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Evaluation of Solar Radiation Measurement Systems: EPRI/NREL Final Test Report

Volume 1

T. Stoffel, C. Riordan, and J. Bigger

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PREFACE

The first step in exploring the possibilities of using renewable energy technologies is the assessment of available resources. In 1990, the Electric Power Research Institute (EPRI) and the National Renewable Energy Laboratory (then the Solar Energy Research Institute) began a joint project to evaluate the various methods available to electric utilities for measuring the solar radiation resources in their service territory. Our goal for the project was to compare several solar radiation measurement systems as options for performing solar radiation resource assessment.

EPRI purchased two rotating shadowband radiometer systems for installation at NREL for comparison with the existing solar radiation monitoring and outdoor radiometer calibration equipment. This report summarizes our 6-month field comparison of these measurement systems for providing solar radiation resource assessment data.

We have divided this final test report into two volumes. The first volume contains the customary technical reporting elements (i.e., summary, background, approach, results and discussion, and conclusions and recommendations). Details of the project are in the second volume (instrument calibrations, daily maintenance records, and daily time series plots of the data). Please refer to the Table of Contents for more information.

Thomas L. Stoffel

Approved for the

NATIONAL RENEWABLE ENERGY LABORATORY

Thomas D. Bath

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EXECUTIVE SUMMARY

Measured solar radiation resource data are needed by electric utilities to evaluate the potential of renewable energy options like photovoltaics in their service territory. In this final test report, we document a cooperative project of the Electric Power Research Institute (EPRI) and the National Renewable Energy Laboratory (NREL) to compare available measurement system options for performing solar radiation resource assessments. We present the detailed results of a 6-month field comparison of thermopile-based pyranometer and pyrheliometer solar irradiance measurement systems with two different implementations of the rotating shadowband radiometer (RSR) concept installed at NREL's Solar Radiation Research Laboratory (SRRL) in Golden, Colorado.

Two manufacturers have developed RSRs that are based on an instrument concept developed at federal laboratories in the early 1980s and reported in the open literature (Wesely 1982; Michalsky et al. 1986; Michalsky et al. 1988). An instrument from each of the two manufacturers was purchased by EPRI and installed by the manufacturers at the SRRL. By January 1991, we incorporated these two systems into the routine maintenance and operation of NREL's Baseline Monitoring System (BMS) of thermopile-based radiometers, automatic sun-following trackers, a manually adjusted shadowband stand, and meteorological instruments.

The RSRs operated under a range of weather conditions that included air temperatures of -18.9° to 36.1°C (-2° to 97°F), wind speeds in excess of 33.5 m/s (75 mph), snow, icing, hail, and rain. NREL provided daily inspections using a procedure developed for each system for the test period to document the operations and maintenance requirements.

The RSRs utilize microprocessor-based data acquisition and control systems, allowing telephone dial-up for collecting the data and observing the equipment operations. From the RSRs, we collected high resolution 1-min recordings of the measured global and diffuse horizontal solar irradiance components and the corresponding computed values of direct normal solar irradiance. Five-min averages of these data were compared with corresponding 5-min averaged measurements of the same solar irradiance components from our BMS for the 6-month project. Additionally, we compared the 1-min RSR data, from 11 selected cloudless days during the project, with 1-min solar component measurements, using our absolute cavity and tracking disk Reference Irradiance System (RIS). Data recovered from all systems exceeded 96% of possible measurements.

Our analyses focused on comparison of direct normal, diffuse, and global horizontal solar irradiance data from the RSRs and thermopile-based instruments in the BMS for 5-min average values by month (we also looked at 15-min and 60-min averages) and for the 6-month period of the project. We prepared an estimate of the measurement uncertainties associated with all systems in this study to better interpret the significance of the statistical data summaries. Our comparisons of the RSRs with data from the BMS show that the coefficients of determination range from 0.97 to 0.99, and 5-min average differences between the RSRs and BMS values are within the measurement uncertainty for global, direct normal, and diffuse measurements.

Based on the results of this 6-month study in Golden, Colorado, both RSRs and instruments used in NREL's BMS can be considered as options for collecting reliable solar irradiance data needed for assessing the solar energy options for electric utilities. It should be recognized that the RSRs are still under development, and long-term (longer than 6-months) experience is needed to document their reliability, such as durability of the moving parts. By design, the RSRs offer the potential advantages of lower maintenance and calibration costs by using a single pyranometer with a diffusing sensor for determining the direct, diffuse, and global solar irradiance rather than using up to three radiometers with glass domes and windows and more complex support equipment (e.g., solar trackers). Their potential disadvantages are temperature sensitivity and less accurate measures of broadband irradiance because of the restricted spectral response of the silicon-based detector used in the pyranometer. The RSR developed by the State University of New York at Albany includes software for postmeasurement adjustments to compensate for temperature and spectral mismatch. For photovoltaic applications in the silicon response region of the solar spectrum, however, the raw data from an RSR may better reflect the energy available for conversion than data from a thermopile-based radiometer. The postprocessing correction software to account for the temperature sensitivity and limited spectral response of the silicon radiometer has since been developed by Ascension Technology, Inc.

If installed properly by a trained technician, all systems can operate automatically, except for manual adjustments of the BMS stationary shadowband stand and tracking disk for changes in solar declination. However, we recommend daily inspections immediately after installation. These inspections should continue until experience dictates otherwise. Daily review of the data collected from the systems is strongly recommended to confirm proper operation. A maintenance record should be kept in a standard log. Remote, real-time data monitoring, via phone line, and quality assessment can identify obvious malfunctions (however infrequent) but not temporary conditions such as snow and ice accumulation, the presence of water droplets, or the need for cleaning. Daily field checks also provide valuable supplemental information for screening data.

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1.0 INTRODUCTION

The Electric Power Research Institute (EPRI) and the National Renewable Energy Laboratory (NREL) completed a joint project to compare the field performance of several types of solar radiation measurement systems available to electric utilities for determining the availability of global, diffuse, and direct solar irradiance resources in their service territories (Stoffel, Riordan, and Bigger 1991).

Two manufacturers have developed instruments called rotating shadowband radiometers (RSRs), which are based on an instrument concept developed at federal laboratories in the early 1980s and reported in the open literature (Wesely 1982; Michalsky et al. 1986; Michalsky et al. 1988). A unit from each of the RSR manufacturers was purchased and installed by the manufacturers at NREL's Solar Radiation Research Laboratory (SRRL), pictured in Figure 1-1, on South Table Mountain in Golden, Colorado (39.74° N, 105.18° W, 1828 m). The SRRL had existing radiometers of different design and manufacturer as part of the Baseline Monitoring System (BMS) used for monitoring solar and meteorological parameters and the Reference Irradiance System (RIS) used for outdoor calibrations of radiometers (Myers et al. 1990). Our objective for the project was to compare the field performance of the two RSRs and the existing radiometers at NREL for measuring direct normal, diffuse, and global horizontal solar irradiance over a 6-month period beginning in January 1991.

In this final test report of the project, we describe the solar radiation measurement systems being compared, our approach to the project, operational experiences during installation and data collection, results of graphical and statistical data analyses, and conclusions.

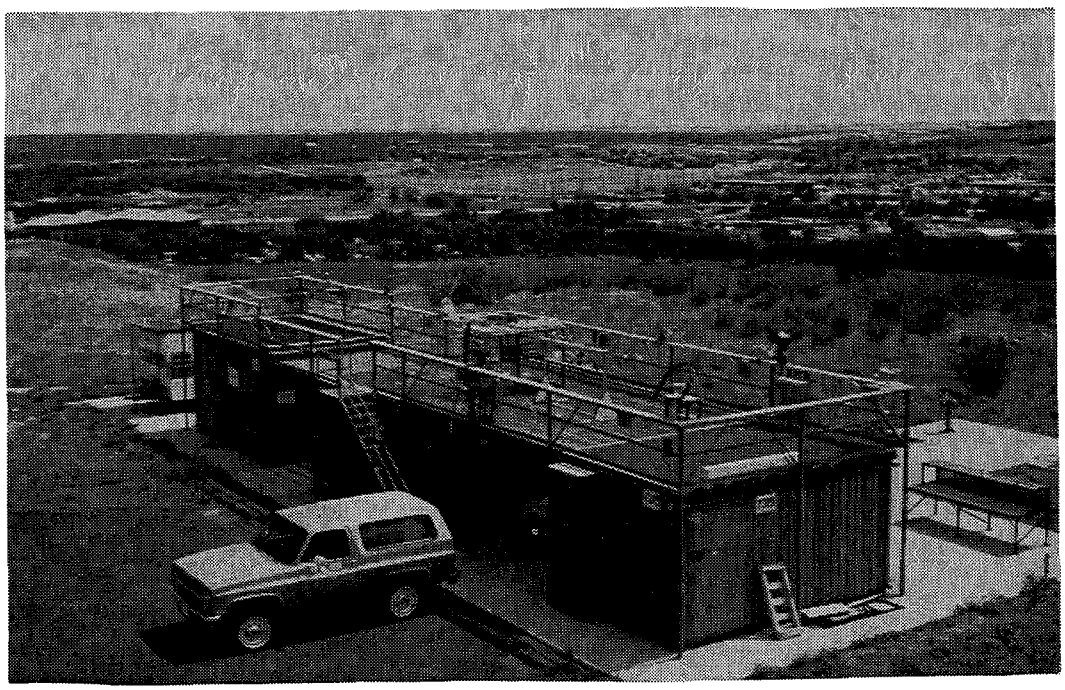


Figure 1-1. NREL's Solar Radiation Research Laboratory on South Table Mountain, Golden, Colorado

2.0 BACKGROUND

In this section, we describe the need, possible applications of the results, and an overview of the solar radiation instrumentation available for this project. All measurements for this project were taken at NREL's Solar Radiation Research Laboratory (SRRL), Golden, Colorado (39.74° N, 105.18° W, 1828 m).

2.1 Project Justification

Data for solar radiation resource availability are needed to evaluate the potential of solar energy options such as photovoltaic (PV) electric power in a utility's service territory. Given the present lack of adequate solar radiation data for the United States, many utility personnel have asked for assistance from EPRI and NREL to develop solar radiation measurement systems, data acquisition systems, data handling procedures, and data evaluation techniques. EPRI initially responded to these needs by producing a manual on data acquisition for PV power plants (Risser et al. 1990). NREL continues to provide advice and technical assistance to utilities, based on field experience at its SRRL and other sites.

Acceptance of the relatively new RSRs by utilities as an option for measuring solar radiation resources depends on demonstrated reliability in the field and documented performance by independent organizations. EPRI and NREL agreed to conduct a joint assessment of RSRs from the two known manufacturers in a side-by-side comparison with existing, well-characterized, solar measurement instrumentation at NREL's SRRL.

2.2 Solar Monitoring Instrumentation

The solar radiation measurement instruments described in the EPRI manual are pyranometers for measuring global horizontal and plane-of-array irradiance, and pyrheliometers with solar trackers for measuring direct normal irradiance (Figure 2-1). There are other options for obtaining global horizontal, plane-of-array, and direct irradiance, such as measuring global horizontal irradiance using a pyranometer and measuring diffuse horizontal irradiance using a pyranometer with an adjustable shadowband (Figure 2-2), then calculating direct and plane-of-array irradiance from the global and diffuse measurements, the sun's zenith angle, and the orientation of the array. The diffuse irradiance, when measured with a fixed shadowband, must be corrected for the presence of the band. By design, the properly adjusted band shades the pyranometer from the direct irradiance component throughout the day. A correction to the pyranometer output is needed because the band also blocks some of the diffuse (sky) component. The Eppley Laboratory, Inc., manufacturer of the shadowband stand used at the SRRL, provides a recommended shadowband correction factor (SBCF) for the middle of each month at selected station latitudes. For this project, we computed a *daily* SBCF for adjusting the diffuse data, using the equations for "average sky" conditions for our station latitude of 39.74° (Iqbal 1983). Figure 2-3 is a graph of the SBCF computed for the SRRL coordinates. We also used a later development of an SBCF (ASME 1986) for producing the daily review plots (see Figure 3-2 and Appendix C in Vol. 2), but concluded the method was not an improvement over the traditional computation method provided by the manufacturer based on comparisons of "corrected" shadowband measurements

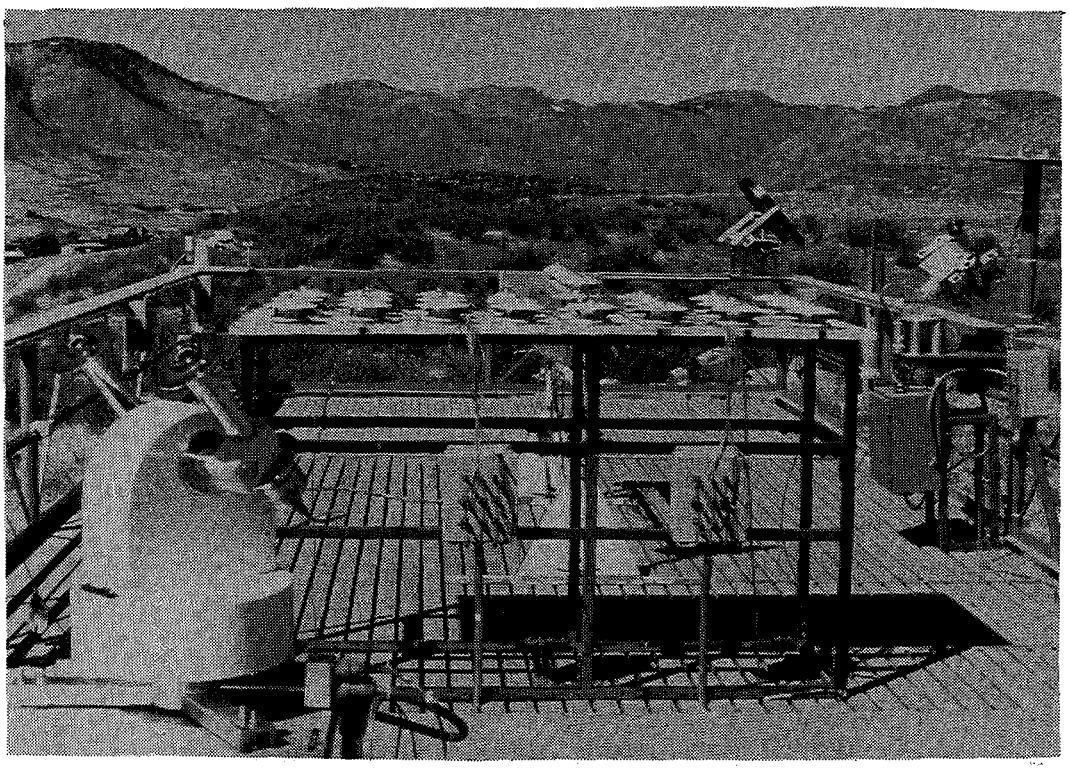


Figure 2-1. Thermopile pyranometers and pyrheliometers for monitoring global horizontal and direct normal solar irradiance

with computatation of the diffuse component made from simultaneous measures of global and direct normal irradiance.

RSRs provide another option for determining global, direct, and diffuse irradiance using a single unit from which plane-of-array irradiance can be calculated (Figure 2-4). RSRs use a commercially available silicon-detector pyranometer to measure global horizontal irradiance, as well as diffuse irradiance, when the rotating shadowband blocks the direct beam during the band's rotation; direct irradiance is calculated by the RSR's controller from the global and diffuse measurements and the solar zenith angle (Z):

Direct normal = (global horizontal - diffuse horizontal)/cos(Z).

There were two commercially available RSRs at the time we began planning this project. Ascension Technology, Inc., had developed a *rotating shadowband pyranometer* system based on commercially available Campbell Scientific, Inc. (Logan, UT) data acquisition and control hardware (Kern and Russell 1991). The design uses a controlled "sweeping" band rotation and 500-Hz data sampling. The high temporal resolution data are processed numerically to measure global and diffuse irradiance and calculate the corresponding direct normal irradiance component. According to the manufacturer, "Corrections are applied to adjust for the amount of diffuse irradiance unavoidably lost when the shadowband covers part of the sky along with the solar disk."

