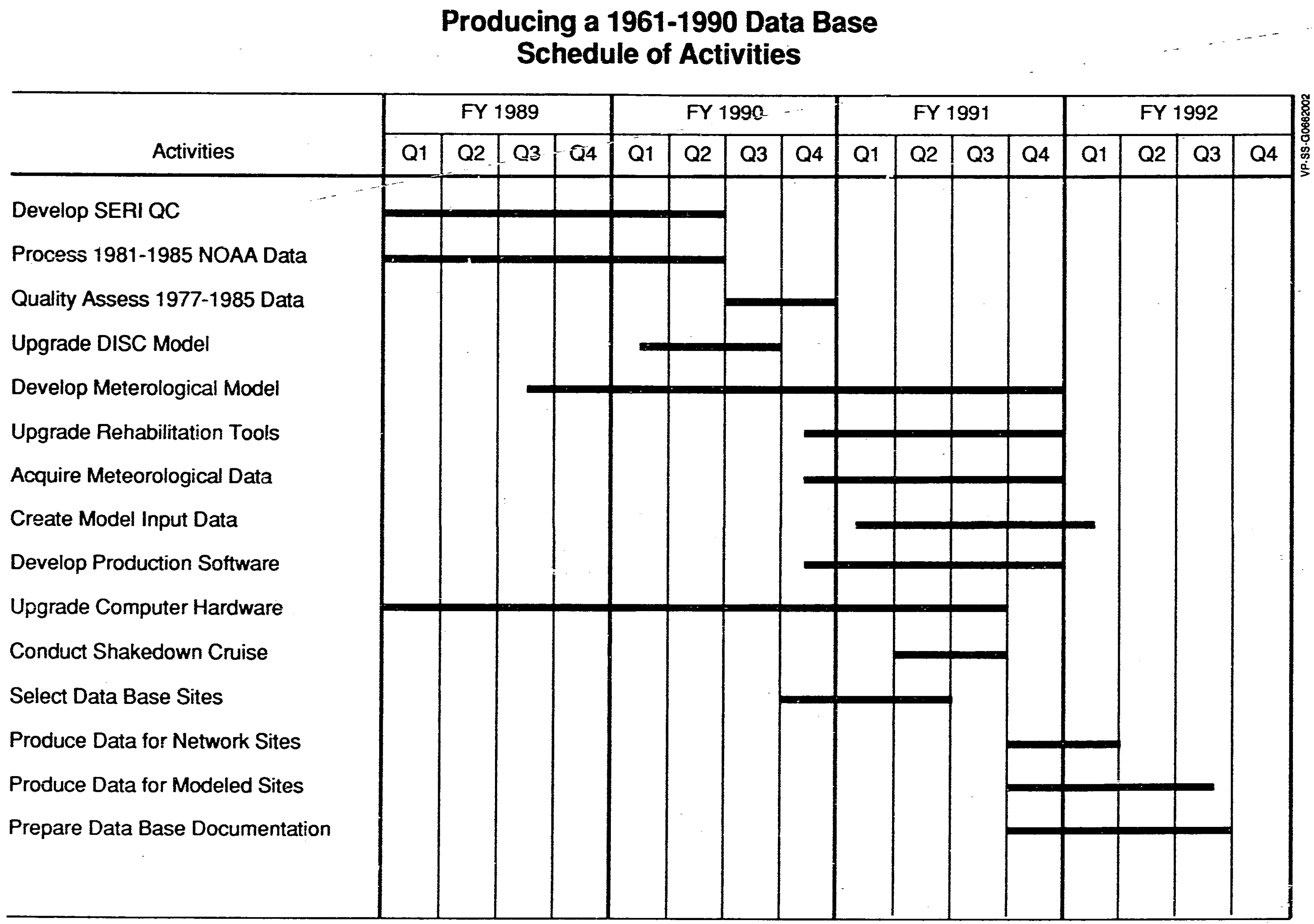


Figure 4-6. Actual and Scheduled Activities in Developing the 1961-1990 Data Base

selected for the data base if they continuously collected meteorological data from January 1961 through December 1990. Some exceptions may be made to include those stations with many years of good solar radiation measurements.

During the second quarter of FY 1991, researchers plan to exercise and evaluate software and hardware to be used in producing the data base. We have dubbed this the "shakedown cruise."

During the third quarter of FY 1991, we will correct problems discovered during the shakedown cruise and work on the data set for those locations having solar radiation measurements. Beginning the fourth quarter of FY 1991 and continuing through the first two quarters of FY 1992, we will be estimating solar radiation values for times and locations at which no solar radiation measurements were made and compiling detailed documentation for the entire data base.

4.3 Quality Assessment of Measured Data

4.3.1 SERI QC: General Description

SERI QC [10] is a postmeasurement quality assessment procedure that compares measured values of solar radiation components with expected values. The components assessed are:

- Global-horizontal solar irradiance
- Direct-normal solar irradiance
- Diffuse-horizontal solar irradiance.

The SERI QC algorithms and software deal with unitless values normalized with respect to extraterrestrial radiation (ETR). These parameters are defined according to the expressions:

$$Kn = I_n / I_o \qquad (4\text{-}1)$$

$$Kt = I_t / (I_o \cos z) \qquad (4\text{-}2)$$

and

$$Kd = I_d / (I_o \cos z)\ , \qquad (4\text{-}3)$$

where

I_o = extraterrestrial direct-normal irradiance

I_n = direct-normal irradiance at the earth's surface

I_t = total global-horizontal irradiance at the earth's surface

I_d = diffuse-horizontal irradiance at the earth's surface

$I_o \cos z$ = extraterrestrial irradiance on a surface parallel to a horizontal surface on the earth

z = solar zenith angle

Kn = normalized direct-beam irradiance

Kt = clearness index or normalized global-horizontal irradiance

Kd = normalized diffuse-horizontal irradiance.

An combination of the three components can be evaluated and assigned a two-digit flag (Table 4-1). The tests are hierarchical:

1. At night, the values must be within ±10 W/m^2 of zero.

2. During times of low solar elevation (less than 10°), the values must not exceed an assigned maximum value.

3. During times of higher solar elevation (greater than 10°), four tests are performed:

   - Each component must reside between expected minimum and maximum values, which are set for each station-month and three solar elevation ranges. If any component falls outside these values, it is flagged accordingly (7 if low, 8 if high) and disregarded in further testing. If the component falls within the range, its flag is set to 1 and it becomes a candidate for further testing.

   - If the normalized direct-normal radiation (Kn) exceeds the normalized global-horizontal (total) radiation (Kt) (a phyiscal impossibility) by more than 5%, the appropriate flags are set in the range of 94 to 97, depending on the severity of the problem, and no further tests are performed.

   - If two components are available for further testing, the position of the data point in Kt - Kn space is compared to a mathematically defined envelope (Figure 4-7). If the data point falls outside the envelope by a distance greater than 0.03, the test has failed and the appropriate flags are set. Otherwise, the flags are set to 2.

   - If all three components are available for further testing, Kt is compared to the sum of Kn and Kd (ideally, Kt = Kn + Kd). If the difference between Kt and Kn + Kd is greater than 0.03, the appropriate flags are set and no further tests are performed.

More detailed explanations of the tests and their rationale are given in SERI's *User's Manual for Quality Assessment of Solar Radiation Data* [10].

Table 4-1. SERI QC Flag Description

Flag	Description
00	Untested (raw data)
01	Passed one-component test; data fell within min-max limits of Kt, Kn, or Kd
02	Passed two-component test; data fell within 0.03 of the envelope boundaries
03	Passed three-component test; data came within 0.03 of satisfying Kt = Kn + Kd
04	Passed visual inspection; this flag not used by SERI QC
05	Failed visual inspection; this flag not used by SERI QC
06	Value estimated; passes all pertinent SERI QC tests
07	Failed one-component test; lower than allowed minimum
08	Failed one-component test; higher than allowed maximum
09	Passed three-component test but failed two-component test by > 0.06
10–93	Failed two- or three-component tests in one of four ways: To determine the test failed and the manner of failure (high or low), examine the remainder (Rem.) of the calculation (flag + 2)/4. Rem / Failure 0 — parameter too low by three-component test (Kt = Kn + Kd) 1 — parameter too high by three-component test (Kt = Kn + Kd) 2 — parameter too low by two-component test (Gompertz boundary) 3 — parameter too high by two-component test (Gompertz boundary) The magnitude of the test failure (fractional K-units) is determined from the calculation: d = INT((flag + 2)/4)/100
94–97	Kn > Kt by amount: Flag 94 — (Kt + 0.05) ≤ Kn < (Kt + 0.10) 95 — (Kt + 0.10) ≤ Kn < (Kt + 0.15) 96 — (Kt + 0.13) ≤ Kn < (Kt + 0.20) 97 — (Kt + 0.20) ≤ Kn
98	Not used
99	Missing data

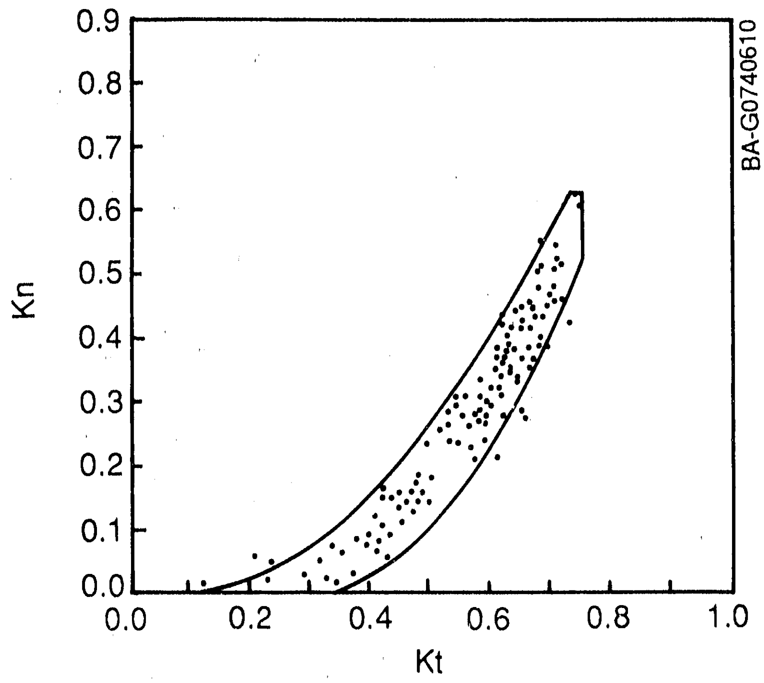


Figure 4-7. Sample Global-Horizontal and Direct-Normal Solar Irradiance Data, Converted to Kt and Kn and Bounded by a Mathematically Defined Envelope

4.3.2 Examples

After quality assessment and flagging of data by SERI QC, associated software prepares tables and figures to generate a report for the data that have been processed. For example, Figure 4-8 provides a summary of all the solar radiation data collected at Albuquerque, New Mexico, from January 1977 through December 1985. The number of hours of data collected for each of the three components of solar radiation is reported, along with the percent of possible hours during each month that this represents. Summary percentages of all possible hours from the first to the last date of data collection are presented for each component at the bottom of the figure.

In addition to the summary of the quantity of data collected, bar charts such as those shown in Figures 4-9 and 4-10 are prepared to indicate the quality of the data collected. Figure 4-9 indicates that the data collected at Albuquerque, New Mexico, during 1977 through 1980 were of very good quality. Most of the data passed the quality assessment checks; and those that failed were not far from the expected values. Because the Albuquerque station measured all three components, we find records of hourly values that passed and failed one-, two-, and three-component tests. This results from one or two instruments being out of operation for various periods of time, such that only one- or two-component tests could be performed.

ALBUQUERQUE, NM WBAN #23050

AVAILABILITY OF SOLAR DATA PER MONTH EXPRESSED AS NUMBER OF DAYLIGHT HOURS AND PERCENT POSSIBLE

MONTH	GLOBAL HRS/PCT	DIRECT HRS/PCT	DIFFUSE HRS/PCT	MONTH	GLOBAL HRS/PCT	DIRECT HRS/PCT	DIFFUSE HRS/PCT	MONTH	GLOBAL HRS/PCT	DIRECT HRS/PCT	DIFFUSE HRS/PCT
1/77	337/99	0/00	0/00	1/80	333/97	333/97	325/95	1/83	338/99	338/99	0/00
2/77	318/98	0/00	0/00	2/80	328/97	285/84	283/84	2/83	316/97	316/97	0/00
3/77	395/98	0/00	0/00	3/80	370/92	354/88	261/65	3/83	395/98	395/98	0/00
4/77	420/100	0/00	0/00	4/80	364/86	359/85	277/65	4/83	420/100	420/100	0/00
5/77	451/100	0/00	0/00	5/80	448/98	445/98	414/91	5/83	441/97	441/97	0/00
6/77	480/100	0/00	0/00	6/80	479/100	475/99	249/51	6/83	445/92	453/94	0/00
7/77	461/99	0/00	0/00	7/80	464/99	460/98	235/50	7/83	400/86	401/86	0/00
8/77	412/93	0/00	0/00	8/80	440/100	420/95	433/98	8/83	437/99	437/99	0/00
9/77	405/99	0/00	202/49	9/80	402/99	402/99	360/88	9/83	397/97	398/97	0/00
10/77	361/97	0/00	363/97	10/80	319/85	310/83	266/71	10/83	370/99	370/99	0/00
11/77	340/99	0/00	340/99	11/80	270/79	270/79	174/51	11/83	340/99	340/99	0/00
12/77	272/87	0/00	272/87	12/80	258/83	248/80	167/53	12/83	309/99	309/99	0/00
1/78	0/00	0/00	0/00	1/81	124/36	124/36	124/36	1/84	337/99	338/99	0/00
2/78	322/99	322/99	310/95	2/81	323/99	323/99	323/99	2/84	336/100	336/100	0/00
3/78	397/99	370/92	359/89	3/81	270/67	270/67	270/67	3/84	397/99	397/99	0/00
4/78	420/100	420/100	323/76	4/81	290/69	289/68	290/69	4/84	413/98	413/38	0/00
5/78	450/99	256/56	351/77	5/81	216/47	216/47	216/47	5/84	267/58	267/58	0/00
6/78	479/99	479/99	302/62	6/81	409/85	410/85	410/85	6/84	184/38	184/38	0/00
7/78	464/99	464/99	447/96	7/81	370/79	370/79	370/79	7/84	302/64	300/64	0/00
8/78	441/100	441/100	439/99	8/81	306/69	306/69	306/69	8/84	0/00	0/00	0/00
9/78	407/100	376/92	401/95	9/81	322/79	322/79	322/79	9/84	170/41	169/41	0/00
10/78	368/98	349/93	362/97	10/81	312/83	312/83	312/83	10/84	291/78	286/76	0/00
11/78	341/100	341/100	340/99	11/81	115/33	115/33	115/33	11/84	333/98	330/97	0/00
12/78	306/98	306/98	304/98	12/81	229/73	229/73	229/73	12/84	71/22	58/18	0/00
1/79	332/97	332/97	324/95	1/82	94/27	94/27	94/27	1/85	65/19	56/16	0/00
2/79	291/89	251/77	291/89	2/82	172/53	172/53	172/53	2/85	322/99	322/99	0/00
3/79	386/96	382/95	337/84	3/82	267/66	267/66	267/66	3/85	172/43	172/43	0/00
4/79	412/98	412/98	398/94	4/82	294/70	294/70	294/70	4/85	145/34	146/34	0/00
5/79	442/98	435/96	424/94	5/82	434/96	434/96	46/10	5/85	230/50	230/50	0/00
6/79	480/100	420/87	452/94	6/82	409/85	409/85	0/00	6/85	238/49	243/50	0/00
7/79	462/99	465/100	272/58	7/82	452/97	452/97	0/00	7/85	303/65	303/65	0/00
8/79	441/100	398/90	225/51	8/82	300/68	300/68	0/00	8/85	201/45	203/46	0/00
9/79	407/100	369/90	214/52	9/82	281/69	280/68	0/00	9/85	254/62	256/62	0/00
10/79	370/99	348/93	226/60	10/82	340/91	339/91	0/00	10/85	238/63	243/65	0/00
11/79	338/99	238/69	220/64	11/82	3/00	3/00	0/00	11/85	0/00	0/00	0/00
12/79	282/90	275/88	278/89	12/82	221/71	222/71	0/00	12/85	0/00	0/00	0/00

GLOBAL HORIZONTAL DATA WERE COLLECTED FROM 1/ 1/77 TO 10/31/85: 82% AVAILABLE.
DIRECT NORMAL DATA WERE COLLECTED FROM 2/ 1/78 TO 10/31/85: 78% AVAILABLE.
DIFFUSE HORIZONTAL DATA WERE COLLECTED FROM 9/15/77 TO 5/ 4/82 73% AVAILABLE.

Figure 4-8. Solar Radiation Data Collected at Albuquerque, New Mexico, from January 1977 through December 1985

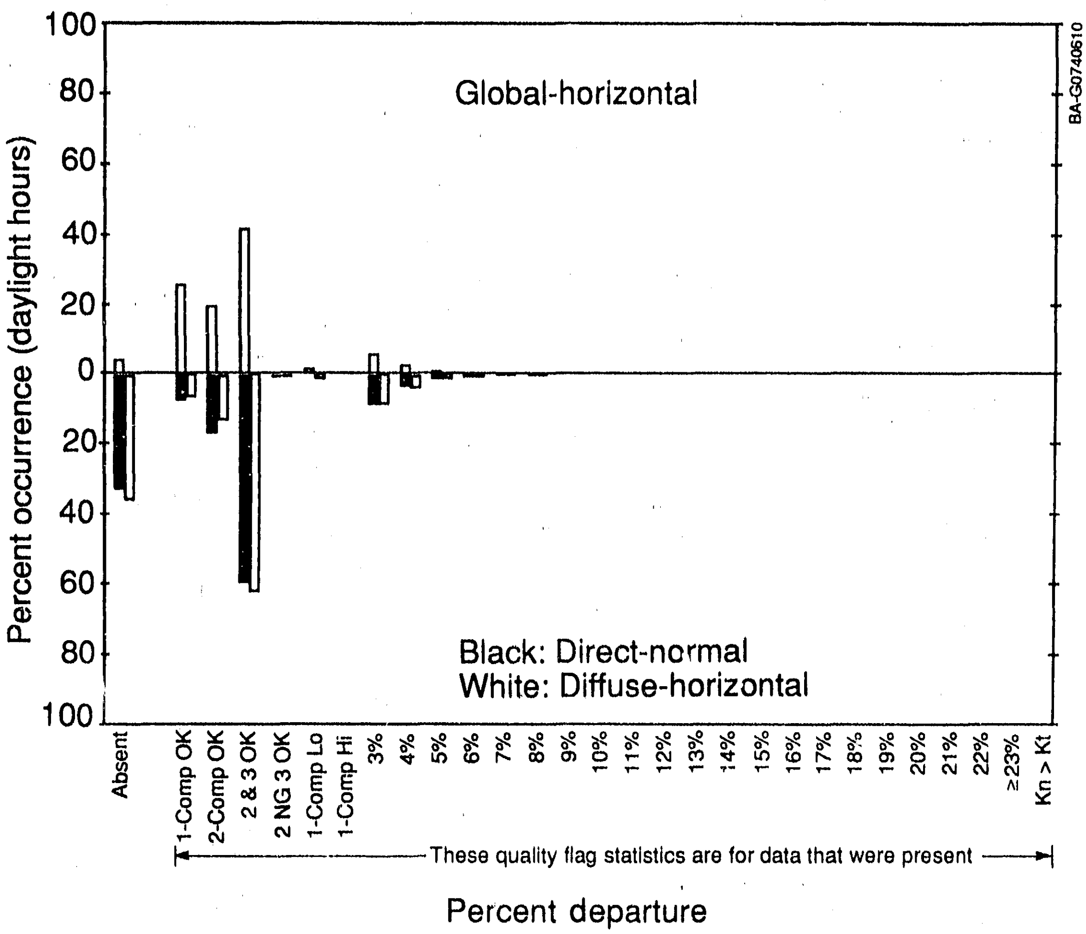


Figure 4-9. SERI QC Bar Chart for Data Collected at Albuquerque, New Mexico, from January 1977 through December 1980

Figure 4-10 shows the results of the quality assessment for Albuquerque for the period from January 1981 through October 1985. Because of the reduction in funding to maintain the network, we find a degradation in the quality of data; as well as a significant decrease in the quantity of data collected. It is interesting in particular to note that a significant percentage of the data fall outside the expected ranges by 23% or more. These data changes might also be attributed to the effects of the 1982 eruption of El Chichon.

In addition to providing a quantitative assessment of the quality and quantity of data being collected by network stations, quality flags are attached to the data to be used in selecting data for any application. For instance, the NOAA network data collected from 1977 through 1980 were used to develop the algorithms needed to simulate solar radiation data to produce the 1961–1990 data base. The quality flags were used to select only those data of very high quality for the model development work.

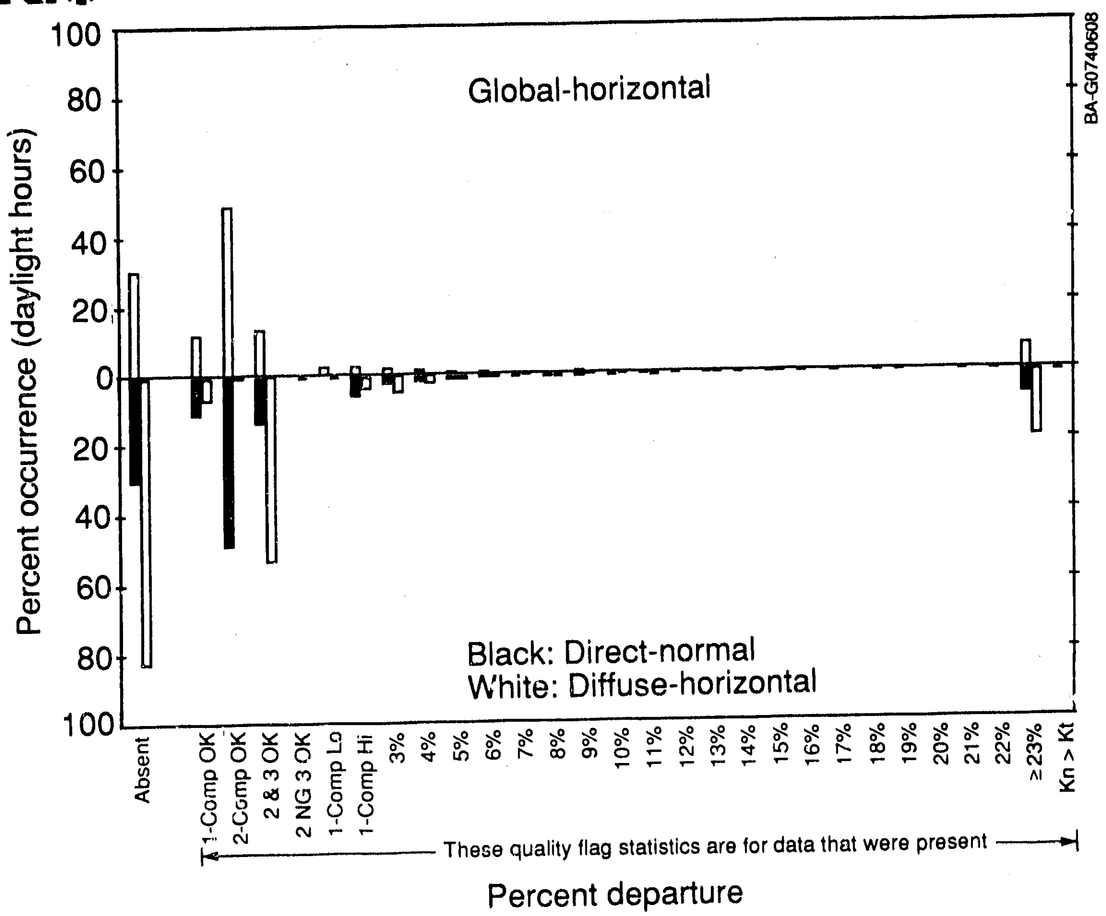


Figure 4-10. SERI QC Summary Bar Chart for Data Collected at Albuquerque, New Mexico from January 1981 through October 1985

4.3.3 Products

The data collected by the NOAA network are archived and are currently available for general distribution at NCDC. The NOAA network data that SERI has obtained from NCDC for producing the 1961–1990 data base will be returned to NCDC with quality assessment flags as the data are processed. In addition to providing data for the 1981–1985 period of record, attaching quality flags to all of the data from 1977 to 1985 increases their value. Other interim products will be made available through NCDC as they are completed. Users with a need for data collected since 1977 should make inquiries at NCDC or SERI to determine availability.

4.4 Solar Irradiance Data Set Simulation

4.4.1 Solar Irradiance Simulator: An Overview

The primary objective of our model development work is to simulate data sets that include the direct-normal, diffuse-horizontal, and global-horizontal estimates of solar irradiance. Furthermore, our objective is to have a data set for a given location exhibit all of the monthly statistics and stochastic characteristics of measured data. The statistical characteristics of interest include the four principal moments (mean, variance, skewness, and kurtosis) and the cumulative frequency distribution. The stochastic characteristics of interest include diurnal patterns, persistence, autocorrelation, and the cross-correlations between the solar radiation components.

It is not our objective to precisely estimate the solar irradiance for a specific site, for a specific hour of a specific day. For instance, under partly cloudy skies, it is possible that for any given hour the clouds might totally block the sun during the entire hour. It is also possible that the sun might shine brightly between the clouds during the entire hour. Therefore, the model we are developing could estimate the direct-normal solar irradiance at 1000 W/m^2 during an hour when the actual measurements indicated 0 W/m^2. This is perfectly acceptable for our objectives, as long as the distribution of values is correct for those cloud conditions and the stochastic characteristics of the data set are representative of actual measurements.