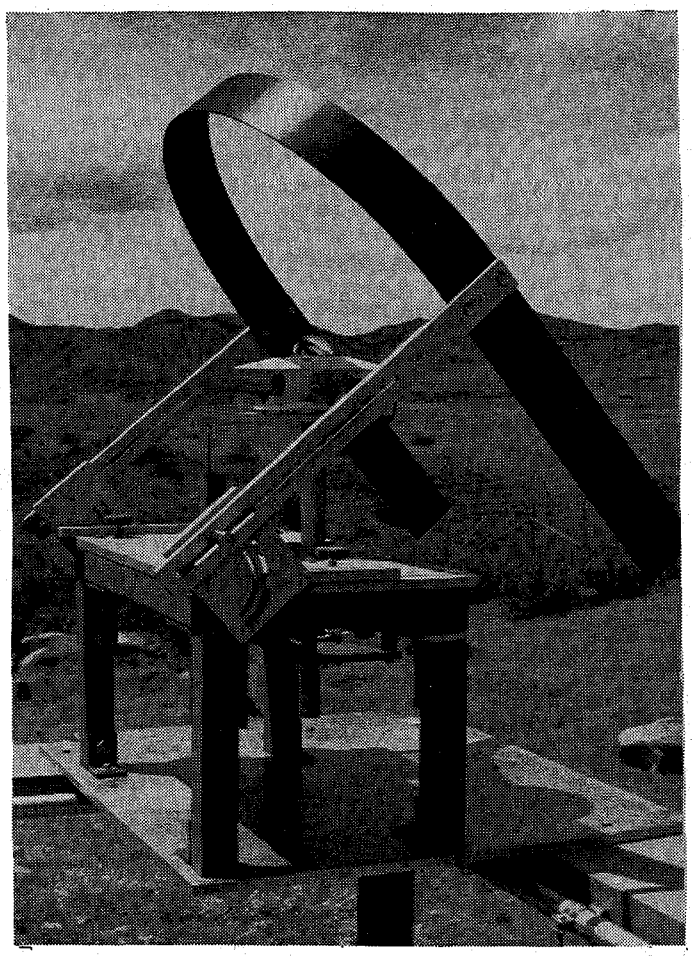


Figure 2-2. A pyranometer mounted under an adjustable shadowband for monitoring the diffuse horizontal solar irradiance

The State University of New York at Albany (SUNYA) developed its RSR from custom-built electronics for data acquisition and control (Harrison 1991). The SUNYA design uses a stepping motor to position the shading band at four precise locations during each measurement cycle. Global irradiance is sampled when the band is below the pyranometer. The band stops before, during, and after occulting the sun's direct rays. The sampled data from this period is used to compute the diffuse irradiance adjusted for the presence of the band that blocks some of the diffuse (sky) irradiance. Direct normal irradiance is calculated from the global and diffuse-horizontal measurements. Postmeasurement data processing software for the SUNYA RSR includes algorithms that make temperature and spectral adjustments to the "raw" RSR data to account for the silicon detector used in the pyranometer.

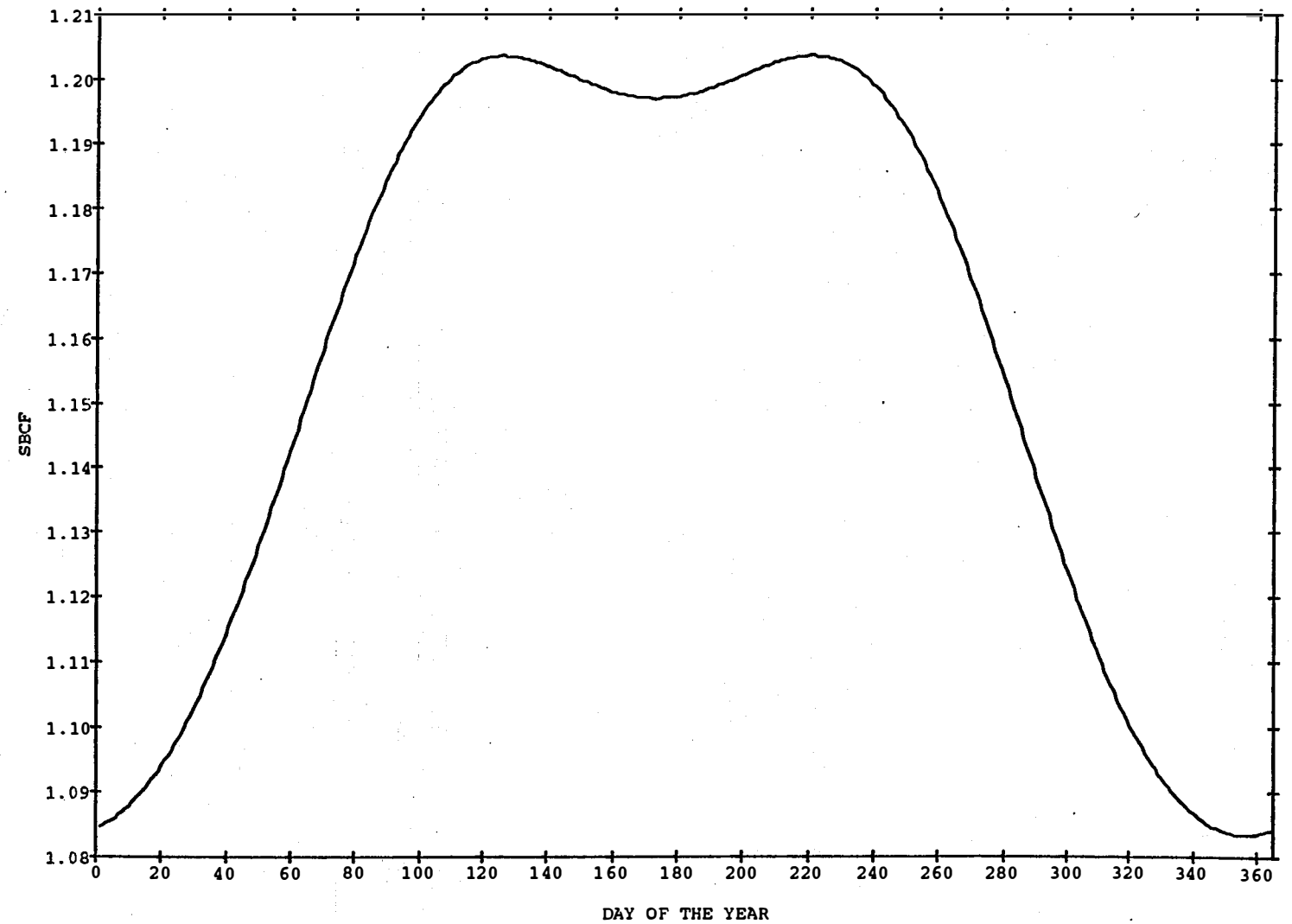
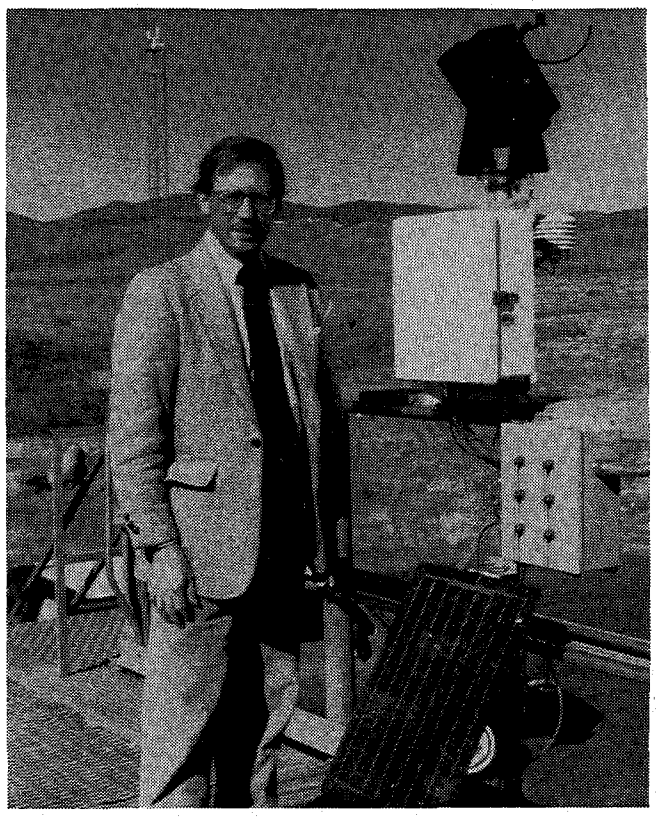


Figure 2-3. Daily computed shadowband correction factor (SBCF) for NREL's Solar Radiation Research Laboratory

(a)



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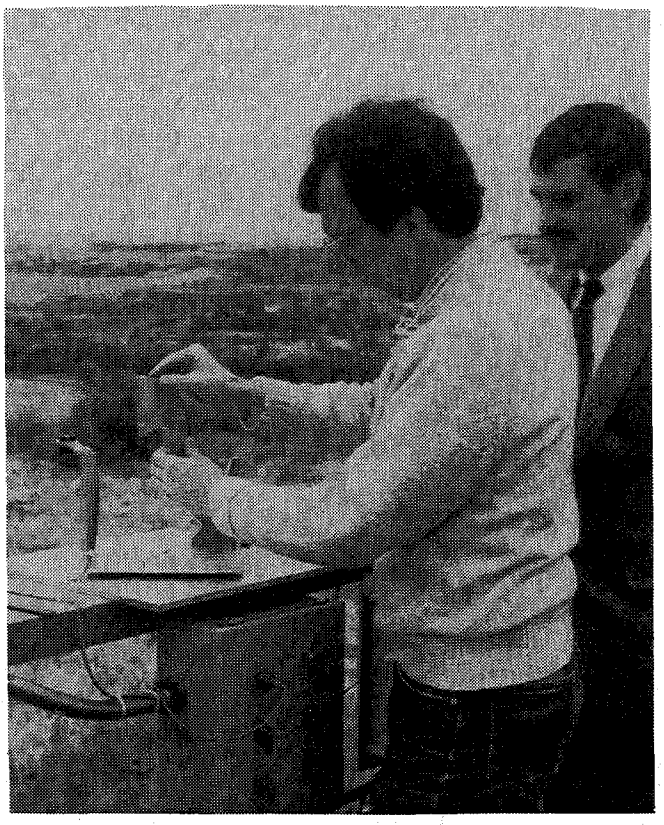
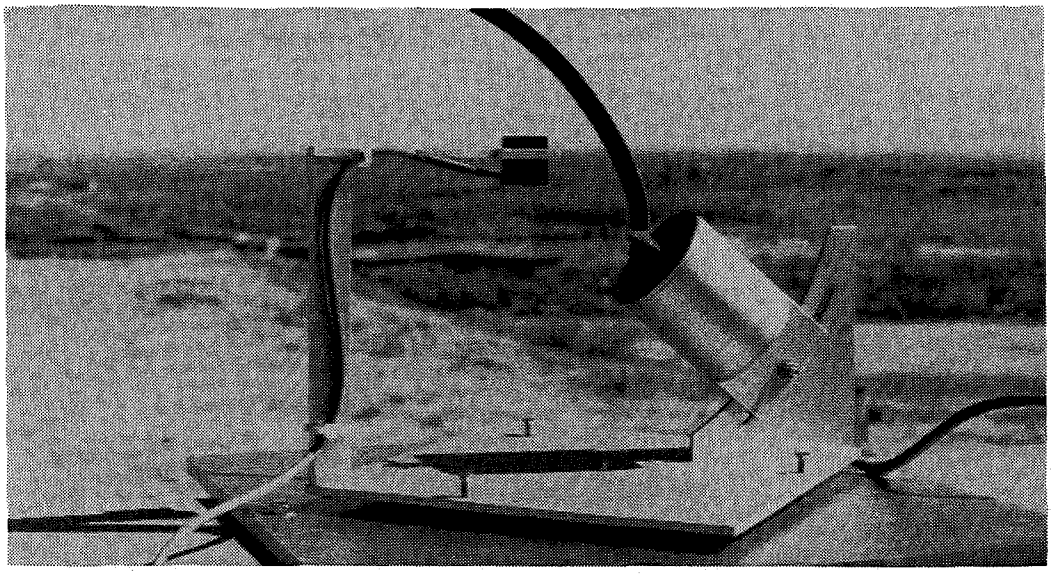




(c)

Figure 2-4. Rotating shadowband radiometers (a) manufactured by Ascension Technology, Inc., and (b,c) manufactured by the State University of New York at Albany and installed at NREL's Solar Radiation Research Laboratory

Differences between the two RSRs include sampling scheme and associated algorithms and treatment of the diffuse irradiance measurements. The RSRs are still under development. There are, however, about 50 to 60 units from the two manufacturers currently being used for atmospheric studies and utility solar resource assessments.

At NREL, radiometer calibration traceability to the international standard World Radiometric Reference (WMO 1978) is based on the absolute cavity radiometer (Myers 1988; Myers and Stoffel 1990). All of NREL's pyranometer and pyrheliometer calibrations are made using NREL's RIS, which is deployed at the SRRL. As shown in Table 2-1, this system comprises, in part, an electrically self-calibrating absolute cavity radiometer (Figure 2-5) for measuring the direct normal irradiance and a separate thermopile-based pyranometer mounted under a tracking disk (Figure 2-6) for measuring the diffuse irradiance. The RIS uses two control radiometers that are in continuous service as part of our BMS, also at the SRRL. By participating in every RIS outdoor calibration exercise, these control radiometers have a well-established calibration history and provide a quality assurance measure for our calibrations.

The radiometers used for measuring direct normal irradiance are mounted in automatic sun-following trackers.

The BMS provides continuous measurements of the various solar radiation components and meteorological parameters listed in Table 2-2. This system samples all radiation measurement channels every 10 s and stores 5-min averages. BMS measurements of global, direct, and diffuse irradiance and air temperature were used for this project.

A notable difference between the silicon- and thermopile-based radiometers is their time response. The time constant for 1/e response of the LI-COR model LI-200 is specified as 10 μs. The comparable specification for the Eppley Laboratory's model PSP time response is 5 s. Our analyses are based on BMS data with 5-min averages of 10-s samples, SUNYA RSR data with 1-min averages of 15-s samples, and ATI RSR data taken on the minute (direct and diffuse) and 1-s samples of global irradiance, and averages over longer time periods up to 60 min.

We summarize the different measurement systems used for this project in Table 2-3.

Table 2-1. Elements of the SRRL Reference Irradiance System

Irradiance Parameter	Instrument	Manufacturer	Model	Serial No.
Direct normal (reference)	Absolute cavity radiometer	Technical Measurements, Inc.	MKVI	68017
Direct normal (control)	Pyrheliometer	The Eppley Laboratory, Inc.	NIP	17836E6
Diffuse horizontal (reference)	Pyranometer under shading tracking disk	The Eppley Laboratory, Inc.	PSP & STD	17802F3
Global horizontal (control I)	Flat plate pyranometer	The Eppley Laboratory, Inc.	FPP	18745
Global horizontal (control II)	Pyranometer	The Eppley Laboratory, Inc.	PSP	25825F3

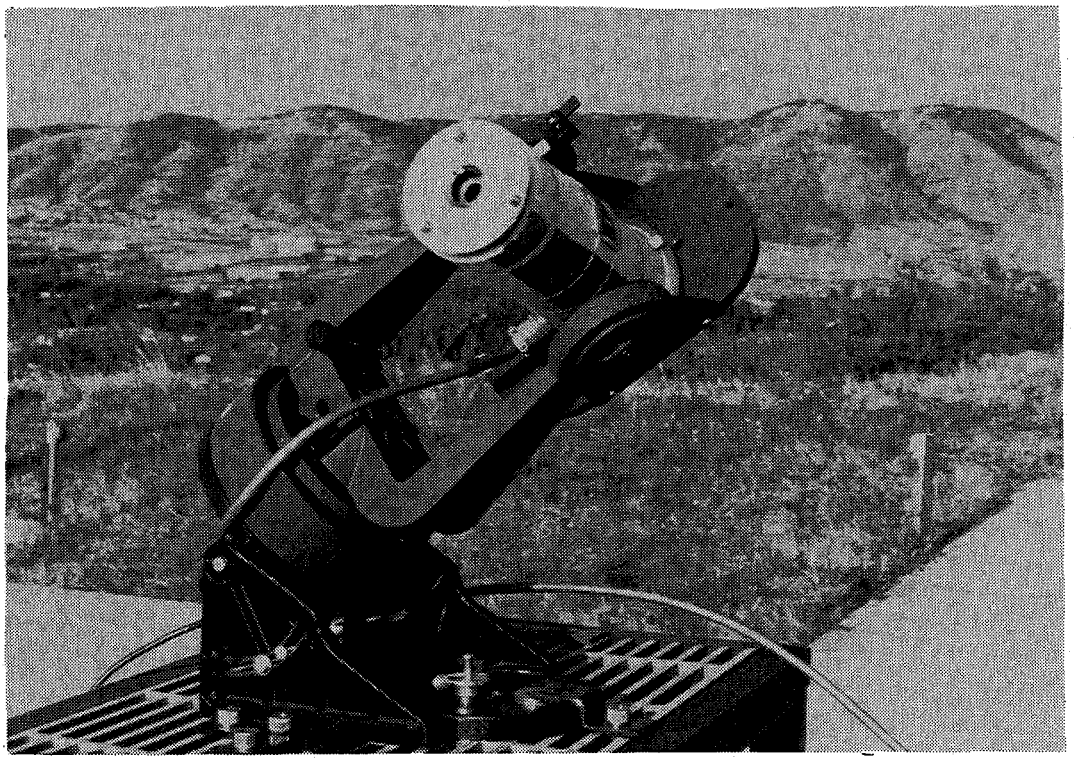


Figure 2-5. NREL's absolute cavity radiometer used in RIS

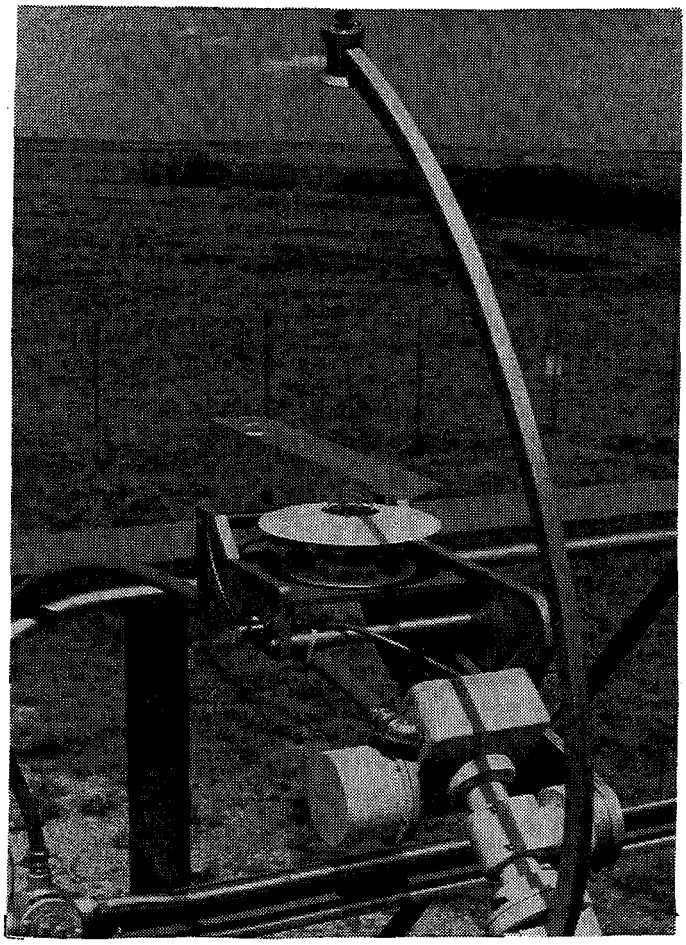


Figure 2-6. Pyranometer mounted under a tracking disk (part of RIS)

Table 2-2. Data Elements for the SRRL Baseline Monitoring System

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

* The following are definitions of instrument abbreviations:

CM-11 = Kipp & Zonen pyranometer, model CM-11
CSI = Campbell Scientific, Inc., temperature probe, model 207
LCSP = NREL-designed low-cost sun photometer (T. Cannon)
NIP = The Eppley Laboratory, Inc., pyrheliometer, model NIP
PSP = The Eppley Laboratory, Inc., pyranometer, model PSP
SBS = The Eppley Laboratory, Inc., shadowband stand, model SBS
SF-III = Pepco Electronics automatic solar tracker, model SF-III
SMT-3 = The Eppley Laboratory, Inc., automatic solar tracker, model SMT-3
ST-1 = The Eppley Laboratory, Inc., automatic solar tracker, model ST-1 (modified by NREL for 1-axis operation)
ST-3 = The Eppley Laboratory, Inc., automatic solar tracker, model ST-3
TGT = Teledyne-Geotech, Inc., wind system
TUVR = The Eppley Laboratory, Inc., photometer, model TUVR (unit for direct normal element has been fitted with view-limiting tube)
YSI = Yellow Springs Instrument Company

Table 2-3. Measurement Systems Summary

Measurement System	Instrument	Data Acquisition & Control	Operation
SRRL/Baseline Monitoring System: Global Horizontal Diffuse Horizontal Direct Normal	Eppley PSP Eppley PSP w/SBS[1] Eppley NIP w/SF-III[2]	Campbell Scientific, Inc. Model CR21XL[7] data logger	Continuous, automated monitoring of 5-min averages of 10-s samples. Data stored on cassette tape for 2 weeks before downloading to personal computer.
SRRL/Reference Irradiance System: Direct Normal Diffuse Horizontal	TMI Absolute Cavity[3] Eppley PSP w/TSD[4]	Fluke Model 2280B data logger	Selected, operator-assisted measurements during clear sky conditions. Reference global irradiance computed from 1-min data for calibrating all radiometers. Data captured by personal computer.
ATI[5] System: Global Horizontal Diffuse Horizontal Air Temperature	Rotating Shadowband Pyranometer	Campbell Scientific, Inc. Model CR10 data logger with PC208 hardware & software for a personal computer	ATI code in the CR10 rotates the continuous sweep shadowband once per minute. Direct normal is calculated using the diffuse and global irradiance. System is powered by a 30-W photovoltaic module and 30 A-h battery. Data downloaded nightly for quality assurance using PC208 software.
SUNYA[6] System: Global Horizontal Diffuse Horizontal Detector Temperature	Rotating Shadowband Radiometer	SUNYA-designed electronics and personal computer software	Custom system controls the stepper motor-driven rotating band for 1-min averages of 15-s samples and computes direct normal irradiance. System powered by 115 VAC with battery backup. Data downloaded every 3-4 days to personal computer via telephone. Spectral and temperature response adjustments to the data are made during postprocessing on a personal computer.

Notes:
1. The Eppley Laboratory, 12 Sheffield Ave., Newport, RI 02840, Shadow Band Stand (Model SBS) used for diffuse horizontal irradiance measurement (requires shadowband correction factor).
2. PEPCO Electronics, Box 395, Boulder City, NV 89005, Sun Follower III automatic solar tracker used for direct normal irradiance measurement.
3. Technical Measurements, Inc., Box 838, La Canada, CA 91011, Model MkVI absolute cavity radiometer used for reference (±0.4%) measurements of direct normal irradiance traceable to the World Radiometric Reference (±0.3%).
4. The Eppley Laboratory Tracking Shading Disk (TSD) used for diffuse horizontal irradiance measurement.
5. Ascension Technology, Inc., P.O. Box 314, Lincoln Center, MA 01773.
6. State University of New York at Albany, Atmospheric Sciences Research Center, 100 Fuller Ave., Albany, NY 12205.
7. Campbell Scientific, Inc., P.O. Box 551, Logan, UT 84321.

3.0 APPROACH

From early January through early July 1991, NREL acquired 1-min data from the two RSRs and 5-min data from the BMS. Additionally, 1-min data for 11 days of clear sky measurements during this period were recorded in conjunction with the RIS. In this section, we describe the RSRs' installation, maintenance and operation, radiometer calibrations, measurement uncertainty analyses, data collection, and data processing activities required for this project.

3.1 Solar Radiation Measurement Options

We considered six options for obtaining global, direct, and diffuse solar irradiance:

1. Ascension Technology, Inc. (ATI) RSR measuring global and diffuse (direct is calculated from the silicon-based pyranometer data)

2. SUNYA RSR measuring global and diffuse (direct is calculated from the silicon-based pyranometer data)

3. Two Eppley Laboratory, Inc. pyranometers (model PSP with thermopile detectors), one with an adjustable shadowband measuring global and diffuse, respectively (direct is calculated)

4. Eppley PSP pyranometer and normal-incidence pyrheliometer (model NIP) measuring global and direct, respectively (diffuse is calculated)

5. Eppley PSP pyranometers measuring global and diffuse and NIP pyrheliometer measuring direct

6. Technical Measurements, Inc. Mark VI electrically self-calibrating absolute cavity radiometer measuring the direct and an Eppley PSP pyranometer under an Eppley tracking shading disk measuring the diffuse (global is calculated).

3.2 Equipment Installation

The RSR hardware was delivered to NREL in November/December 1990 and was operational at the SRRL in January 1991. Copies of the installation and calibration information provided by the manufacturers is presented in Appendix A of Volume 2 of this report. Detailed records of the installation are available in Appendix B of Volume 2.

3.2.1 ATI RSR

A preproduction version of the ATI system was delivered to NREL on 6 December 1990. After G. Kern from Ascension Technology, Inc. instructed us on the operation and maintenance of the system, we completed the installation at SRRL in less than 6 h. On 8 January 1991, we replaced the "head" portion of the system at SRRL with the latest production version. This design configuration remained in place for the 6-month comparisons. A user's guide and installation

manual was not included with the RSR because ATI normally provides installation and data processing as part of their services.

3.2.2 SUNYA RSR

The SUNYA system was delivered to NREL on 30 November 1990 and tested indoors while the necessary hardware mounting items were made to install the unit at SRRL (described in Appendix B of Volume 2). A very thorough user's manual accompanied the system. J. Michalsky and L. Harrison from the SUNYA also provided instruction on the use of the system and assisted with the final installation at SRRL on 5 December 1990. The installation was accomplished in less than 10 h and required a change in modems and control boards because of the relatively high radio frequency and electromagnetic interference environment at SRRL. Data collection began 13 December 1990.

3.2.3 SRRL BMS and RIS

The SRRL BMS and RIS data collection systems have been installed and in operation since 1985. All radiometric data are measured by thermopile-based or electrically self-calibrating absolute cavity radiometers. The BMS provides semiautomated continuous monitoring of the solar irradiance. Operation of the RIS is labor intensive and is deployed only during selected cloudless sky conditions.

3.3 Instrument Operation and Maintenance

An important aspect of the comparison of the RSRs and thermopile-based radiometer systems is the amount of maintenance (scheduled or unscheduled) each of the systems will require in resource assessment applications. To ensure the adequate collection of operation and maintenance data, we developed an NREL standard laboratory practice (SLP) for the routine maintenance of the two RSR systems used in this project. We continued to use the existing SLP for maintaining the BMS for comparison measurements of global, direct, and diffuse irradiance using thermopile-based radiometers. Both SLPs specified daily maintenance inspections of the systems. An example of the detailed records of the instrument and support equipment conditions, data transfer, and brief sky and weather observations is shown in Figure 3-1. The complete record of individual logs for 179 days is presented in Appendix C, Volume 2. A summary of our experiences is presented in Section 4.2.

3.4 Radiometer Calibrations

Our original intent was to use the RSR calibration factors provided by the manufacturers. However, SUNYA staff alerted us to a probable need for reestablishing the calibration factor for the pyranometer in its RSR. This recalibration, along with checks on the adequacy of the existing instrument calibrations for the remaining instruments, was accomplished using RIS data acquired during 11 days of clear skies throughout the project. This recalibration obviously reduces the differences between the SUNYA and BMS instruments that could be attributed to calibration. ATI's RSR calibration factor was within 1.2% of the pyranometer calibration

Page 1

MAINTENANCE LOG
SERI/EPRI Solar Radiation Monitoring Comparisons

DATE: 1 / 19 /91 **DAY:** 019 **TIME:** 07 : 30 **MST** **Observer:** Jim T.

		ATI	SUNYA	PSP	NIP	SBS
Sensor		✓	✓	✓	✓	✓
Band or Tracker		✓	✓		✓	✓
Data Acquisition		6 SEC SLOW	✓ 2 SEC FAST	✓	✓	✓
Readings:	Temp =	5.97		22.8	160	14.8
	Glo =	25.2				
	Dir =	170				
	Dif =	18.6				
	Bat =	11.9				

Clouds: Total = 6/10 Opaque = 2/10 Loc. Cs Low E. Horizon
Visibility: N = UNL mi E = UNL mi S = UNL mi W = UNL mi
Temperature: Current = 40 F Max = 46 F Min = 34 F
Comments: ATI CLOCK RESET. DATA DOWNLOADED OK

Figure 3-1. Completed maintenance log form summarizing systems' status and atmospheric conditions at time of site visit

factor derived by NREL through this experiment and was not changed for this project. This 1.2% factor could have been applied to the ATI calibration, but it was within the calibration uncertainty. We used the calibration factors assigned to the BMS instruments from their most recent routine calibration cycle. As all participants were aware, if the calibration factors were not properly derived or not periodically checked, very significant errors could occur in the solar radiation values recorded for resource assessment.

3.4.1 Initial Calibration Factors

Both RSRs use a LI-COR model LI-200 pyranometer as the sensing element. ATI incorporated the original LI-COR calibration factor of 87.6 mA per Wm^{-2} into the data acquisition and control program of its RSR. A copy of the calibration certificate can be found in Appendix A, Volume 2. All irradiance data from ATI were collected based on this calibration value.

The SUNYA RSR design includes a temperature correction for the LI-COR pyranometer. This requires the installation of a temperature sensor on or near the silicon detector of the LI-200. Because the pyranometer was disassembled for the installation of the temperature sensor, SUNYA recalibrated its pyranometer after completing the modifications. SUNYA's calibration was accomplished using outdoor comparison data collected with an Eppley model PSP pyranometer. The data from this side-by-side comparison were used by SUNYA to provide the calibration value of 0.300 Wm^{-2} per count, as found in Appendix A of Volume 2. We used this value for the initial processing of the binary data files retrieved from the system (see Section 3.7 for details about the data processing). SUNYA requested that we compare the output of its RSR, especially the global irradiance, during clear sky conditions in order to confirm SUNYA's calibration value. The data from the SUNYA RSR were reprocessed using a revised calibration factor (0.334) based on these later comparisons.

The Eppley radiometers used in the BMS for measuring direct and global irradiance are also control instruments for our established **B**roadband **O**utdoor **R**adiometer **CAL**ibration (BORCAL) operations conducted at the SRRL for NREL. As a result, these two radiometers are recalibrated at least three times annually for each BORCAL episode. The pyranometer used in conjunction with an Eppley (nonrotating) shadowband for measuring diffuse irradiance is calibrated annually during one of the BORCALs. Each instrument displayed a valid NREL calibration label at the start of the comparisons, indicating the latest calibration factors. All BORCAL results are traceable to the World Radiometric Reference as described in Section 2.2.

3.4.2 Clear Sky Analyses

We collected 1-min calibration data from our RIS on 11 selected days under cloudless sky conditions (see option 6 in Section 3.1). Using the analysis methods prescribed for all NREL BORCALs, we computed the mean and standard deviations of the ratios of the global and direct normal irradiance as measured by the RSRs and the RIS reference irradiance (global) and absolute cavity (direct) data. We restricted our computations to solar zenith angles between 45° and 55°. Sample graphs of the data for 1 day of measurements are presented in Figures 3-2a through 3-2c. Our final results, summarized in Table 3-1 and fully presented in Appendix D of Volume 2, confirmed that the calibrations of the ATI and BMS instruments were within measurement uncertainties (as discussed in Section 3.5), with the possible exception of the diffuse measurement uncertainty for the PSP/shadowband stand. The SUNYA calibration factor needed to be increased by 11.4%, from 0.300 to 0.334 counts/W/m^2, to be consistent with the other radiometers. With the manufacturer's approval, all data from the SUNYA RSR were reprocessed using this revised calibration factor.

Table 3-1. NREL Calibration Summary

Statistic	ATI[1] Global	ATI[1] Direct	SUNYA[2] Global	SUNYA[2] Direct	BMS[3] Global	BMS[3] Direct
Mean[4]	1.012	0.992	0.334[5]	0.329	9.640	8.441
Standard Deviation	0.008	0.010	0.003	0.003	0.067	0.028

Notes:
1. Ratio of ATI irradiance component to RIS reference value
2. Ratio of SUNYA RSR output (Counts) to RIS reference (Wm^{-2})
3. Ratio of BMS radiometer output (μV) to RIS reference (Wm^{-2})
4. From 45° to 55° solar zenith angle
5. This value used to process all data (global, direct, and diffuse) from SUNYA RSR

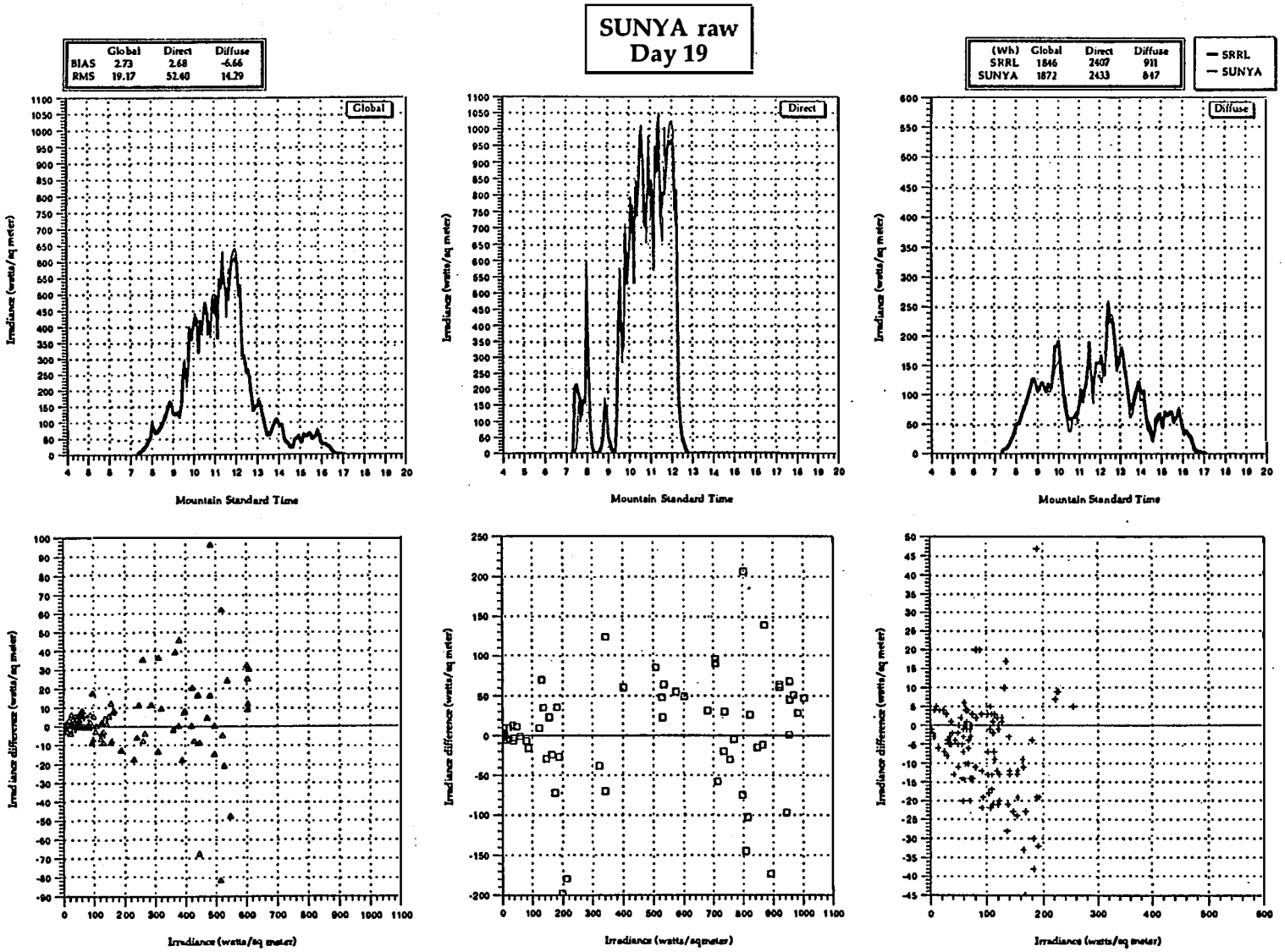


Figure 3-2a. Sample of daily graph showing 5-min data time series, daily total irradiances, bias and root mean square (RMS) differences, and irradiance differences as a function of the BMS data. Plots are for global, direct, and diffuse (left to right).