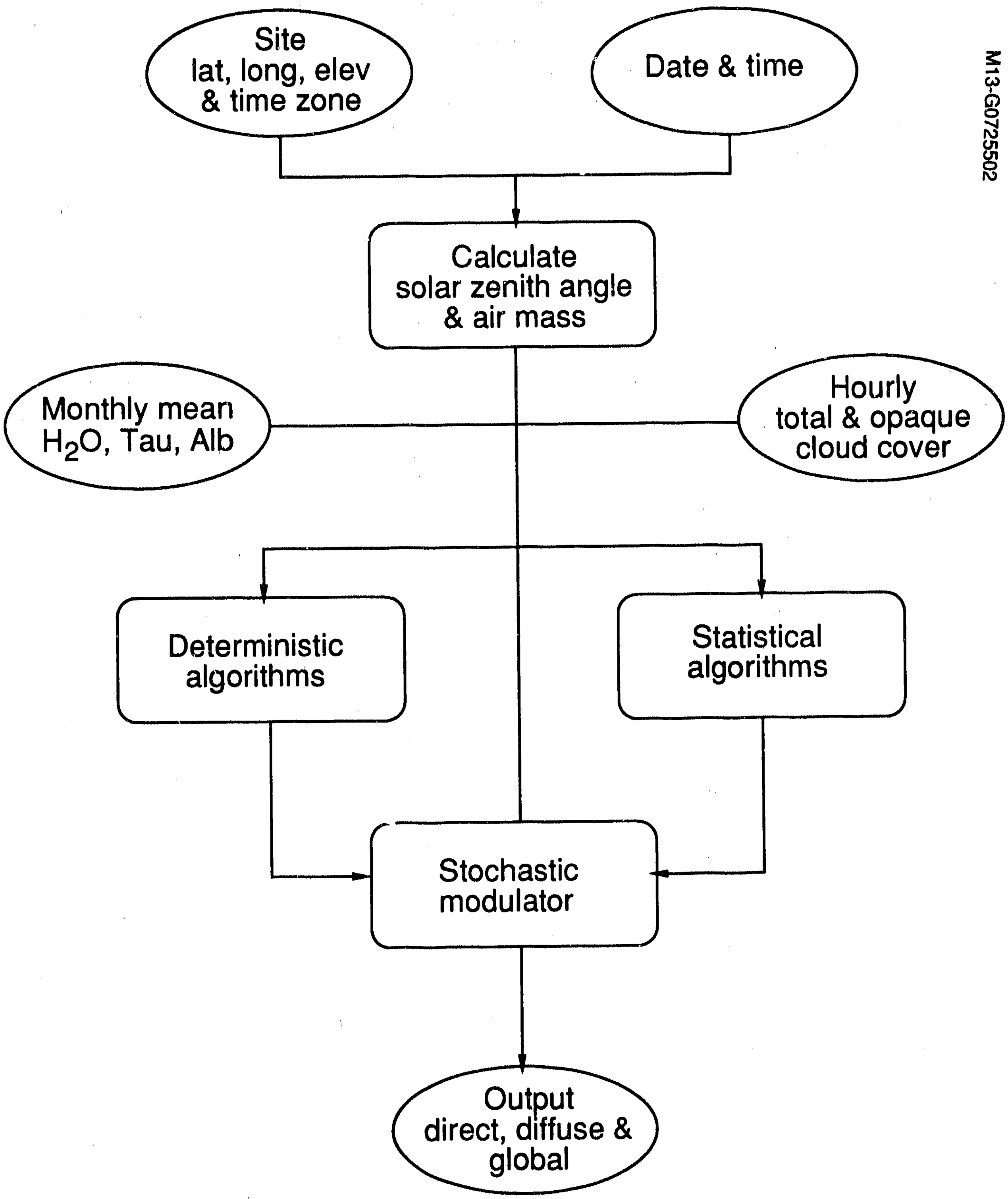
Our approach to meeting these objectives is shown in Figure 4-11. This diagram is designated as a solar irradiance data set simulator (SIDSS) to distinguish it from solar radiation models, which are most often designed to estimate instantaneous, hourly, or daily values of solar radiation for specific points in time. The inputs to the simulator are the site specifics (latitude, longitude, elevation, and time zone); date and time; monthly mean precipitable water vapor, broadband turbidity, and surface albedo; and hourly total and opaque cloud cover. The site specifics and date and time are used to calculate solar zenith angle and air mass. These become inputs to the deterministic, statistical, and stochastic algorithms, along with the monthly mean and hourly data indicated.

Under cloudless skies, the deterministic algorithms function much the same as any solar radiation model because the calculations of the direct-normal, diffuse-horizontal, and global-horizontal solar radiation for a given hour should be nearly as accurate as the input data provided. In other words, if the water vapor, turbidity, and albedo data accurately represent the values for a given hour, then the estimates of solar radiation will be accurate for that hour.

When clouds are present, however, the deterministic algorithms are only expected to accurately estimate the mean solar radiation values for a large population of hours having the same total and opaque cloud cover. We expect that the deterministic algorithms under partly cloudy conditions will have small mean bias errors (MBE) but large root-mean-square errors (RMSE).

The statistical algorithms will estimate deviations from the mean values so as to reproduce the four statistical moments and the cumulative frequency distributions of actual data. A random number generator and the cumulative frequency distribution curves (ogives) representative of the monthly and hourly input data will be used to calculate deviations from the means. We plan to develop statistical algorithms that will produce data sets having representative cross-correlations between the three fundamental solar radiation components.

The stochastic modulator shown on Figure 4-11 will first determine if the modulation of the output of the deterministic algorithms by the output of the statistical algorithms has produced diurnal, autocorrelation, and persistence characteristics representative of measured data. If not, the stochastic modulator will adjust the series of values to achieve proper stochastic properties.



M13-G0725502

Figure 4-11. The Solar Irradiance Data Set Simulator (SIDSS)

The persistence characteristics of the simulated data may automatically be satisfied by using hourly cloud cover data, because the persistence patterns of solar radiation are dominated primarily by the movement of weather systems and the associated changes in cloud cover. The typically smooth diurnal patterns under cloudless-sky conditions will be accomplished by allowing the statistical algorithms to operate only on a daily basis.

4.4.2 Development Approach

The four years of data collected by the stations in the NOAA network from 1977 through 1980 provided good-quality data representing all of the major climates within the continental United States. Most solar radiation model development in the past has used data from individual stations or from a group of stations, one station at a time, when developing and testing the model algorithms. Typically, a small group of stations is used in the development of the model; another group of stations, not used during the model development, is used for model validation. This represents a sound scientific approach, but it has often produced results that are site or climate specific. Because a set of data for a given station incorporates a wide range of atmospheric conditions, it was difficult to develop the model algorithms to be representative of specific atmospheric conditions (such as precipitable water vapor and cloud cover) rather than average site conditions.

In contrast to model development based upon site and seasonal conditions, all of the NOAA data available from 1977 through 1980 for approximately 30 locations in the United States were used to form subsets of data with specific atmospheric characteristics. Table 4-2 gives the general parametric ranges that were used to form data subsets for developing the solar radiation algorithms. For example, a subset identified as G240225 is made up of all hours of data from all stations and all months of the year during which the air mass was between 1.7 and 2.3; opaque cloud cover was 3, 4, or 5 tenths; translucent cloud cover was 0; monthly mean precipitable water vapor was between 0.80 and 2.40 cm; the turbidity value was between 0.05 and 0.09; and surface albedo was between 0.0 and 0.51.

Table 4-2. General (G) Parametric Ranges Used to Form Data Subsets for Developing Solar Radiation Algorithms

Range	Air Mass	Opaque Cloud Cover	Translucent Cloud Cover	Water Vapor	Turbidity	Albedo
0	1.3–1.7	0	0			
1	1.0–1.2			0.40–1.40	0.005–0.055	0.000–0.280
2	1.7–2.3	1–3	1–3	0.80–2.40	0.050–0.090	0.300–0.500
3	2.5–2.6			1.10–2.80	0.085–0.135	0.600–0.660
4	3.5–4.7	3–5	3–5	1.20–3.40	0.125–0.185	
5	4.3–5.9			2.50–4.60	0.175–0.275	0.000–0.510
6	5.0–7.3	5–7	5–7		0.270–0.400	
7						
8	7.0–9.5	7–9	7–9			
9						
A		10	10			

Any combination of the ranges designated for the six parameters given in Table 4-2 could be used in forming a subset. Although all combinations were not used because they were not all useful for developing the model algorithms, over 1000 subsets were created for this work. Figure 4-12 identifies the 252 subsets that were used specifically for developing algorithms to estimate the effect of opaque cloud cover on the direct-normal and diffuse-horizontal components of solar radiation. Note that translucent cloud cover was maintained at a value of 0 for all of these subsets. A wide range of air mass, turbidity, and water vapor values was incorporated to account for any relationship these parameters had on opaque cloud cover effects.

A similar group of subsets was used to develop the algorithms for translucent cloud cover. Transcluent cloud cover is calculated by subtracting opaque cloud cover from total cloud cover. The effect of thick, opaque clouds on solar radiation is different from the effect of thin, translucent clouds; therefore, separate algorithms were designated for these two very broad cloud categories.

In addition to the general parametric ranges shown in Table 4-2, other ranges were used to form other subsets for developing specific algorithms. For example, in Tables 4-3 and 4-4 the total spread of turbidity and water vapor values is divided into smaller ranges that were particularly useful when developing the clear-sky algorithms for turbidity and water vapor. The other parameters were held constant so as to reduce their effect on the solar radiation values found in these subsets.

The success of this approach for forming data subsets for model development is indicated in part in Figures 4-13a, 4-13b and 4-14a, 4-14b. These figures contain histograms of the frequency of occurrence of hourly data for each of the 29 stations and each of the 12 months. Note that for Figure 4-13a, 19 of the 29 stations are represented and for Figure 4-13b all 12 months are represented. Similar representation is found for the subset used to form Figures 4-14a and 4-14b. It is interesting to note that for the low turbidity and low water vapor values selected for the subset in Figures 4-13a and 4-13b, most of the data come from fall, winter, and spring months. In contrast, the very wet and turbid data used to form the subset in Figures 4-14a and 4-14b are found more frequently in summer months.

The model is verified by comparing modeled and measured solar radiation data for the subsets. Model validation will be accomplished using monthly subsets of data from individual stations. In other words, the model will be tested against all of the atmospheric conditions found for a given station during a given month. All of the data from 1977 to 1980 for all stations are used for both model development and model validation. However, using subsets grouped according to parametric ranges for model development, and using station-months of data for model validation, addresses the need for using independent development and validation data sets. Still, for validation we will also use station-month data sets collected between 1988 and 1990, in addition to data from stations outside the United States (when possible).

4.4.3 Status of Algorithm Development

We have completed most of the deterministic algorithms and begun some analyses of data subsets selected for the design of the statistical algorithms. Current plans call for completing the statistical algorithms by January 1991. A working version of the stochastic modulator is scheduled for completion by the end of February 1991.

G100115	G000115	G200115	G300115	G400115	G600115	G800115
G120115	G020115	G220115	G320115	G420115	G620115	G820115
G140115	G040115	G240115	G340115	G440115	G640115	G840115
G160115	G060115	G260115	G360115	G460115	G660115	G860115
G180115	G080115	G280115	G380115	G480115	G680115	G880115
G1A0115	G0A0115	G2A0115	G3A0115	G4A0115	G6A0115	G8A0115
G100225	G000225	G200225	G300225	G400225	G600225	G800225
G120225	G020225	G220225	G320225	G420225	G620225	G820225
G140225	G040225	G240225	G340225	G440225	G640225	G840225
G160225	G060225	G260225	G360225	G460225	G660225	G860225
G180225	G080225	G280225	G380225	G480225	G680225	G880225
G1A0225	G0A0225	G2A0225	G3A0225	G4A0225	G6A0225	G8A0225
G100335	G000335	G200335	G300335	G400335	G600335	G800335
G120335	G020335	G220335	G320335	G420335	G620335	G820335
G140335	G040335	G240335	G340335	G440335	G640335	G840335
G160335	G060335	G260335	G360335	G460335	G660335	G860335
G180335	G080335	G280335	G380335	G480335	G680335	G880335
G1A0335	G0A0335	G2A0335	G3A0335	G4A0335	G6A0335	G8A0335
G100445	G000445	G200445	G300445	G400445	G600445	G800445
G120445	G020445	G220445	G320445	G420445	G620445	G820445
G140445	G040445	G240445	G340445	G440445	G640445	G840445
G160445	G060445	G260445	G360445	G460445	G660445	G860445
G180445	G080445	G280445	G380445	G480445	G680445	G880445
G1A0445	G0A0445	G2A0445	G3A0445	G4A0445	G6A0445	G8A0445
G100555	G000555	G200555	G300555	G400555	G600555	G800555
G120555	G020555	G220555	G320555	G420555	G620555	G820555
G140555	G040555	G240555	G340555	G440555	G640555	G840555
G160555	G060555	G260555	G360555	G460555	G660555	G860555
G180555	G080555	G280555	G380555	G480555	G680555	G880555
G1A0555	G0A0555	G2A0555	G3A0555	G4A0555	G6A0555	G8A0555
G100565	G000565	G200565	G300565	G400565	G600565	G800565
G120565	G020565	G220565	G320565	G420565	G620565	G820565
G140565	G040565	G240565	G340565	G440565	G640565	G840565
G160565	G060565	G260565	G360565	G460565	G660565	G860565
G180565	G080565	G280565	G380565	G480565	G680565	G880565
G1A0565	G0A0565	G2A0565	G3A0565	G4A0565	G6A0565	G8A0565

Figure 4-12. Subsets Used to Develop Opaque Cloud Cover Algorithms

Table 4-3. Turbidity Ranges Used to Form Data Subsets for Developing a Turbidity Algorithm for the Solar Radiation Simulator Model

Range	Water Vapor	Turbidity	Albedo
1		0.020–0.060	
2	1.10–2.30	0.040–0.080	
3		0.060–0.100	
4		0.080–0.120	
5	2.50–4.60	0.100–0.140	0.000–0.510
6		0.120–0.160	
7		0.140–0.180	
8		0.170–0.230	
9		0.210–0.270	
0		0.240–0.330	

Note: The air mass ranges were the same as those used for the "general" ranges. Only data under cloudless skies were allowed (opaque and translucent cloud cover equal zero for all hours in all subsets).

Table 4-4. Water Vapor Ranges Used to Form Data Subsets for Developing a Water Vapor Algorithm for the Solar Radiation Simulator Model

Range	Water Vapor	Turbidity	Albedo
1	0.60–1.00	0.050–0.090	
2	0.80–1.20		
3	1.00–1.40		
4	1.20–1.60		
5	1.40–1.80		0.000–0.510
6	1.60–2.00		
7	1.80–2.20		
8	2.00–2.40		
9	2.20–3.00		

Note: The air mass ranges were the same as those used for the "general" ranges. Only data under cloudless skies were allowed (opaque and translucent cloud cover equal zero for all hours in all subsets).

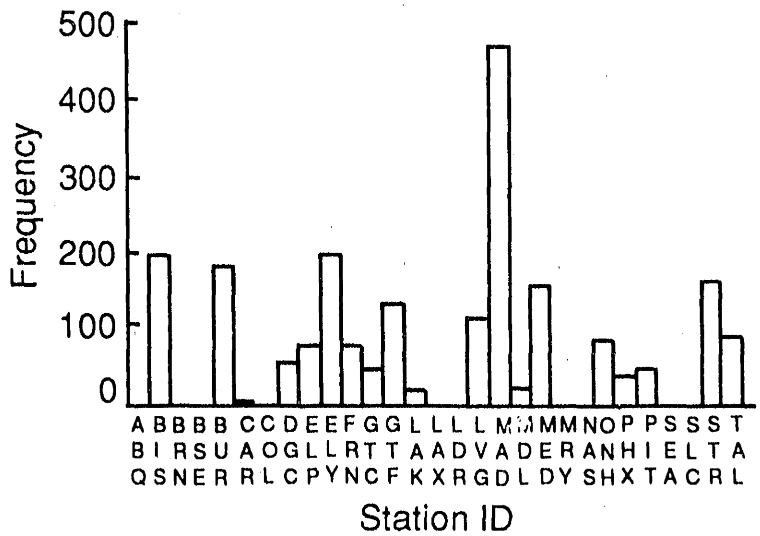


Figure 4-13a. **Frequency of Occurrence by Stations for Hourly Data in a Subset with a Mean Air Mass of 2.0 and Clean-Dry Atmospheric Conditions**

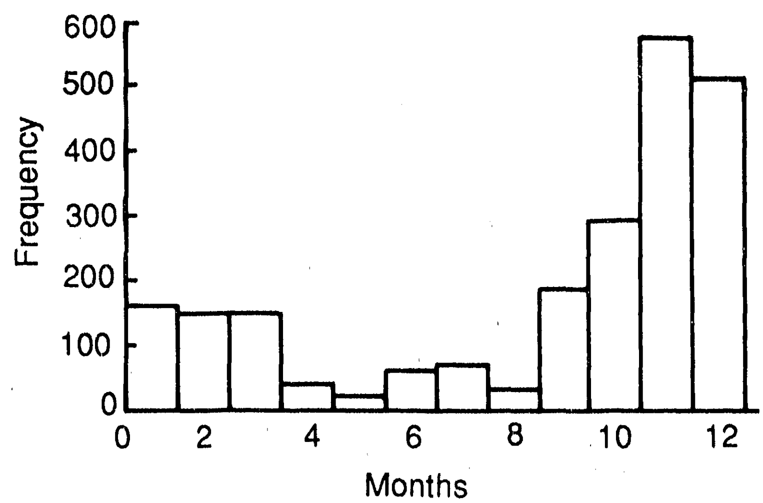


Figure 4-13b. **Frequency of Occurrence by Month for Hourly Data in a Subset with a Mean Air Mass of 2.0 and Clean-Dry Atmospheric Conditions**

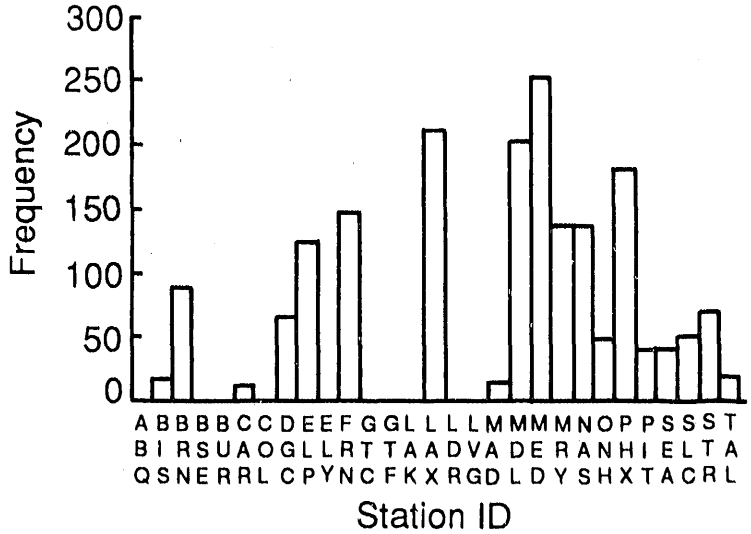


Figure 4-14a. Frequency of Occurrence by Stations for Hourly Data in a Subset with Mean Air Mass of 2.0 and Dirty-Wet Atmospheric Conditions

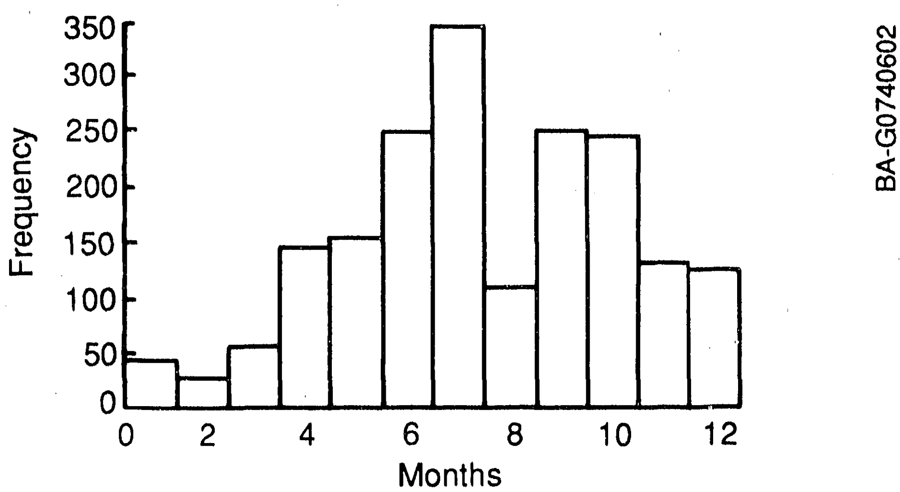


Figure 4-14b. Frequency of Occurrence by Month for Hourly Data in a Subset with Mean Air Mass of 2.0 and Dirty-Wet Atmospheric Conditions

The development of the cloudless-sky deterministic algorithms began with the Bird clear-sky model [11]. We found good agreement between the Bird model and measured direct-normal data, but we determined that improvements could also be made in the direct-normal components. The agreement with diffuse-horizontal data was not satisfactory.

Specifically, we modified the algorithm calculating the transmittance for water vapor to agree with the results of Bird and Riordan's SPCTRAL2 model [12] when the output from that model is integrated over the solar spectrum. The form of the water vapor algorithm was not changed; only the coefficients required modifications. We simplified the turbidity algorithm to the form of Beer's Law with a small air-mass modifier.

Figures 4-15 through 4-18 show comparisons between measured and modeled data for both the Bird model and the simulator (SIDSS) (i.e., the meteorological model—METMOD). The improvements in estimating the direct-normal component (Kn) are found primarily in the reduction of variations with changing water vapor and turbidity values. Each data set for the seven air-mass values contained sky conditions wherein water vapor varied from 0.5 to 4.0 cm and broadband turbidity varied from 0.05 to 0.4. The new model performs better than the Bird model (the standard deviation of ΔKn is less) for all air-mass values.

The major improvement in the model is noted for the diffuse component (Figure 4-17); although this improvement also applies to the global component.

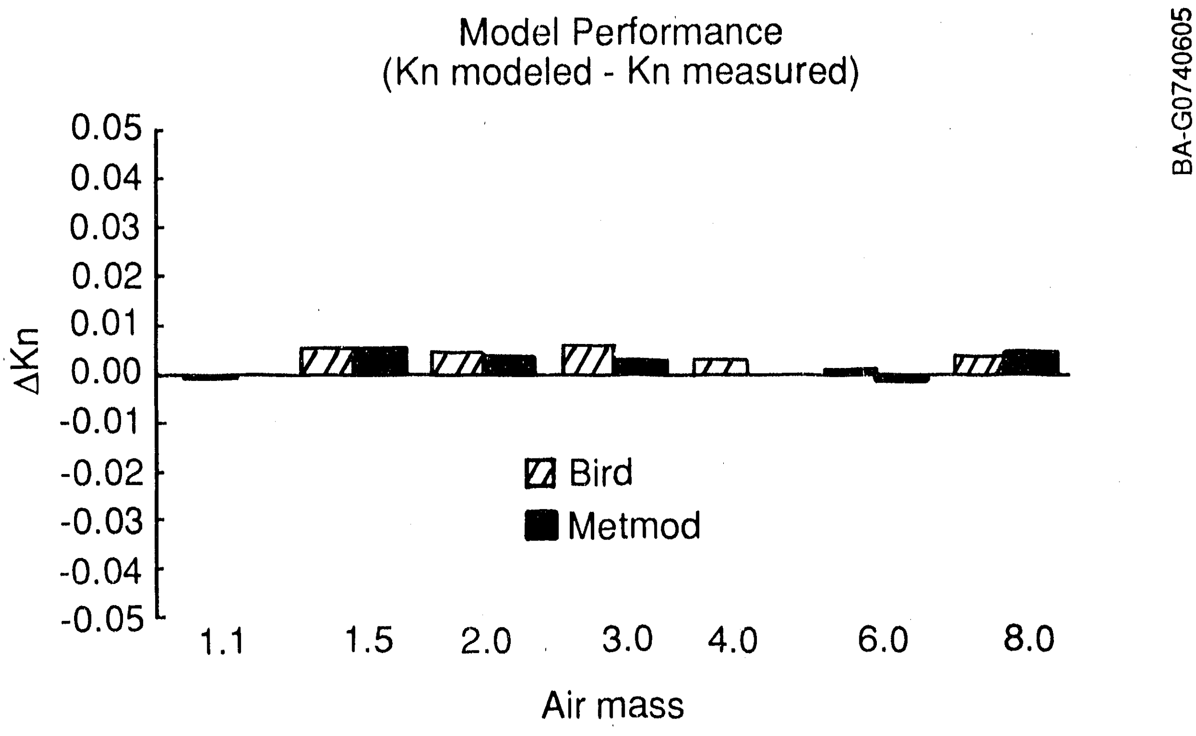


Figure 4-15. Measured versus Modeled Data for the Bird Model and the Solar Irradiance Data Set Simulator

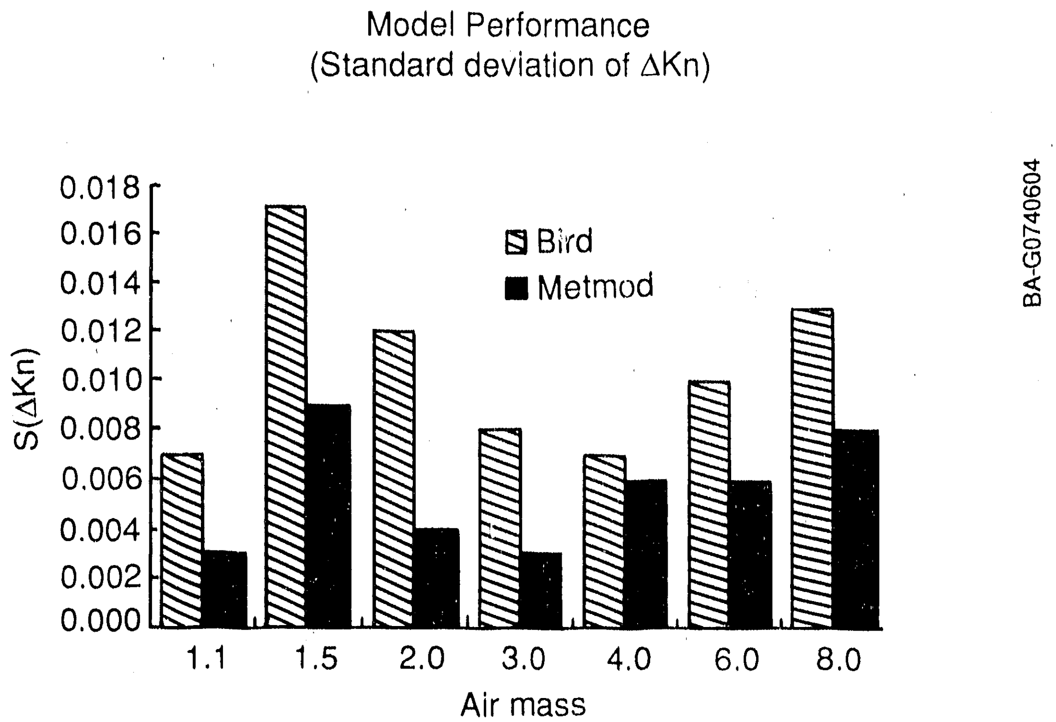


Figure 4-16. Measured versus Modeled Data for the Bird Model and the Solar Irradiance Data Set Simulator

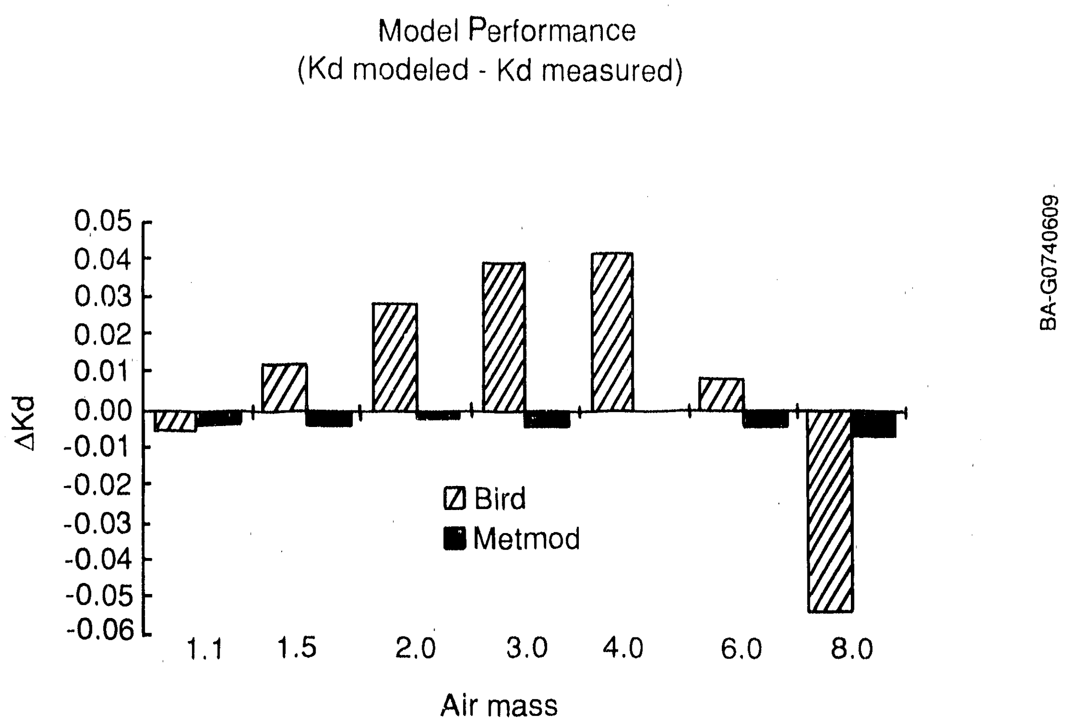


Figure 4-17. Measured versus Modeled Data for the Bird Model and the Solar Irradiance Data Set Simulator