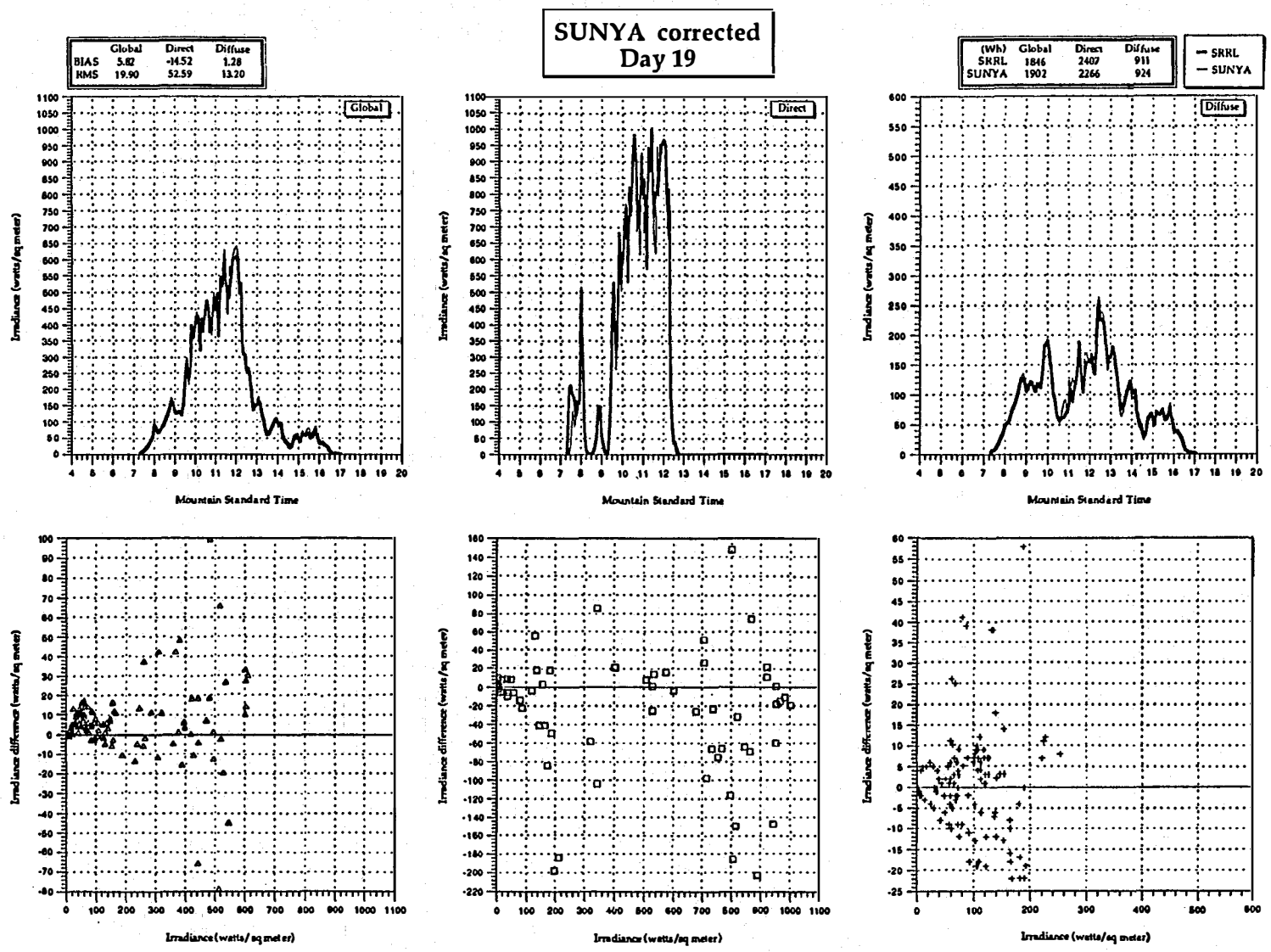


Figure 3-2b. Sample of daily graph showing 5-min data time series, daily total irradiances, bias and RMS differences, and irradiance differences as a function of the BMS data. Plots are for global, direct, and diffuse (left to right).

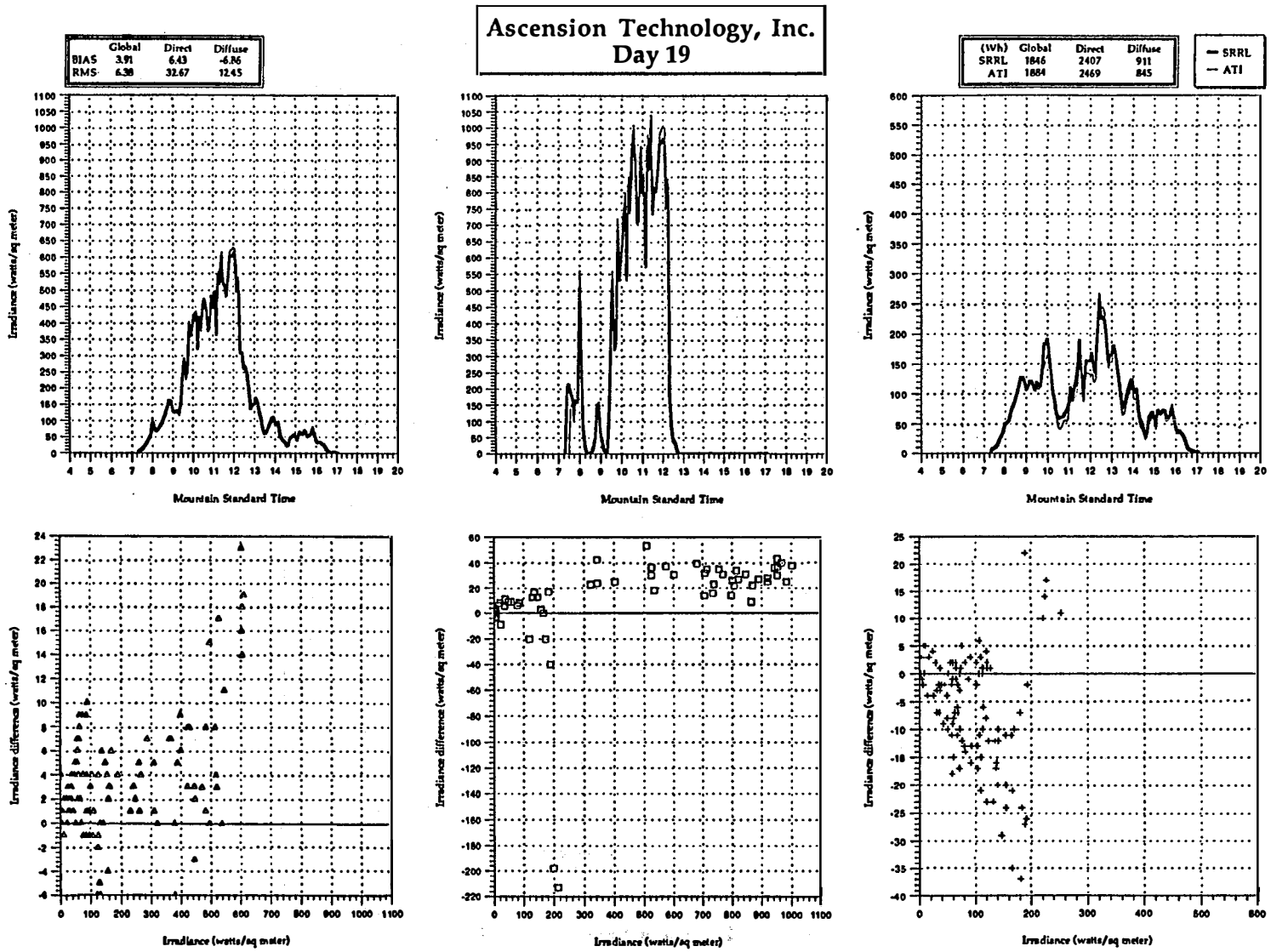


Figure 3-2c. Sample of daily graph showing 5-min data time series, daily total irradiances, bias and RMS differences, and irradiance differences as a function of the BMS data. Plots are for global, direct, and diffuse (left to right).

We also evaluated options 3 and 4 described in Section 3.1. Figures 3-3 and 3-4 were produced from data collected by the BMS and RIS during the 11 selected days with clear skies. We see good agreement between the measured (RIS) and computed (BMS) values of direct and diffuse irradiance using these options.

3.5 Measurement Uncertainty Analyses

"*Uncertainty* is an estimate of the largest error that may reasonably be expected for the measurement process...errors larger than the uncertainty should rarely occur" (ASME 1986).

Before designing an experiment, good quality assurance practices dictate a pre-experiment estimate of the measurement uncertainties. For our purpose, if these uncertainty estimates are larger than the desired limits for a valid comparison of the radiometers, then the experiment should not be attempted. We completed a pre-experiment measurement uncertainty analysis based on some of the anticipated larger sources of error and uncertainty. The summary of our analyses is presented in Table 3-2. Our measurement uncertainty estimates are based on a 95% confidence level by combining all contributing factors (manufacturer's nominal accuracy statements, instrument calibration uncertainties, etc.) using the root sum square method (Myers 1988). We considered nine contributing factors to the total measurement uncertainty of each system. The largest single contribution to the total uncertainty estimates (as found in the "Field Data Uncertainty" column of the table) is the instrument calibration uncertainty.

From the conservative estimates of the pre-experiment uncertainty analysis shown in Table 3-2, we find our measurements of direct normal irradiance with the *lowest measurement uncertainty* are available from the absolute cavity radiometer (±0.41%). Global horizontal irradiance is *best* determined from cavity and tracking disk measurements (±1.16%). Similarly, the *lowest measurement uncertainty* for diffuse horizontal irradiance is associated with data taken from a pyranometer under a tracking disk (±4.32%). Estimated measurement uncertainty for diffuse measurements made with the PSP/shadowband stand is ±4.80%; however, comparisons made with the PSP/tracking disk clear skies suggest higher measurement uncertainty that may be attributed to uncertainty in the shadowband correction factor. These measurements should be repeated. Estimated measurement uncertainty for direct normal measurements made with the Eppley NIP is ±2.07%. Our nominal estimated uncertainty of the RSR measurements ranges from ±6.32% for global irradiance to ±6.56% for diffuse irradiance. We estimate the uncertainty associated with the computed values of direct normal from the RSRs to be ±6.43 to ±6.47%. Observed differences *greater* than the amounts shown in Table 3-2 could indicate a *real* performance difference between instruments.

A rigorous comparison of the final results would be based on the final measurement uncertainty analyses, using data acquired from the experiment and a postexperiment uncertainty analysis.

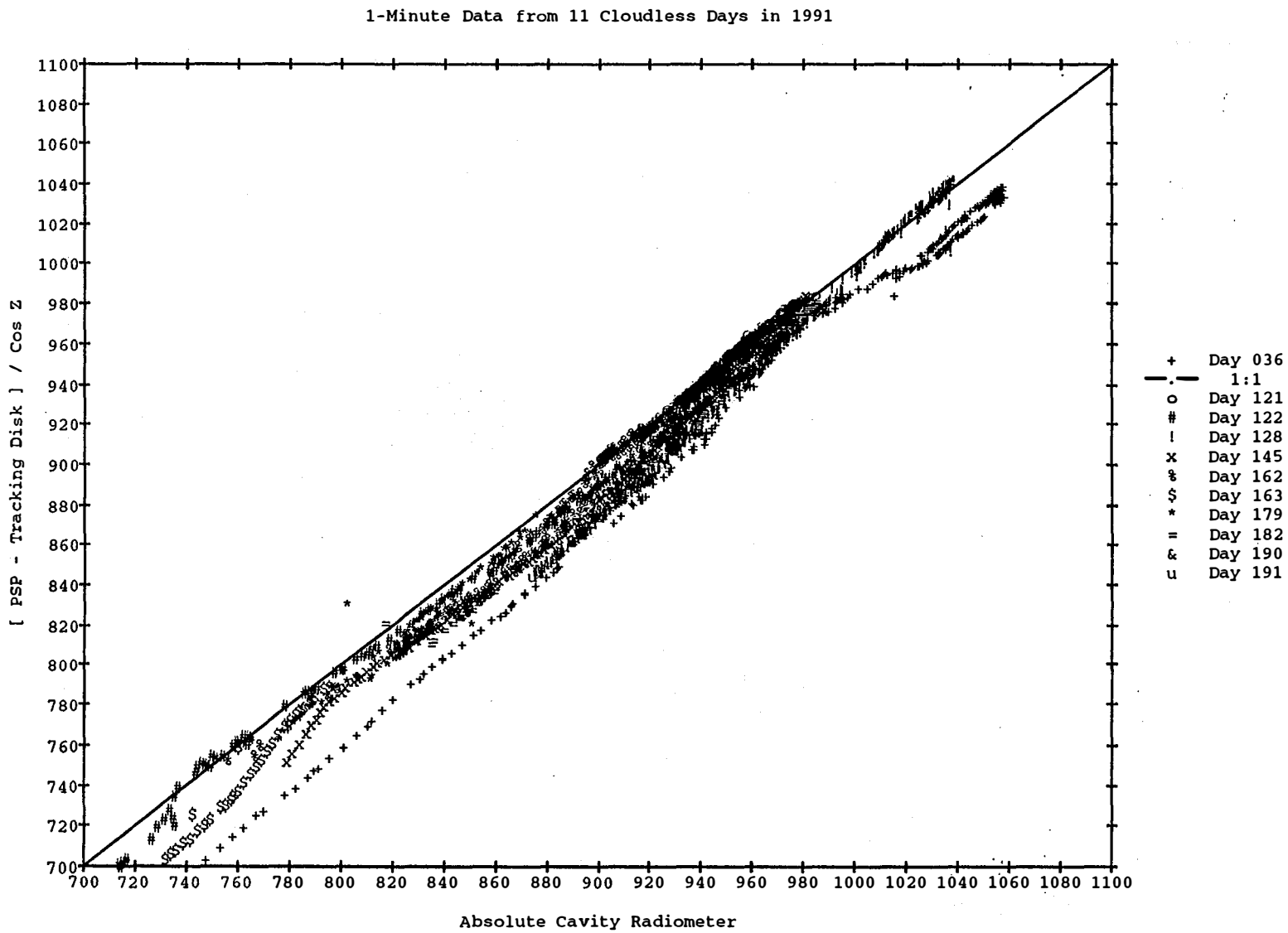


Figure 3-3. Comparison of computed direct normal irradiance from BMS global and RIS diffuse with RIS absolute cavity measurements (units: watts/sq meter)