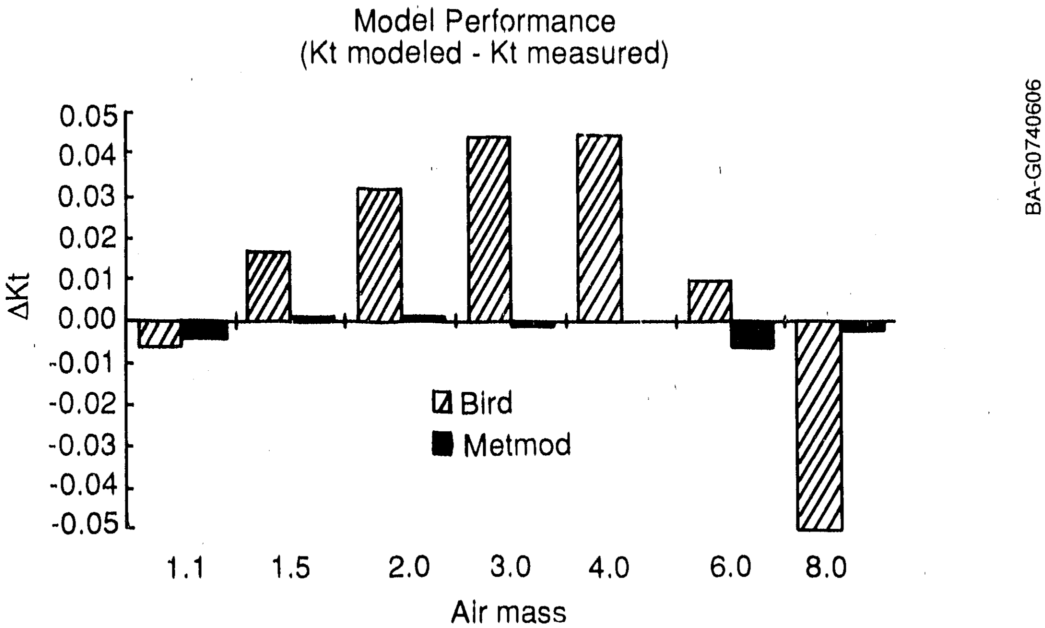


Figure 4-18. Measured versus Modeled Data for the Bird Model and the Solar Irradiance Data Set Simulator

4.5 Rehabilitation of Historical Data

When NOAA undertook the preparation of the SOLMET data base, they found that they could not establish calibration factors for the radiometers within an acceptable degree of certainty. A number of factors contributed to the uncertainty regarding radiometer calibrations; these included lost records, the use of different calibration methods, and changes in the solar radiometric scale between 1952 and 1975. Therefore, a clear solar noon/standard year irradiance (CSN/SYI) method was used to synthesize calibration factors for the SOLMET global-horizontal data. This method compares measured solar irradiance for clear solar noons with modeled solar irradiance for clear solar noons. The modeled clear solar noon values for each day of the year are the standard year irradiance (SYI) values. The Hoyt model [13] was used to calculate the SYI values using monthly mean precipitable water vapor from radiosonde measurements [14] and turbidity values extracted from three publications of the Environmental Data Information Service in Asheville, North Carolina [15-17].

Using CSN values to establish synthetic calibration factors avoids most of the effects of variations in response of the pyranometer with azimuth and zenith angles and uses the time of day when the path length of the solar beam through the atmosphere is shortest; this in turn reduces the potential for modeling errors. The CSN/SYI method was used to calculate a synthetic calibration factor every time a clear solar noon occurred. The procedure allowed for frequent adjustment of the calibration factor, which partially corrected for the zenith angle response of the radiometer. However, it also resulted in some smoothing of seasonal and long-term variations of water vapor and turbidity. The restrictions to clear solar noons also limited the quantity of data available for establishing calibration factors.

4.5.1 Opportunities for Improvement

If the zenith and azimuth angle response of each of the pyranometers were known, it would be possible to use more hours of the day for calculating synthetic calibration factors. Therefore, SERI is working to determine the variations of the pyranometer responses as a function of zenith and azimuth angles. This will not only improve the definition of synthetic calibrations, but it also offers the opportunity to adjust the calibration factor as a function of zenith and azimuth angles. However, the effects of angular response characteristics are different for clear skies, partly cloudy skies, and cloudy skies. Therefore, the full implementation of this method becomes quite complex. At the close of FY 1990, these studies were not complete; therefore, the final determination of synthetic calibration methods and the use of angular response corrections have not been made.

In addition to potentially improving the derivation of synthetic calibrations, improved models are now available for estimating direct-normal and diffuse components from the rehabilitated global-horizontal values. The ADIPA and ETMY models that were used for the SOLMET/ERSATZ data base were derived from very limited direct-normal data [18]. Data for only five locations for no more than two years were used in developing these models.

As indicated by Figure 4-3, 2300 station-months of direct-normal data were available for developing improved models. An improved version of SERI's DISC model and the SIDSS model developed for estimating solar irradiance in the absence of measured data will be considered for estimating the direct-normal and diffuse components during the historical data period.

4.5.2 Current Status

SERI has characterized the angular response of a number of light-bulb-type pyranometers, as well as Eppley PSP and Spectro Lab SR-75 pyranometers used in the post-1976 network. We have confirmed that the angular response characteristics of the light-bulb pyranometers were quite variable and significantly different from the more modern pyranometers. However, our investigations have shown that only a limited number of the light-bulb pyranometers used from 1952 to 1975 are still available for characterization. Many of them were broken during removal and shipment from the stations, and others appear to have been lost. Therefore, it will be impossible to determine angular characteristics from laboratory or field measurements.

Given that laboratory measurements cannot be used to characterize the actual instruments used in the pre-1976 network, we are investigating an alternative method for determining angular response characteristics. This method will compare measured with modeled global-horizontal irradiance under clear skies. Recent determinations of broadband turbidity, along with radiosonde measurements of precipitable water vapor, will be used as input to the SIDSS model. This entire procedure will be evaluated using side-by-side comparisons of light-bulb and PSP pyranometer data taken between 1982 and 1985. We will be able to validate this entire procedure using this simultaneous collection of data, along with direct-beam measurements, and modeled data.

5.0 SOLAR RADIATION NETWORKS

5.1 Background

An appropriate role for SERI's resource assessment program would be to serve as a national focus for independent, regional resource assessment efforts. However, with our current priority on the national data base development, we have not devoted resources to maintaining a comprehensive data base of all solar monitoring networks in the United States. We focus our attention on the national network, staying current with the operations and obtaining the data as they become available. We collect descriptive information about other regional networks in the United States and, to a lesser extent, other international solar monitoring programs. The following sections overview selected networks of national interest.

5.2 NOAA Solar Radiation Network

NOAA is responsible for the nation's SOLRAD monitoring network (Figure 5-1). The SOLRAD network is the principal source of data for the 1961–1990 solar radiation data base currently in development (see Section 4.0).

Three organizational elements within NOAA are involved with the network operations: the NWS, the Climate Monitoring and Diagnostics Laboratory (CMDL), and the national Climatic Data Center (NCDC). The NWS operates and maintains the radiometers, solar trackers, and data acquisition systems on a day-to-day basis. Hourly measurements of global-horizontal and direct-normal solar irradiance were collected at the 29 SOLRAD stations in FY 1990 (see Table 5-1). These data are sent to the NWS Climate Analysis Center for processing with other routine meteorological observations. Radiometer calibrations and solar tracker maintenance are assigned to the CMDL Solar Radiation Facility (SRF). Final data quality assessment and archiving are accomplished at NCDC.

SERI has provided limited funding and technical support to the SOLRAD network. We have assisted the SRF with upgrading automatic solar trackers to improve the reliability of the direct-normal irradiance measurements. By the end of FY 1990, 12 of the 29 operating NWS stations had installed new microprocessor-controlled Eppley Laboratory Model SMT-3 solar trackers. The trackers had not been installed at the other sites for a variety of reasons, including the need to modify the stepping motor drive circuits. Installation at some stations was delayed by the need to modify station facilities to accommodate the new tracker and by the lack of funding to do so. IBM personal computers (PCs) were installed at the network sites to provide data recording and in-field quality control functions. SERI provided newly developed solar irradiance data quality assessment software to NCDC. This allowed for data quality "flags" to be assigned to each data point in the archive through computer software tests.

During FY 1990, measurements from the SOLRAD network for 1988 were available from NCDC. Figure 5-2 summarizes the percent of the possible data that were collected for each network station. A review of the hourly archive in TD-3281 format indicated an average network data recovery rate of about 85%. The minimum data recovery from a single station was about 45% at Pittsburgh. The maximum data recovery was greater than 97% at Caribou, Maine. Both SERI and NOAA are investigating actions to improve this performance.