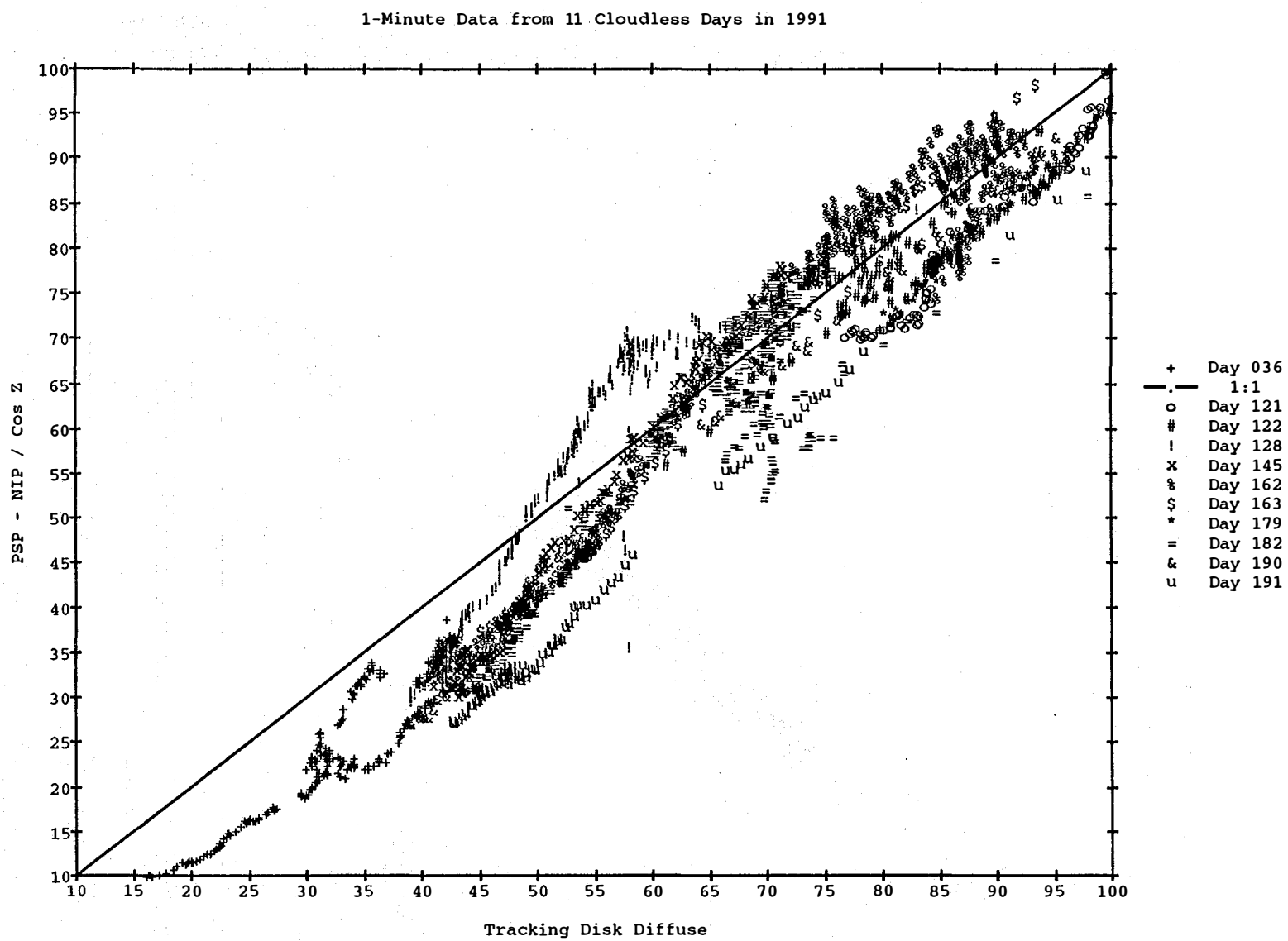


Figure 3-4. Comparison of computed diffuse horizontal irradiance from BMS global and direct with tracking disk measurements (units: watts/sq meter)

Table 3-2. Pre-experiment Measurement Uncertainty Estimates (Conservative Estimates Based on Available Information, Previous Experience, and NREL's Engineering Judgments)

Instrument + Measurement	Mfgr's Nom. Acc.[1]	Instru. Calibr. Uncert.[3]	Point. Contr.[4]	Timing Contr.[7]	Shadow-band Uncert.[8]	Spectral Contr.[9]	DAS Contr.[10]	Direct Temp. Contr.[11]	Field Data Uncert.[12]
Cavity Radiometer: Direct Normal	±0.5%	±0.4%	±0.02%[5]				±0.01%	±0.1%	±0.41%
SRRL PSP + Tracking Disk: Diffuse	±1%[2]	±3.6%	±1.3%[6]		±0.2%	±0.2%	±1.0%	±1.7%	±4.32%
SRRL BMS NIP: Direct Normal	±1%[2]	±1.8%	±0.02%[5]			±0.1%	±0.2%	±1.0%	±2.07%
SRRL BMS PSP + Shadowband: Diffuse	±1%[2]	±3.6%	±1.3%[6]		±2%	±0.2%	±1.2%	±1.7%	±4.80%
SRRL BMS PSP: Global Horizontal	±1%[2]	±3.4%	±1.3%[6]			±0.2%	±0.2%	±1.7%	±4.03%
Computed Values									
Reference Global Horizontal: Cavity x Cos (Z) + Diffuse (Track Disk)				±1%					±1.16%
SRRL BMS Global Horizontal: [BMS Direct x Cos (Z)] + BMS Diffuse				±1%					±2.35%
SRRL BMS Direct Normal: [(BMS Global Hor. - BMS Diffuse)/Cos (Z)]				±1%					±4.18%
SRRL BMS Diffuse: [BMS Global-(BMS Direct x Cos (Z))]				±1%					±4.64%

BMS = Baseline Measurement System RSS = Root Sum Square (95% coverage)

1. Manufacturer's nominal accuracy (or other as noted).
2. Based on World Meteorological Organization Class 1 specifications for the basic sensor only. Additional uncertainties to be added for shading devices, angular and temperature responses, etc. These uncertainties are included in Field Data Uncertainty.
3. Instrument calibration uncertainty, as calibrated at NREL.
4. Pointing (tracking) or leveling error contributions.
5. Based on frequent checks of tracker alignment.
6. Based on 0.75° sensitivity of bubble levels at 45° zenith angle (0.75° leveling error ranges from ±0.6% at 23° to ±7.4% at 80° zenith angle).
7. Timing error contribution based on 1-minute maximum error (35 seconds in equation-of-time, 25 seconds on data acquisition timing error).
8. Shadow band or shading disk correction error uncertainty, estimated.
9. Contributions to uncertainty due to spectral response characteristics of windows, domes, etc.
10. Contributions due to specific data acquisition systems used in each measurement system.
11. Contributions due to directionality (cosine and azimuth) and temperature during outdoor field experiment.
12. Final RSS uncertainty in field data, or computed values from field data. Clear sky with 10% diffuse component.

3.6 Data Collection

Our objectives for the data collection were to be able to:

1. Compare 5-min averages and hourly and daily totals of global, direct, and diffuse solar radiation values from the various instrument systems under weather conditions occurring from January into early July 1991 in Golden, Colorado.

2. Record operational reliability of the instrumentation under the weather conditions occurring in Golden during the test period.

3. Evaluate the feasibility of unattended operation of the measurement systems.

After incorporating the manufacturer's latest hardware modifications and completing our familiarization with the RSRs, we began routine data collection on 8 January 1991. Throughout the 6-month comparison, we immediately notified the manufacturers of any failures so that they could be corrected and the data collection continued. In addition, operational and maintenance inspections for all systems were recorded daily, along with cloud observations, during the 6-month data-collection period. The cloud observations for up to three times a day are presented in Appendix E of Volume 2.

EPRI provided NREL with a personal computer for data collection at SRRL. Both RSR systems permit telephone communications via modems to monitor system status and transfer data from internal memory to a personal computer. Both manufacturers were permitted to communicate with their RSR system for an initial 2-week period of operation to confirm adequate functioning. After confirming proper operations, we changed the telephone connections to prohibit system access by the manufacturers for the 6-month data collection period.

We recognized the need to maintain an accurate time base in each of the three system clocks. As part of our maintenance practice, we kept each clock to within 3 s of the National Institute of Standards and Technology's atomic clock.

More than 96% of the possible data records were collected from the systems used for this project. This high data recovery is partly due to daily inspections to note any operational problems and partly due to the reliability of the instruments. Figure 3-5 illustrates the data collection path developed for this project.

3.6.1 ATI RSR

The ATI RSR was programmed by the manufacturer to measure global, diffuse, and air temperature and estimate the solar zenith angle and direct irradiance component once each minute during daylight periods. The computed solar zenith angle is used by the RSR controller to determine periods of daylight. The system can store up to 4 days of these 1-min data before overwriting the data acquisition internal memory. Additionally, an hourly "diagnostic" data file, indicating band rotation status and other system performance data, was programmed by ATI to

EPRI/RSR Data Processing: Continuous Data Sets

	ATI		SUNYA	BMS/RIS
RAW DATA	PC Diskette 1-minute Multi-Day Sunrise/Sunset ASCII/CR10 [W/m^2] 3-Components & Air Temperature		PC Dickettes 1-minute Multi-Day 24-Hours Binary [Counts] 3-Components & Detector Temperature	Cassette Tapes 5-minute Multi-Week 24-Hours CR-21XAFSK [W/m^2] 17-Channels
PRE-PROCESS	Copy to PC/386		Copy to PC/386 CONV-87.EXE	Tape-to-ASCII/PC/386 Disk Move to VAX: Sudays.for (Daily Files)
		RAW (ASCII-Counts)	CORRECTED (ASCII-W/m^2)	
PREP	Prepat.for	Prepsyr (ASCII-W/m^2)	Prepsyc.for	Move to PC: Prepsu.for
	--------Daily Files; Missing Data Filled by 9's--------			(Selects 3-components & Temp.)
PROCESS	5-Atproc.for 1-Atproc.for	5syprocr 1syprocr	5syprocc.for 1syprocc.for	Suproc.for (Applies SBCF to Diffuse)
OUTPUT	----------Comb5.for (FORMATI = 5-minute)---------- ----------Comb1.for (FORMAT III = 1-minute)----------			

Data Archive Format I (5-minute) now ready for input to Daily Graphics Software on MAC IIci System

Figure 3-5. Data collection path schematic (showing RSRs, BMS, and RIS systems links to PC)

be stored in the RSR's memory. Software for a personal computer was provided by ATI to automatically download a day of data (1-min observations/estimates and hourly diagnostic files) at 00:02 a.m. each night to a disk file in ASCII format. The telecommunications capabilities included the ability to monitor the RSR system status and measured/estimated data in real time. We recorded this system status information during our routine maintenance visits (described in Section 4.2).

3.6.2 SUNYA RSR

The SUNYA RSR was programmed by the manufacturer to measure global, diffuse, and detector temperature and estimate the direct irradiance component four times each minute and store the averaged values on the minute. Twenty-four hours of 1-min data records are stored in binary format by the RSR. Using the telecommunications ability of the system, we downloaded the stored data from RSR memory to the personal computer during routine maintenance visits (described in Section 4.2). We were also able to check the system clock and memory usage, via our personal computer, with commercially available telecommunications software.

3.6.3 SRRL BMS

The SRRL BMS samples 17 data channels each 10 s and stores the averaged values on audiocassette tape at the end of 5-min intervals (except for the wind speed, wind direction, and air temperature, which are stored as instantaneous samples taken at the 5-min interval). A summary of the BMS data channels is presented in Table 2-2. We exchanged the cassette tapes once a week for processing. The data logger permits real-time inspection of the data and system clock. Using a standard log, we recorded selected information from the BMS during each maintenance visit (described in Section 4.2).

3.6.4 SRRL RIS

We have previously developed the SRRL RIS to meet our needs for outdoor radiometer calibrations. This measurement system consists of a working group of electrically self-calibrating absolute cavity radiometers, thermopile-based pyranometers, and support equipment to measure direct, diffuse, and global irradiance with the lowest possible uncertainties. Because the absolute cavity radiometer and tracking disk units require constant attention during operation, data from the RIS are available only during select periods of clear-sky conditions. Data are collected as 1-min samples and stored on personal computer diskettes. We collected RIS data for portions of 11 days during this project.

3.6.5 Days with Snow and Ice

To determine the relative effects of snow and ice on the performance of the RSRs and thermopile radiometers at SRRL, we selectively cleaned the instruments and photodocumented the conditions on 8 days during the project. Using the maintenance procedures described in Section 4.2, we cleared ice and snow from the instruments using a rotating schedule for each occurrence of snow and ice:

- Clean only the thermopile-based radiometers
- Clean only the RSRs
- Do not clean the optical surface of any instrument
- Clean all instruments.

We have described the data collected during one episode of snow in Section 4.3.7.

3.7 Data Processing

In this section, we describe the four different measurement system data sources, our software developed to merge these data into one of three archive formats, and our methods for producing the statistical data summaries in tabular and graphical formats as presented in the next section.

3.7.1 Input Data

The data for this project were simultaneously collected at SRRL from the ATI and SUNYA rotating shadowband systems, the BMS, and the RIS (on 11 selected clear days) as shown in Table 2-1. Examples of the 1-min data captured from the ATI and SUNYA RSRs are shown in Figures 3-6 and 3-7, respectively. The data from the SUNYA RSR are available in two forms: raw counts and converted irradiance. As the name implies, the raw data are ASCII representations of the counts stored in binary format within the RSR electronics. The converted irradiance is produced during postprocessing of the data files using the "CONV-87" software available from the manufacturer. Spectral and temperature corrections to the data are also applied to the irradiance values during the conversion process as a user option. We processed both raw and corrected data files. Examples of the 5-min BMS and 1-min RIS data are shown in Figures 3-8 and 3-9, respectively. These data from four independent measurement systems operating at two different sampling and averaging intervals required us to develop software for merging these data into three formats of time-sorted data suitable for importing the data for spread sheet style analyses.

3.7.2 Software Development

We designed three merged-data formats, as shown in Figures 3-10a through 3-10c, for use in producing statistical and graphical summaries and to serve as a final archive of all data collected during the project. Data Format I required us to compute 5-min averages of the original 1-min data available from both of the RSRs. We set the 5-min averaged data point to the "missing" element value of "9999.9" if more than one 1-min data sample was missing during the interval. Data Format II contains the 1-min data from the 11 clear sky periods when data were available from both the RSRs and the RIS. Data Format III contains the 1-min data for all days from the two RSR systems.

```
PGM
 | DOY
 |  |  MST
 |  |   |  TEMP
 |  |   |   |     GLO
 |  |   |   |            DIR
 |  |   |   |                 DIF
 |  |   |   |                       COS(Z)
 |  |   |   |     |       |    |       |
210,60,700,4.489,22.64,4.699,22.37,.06062
210,60,701,4.91,23.89,.58,23.86,.06387
210,60,702,4.796,25.17,2.723,24.99,.06711
210,60,703,4.202,26.16,3.901,25.89,.07036
210,60,704,3.698,27.17,1.426,27.07,.0736
210,60,705,3.628,28.38,1.776,28.24,.07684
210,60,706,3.43,29.34,3.076,29.1,.08007
210,60,707,3.544,30.57,3.09,30.32,.0833
210,60,708,4.442,31.53,.909,31.45,.08653
210,60,709,5.213,32.77,1.11,32.67,.08975
210,60,710,5.798,33.79,0,33.79,.09297
210,60,711,5.886,35.1,0,35.1,.0962
210,60,712,6.088,36.21,.578,36.15,.09941
210,60,713,6.098,37.47,4.075,37.05,.10262
210,60,714,6.019,38.57,3.261,38.23,.10582
210,60,715,6.121,40.05,3.116,39.72,.10903
210,60,716,6.317,40.95,0,40.95,.11222
210,60,717,6.435,42.45,0,42.45,.11542
210,60,718,6.492,43.72,0,43.72,.11861
210,60,719,6.5,45.26,0,45.26,.1218
210,60,720,6.701,46.48,0,46.48,.12498
210,60,721,6.794,47.69,0,47.69,.12816
210,60,722,6.561,48.95,1.11,48.8,.13133
210,60,723,6.055,49.9,0,49.9,.13451
210,60,724,5.455,51.07,1.701,50.84,.13767
210,60,725,5.159,52.21,3.404,51.74,.14083
210,60,726,5.235,53.07,1.084,52.92,.14399
210,60,727,5.563,54.28,1.273,54.09,.14715
210,60,728,5.843,54.97,.104,54.95,.15029
210,60,729,5.681,56.08,0,56.08,.15343
210,60,730,5.434,57.08,0,57.08,.15657
```

Figure 3-6. Example of 1-min data available from the ATI Rotating Shadowband Pyranometer System

DATE	MST	MST	DIR (Counts)	DIF (Counts)	GLO (Counts)	TEMP (K x 10)
03/01/91	7.0164	07:00:59	0	69	69	2771.0
03/01/91	7.0331	07:01:59	0	73	73	2773.0
03/01/91	7.0497	07:02:59	0	77	76	2772.0
03/01/91	7.0664	07:03:59	0	80	79	2769.0
03/01/91	7.0831	07:04:59	0	83	82	2768.0
03/01/91	7.0997	07:05:59	0	86	85	2766.0
03/01/91	7.1164	07:06:59	0	89	89	2765.0
03/01/91	7.1331	07:07:59	0	93	92	2768.0
03/01/91	7.1497	07:08:59	0	96	95	2773.0
03/01/91	7.1664	07:09:59	0	100	99	2779.0
03/01/91	7.1831	07:10:59	0	103	102	2783.0
03/01/91	7.1997	07:11:59	0	106	106	2785.0
03/01/91	7.2164	07:12:59	0	110	109	2786.0
03/01/91	7.2331	07:13:59	0	114	113	2786.0
03/01/91	7.2497	07:14:59	0	117	117	2787.0
03/01/91	7.2664	07:15:59	0	121	121	2789.0
03/01/91	7.2831	07:16:59	0	126	125	2790.0
03/01/91	7.2997	07:17:59	0	129	128	2790.0
03/01/91	7.3164	07:18:59	0	133	132	2791.0
03/01/91	7.3331	07:19:59	0	137	136	2791.0
03/01/91	7.3497	07:20:59	0	141	140	2792.0
03/01/91	7.3664	07:21:59	0	144	144	2792.0
03/01/91	7.3831	07:22:59	0	148	147	2791.0
03/01/91	7.3997	07:23:59	0	151	150	2787.0
03/01/91	7.4164	07:24:59	0	154	153	2785.0
03/01/91	7.4331	07:25:59	0	157	156	2784.0
03/01/91	7.4497	07:26:59	0	160	159	2783.0
03/01/91	7.4664	07:27:59	0	163	162	2784.0
03/01/91	7.4831	07:28:59	0	166	165	2785.0
03/01/91	7.4997	07:29:59	0	168	168	2784.0
03/01/91	7.5164	07:30:59	0	170	170	2784.0

NOTE: Original calibration certificate from SUNYA indicates 0.334 watts/sq meter per count.