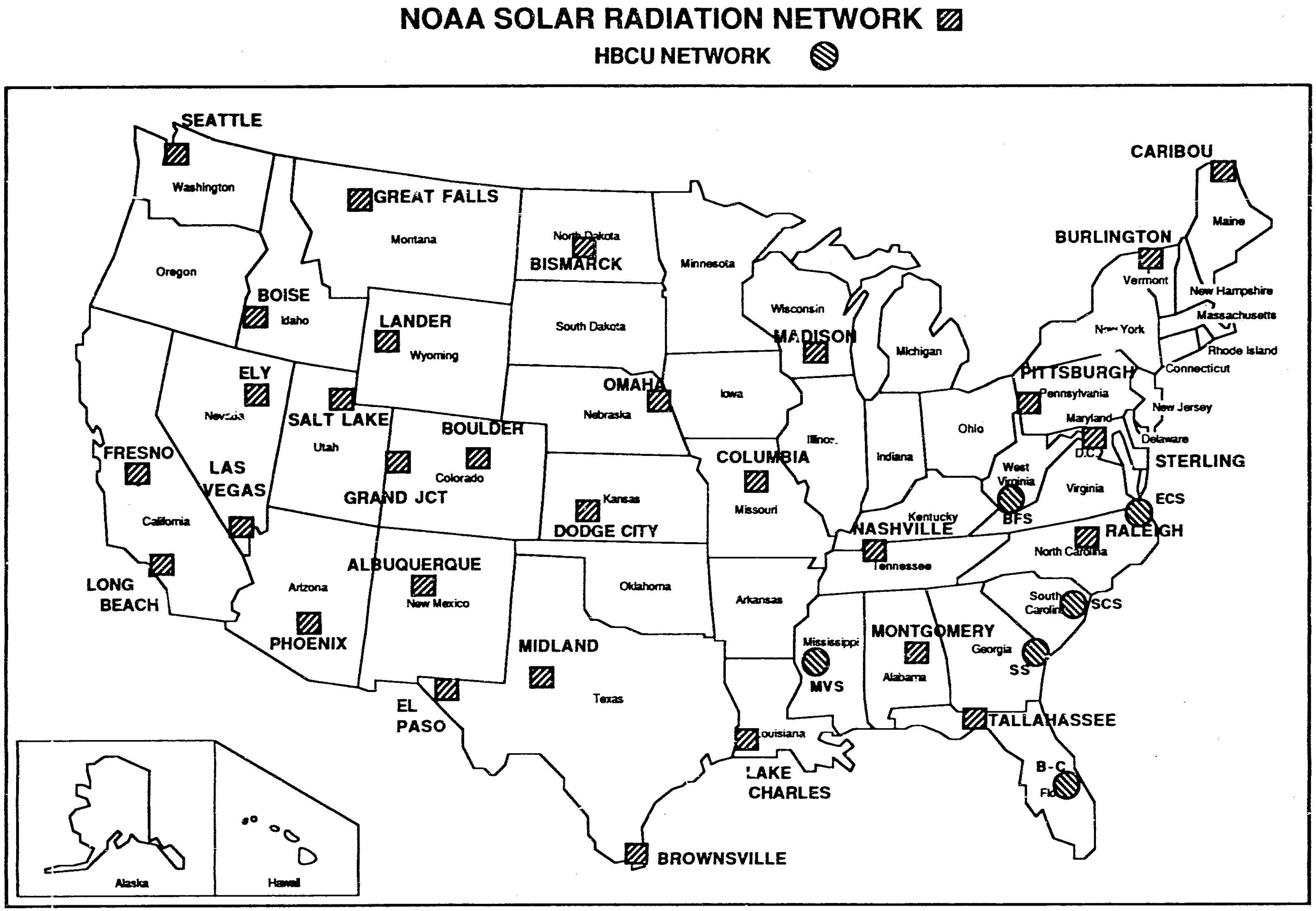


Figure 5-1. NOAA and HBCU Solar Radiation Monitoring Networks

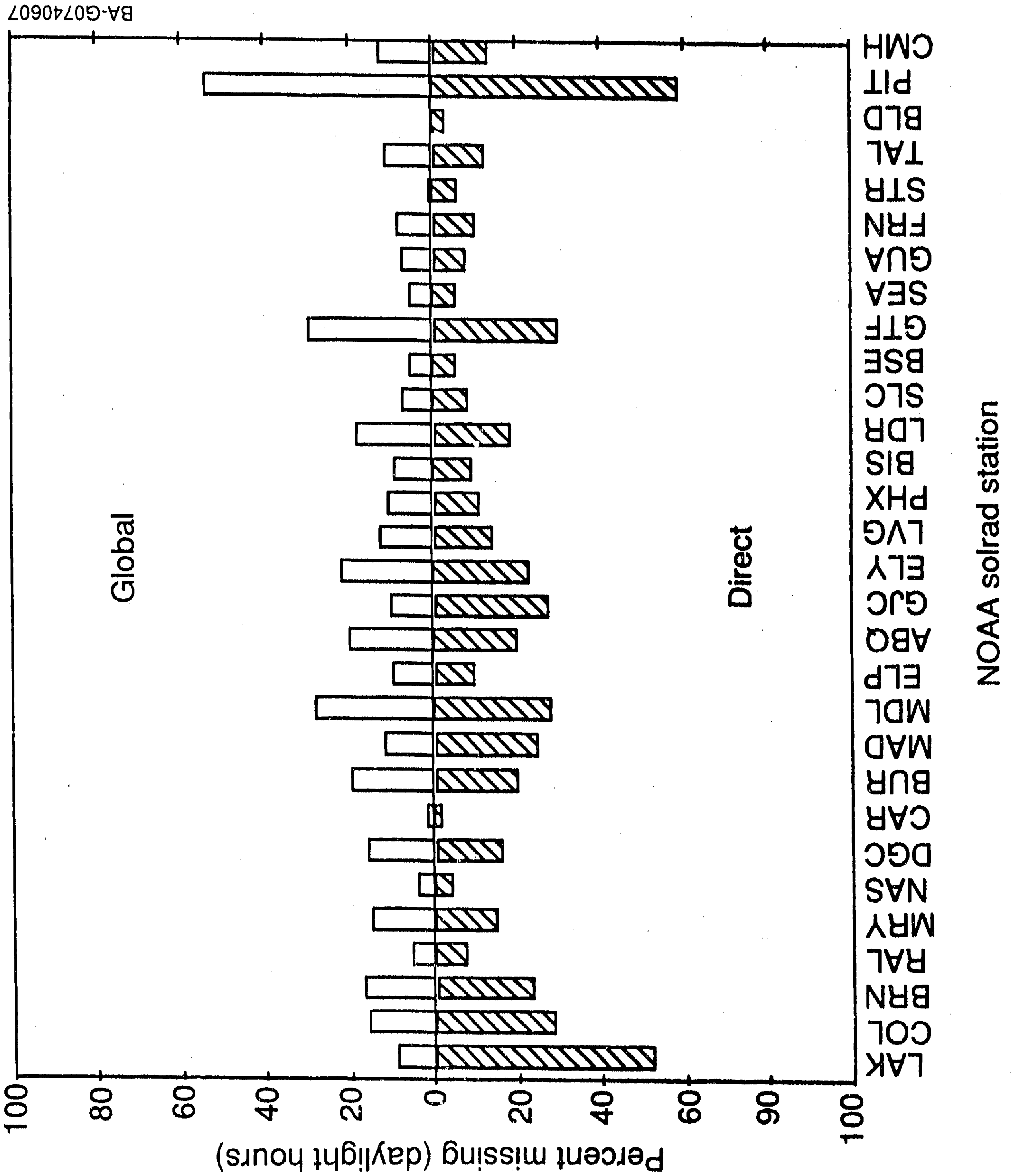


Figure 5-2. Summary of Network Data Collected in 1988

Table 5-1. SOLRAD Network Stations

Albuquerque, NM	Bismarck, ND	Boise, ID
Boulder, CO	Brownsville, TX	Burlington, VT
Caribou, ME	Columbia, MO	Concord, NH
Dodge City, KS	El Paso, TX	Ely, NV
Fairbanks, AK	Fresno, CA	Grand Junction, CO
Great Falls, MT	Guam	Honolulu, HI
Indianapolis, IN	Lake Charles, LA	Lander, WY
Las Vegas, NV	Miami, FL	Madison, WI
Medford, OR	Nashville, TN	Midland, TX
Montgomery, AL	Pittsburg, PA	Omaha, NE
Phoenix, AZ	San Juan, PR	Raleigh, NC
Salt Lake City, UT	Tallahassee, FL	Seattle-Tacoma, WA

The future prospects for the NOAA SOLRAD network are not promising. Planned modernization of the NWS stations presents serious problems for the SOLRAD network. Eight of the current SOLRAD stations are destined to become unmanned Automatic Surface Observation System (ASOS) stations. This will eliminate solar monitoring because operating solar radiation instruments requires daily maintenance. Fifteen of the current stations will move into new next generation radar (NEXRAD) facilities. Most (if not all) of these NEXRAD facilities cannot accommodate solar radiation instruments. Only seven of the current stations will apparently be unaffected by NOAA's modernization program.

SERI is communicating with NOAA and DOE regarding this situation and is investigating various options for maintaining or even expanding the current network. A solution for maintaining the visibility of the network is critical because the siting and design of future solar radiation energy systems require the continuous monitoring of solar radiation.

5.3 SERI/HBCU Solar Monitoring Network

The SERI/HBCU (Historically Black Colleges and Universities) Solar Monitoring Network has been in operation at six locations in the southeastern and eastern United States since 1985 (see Figure 5-1):

- 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.

The data acquisition system records five-minute averages for global-horizontal and diffuse-horizontal solar radiation at all stations, and direct-normal solar radiation at two stations. SERI processes data monthly, producing data in the SERI standard broadband format (SBF) [19], printed monthly tabular reports, and time-series plots.

From the monthly reports, we derived the following network statistics for October 1989 through September 1990:

Data recovery:	98.3% of possible daylight hours.
QC failures:	3.5% failed the 15% QC threshold.

During FY 1990, SERI implemented several improvements for the network:

- We increased annual funding for each station in the network from $1800 to $2000.
- We developed a data-processing manual for all aspects of routine acquisition, reduction, and quality assessment of monthly network data sets.
- We developed an off-site storage procedure for safeguarding network data.
- We hired a part-time student (32 hours per month) to assist with network data processing.
- We exchanged all data loggers with recalibrated units. (All cassette recorders were replaced with units that had been cleaned and aligned.)

The monthly sets of raw data we receive from each station are processed, archived, and sent back in report form to each station within a month. We continue to produce a monthly newsletter, which keeps network personnel updated with network news, events, problems, and new developments.

These means of communications underscore our philosophy that 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 corrective action must be taken.

5.4 Pacific Northwest Network

The University of Oregon Solar Monitoring Laboratory has operated a regional solar radiation network since 1977 [20]. Measurements started at Eugene, Oregon, in April 1975 provide the longest record of continuous measurements of both global-horizontal and direct-normal solar irradiance components in the United States. The number of stations in the network has changed over the years as funding for the network fluctuated. The sites in operation in Oregon during FY 1990 were Eugene, Hermiston, Burns, Coos Bay, Bend, and La Grande.

5.5 Pacific Gas and Electric Company SIMP Network

The Pacific Gas & Electric Company (PG&E) has operated their Solar Insolation Monitoring Project (SIMP) network since 1984 [21]. Developed to survey the solar radiation resources of the PG&E service area in California, the network consists of 14 stations. Each station measures global-horizontal solar irradiance. Six of the stations also measure the direct-normal component using an Eppley Laboratory Model normal incidence pyrheliometer (NIP) mounted in a LI-COR Model 2020 automatic solar tracker. PG&E maintains the equipment and provides for regular instrument calibrations.

5.6 Illinois State Water Survey

The Illinois State Water Survey established a solar monitoring network in 1983. Seventeen stations were established to continuously monitor solar radiation, air temperature, humidity, wind speed and direction, soil temperature, and soil moisture. The Survey checks the data for errors, produces summaries, and archives the data.

5.7 Oklahoma MESONET

The University of Oklahoma and Oklahoma State University will share $2 million in oil overcharge refunds to the state to establish a statewide network (MESONET). The 107-station environmental network is planned to be fully operational by 1993. Network observations in all 77 Oklahoma counties will include 9 to 10 environmental parameters, including solar radiation, every 15 minutes. MESONET information then will be linked to the Oklahoma Department of Public Safety's Law Enforcement Telecommunications System, which will permit near real-time access to the data from several hundred locations throughout the state.

Currently, a minimum of more than 100 school systems are prepared to conduct educational activities associated with the network. There is a potential for 100,000 students to conduct realistic scientific activities based on the information available from the network.

5.8 CLIMIS

The California Department of Water Resources has established a state network (CLIMIS) for monitoring parameters to determine evapotranspiration rates, global-horizontal solar irradiance, dry- and wet-bulb temperatures, and wind speed and direction.

5.9 GEBA

The Geographical Institute (Geographisches Institut) in Zurich, Switzerland, has been assembling an international meteorological data base, the Global Energy Balance Archive (GEBA), since 1987. We have contributed printed summary information from our files, describing available data and network contacts in the United States. Funded by the Swiss National Science Foundation, the data base will be made widely available through central computing networks and on optical disks.

6.0 SITE-SPECIFIC SOLAR RADIATION ESTIMATION

6.1 Background

After completing the 1961–1990 national data base, the Solar Radiation Resource Assessment Project will focus more attention on producing products (maps, design-year data sets, and manuals) and developing methods to estimate solar radiation between the data-base sites (site-specific solar radiation estimates). In the interim, we are staying abreast of research in these areas by participating in International Energy Agency (IEA) tasks addressing these topics.

6.2 Participation in IEA

The IEA Solar Heating and Cooling Program (IEA-SHCP) Task 9 was formally initiated in October 1982 to advance the state of the art in the measurement and estimation of solar radiation. The initial three subtasks of Task 9 were completed in 1987. Three new subtasks were formed and approved in September of 1987. During FY 1989 and FY 1990, SERI participated in these new subtasks:

- Subtask D, Techniques for Supplementing Network Data for Solar Energy Applications (Subtask Leader: A. Zelenka, Switzerland)
- Subtask E, Representative Design Years for Solar Energy Applications (Subtask Leader: H. Lund, Denmark)
- Subtask F, Irradiance Measurements for Solar Collector Testing (Subtask Leader: D. Wardle, Canada)

DOE and SERI have been formally participating in Subtask D and have also provided input to Subtasks E and F. Specifically, solar radiation and meteorological data were provided for Subtask E to develop a representative design-year data set for one location in the United States. SERI has also completed a study of the aging (decrease in sensitivity) of pyranometers. A draft report on this subject was presented at the meeting at Turku, Finland, in August 1990.

Task 9 is scheduled for completion at the end of June 1991; plans for a follow-on task are being made. The follow-on task will be Task 17, which will study spectral solar irradiance in contrast to the broadband studies under Task 9. The initial planning for Task 17 took place during FY 1990.

The solar resource assessment programs of many other countries participating in IEA Task 9 have been strongly and continuously funded for more than a decade. Therefore, in some cases they have more experience and better quality data than does the United States. Furthermore, the physicists and meteorologists involved in these programs have a great deal of experience from which the United States can benefit. The total funding in the other countries just for Task 9 work is comparable to the combined DOE and NOAA funding for solar radiation measurements and solar resource assessment. For this reason, SERI's participation in IEA Task 9 results in a strong return on the small investment made.

6.3 IEA Tasks 9 and 17 Activities

Although the funding available for Task 9 during FY 1990 was quite limited, in part because of our emphasis on producing the 1961–1990 data base, a number of important activities were undertaken:

- We provided partial support for the participation of R. Perez, State University of New York at Albany, in Subtask 9D. Perez prepared a surface and satellite data set for the northeastern United States; this was added to the other two data sets provided by SERI and data sets provided by Switzerland, Germany, and Sweden. Perez also undertook an evaluation of mathematical interpolation techniques with the data set for the Northeast.

- We evaluated pyranometer calibration data, examined the results of pyranometer calibrations performed by others, and prepared a draft report on pyranometer aging (Appendix).

- We have communicated the results of our meteorological (cloud-based) solar radiation model development at the recent Task 9 experts meetings in Genova, Italy, and Turku, Finland. This model development is of interest to both Subtasks D and E.

- As the U.S. representative to Task 9, E. Maxwell, attended the expert's meetings held at Genova, Italy, in November 1989 and Turku, Finland, in August 1990. Maxwell presented reports on SERI's related activities at both of these meetings.

- At the last Task 9 meeting held at Turku, Finland, detailed plans were made for the preparation of the final report for Subtask 9D. SERI will be providing input to this report and will also support the final editing. Final editing support is important because English is not the native language of any of the other participants in this subtask.

- We also attended the Task 17 planning workshop held at Stockholm, Sweden, just prior to the Task 9 meeting in Turku, Finland. At this meeting, the German and U.S. (SERI) representatives offered to provide leadership for the subtask on spectral radiometry. We have also agreed to host the next Task 17 planning workshop to be held in February 1991. Although Germany has been chosen to lead the subtask on spectral radiometry, U.S. participation in this subtask is planned if approved by DOE.

7.0 SPECTRAL SOLAR RADIATION DATA BASES AND MODELS

The long-range goals of the research on spectral solar radiation are to develop a research-quality data base of measured spectra and spectral simulation model(s) for the 290–3000-nm wavelength range for different climate conditions. The data and models are needed to characterize the natural, outdoor spectral variability of solar radiation resources for the various solar technologies that require spectral information, such as photovoltaics or spectrally selective window coatings. Having data on the spectral distribution of solar radiation enables researchers to evaluate the spectral sensitivity of their solar conversion devices, to design devices to optimize performance for a range of spectral conditions, and to understand their outdoor performance.

Only a small part of the project activities (less than 25%) was directed toward spectral solar radiation data bases and models in FY 1990 because of the project emphasis on the 1961–1990 data base development (Section 4.0). Two reports on work completed in FY 1989 were printed and distributed. One report describes the effects of urban air pollution on spectral solar radiation [22], and the other is a two-volume manual documenting the spectral solar radiation data base at SERI that contains 3000 measured spectra and simultaneous meteorological and broadband data [23]. The major activity during FY 1990 was to analyze the effects of cloud cover on spectral irradiance.

From January through September 1990, a visiting scientist from the Centre for Solar Energy and Hydrogen Research in Germany worked at SERI. He and the project staff studied cloud effects on spectral irradiance using both SERI's and Germany's extensive spectral irradiance data sets. Preliminary results of this work were presented at a photovoltaic specialists conference in May 1990 [24], and a final paper has been accepted for publication in the *Journal of Applied Meteorology* [25].

The major conclusions from these analyses were as follows: there is a relatively higher transmission of ultraviolet and visible irradiance compared to near-infrared irradiance under cloudy skies (up to about 30% in the ultraviolet spectral region); there is increased absorption of solar radiation in the near-infrared absorption bands (absorption by water vapor and cloud droplets); and spectral ground albedo effects are observable (for example, green vegetation can cause enhancements in the near-infrared spectral region under overcast skies because of its high reflectivity in the near-infrared wavelengths).

The measurements available in the SERI and German data bases cover the 300–1100-nm region. Measurements are needed in the 290–3000-nm region to verify cloud effects over the entire ultraviolet to near-infrared region. An extended-wavelength spectroradiometer under development in SERI's Photovoltaic Advanced Research and Development Project was not available in FY 1990 to apply to our spectral model development or add to our spectral solar radiation data base.

8.0 LABORATORIES AND TECHNICAL INFORMATION TRANSFER

Two projects at SERI, the Solar Radiation Resource Assessment Project and the Photovoltaic Advanced Research and Development Project, provide funds to maintain and operate the Solar Radiation Research Laboratory and the Solar Radiation Data Processing Laboratory. These laboratories are required to maintain SERI's expertise as DOE's lead laboratory for solar radiation resource assessment and to develop products and transfer technology to the solar community.

8.1 Solar Radiation Research Laboratory

The Solar Radiation Research Laboratory (SRRL) (Figure 8-1) provides the outdoor research measurement capabilities needed by the project. Since 1979, the development and operation of the laboratory have been focused on the following:

- Building a research data base that characterizes the solar radiation available to various types of solar collectors (e.g., two-axis and one-axis tracking collectors, concentrator collectors), along with meteorological conditions
- Providing a facility for outdoor calibrations of radiometers traceable to international standards
- Providing various solar radiation measurements in support of activities at SERI to develop solar radiation instruments, atmospheric models, and solar energy conversion devices
- Establishing a long-term solar radiation and meteorological/climatological data base for South Table Mountain in Golden, Colorado.

In July 1990, the set of 16 baseline measurements was modified to include direct-normal ultraviolet measurements needed by SERI's Mechanical and Industrial Technology Division. This required adding a seventeenth channel (see Table 8-1) and upgrading the data logger. At the same time, a modem was added for eventual dial-up capabilities using the SERI local area network.

The battery-powered data acquisition system was programmed to continuously monitor the 17 data channels, storing five-minute averages of all but the wind speed and wind-direction data, which are instantaneous samples. Data are stored on audio cassette tape for 14 days and are then downloaded to a MicroVAX II in the Solar Radiation Data Processing Laboratory. Maintenance checks are performed at the laboratory daily, except weekends and holidays.

More than 100 radiometers were calibrated outdoors at the laboratory during FY 1990. Pyrheliometers are calibrated by comparing the voltage signal from the radiometer being tested with the direct-normal solar irradiance as measured with an electrically self-calibrating absolute cavity radiometer. Typically, the average of more than 500 such comparisons are used in determining the mean calibration factor (in $\mu V/W/m^2$). Pyranometers are calibrated by summing measurements of the direct-normal solar component as measured with an absolute cavity radiometer and the diffuse-horizontal component as measured with a thermopile-based pyranometer with a tracking disk. The reference solar irradiance is calculated from the sum of these two components, incorporating the effect

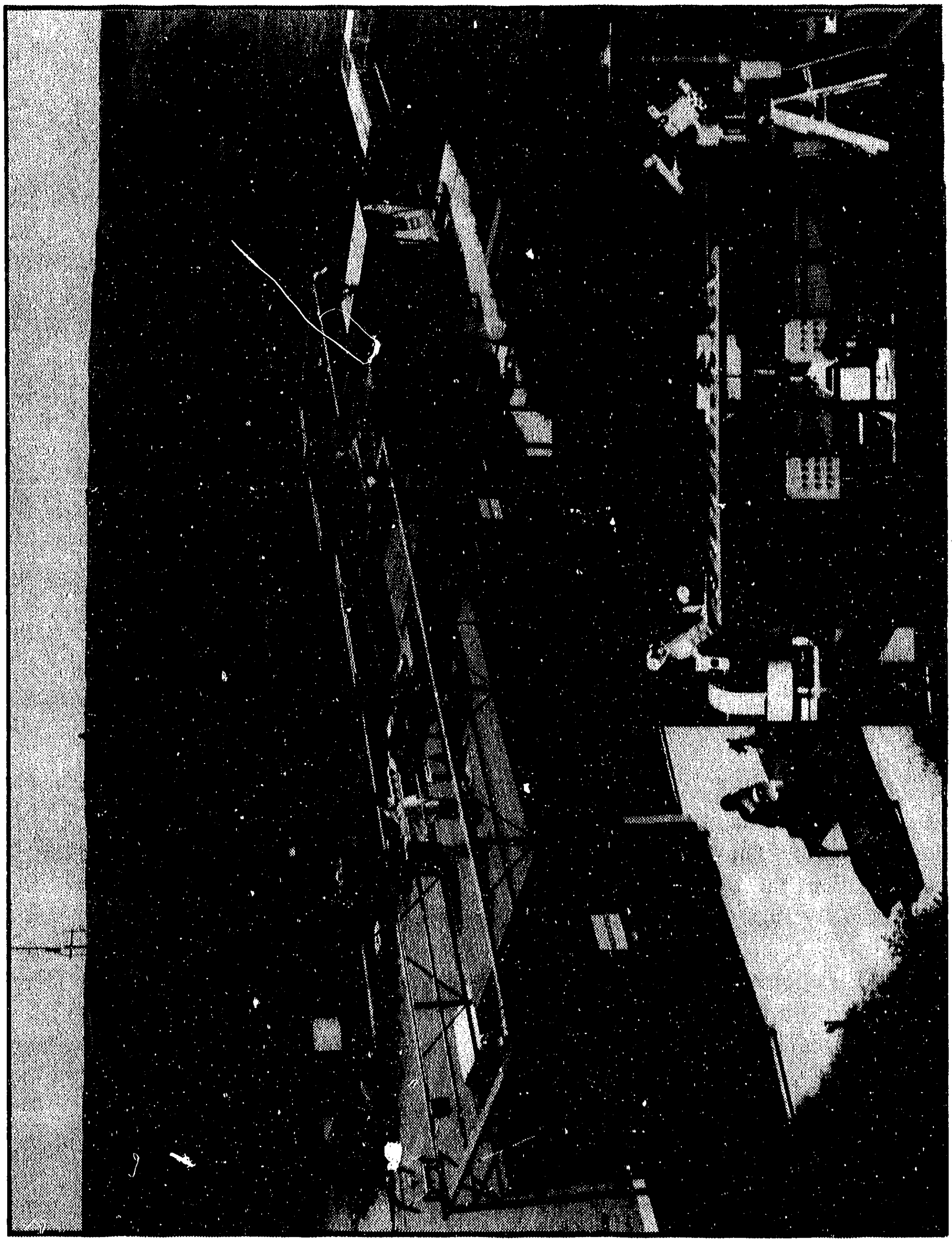


Figure 8-1. Solar Radiation Research Laboratory

Table 8-1. Data Channels for the SRRL Baseline Monitoring System

Channel No.	Measurement Parameter	Instrument*	Units
1	Global-horizontal irradiance (300–3000 nm)	PSP	W/m^2
2	Diffuse-horizontal irradiance (300–3000 nm)	PSP	W/m^2
3	Direct-normal irradiance (300–3000 nm)	NIP	W/m^2
4	Global irradiance on a 40° south-facing tilt (300–3000 nm)	PSP	W/m^2
5	Global normal irradiance on a two-axis tracking surface (300–3000 nm)	PSP	W/m^2
6	Global irradiance on a one-axis tracking surface (horizontal, north-south axis) (300–3000 nm)	CM-11	W/m^2
7	Global-horizontal irradiance (780–3000 nm)	PSP	W/m^2
8	Direct-normal irradiance (780–3000 nm)	NIP	W/m^2
9	Total ultraviolet irradiance (295–385 nm)	TUVR	W/m^2
10	Ground-reflected irradiance (300–3000 nm)	PSP	W/m^2
11	Direct-normal irradiance (500 nm)	LCSP	counts
12	Wind speed, 10 m above ground level	TGT	m/s
13	Wind direction, 10 m above ground level	TGT	degrees
14	Dry-bulb temperature	CSI	degrees C
15	Relative humidity	CSI	percent
16	Barometric pressure	YSI	millibar
17	Direct-normal ultraviolet irradiance (295–385 nm)	TUVR	W/m^2

*Types of instruments:
CM-11 = Kipp & Zonen pyranometer, Model CM-11
CSI = Campbell Scientific, Inc., Model 207 probe
LSCP = SERI-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

of the solar zenith angle at the time of the measurement. The reference irradiance is then compared with the voltage signal from each pyranometer tested to determine the calibration factor (in $\mu V/W/m^2$).

During FY 1990 we improved the broadband radiometer calibration procedures. We introduced a refraction correction for zenith angle and limited the range of zenith angles in determining the calibration factor to between 45° and 55° and modifying the total measurement uncertainty calculation to reflect variations in the calibration factor over a full range of zenith angles. We also improved the calibration reports by including plots of solar position with calibrations and temperature data. We updated the procedure manual to reflect these changes.

In September and October 1990, we attended the international intercomparison of cavity radiometers at the World Radiation Center in Davos, Switzerland. This intercomparison provides our traceability to international radiometric standards (the World Radiometric Reference).

8.2 Solar Radiation Data Processing Laboratory

The major components of the Solar Radiation Data Processing Laboratory are a VAX 11/730 with an attached Geographic/Image Analysis System, a MicroVAX II, and a VAXstation 3100. These components and their peripherals are described in detail in the FY 1989 annual progress report [4].

The VAX system is central to all data acquisition, processing, and analysis activities in the project. The following are examples of important applications:

- Reading and processing data from several hundred 9-track computer tapes containing historical solar radiation and meteorological data required for developing the 1961–1990 national solar radiation data base (see Section 4.0)
- Developing and applying sophisticated quality assessment software to evaluate solar radiation and meteorological data (see Section 4.0)
- Developing and applying models to estimate solar radiation from meteorological data (see Section 4.0)
- Formatting, quality assessing, and archiving data from the HBCU network station (see Section 5.0)
- Maintaining and analyzing over 3000 data sets in the spectral solar radiation data base (see Section 6.0)
- Producing statistical analysis and graphs of outdoor radiometer calibration results (see previous Section 8.1).

We have ordered an erasable optical disk system and will transfer much of the historical solar radiation and meteorological data to these media for data base processing. With this new system, we will be able to store and access large quantities of data much more efficiently than we can with the current set of 9-track magnetic tapes.

Several components in the Geographic/Image Analysis System have failed. They could not be replaced because no capital equipment funds were allocated to the Solar Radiation Resource Assessment Project in FY 1990.

8.3 Technology Transfer

A very important and significant part of all project activities is technical information transfer. We receive over 20 requests per month for technical information, data, models, and assessments. If the information is available from NCDC, requestors are referred to the center. If the request can be filled without significantly affecting the research schedule, the information is provided. In other cases, recovery of costs may be required or the request may be referred to the DOE program manager. Every attempt is made to respond to requests without compromising research directives from DOE.

During FY 1990, we began a record-keeping system to document the technical requests, as recommended by the Science and Technology Review Committee. Examples of the type of requests taken from these records are as follows:

- Clear-sky solar radiation models (Colorado State University, U.S. Geological Survey)
- Ultraviolet solar radiation data/information (Pacific Northwest Laboratories, Cancer Research Center, Environmental Protection Agency, British Petroleum, U.S. Materials Testing Laboratory)
- Direct-normal solar radiation data (LUZ International, Boeing, U.S. Air Force Astronautics Laboratory)
- Direct-normal solar radiation model, DISC (LUZ International, University of Houston)
- Spectral solar irradiance model, SPCTRAL2 (Jet Propulsion Laboratory)
- Spectral solar irradiance data (Forestry Canada, Pacific Northwest Laboratories, TRW)
- Air mass 1.5 spectral data sets (San Diego State University)
- Direct-normal data analysis (Arizona Public Service Company)
- Satellite techniques for estimating solar radiation (Augustyn + Company, Electric Power Research Institute, Florida Solar Energy Center)
- Worldwide solar radiation data (Solar SineAge, Bechtel, University of Colorado)
- Solar radiation data for Guam, Puerto Rico, Hong Kong, Africa, Eastern Europe, and Australia (various requestors)
- Radiometer calibration procedures (Augustyn + Company)

- Solar Radiation Research Laboratory data (State University of New York, SERI Environmental Safety and Health, SERI Facilities Branch)
- LI-COR solar trackers (Sandia National Laboratories)
- Solar radiation measurement network procedures and instruments (Arkansas Public Service Commission)
- HBCU data (South Carolina State Climatologists Office).

Interacting with other agencies and users at national conferences is critical for determining the relevance and application of the project's products. In FY 1990, we presented two papers [26, 27] at the annual conference of the American Solar Energy Society (ASES), participated in the ASES Resource Assessment Division meeting, and distributed over 400 brochures describing the 1961–1990 data base development. We also attended the annual meeting of the American Association of State Climatologists and presented an overview of the resource assessment activities, and we attended winter and annual meetings of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and represented SERI on Technical Committee 4.2 (Weather Information). SERI provided funds to the State University of New York, Albany, to improve solar radiation models, and the models will be used in fiscal year 1991 to upgrade the Weather Year for Energy Calculations (WYEC) data set for ASHRAE. Finally, we submitted four abstracts for the International Solar Energy Society meeting in August 1991. Other special publications with contributions from resource assessment project scientists are listed in the references [28-30]. To reduce travel costs, we did not attend the Atmospheric Radiation Conference, or the Air Force Geophysics Laboratory Atmospheric Transmission Conference, nor did we arrange for a special meeting with Sandia National Laboratories, as planned.