Figure 3-7. Example of 1-min data available from the SUNYA Rotating Shadowband Radiometer System

[These data have been transferred from cassette tape to PC diskette (ASCII) and processed by SUDAYS.FOR on the VAX]

DATE	MST	GLO (W/m2)	DIF (W/m2)	DIR (W/m2)	40-S (W/m2)	2-AX (W/m2)	1-AX (W/m2)	G780 (W/m2)	D780 (W/m2)	UV (W/m2)	ALB (W/m2)	LCP (Vdc)	WS (m/s)	WD (Deg)	TEMP (C)	RH (%)	PRES (mB)	UV-DIR (Vdc)
60	7:00	19.8	18.3	-1.2	19.1	13.5	14.3	6.2	-0.5	1.4	0.0	0.0	3.1	271.5	3.7	34.9	785.3	0.04
60	7:05	25.9	24.0	-0.8	24.7	17.7	18.6	8.8	-0.8	1.8	0.0	0.0	2.5	303.6	3.5	35.6	785.3	0.04
60	7:10	31.4	28.9	0.0	29.8	21.7	22.1	10.7	0.2	2.2	0.0	0.0	3.8	315.3	4.1	34.8	785.4	0.04
60	7:15	39.8	35.9	-0.2	38.5	27.3	27.9	13.9	2.5	2.6	0.0	0.0	4.0	318.4	5.1	32.5	785.7	0.04
60	7:20	46.3	42.0	-0.3	44.9	33.7	33.7	16.9	1.6	3.0	0.0	0.0	3.1	306.2	5.6	31.2	785.6	0.04
60	7:25	51.7	47.1	-2.2	50.2	40.3	40.5	19.1	-0.5	3.5	0.0	0.0	3.4	290.8	5.4	31.7	785.7	0.04
60	7:30	56.2	51.2	-1.0	53.9	47.8	47.6	20.4	-1.1	4.0	0.0	0.0	3.5	289.9	5.2	31.8	785.7	0.04

NOTES:

40-S = Global on 40 deg south-facing tilt
2-AX = Global on 2-axis tracker
1-AX = Global on 1-axis tracker, horizontal N-S axis of rotation
G780 = Global on horizontal, RG780 filter
D780 = Direct-Normal, RG780 filter
UV = Eppley TUVR, horizontal ultraviolet
ALB = Reflected global (inverted pyranometer) (out of service 6/90 to 3/91)
LCP = Low-Cost Photometer, 500nm, narrow field of view (2 deg)
WS = Wind Speed at 10m AGL
WD = Wind Direction at 10m AGL
TEMP = Air Temperature (2m AGL)
RH = Relative Humidity
PRESS = Barometric Pressure
UV-DIR = Eppley TUVR in sun-following tracker, 5.7 deg FOV.

All data are 5-minute averages of 10-second scans.

Figure 3-8. Example of 5-min data available from the SRRL Baseline Monitoring System

```
BEGIN SCAN GROUP 0   05 FEB 91  09:15:00
EPRI-RSR

C   0 CAVITY 68018       94.13 MW/CM2
C   1 DIFFUSE 17802F3    0.260 MV
C   2 25825F3            3.379 MV
C   3 17836E6            7.983 MV
C   4 18041F3 SB         0.207 MV
C  40 CAL TABLE TEMP      14.0 DEG C

END SCAN GROUP 0     05 FEB 91  09:15:00


BEGIN SCAN GROUP 0   05 FEB 91  09:16:00
EPRI-RSR

C   0 CAVITY 68018       94.18 MW/CM2
C   1 DIFFUSE 17802F3    0.261 MV
C   2 25825F3            3.409 MV
C   3 17836E6            7.997 MV
C   4 18041F3 SB         0.209 MV
C  40 CAL TABLE TEMP      14.6 DEG C

END SCAN GROUP 0     05 FEB 91  09:16:00

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - -


Channel Assignments:

C       0       = TMI Absolute Cavity Radiometer s/n 68018
C       1       = Tracking Disk Diffuse   (Eppley PSP s/n 17802F3)
C       2       = SRRL Global Horizontal  (Eppley PSP s/n 25825F3)
C       3       = SRRL Direct Normal      (Eppley NIP s/n 17836F3)
C       4       = SRRL Diffuse/Shadowband (Eppley PSP s/n 18041F3)
C       40      = Calibration Table Temperature (T-type thermocouple)

The Fluke Model 2280B data logger is programmed to store 1-minute samples.
Data are transferred to PC diskettes for processing at SERI research data lab.
```

Figure 3-9. Example of 1-min data recorded by the SRRL Reference Irradiance System using a Fluke Model 2280B data logger and personal computer to capture the ASCII data

Data Format I: 5-minute Archive

DOY	MO	DAY	YR	MST	MST	SRRL GLOBAL	SRRL DIRECT	SRRL DIFFUSE	SRRL TEMP	ATI GLOBAL	ATI DIRECT	ATI DIFFUSE	ATI TEMP	ATI COS(Z)
311.4583	11	7	91	11:00:00	11.000	565.4	839.5	117.6	8.2	546.9	791.6	120.9	1.4	0.5385
311.4618	11	7	91	11:05:00	11.083	564.6	842.9	115.6	8.7	546.5	792.2	117.6	1.7	0.5416
311.4653	11	7	91	11:10:00	11.167	570.8	851.1	117.4	8.6	551.4	796.4	118.0	2.4	0.5443
311.4688	11	7	91	11:15:00	11.250	660.3	868.7	204.9	8.5	639.3	823.8	189.0	3.0	0.5467
311.4722	11	7	91	11:20:00	11.333	784.8	845.0	349.1	6.2	765.6	809.4	321.8	2.8	0.5487
311.4757	11	7	91	11:25:00	11.417	661.8	567.1	346.6	7.1	650.4	544.6	351.0	3.0	0.5504
311.4792	11	7	91	11:30:00	11.500	531.2	362.6	311.2	6.6	526.3	356.1	329.9	2.9	0.5518
311.4826	11	7	91	11:35:00	11.583	738.1	796.1	307.5	6.9	720.8	762.6	299.2	3.3	0.5527
311.4861	11	7	91	11:40:00	11.667	574.3	457.6	300.0	6.5	553.2	428.0	316.4	2.9	0.5534
311.4896	11	7	91	11:45:00	11.750	347.2	196.1	208.0	5.8	339.2	177.1	237.0	2.9	0.5537
311.4930	11	7	91	11:50:00	11.833	470.1	398.0	226.3	4.8	461.6	384.3	248.9	2.6	0.5536
311.4965	11	7	91	11:55:00	11.917	675.3	806.3	243.1	6.3	659.0	769.4	233.4	3.0	0.5532
311.5000	11	7	91	12:00:00	12.000	590.9	836.8	134.6	6.8	576.8	801.0	134.3	3.0	0.5524
311.5035	11	7	91	12:05:00	12.083	575.9	840.8	121.4	5.4	562.9	801.2	121.0	3.6	0.5513
311.5070	11	7	91	12:10:00	12.167	573.9	846.6	118.0	5.1	564.2	812.0	117.6	3.5	0.5498
311.5104	11	7	91	12:15:00	12.250	563.4	851.9	106.4	5.4	557.5	821.6	107.0	3.6	0.5480

R-SUNYA GLOBAL	R-SUNYA DIRECT	R-SUNYA DIFFUSE	R-SUNYA TEMP	C-SUNYA GLOBAL	C-SUNYA DIRECT	C-SUNYA DIFFUSE
497.1	706.2	112.0	8.2	559.0	732.0	153.0
497.2	706.3	109.9	8.9	559.0	732.0	150.0
501.1	709.1	110.1	9.5	563.2	734.8	150.4
580.6	732.4	175.0	10.1	645.6	762.2	216.6
693.7	720.5	293.5	10.1	759.0	748.2	334.4
593.5	488.8	321.0	9.0	651.8	505.2	365.0
479.2	304.0	309.3	7.3	532.0	312.4	355.2
655.7	683.9	272.9	7.3	726.2	713.0	321.8
485.0	335.9	296.8	7.6	539.4	345.2	341.2
307.1	163.0	215.6	5.9	346.2	171.4	248.2
438.3	367.0	232.4	5.4	490.2	384.4	272.2
597.2	688.6	211.4	7.4	664.2	717.6	257.6
523.6	711.0	125.8	7.1	589.6	737.8	172.0
509.0	708.0	113.5	7.7	572.8	734.2	155.2
509.1	717.5	109.4	7.6	572.6	745.2	150.8
499.3	719.9	99.7	7.6	560.8	753.0	143.0

Figure 3-10a. Data Format I for merged 5-min data from the ATI and SUNYA rotating shadowband radiometers and SRRL Baseline Monitoring System

Data Format II: 1-Minute Archive (With Absolute Cavity System)

DOY	MO	DAY	YR	MST	MST (Hour)	ABSOLUTE CAVITY	TRACKING DISK	GLOBAL REF	COS(Z)	SRRL GLOBAL	SRRL DIRECT	SRRL DIFFUSE	SRRL TEMP	ATI GLOBAL
121.4583	5	1	91	11:00:00	11.000	973.6	102.1	860.2	0.8836	956.2	971.9	109.5	15.5	938
121.4590	5	1	91	11:01:00	11.017	970.2	102.1	858.0	0.8844	954.4	967.6	109.2	14.1	938
121.4597	5	1	91	11:02:00	11.033	970.2	102.2	858.8	0.8852	955.1	968.9	109.2	15.3	937
121.4604	5	1	91	11:03:00	11.050	972.5	102.3	861.6	0.8859	959.1	970.9	109.5	15.4	939
121.4611	5	1	91	11:04:00	11.067	974.1	101.9	863.7	0.8867	961.0	973.0	109.5	15.8	941
121.4618	5	1	91	11:05:00	11.083	974.6	101.5	864.9	0.8874	961.0	973.2	109.2	15.7	942
121.4625	5	1	91	11:06:00	11.100	974.5	101.0	865.5	0.8882	961.4	974.4	108.3	16.3	943
121.4632	5	1	91	11:07:00	11.117	975.8	100.7	867.4	0.8889	964.1	975.1	108.3	16.7	944
121.4639	5	1	91	11:08:00	11.133	975.5	100.5	867.8	0.8896	964.4	975.5	108.5	16.6	945
121.4646	5	1	91	11:09:00	11.150	974.4	100.6	867.5	0.8903	964.1	972.3	108.8	16.1	944
121.4653	5	1	91	11:10:00	11.167	976.1	100.7	869.7	0.8910	966.4	973.2	109.3	16.0	946
121.4660	5	1	91	11:11:00	11.183	974.2	100.7	868.6	0.8916	966.0	971.5	109.5	15.6	946
121.4667	5	1	91	11:12:00	11.200	974.1	100.7	869.2	0.8923	966.5	971.9	109.5	16.4	946
121.4674	5	1	91	11:13:00	11.217	975.6	101.0	871.1	0.8929	969.7	973.0	109.5	15.7	947
121.4681	5	1	91	11:14:00	11.233	975.4	101.4	871.5	0.8935	970.6	971.7	110.2	15.1	949
121.4688	5	1	91	11:15:00	11.250	974.7	101.7	871.5	0.8941	970.4	970.6	110.5	15.1	949

ATI DIRECT	ATI DIFFUSE	ATI TEMP	ATI COS(Z)	R-SUNYA GLOBAL	R-SUNYA DIRECT	R-SUNYA DIFFUSE	R-SUNYA TEMP	C-SUNYA GLOBAL	C-SUNYA DIRECT	C-SUNYA DIFFUSE
970	84.2	7.7	0.8805	2827	2932	236	2887	965	940	139
969	84.2	7.7	0.8813	2825	2926	236	2889	964	938	139
967	84.5	7.5	0.8821	2825	2922	238	2885	964	936	140
968	85.1	7.9	0.8829	2832	2927	238	2886	967	938	140
970	84.2	8.2	0.8837	2837	2930	238	2887	968	939	140
972	82.9	8.2	0.8844	2839	2936	233	2887	969	941	137
972	83.0	8.2	0.8851	2839	2937	230	2888	969	941	135
972	83.3	8.2	0.8859	2846	2938	233	2891	971	941	137
972	83.1	8.3	0.8866	2848	2938	234	2892	972	941	138
972	82.4	8.2	0.8873	2847	2934	234	2890	972	940	138
973	82.0	7.9	0.8879	2849	2936	232	2886	973	941	137
973	82.4	7.8	0.8886	2851	2936	232	2882	974	941	137
972	82.3	7.8	0.8892	2853	2933	235	2881	974	940	138
972	82.1	8.0	0.8899	2856	2936	233	2883	975	941	137
973	82.6	8.0	0.8905	2859	2938	233	2881	976	942	137
973	82.7	7.9	0.8911	2859	2935	234	2877	977	941	138

Figure 3-10b. Data Format II for merged 1-min data from the ATI and SUNYA rotating shadowband radiometers and the SRRL Reference Irradiance System (used for 11 days)

Data Format III: 1-minute Archive (No Absolute Cavity Values)

DOY	MO	DAY	YR	MST	MST	ATI GLOBAL	ATI DIRECT	ATI DIFFUSE	ATI TEMP	ATI COS(Z)	R-SUNYA GLOBAL	R-SUNYA DIRECT	R-SUNYA DIFFUSE	R-SUNYA TEMP
311.4583	11	7	91	11:00:00	11.000	534.2	775	115.9	1.3	0.5398	1604	2286	354	2814
311.4590	11	7	91	11:01:00	11.017	546.6	788	121.1	1.3	0.5404	1660	2350	374	2815
311.4597	11	7	91	11:02:00	11.033	561.9	808	125.1	1.4	0.5410	1701	2388	393	2817
311.4604	11	7	91	11:03:00	11.050	554.2	802	119.8	1.6	0.5416	1675	2378	371	2821
311.4611	11	7	91	11:04:00	11.067	538.3	786	112.1	1.9	0.5422	1629	2329	351	2825
311.4618	11	7	91	11:05:00	11.083	531.7	777	110.1	2.2	0.5427	1621	2327	342	2826
311.4625	11	7	91	11:06:00	11.100	534.2	779	111.2	2.5	0.5433	1620	2306	351	2827
311.4632	11	7	91	11:07:00	11.117	538.9	780	114.8	2.4	0.5438	1640	2313	366	2828
311.4639	11	7	91	11:08:00	11.133	550.1	792	119.1	2.4	0.5443	1667	2354	369	2826
311.4646	11	7	91	11:09:00	11.150	566.5	818	121.0	2.4	0.5448	1704	2417	370	2827
311.4653	11	7	91	11:10:00	11.167	567.2	813	124.1	2.5	0.5453	1721	2429	379	2829
311.4660	11	7	91	11:11:00	11.183	586.5	833	132.0	2.7	0.5458	1781	2482	409	2833
311.4667	11	7	91	11:12:00	11.200	599.1	823	149.9	3.1	0.5463	1811	2441	460	2836
311.4673	11	7	91	11:13:00	11.217	622.3	803	183.7	3.1	0.5467	1893	2388	570	2834
311.4680	11	7	91	11:14:00	11.233	675.5	823	225.1	3.2	0.5472	2042	2412	705	2832
311.4688	11	7	91	11:15:00	11.250	713.0	837	254.5	3.0	0.5476	2150	2484	773	2831

C-SUNYA GLOBAL	C-SUNYA DIRECT	C-SUNYA DIFFUSE
541	711	145
560	731	153
574	743	161
565	739	152
549	724	144
547	723	140
546	717	144
553	719	150
562	732	151
575	751	152
580	755	155
600	771	167
605	764	176
633	747	218
677	753	249
713	776	273

Figure 3-10c. Data Format III for merged 1-min data from the ATI and SUNYA rotating shadowband radiometers

The 15 software modules developed for this project to generate the three final merged data formats are identified in Table 3-3. These modules were written in Lahey FORTRAN on a 386-based personal computer (PC). Table 3-3 shows the input and output file naming convention developed for this software. The file name indicates the source date and measurement system of the data in each file:

- AT = Ascension Technology, Inc.
- SY = State University of New York at Albany
- SU = SRRL Baseline Monitoring System with Ultraviolet radiation
- A = SRRL Reference Irradiance System with an Absolute cavity radiometer
- 91 = Year of data
- nnn = Day number of data (008 = January 8).

Complete software listings used for this project are found in Appendix F in Volume 2 of this report.

3.7.3 Data Analysis Products

Once we merged the data into the three archive formats described above, we looked for efficient methods of displaying and summarizing the data. Two separate paths were chosen for further analyses.

First, daily plots and statistical comparisons between each RSR and the data from SRRL/BMS were generated by a software package on a Macintosh IIci. These daily presentations are available for each of the three irradiance components, as shown in Figure 3-2. This is the only analysis product showing the raw data and the converted SUNYA data. All other analyses use only the converted SUNYA data. We reviewed these products to identify periods of unrepresentative data during the project resulting from equipment maintenance, unusual weather conditions, or other conditions producing atypical data that we judged unsuitable for statistical comparison. This is described further in Section 4.3.2. However, the data were not processed through a rigorous quality program that would flag unexpected data according to criteria specified in a resource assessment program (which would destroy the integrity of our 6-month test). Secondly, the 5-min (Format I) and 1-min (Format III) merged data files were processed using additional FORTRAN programs on a 386-based PC into 15-min and hourly data files. These new time-averaged intervals provided us with an opportunity to examine the systems for time scales comparable to utility load data and the historical climate records.

We then developed procedures within a software package for the PC to generate monthly graphs and statistical comparisons of each system by irradiance component. All of the graphical summaries for the project are available in Volume 2: Appendix G for hourly data, Appendix H for the 15-min averaged data, and Appendix I for 5-min averaged data. The statistics computed and displayed on the 60-min, 15-min, and 5-min comparisons of BMS and RSR data (Appendices G, H, I) contain points that might be screened out in a rigorous quality assessment program.

Table 3-3. Summary of Data Processing Software Modules

Software modules	Input files	Output files
Preprocessors		
prepsyc (SUNYA corrected)	keyboard \sunya\SYxxxxx.cor	\prep\SY\xxxxxc.dat
prepsyr (SUNYA raw)	keyboard \sunya\SYxxxxx.raw	\prep\SYxxxxx.dat
prepat (Ascension Tech.)	keyboard \ati\ATxxxxx.raw	\prep\ATxxxxx.dat
prepsu (SRRL/BMS)	keyboard \srrl\SUxxxxx.raw	\prep\SUxxxxx.dat
prepcav (Cavity)	keyboard \cavity\Axxxxx.cav	\prep\Axxxxx.dat
Processors		
5syprocc (5-minute SUNYA corrected)	\prep\SYxxxxxc.dat \sunya\SYFILES	\proc\SYxxxxxc.da1
5syprocr (5-minute SUNYA raw)	\prep\SYxxxxx.dat \sunya\SYFILES	\proc\SYxxxxx.da1
5-atproc (5-minute Ascension Technology)	\prep\ATxxxxx.dat \ati\ATFILES	\proc\ATxxxxx.da1
suproc (5-minute SRRL/BMS)	\prep\SUxxxxx.dat \srrl\SUFILES	\proc\SUxxxxx.da1
1syprocc (1-minute SUNYA corrected)	\prep\SYxxxxxc.dat \sunya\SYFILES	\proc\SYxxxxxc.da0
1syprocr (1-minute SUNYA raw)	\prep\SYxxxxx.dat \sunya\SYFILES	\proc\SYxxxxx.da0
1-atproc (1-minute Ascension Technology)	\prep\ATxxxxx.dat \au\ATFILES	\proc\ATxxxxx.da0
cavproc (1-minute cavity)	\prep\Axxxxx.dat \cavity\CAVFILES	\proc\Axxxxx.da0
Combine files		
comb5 (5-minute combined)	\proc*.da1 \comb\CFILES	\comb\5-xxxxx.all
comb1 (1-minute combined)	\proc*.da0 \comb\CFILES1	\comb\1-xxxxx.all \comb\1-xxxxx.noc

4.0 RESULTS AND DISCUSSION

In this section, we summarize our experiences with the installation, operation, maintenance, and data analyses performed for various time scales based on laboratory notes beginning in November 1990 and data collection beginning in January 1991.

4.1 Installation

Both RSR manufacturers performed indoor functional tests of their systems at an NREL electronics laboratory. The final installation and checkout of the two RSRs were accomplished at the SRRL, making use of an existing instrumentation/safety rail. We designed this structure at the laboratory to provide a stable and adaptable mounting surface with excellent solar access for research hardware such as the RSRs. Additionally, the needed telephone service for communicating with the RSRs was in place except for the actual connections to the control units. As a result, the time needed for installing the equipment may be less than that needed to prepare a new site for RSR installation.

EPRI provided an XT-class PC for data acquisition during the project. We did experience difficulty using this PC with an internal modem for establishing telecommunications with the RSRs. An external modem solved the problems associated with the high levels of interference within the PC chassis that appeared to disrupt communications when using the internal modem.

Detailed installation notes from the NREL Technical Record Book are available in Appendix B (Volume 2).

4.1.1 ATI RSR

The indoor functional testing and final installation of this system required about 2 days. This included a review of the system operation and maintenance by the manufacturer while on site for the final installation at the SRRL. This RSR must be mounted on a stable platform and adjusted for proper (horizontal) alignment. We were able to attach the vertical support post to the SRRL instrument/safety rail and roof decking. The north alignment was set to within 5° of true north by visual reference to other equipment at the SRRL already aligned for solar tracking. The installation of this system was simplified by the availability of a photovoltaic/battery charging system, which eliminated the need for commercial electrical power connections. The data acquisition and control system is based on a Campbell Scientific, Inc., model CR10 Micrologger™. The user manual for the CR10 and associated telecommunications software were provided by ATI. On 8 January 1991, after the initial installation but before starting data collection for the project, the manufacturer returned to the SRRL to replace the preproduction "head" subsystem with a final production version. Installation required less than 4 h. Data for this project were collected from this version of the RSR beginning on 9 January 1991.

4.1.2 SUNYA RSR

The indoor functional testing and final installation of this system required about 6 days. This included a review of the detailed user's manual and the postprocessing software used to convert the data from binary to "raw" and "spectral and temperature corrected" formats. Hardware installation required some minor fabrication, as described in Appendix B (Volume 2). The RSR must be carefully aligned with true north for proper band alignment, and mounted on a stable horizontal platform. We confirmed the leveling with a machinist level and observed the vertical shadows from the RSR supports at precisely local solar noon. The single printed circuit board was replaced with a better shielded unit designed to operate in areas of high radio frequency and electromagnetic interference such as those found at the SRRL. Data collection began 13 December 1991.

4.1.3 SRRL BMS and RIS

The two measurement systems at the SRRL were in place and operational at the start of the project. Based on recent experiences from a similar project to monitor the global, direct, and diffuse solar irradiance resources at a nearby utility site, we can estimate 1 to 2 weeks to deploy conventional thermopile-based radiometers, a shadowband stand, an automatic sun-following tracker, a microprocessor-based data acquisition system (Campbell Scientific, Inc., model CR10), a personal computer for data display and capture, and an uninterruptable power supply. About 30 days were required to develop a suitable work platform to accommodate all the equipment, plus about 30 days to develop the software for a graphical display interface between the data logger and the personal computer.

4.2 Operation and Maintenance

The instruments operated under a range of weather conditions at the SRRL from January through July 1991, which included temperatures of -18.9° to 36.1°C (-2° to 97°F); wind speeds in excess of 33.5 m/s (75 mph); snow, icing, hail, and rain; as well as clear, calm conditions. We performed daily maintenance of the RSRs and the BMS equipment using standard procedures. This helped in the recovery of more than 96% of the possible data from all systems. However, as described below, equipment problems could have affected the data collection if not immediately corrected.

4.2.1 Standard Procedures

Four maintenance activities are fundamental to all of the measurement systems used in this project:

- Clean sensor optics
- Maintain accurate data logger clock settings

- Observe present instrument values
- Perform regular data capture and transfer.

We developed an NREL standard laboratory practice (SLP) for the operation and daily maintenance of the two RSRs. The full SLP and the previously developed SLPs for the SRRL BMS and RIS are presented in Appendix J (Volume 2). Our detailed notes from the maintenance visits are in Appendix C (Volume 2) with the corresponding daily profiles of irradiance data.

On the average, a trained technician needed about 1.5 to 2 h per day to accomplish the routine maintenance of the two RSRs and BMS. This includes 30-min travel time to reach the SRRL on South Table Mountain and return to the NREL offices.

4.2.2 General Observations

The microprocessor-based system controllers used in the RSRs provide a high degree of operational flexibility and reliability. The user can poll the systems, via the telephone, using a personal computer to display status and capture data. Similar opportunities exist for data acquisition systems collecting measurements from instrument configurations similar to our BMS.

We found the LI-COR pyranometers used in the RSRs to be slightly less susceptible to water and dust contamination than the thermopile radiometers. The BMS instruments required cleaning in only six instances in which the RSRs were not visibly contaminated. This was always the result of dust spots on the PSP domes following a light rain or thunderstorm. The pyrheliometer window generally required less cleaning than the pyranometer domes. This could be the result of the constantly changing orientation of the pyrheliometer, which is mounted in an automatic sun-following tracker. The instrument's window is facing downward during the nighttime and is shielded from dew and other contaminant formations. We also observed that insects were attracted to the LI-COR pyranometer sensing area. We suggest that this may be caused by the warming of the black area around the white diffuser (a recessed area formed by the artificial horizon of the instrument), resulting in a comfortable nesting environment. The RSRs tended to shed snow and ice accumulations faster than the thermopile radiometers, as reviewed in Sections 3.6.5 and 4.3.7. A separate study, using duplicate hardware, should be made to evaluate the minimum maintenance frequency requirements. One set of hardware should be well-maintained and the other left uncleaned but its condition photodocumented over time and compared with the measured data from the other unit.

On three occasions, we experienced telecommunications failures because of poorly insulated underground telephone cabling. Each occurrence followed moderate to heavy precipitation that apparently created a short circuit in the NREL telephone lines used at the SRRL. No data were lost as a result of this problem because all systems can retain at least 4 days of data in their internal memory. Phone service was restored within this time limit.

We marginally achieved our goal of maintaining all system clocks to within 3 s of National Institute of Standards and Technology (NIST) Coordinated Universal Time. The BMS data logger clock progressed from about 2 or 3 s fast per day to 5 s fast per day at the end of the project. This meant we adjusted the time in our data logger at nearly every maintenance visit because there are no provisions for adjusting the clock frequency. The two RSRs were better behaved and could be kept within our timing goal with adjustments required at 15- to 30-day intervals.

4.2.3 ATI RSR

The system operates on a 12-V direct current battery charged by a 30-W PV panel and controller. During the project, three failures of the battery-charging circuit were experienced. At different times, these failures were traced to a blown fuse, an inoperative voltage controller, and an open circuit within the solar panel. At the direction of the manufacturer, we substituted a 12-V DC battery charger when needed to maintain adequate battery voltage during these failures. We found that the battery could provide adequate power to the data acquisition and control system for up to 45 days. The solar panel failed after aerodynamic flutter produced an open circuit within the grid. A replacement panel with a braced support to reduce the "oil canning" flexure of the array was installed in May 1991 and continued to operate normally.

Approximately 4 days of 1-min data can be stored internally in the data logger. When the memory becomes full, the oldest data are overwritten by the newest. Each night at 00:02 h, data for the previous day are automatically recovered from the logger, as ASCII files on a disk, by software running on a dedicated PC with a modem. These data files include the 1-min irradiance values and an hourly diagnostic data file containing information about the band rotation and logger status. Using specific instructions from the RSR SLP, these data files were transferred every Monday, Wednesday, and Friday from the PC internal disk drive to diskettes for off-site processing as described in Section 3.7. We found the user interface to this system easy to use.

The available diagnostic information for this RSR included messages to the operator to adjust the system clock based on the time kept by the PC used to poll the system each night. The manufacturer provided us with software to set the internal clock of the personal computer using dial-up access to the NIST in Boulder. We found it necessary to reset the clock in the RSR about one to two times per month, depending on the air temperature extremes. This is within specifications of the Campbell Scientific, Inc. model CR10 unit used in the RSR. Also provided with the system was the ability to monitor the output data and system clock in near real time. This information was recorded in the maintenance logs and used to confirm proper system functions.

4.2.4 SUNYA RSR

This system controls the position of the shadowband in order to determine the global, raw and corrected diffuse, and the direct normal irradiance. (See Section 3.2 for a description of the RSRs operation.) During our daily maintenance inspections from January to July 1991, we discovered four instances, about 1 month apart, in which the band was not completely shading the sensing element of the pyranometer. As noted in the maintenance logs in Appendix C (Volume 2), we found sunlight impinging on either the eastern or western edge of the sensing element. After discussions with the manufacturer, we reset the mechanical alignment of the band on the stepping motor shaft after each of the four occurrences. In August 1991, during a visit to NREL, the manufacturer checked the mounting position of the pyranometer in the RSR support structure using a machined tool designed expressly for this purpose. He found the instrument to be about 0.8 cm (0.3 in.) below the optimal position and relocated the pyranometer in its holder at the proper height. We have not found it necessary to make any further band alignment adjustments since that time.

The user interface for this RSR is based on an IBM-type PC. To maximize storage use, data are stored in the RSR and transmitted to the PC as binary files. We used a downloading procedure to capture previous days' data, which requires the operator to interrupt the RSR for the time of data transmission, usually less than 4 min at 1200 baud. The SLP specified that the data memory was to be cleared after each data download operation (MWF) to eliminate duplicate data and overlapping data files that could result from transmitting the entire first-in-last-out memory. In spite of the written procedures to avoid clearing the data memory *before* data transmittal, 9 days of data were lost because of operator error during the project. The manufacturer has stopped his software development on the PC-based system and continues to develop a more user-friendly interface based on the Macintosh-class PC.

4.2.5 SRRL BMS and RIS

Our BMS and RIS systems are by design more complex than an RSR. Three radiometers are used to independently measure the global horizontal, diffuse, and direct normal solar irradiance. A microprocessor-controlled automatic sun-following tracker continuously aligns the pyrheliometer. The adjustable (fixed) shadowband requires manual alignment changes from once a day to once every 3 days, depending on the rate of change in solar declination. With this added complexity comes a benefit of improved opportunities for data quality assessment. Data from each instrument can be compared with that from the other two for consistency with the relationship presented in Section 2 [direct normal = (global horizontal -diffuse horizontal)/Cos(Z)].

During this 6-month project, we experienced problems with the "fast" data logger clock, as described in Section 4.2.2, and three separate failures of our automatic sun-following tracker. The tracker failures resulted in the loss of partial days of direct normal irradiance because the unit was realigned only at the time of regularly scheduled maintenance. We attribute the failures to two causes: (1) improper loading of the tracker during the installation of additional pyrheliometers to be recalibrated and (2) a single power failure in June.

We experienced no problems with the RIS data collection, with the exception of system design limitations restricting the measurement of diffuse irradiance from the BMS shadowband to periods outside the scheduled BORCAL data collection intervals. The RIS data reduction software does not account for a pyranometer to be shaded from the direct solar component unless it is the reference tracking disk unit needed to compute the reference irradiance. No 1-min comparisons of the BMS shadowband performance under clear skies are available for days of BORCAL data collection.

4.3 Data Analyses

In this section, we compare RSR and BMS values of global, direct normal, and diffuse irradiance values for time scales of 5, 15, and 60 min. Our data analyses are based on 179 days of measurements taken by the two RSRs and BMS. We also compared RIS data with other measurement systems on 11 days, from 11 January through 8 July 1991. We include the measurement uncertainty limits associated with each system, which are useful for determining measurable performance differences. A brief description of our quality assurance methods is also presented. The analyses of data collected during 11 days, was for clear sky periods, and the complete 179-day record represented a variety of atmospheric conditions encountered in Golden, Colorado.

4.3.1 Measurement Uncertainty Estimates

As we discussed in Section 3.5, we completed a pre-experiment estimate of the total measurement uncertainties associated with each system used in this project. Any differences among measurement systems must be evaluated with respect to these measurement uncertainty estimates.

4.3.2 Data Quality Assurance

We addressed data quality assurance for this project in the following manner. Our daily field maintenance checks helped ensure adequate data quality control by correcting system problems as soon as possible. Our software development included a verification process using sample data comparisons with independent computations. We reviewed each of the daily 5-min graphs (see Figure 3-11) in conjunction with our maintenance records (as found in Appendix C of Volume 2) and technical record book entries (Appendix B of Volume 2) to identify days with periods of data unsuitable for comparison analyses. These days are listed in Table 4-1. These data include periods of special maintenance practices for evaluating the effects of snow and ice on the systems and system failures resulting in periods of missing or erroneous data, e.g., tracker failure, etc. We did not exclude data that might be screened out in a rigorous quality assessment procedure developed as part of a resource assessment program. Finally, as described in Section 3.4.2, we monitored the clear sky calibration factors for all instruments for 11 days during the project.