Project scientists worked with the Solar Technical Information Program staff at SERI to produce a publication titled *Solar Radiation Resource Assessment - An Overview*. The publication is 95% complete and expected to be printed in early FY 1991. It is directed toward an educated audience, not necessarily familiar with solar radiation resource assessment, and it discusses why solar radiation is important and presents the basics of resource assessment.

A color poster showing annual average daily solar radiation resources for the United States was produced and distributed to over 150 people in the solar community. This poster serves a need for broad-scale resource information, a common request of SERI. The poster includes global solar radiation on horizontal and tilted surfaces and also direct-normal solar radiation.

The *Insolation Data Manual* [31] and the *Direct Normal Solar Radiation Data Manual* [32] are often requested but have been out of print for several years. In a cooperative project with the Solar Technical Information Program, we reprinted these two manuals in a combined volume [33] and have distributed several hundred copies to requestors. These manuals will be updated after completion of the 1961–1990 national solar radiation data base, scheduled for FY 1992.

9.0 PROGRAM MANAGEMENT

Program management activities include interagency interactions; monthly, quarterly, semiannual, and annual reporting; six-month self-performance assessments; program review meetings; special publications; and continuous management of budgets, schedules, and milestones. The following are a few of the significant activities in FY 1990.

A program review was held at DOE headquarters in April 1990. DOE and SERI agreed on program priorities, and the results were incorporated into the first *Resource Assessment Program 5-year Plan FY 1991- FY 1995* [5]. The draft plan was distributed to 20 reviewers prior to publication to obtain user input.

Project scientists met quarterly to review progress on the key activities and make schedule adjustments. The recommendations of the Science and Technology Review Committee were reviewed at these quarterly meetings. The next meeting of the review committee was planned for August 1990 but was postponed to December 1990 because the chairman was unavailable. Some of our activities in response to the review committee's recommendations were as follows:

- Interacting with the climate community. We attended the meeting of the state climatologists. Also, R. Hulstrom is participating in DOE's Atmospheric Radiation Measurements Program, which is addressing climate-change research. This program has ties to the Global Surface Radiation Baseline Measurements Network.

- Using outside expertise. We issued a subcontract to the State University of New York, Albany, to provide an upgraded version of E. Maxwell's DISC model. Also, Maxwell obtained input from the International Energy Agency Task 9 participants on his models to estimate solar radiation using meteorological data.

- Contributing to ultraviolet solar radiation assessment. We initiated a project with SERI's Solar Thermal Technology Program, which is investigating possibilities of detoxifying hazardous wastes using concentrated ultraviolet solar radiation. The Solar Thermal Technology Program provided partial support for direct-normal spectral ultraviolet measurements, measurements of direct-normal ultraviolet solar radiation at the Solar Radiation Research Laboratory, and preparation of a report reviewing ultraviolet solar radiation resources [34].

10.0 ISSUES AND INITIATIVES

All of the needs for solar radiation resource assessments, data, and information cannot be met with the available staff and budget. Efforts must focus on high-priority activities, such as development of the national 1961-1990 solar radiation data base. Specific needs that should be addressed if additional funds become available include the following:

- Assistance to the NOAA/NWS solar radiation measurement network (SOLRAD) to assure high-quality data collection at the existing sites, followed by expansion of the network for better spatial coverage in the United States

- Support for other solar radiation measurement networks and establishment of a central location for data archival/dissemination, quality assessment, and instrument calibration to assure high-quality data for different climate regions in the United States

- An increased level of effort toward developing methods to estimate solar radiation among measurement sites, perhaps using satellite methods, so that requests for solar radiation information at any location can be accommodated as the need arises

- Participation in international solar radiation measurement programs, such as the International Daylighting Measurement Program and the World Meteorological Organization's Global Surface Radiation Baseline Measurement Network, and also in standards activities

- Worldwide solar radiation resource assessment to support United States industry activities to market solar energy technology outside the United States and to encourage worldwide renewable energy resource development

- More interaction with users and industry to deliver specific solar radiation information that will enhance the development of solar technologies; for example, specific programs with utilities to map solar radiation (and other renewable resources in their service territories) to encourage development of renewables

- More subcontracts to universities and the private sector to obtain valuable solar radiation data and research interactions and to take advantage of national scientific expertise

- Improved solar radiation measurement instrumentation to meet the growing need for accurate climate change data

- An integrated federal resource assessment activity and assistance center to characterize all renewable resources, including solar radiation, wind, hydropower, biomass, and geothermal.

With respect to these needs, two initiatives are described in the DOE Resource Assessment Program 5-year Plan. One is to establish a comprehensive renewable energy resource assessment project to coordinate federal resource assessment activities for all renewable resources and provide one-stop shopping for resource assessment assistance. The second initiative addresses the need for a solar radiation energy network in the United States to ensure the collection of good-quality solar radiation data needed to support the design, development, and deployment of renewable energy technologies.

This second initiative was presented at DOE headquarters in July 1990. These two projects and the other activities listed above would require funding above the core solar radiation resource assessment research project funding.

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APPENDIX

REPORT TO SUBTASK 9F ON PYRANOMETER AGING

The following reports and calibration records were examined in an attempt to address the effects of exposure (to solar radiation) on the sensitivity of pyranometers.

Reports

Edwin C. Flowers and Parke P. Starke, 1967, Results of a Field Trip to Compare Pyranometers, National Oceanic and Atmospheric Administration.

Edwin C. Flowers, 1973, The "So-Called" Parson's Black Problem with Old-Style Eppley Pyranometers, National Environmental Research Center, Research Triangle Park, North Carolina.

J.R. Latimer and J. H. Wilson, 1976, On the Calibration Stability of Kipp and Zonen Pyranometers, Atmospheric Environment Service, Downsview, Ontario.

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D.I. Wardle, 1984, The Canadian Radiation Network and Long Term Records of Pyranometer Calibration 1960-1984, Atmospheric Environment Service, Downsview, Ontario.

M. Bin Mahfoodh, M.S. Imamura*, M. Al-Khaldi, 1987, Long-Term Outdoor Performance Characteristics of Silicon & Thermopile Solar Irradiance Sensors, King Abdulaziz City for Science & Technology, Riyadh, Saudi Arabia; *Midwest Research Institute, Kansas City, Missouri.

Calibration Records

NOAA calibrations of 22 Spectrolab Model SR-75 from 1976 to 1987.

NOAA calibrations of eight Eppley Model PSPs from 1976 to 1987.

Sandia National Laboratories calibrations of Eppley PSP 13683 from 1977 to 1983.

Eppley and Florida Solar Energy Center calibrations of 12 Eppley PSPs from 1975 to 1986.

Smithsonian Institution calibrations of 18 Eppley PSPs from 1970 to 1981.

Results

The results of our initial examination of these reports and calibration records show the need to develop standards for calibrating pyranometers. With just a few exceptions, changes in calibration methods, measurement scales, and other uncertainties affecting the response of the pyranometers are as great or greater than the evidence of aging. Nevertheless, there is some evidence that certain types of pyranometers have aged under certain conditions of exposure. The evidence also indicates that degradation of the paint or other material used to coat the absorbing receiver surface is the primary cause of aging, although other factors are involved, such as fogging of the glass domes.

The reports by Flowers and Starke (1967) and Flowers (1973) provide the most definitive evidence of pyranometer aging. The pyranometers were the old Eppley "light bulb" type that used concentric black and white rings connected by thermocouples. Both of these reports discuss the results of a calibration field trip taken in 1966. The main purpose of the field trip was to investigate large changes in the apparent cloudless-sky transmission of solar radiation at a number of locations across the United States. An apparent decrease in transmission from 1960 to 1966 had reached 10% to 15% at stations such as Albuquerque, New Mexico; Phoenix, Arizona; and Great Falls, Montana.

Four standard pyranometers of the same type were calibrated in the NWS integrating sphere before and after the field comparisons. Each standard pyranometer was exposed for one day at each field site along with the field pyranometer. The pyranometer comparisons made during the field trip determined that most, if not all, of the indicated decreases in transmission were the result of instrument degradation.

All of the instruments' absorbing receiver surfaces that degraded were coated with Parson's Black paint, which Eppley began using in 1956. The Parson's Black paint was observed to change color from black to gray to green at locations receiving high levels of solar irradiance. At Phoenix, the pyranometer changed from black to gray-green in about four years. The same change occurred over six to seven years at Great Falls and Bismarck. Instruments in storage (not exposed to sunlight) did not degrade and did not change significantly in sensitivity.

Two of the pyranometers compared on this field trip had receivers coated with lampblack. Both of these instruments had increased in sensitivity. In fact, at China Lake, California, a location with quite high irradiance values and high temperatures, the lampblack pyranometer sensitivity had increased 18% in six years. This increase had been noted in apparent increases in solar irradiance at that site. No explanation for the increased sensitivity of this instrument was ever found.

The three reports by Latimer and Wilson and Wardle document the calibration records for Kipp and Zonen CM-5 pyranometers and Eppley PSP pyranometers used in the Canadian Radiation Network. When the initial Canadian calibrations are compared with later calibrations, there is no evidence of a degradation in sensitivity. All of the National Atmospheric Radiation Centre calibrations have been performed in an integrating sphere using unchanging procedures. This is one of the few instances when a consistent calibration procedure has been used for radiometers that were being evaluated for sensitivity degradation.

The paper by Mahfoodh, Imamura, and Al-Khaldi reports on apparent reductions in sensitivity for Eppley PSP pyranometers in use near Riyadh, Saudi Arabia, over a five-year period. Although their calibrations show a consistent loss of sensitivity in all but one instance, the calibration in Saudi Arabia was being compared with the original integrating sphere calibration by Eppley. The calibrations in Saudi Arabia were outdoor calibrations in a hot environment. Even if these calibration changes are valid, they all indicate a degradation of less than 1% per year. A two-year separation between calibrations of one PSP in Saudi Arabia showed only 0.25% change per year.

SERI examined calibration records received from NOAA for 22 Spectrolab SR-75 pyranometers and 8 Eppley PSPs. The calibration records covered the period from 1976 to 1987. The Spectrolab records show an average decrease in sensitivity of 0.29% per year for the eight-year period from 1976 to 1984. From 1984 to 1987, the pyranometers were in storage and were not exposed to any radiation. The calibration factors before and after the three years of nonexposure were the same within +0.05%.

The NOAA records seem to indicate a slow decrease in sensitivity when the instruments are exposed to radiation. However, changes in calibration procedures are known to have occurred during the period from 1976 to 1984. Hence, these results cannot be considered to be definitive evidence for the aging of pyranometers. However, it should be noted that 8 Eppley PSP pyranometers that underwent the same calibration procedures over the same periods of time show a reduction in sensitivity of about 0.72% per year. This difference between the performance of the Spectrolab and Eppley pyranometers might be significant. Currently, it is unknown if there was a difference in the paints used by Spectrolab and Eppley in these instruments.

The calibration of Eppley PSP 13683 by Sandia National Laboratories, covering the period from 1977 to 1983, provides evidence of a reduction in sensitivity. This instrument was calibrated more than once a year using the response of the instrument at a solar elevation of 45° for the calibration factor. It was continuously exposed at this high-desert climate during this entire period. The results for this instrument show an average loss in sensitivity greater than 0.6% per year during the six-year period. However, if only the first four-and-one-half years are examined, the degradation is only 0.3% per year. From an examination of their data, one could conclude that a step change in sensitivity occurred between the fourth and fifth years.

Twelve Eppley PSP pyranometers were calibrated over a period of 10 years by both the Eppley Laboratory (using their integrating sphere) and the Florida Solar Energy Center (FSEC) (outdoors using absolute cavity radiometer and shading disk techniques). The results of calibrations by both laboratories show an average reduction in sensitivity of about 1.2% per year. Given the similarity of these results from two different laboratories using stable calibration procedures over the period of record, these become the most definitive results that indicate significant aging of Eppley PSP pyranometers. The Eppley calibrations were performed on an annual basis, whereas the FSEC calibrations were less frequent. The Eppley calibrations show a steady decrease in sensitivity from the first to the last calibration for virtually all of the instruments.

The calibration records obtained from the Smithsonian Institution for 18 Eppley PSPs used in their three-station network from 1970 to 1981 yielded inconclusive results. Unfortunately, the calibrations were few and the procedures used were not consistent. These data were of particular interest because each of the six pyranometers at each station were exposed to different parts of the solar spectrum. Although there was an indication of decreased sensitivity between the initial and final calibrations, random variations in calibration results were larger than the mean difference. There was no conclusive evidence of any difference in decreased sensitivity with respect to the exposure to different parts of the solar spectrum.

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Conclusions

The evidence is quite conclusive that pyranometers manufactured with Parson's Black paint aged with exposure to sunlight. This aging was evidenced in the visible color of the absorbing receiver surface, the results of repeated calibrations, and the solar radiation data obtained with the instruments. The evidence regarding the aging of Eppley PSP, Spectrolab, and Kipp and Zonen pyranometers is less definitive. There is strong evidence from Canada that these pyranometers do not age. There is also strong evidence from Sandia National Laboratories and from the FSEC that they do age.

There does not seem to be any conclusive evidence that any of the pyranometers currently in use will age significantly more than 1% per year under any exposure or environmental conditions. This supports annual calibrations of instruments under most conditions. There is more reason to be concerned about the uncertainty of calibrations than the degradation of the radiometers.

To definitively resolve the issue of pyranometer aging, it seems likely that a group of instruments from different manufacturers would have to be exposed for several years under each of several different exposure and environmental conditions. Calibrations would have to be performed every six months to obtain a sufficient number of calibration records. All of these calibrations should be performed under identical, stable conditions to minimize calibration uncertainties. The period of time required to carry out such a definitive experiment is estimated at about 10 years. Rather than expending the time and effort to undertake such a time-consuming project, it is recommended that the same magnitude of effort be put into materials research, the development of improved pyranometers, and the improvement of characterization and calibration equipment and methods.

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