Table 4-1. Inventory of Days Excluded from Monthly Analyses

Day	Date	System	Comments
020	1-20-91	BMS	Snow covering PSP[a] domes (3 to 5 in. on ground)
026	1-26-91	ALL	Snow and ice on all sensors except NIP. Left ice on all instruments for testing.
029	1-29-91	ALL	Snow and ice on all sensors except NIP. Cleaned only BMS units.
067	3-6-91	BMS	Missing data on cassette tape.
068	3-7-91	SUNYA	Missing data because of operator error.
069	3-8-91	BMS	Missing data on cassette tape.
070	3-9-91	SUNYA	Missing data because of operator error.
071	3-10-91	BMS	Missing data on cassette tape.
072	3-11-91	SUNYA	Missing data. Band position error.
098	4-6-91	SUNYA	Data missing.
099	4-7-91	SUNYA	Data missing.
100	4-8-91	SUNYA	Data missing.
109	4-17-91	BMS	Missing data on cassette tape.
110	4-18-91	SUNYA	Missing data because of operator error.
111	4-19-91	BMS	Missing data on cassette tape.
120	4-28-91	ALL	Snow and ice. Modified maintenance.
135	5-15-91	ALL	Moderate to heavy rain.
136	5-16-91	BMS	Sun tracker failure, NIP[b] not aligned.
137	5-17-91	ATI	Data file not captured by technicians.
138	5-18-91	ATI	Data file not captured by technicians.
139	5-19-91	ATI	Data file not captured by technicians.
156	6-3-91	BMS	Sun tracker stopped because of power failure.
157	6-4-91	BMS	Sun tracker not aligned correctly.
171	6-18-91	SUNYA	Missing data because of operator error.
172	6-19-91	SUNYA	Missing data because of operator error.
173	6-20-91	SUNYA	Missing data because of operator error.
174	6-21-91	SUNYA	Missing data because of operator error.
183	6-30-91	SUNYA	No data after 11:00 h.
190	7-7-91	BMS	Missing data on cassette tape.

[a] Precision spectral pyranometer.
[b] Normal incidence pyrheliometer.

4.3.3 Daily Summaries of 5-Min Data

Figure 4-1 shows examples of comparisons of 5-min averages of global, direct, and diffuse solar radiation measured by the two RSRs and the BMS (option 5 from Section 3) for partly cloudy skies on day 22 and clear sky conditions on day 90. The BMS diffuse data were corrected for the presence of the shadowband as described in Section 2.2. All systems show similar structure in the daily profiles of 5-min averages. The irradiance differences (W/m^2) are plotted as a function of the BMS component irradiance for each day.

This 2-day example is representative of the full period. In reviewing the daily plots in Appendix C (Volume 2), we find good agreement between the "raw" SUNYA and ATI data for the diffuse horizontal irradiance component. The corrections made as part of SUNYA's internal postprocessing of the diffuse data for day 90 reduces the differences between the RSR and BMS values from -35% to +12% at 100 W/m^2. Appendix C (Volume 2) presents the full complement of daily plots comparing the RSRs with the BMS data.

4.3.4 Monthly Summaries of 5-Min Data Comparisons

We compared, by month, 5-min averages of direct normal, global horizontal, and diffuse irradiance data from the RSRs with the three SRRL BMS measurements. Sample graphs and statistics for March 1991 are shown in Figures 4-2a and 4-2b. Similar graphs for each month of the project are presented in Appendix I (Volume 2).

The statistics computed for each month in the test period confirm the relationships shown in the daily graphs (Figure 3-11 and Appendix C in Volume 2). The ATI direct normal values are generally higher and the SUNYA values are lower than the BMS measurements of direct irradiance. The average monthly differences are within our measurement uncertainty estimates as a percent of the BMS nominal irradiance values (i.e., ±2.07% at 750 W/m^2). The ATI and SUNYA global horizontal values are generally higher than the BMS measurements of global, but are also within the BMS measurement uncertainty limits (i.e., ±4.03% at 500 W/m^2). The diffuse comparisons show that the uncorrected ATI data are lower than the values obtained from a thermopile radiometer under a fixed shadowband, and the SUNYA corrections result in diffuse irradiance values that are larger. However, the monthly mean differences between the BMS and RSRs' diffuse irradiance are within the BMS measurement uncertainty of ±4.80% at a nominal irradiance of 300 W/m^2. More rigorous measurement uncertainty analysis, data screening, and statistical analyses could be performed to improve and expand upon these conclusions.

We made our comparisons with thermopile-based radiometers, which are also subject to measurement problems, as indicated by the two data points in Figures 4-2a and 4-2b. In these graphs, at about 100 W/m^2, there are two points above the diagonal on both the RSR comparisons. This indicates the dome on the global pyranometer was contaminated or shaded at the time of measurement, resulting in a low value from the BMS.

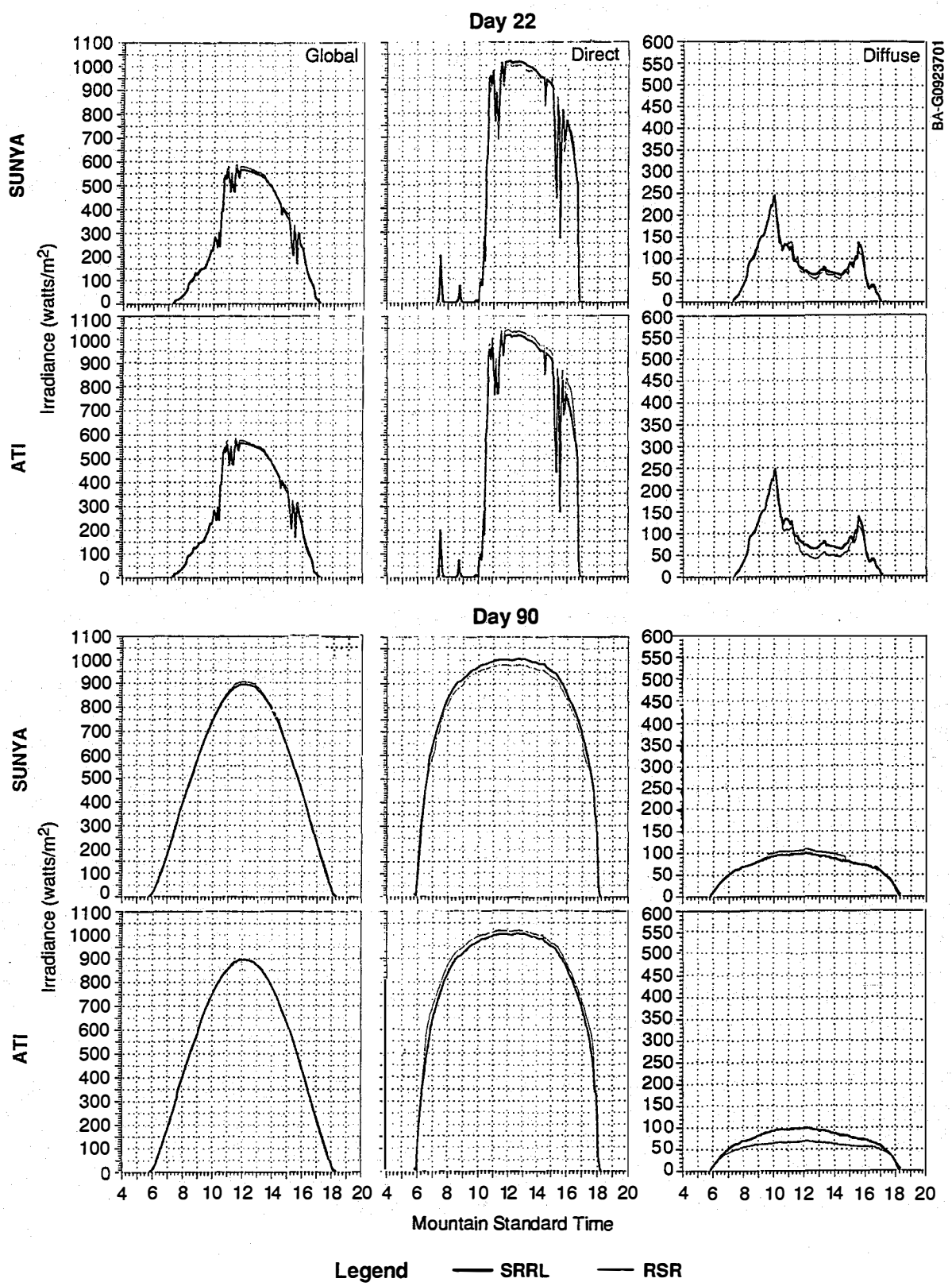


Figure 4-1. Data from days 22 and 90

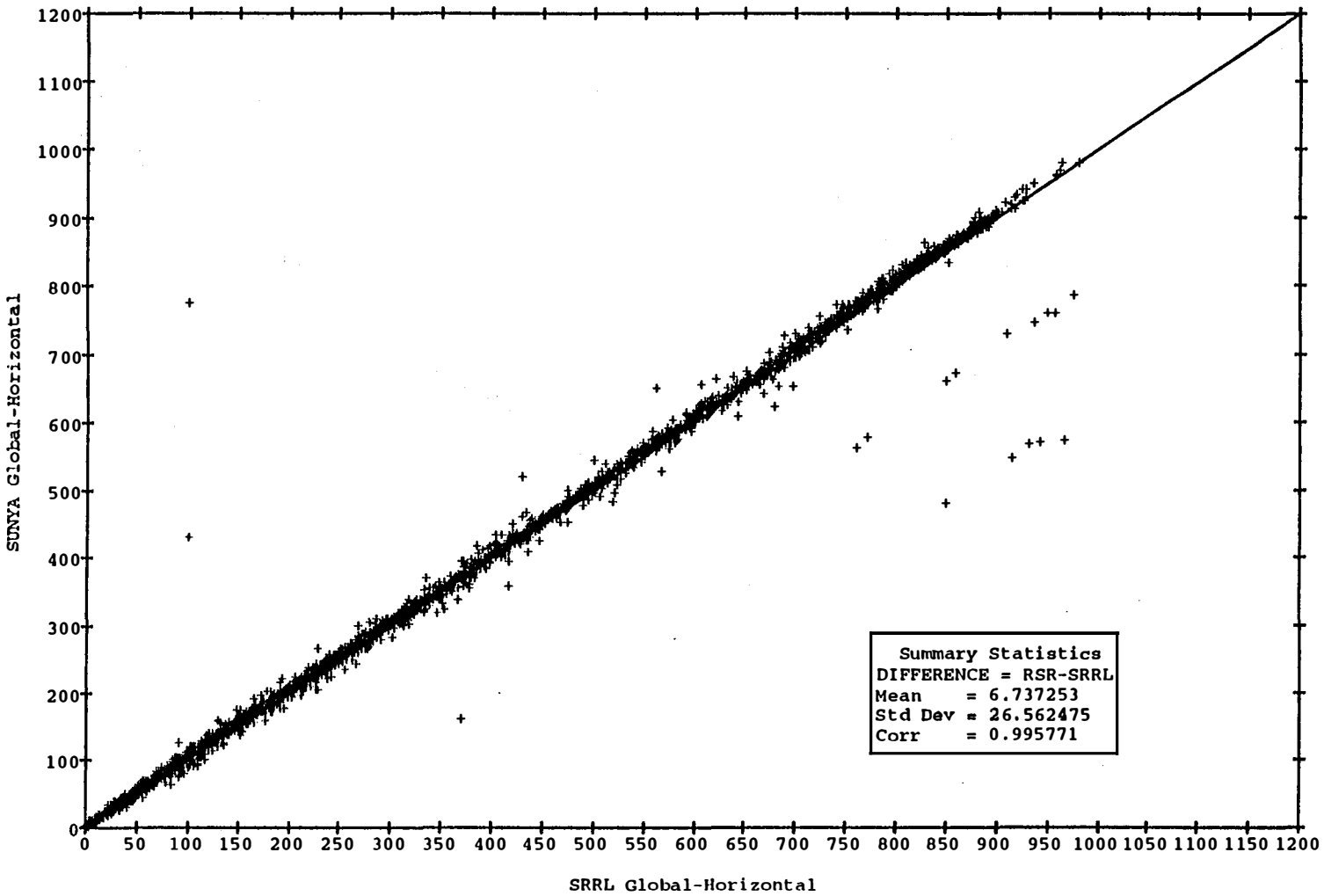


Figure 4-2a. Monthly comparison of 5-min data for March 1991 (units: watts/sq meter)

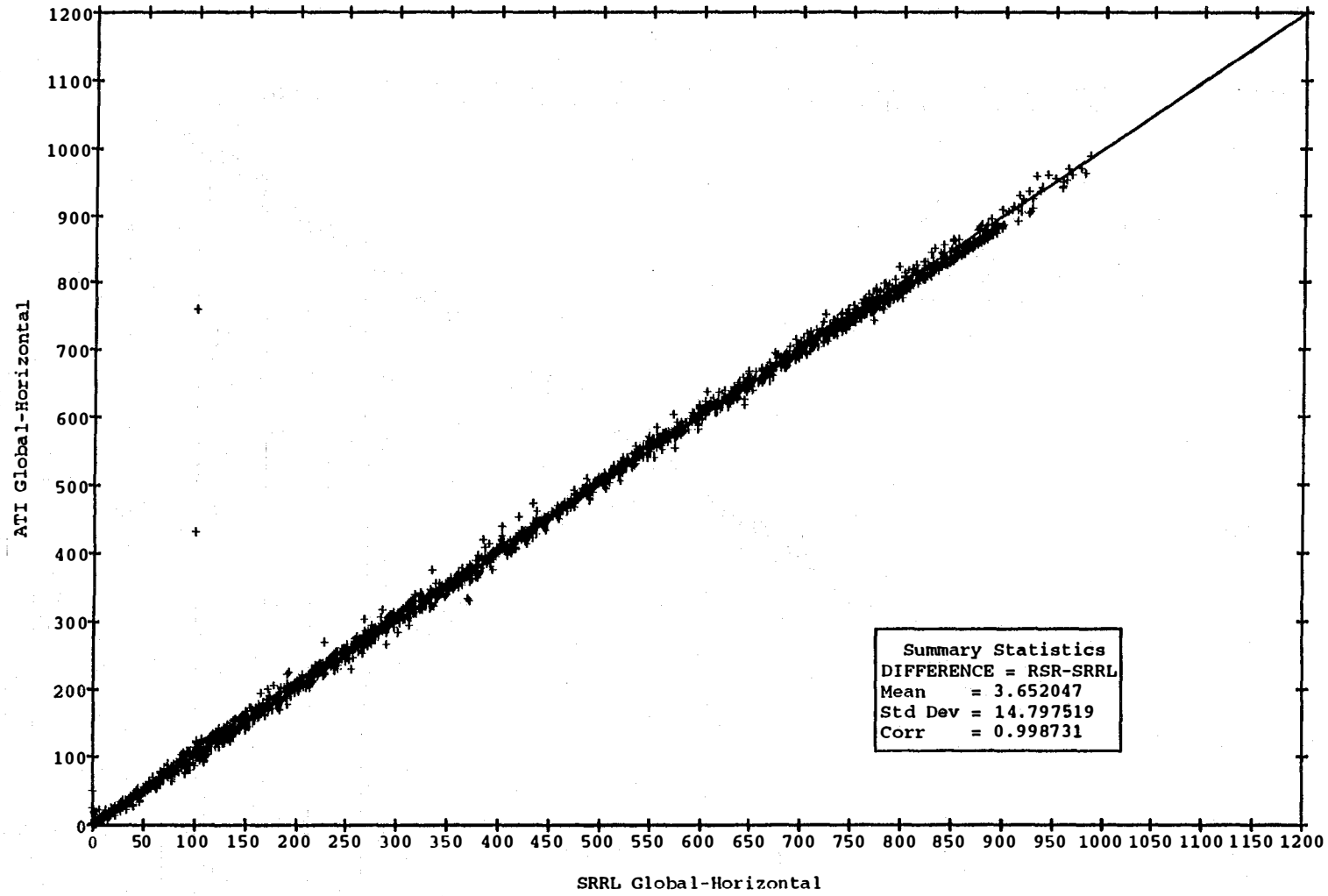


Figure 4-2b. Monthly comparison of 5-min data for March 1991 (units: watts/sq meter)

4.3.5 Monthly Summaries of 15-Min Data Comparisons

We compared, by month, 15-min averages of direct normal, global horizontal, and diffuse irradiance data from the RSRs with the SRRL BMS. Sample graphs and statistics for March 1991 are shown in Figures 4-3a and 4-3b. Similar graphs for each month of the project are presented in Appendix H of Volume 2. The increased averaging period generally results in slightly smaller average differences between the RSRs and the BMS, lower standard deviations of the differences, and higher coefficients of determination than for the 5-min averaged data.

4.3.6 Monthly Summaries of 60-Min Data Comparisons

We compared, by month, 60-min averages of direct normal, global horizontal, and diffuse irradiance data from the RSRs with the SRRL BMS. Sample graphs and statistics for March 1991 are shown in Figures 4-4a and 4-4b. Similar graphs for each month of the project are presented in Appendix G of Volume 2. The increased averaging period results in slightly smaller average differences between the RSRs and the BMS and smaller standard deviations than those from the 5- and 15-min averaged data. Similarly, the coefficients of determination are higher than for the 5- and 15-min averaged data.

4.3.7 Effects of Snow and Ice on Instrument Performance

Here we discuss one particular example of the snow episodes during the test period.

A moderate snowfall began on the evening of 29 April 1991 (day 119) and continued until about 09:30 h on 30 April 1991. The mean snow depth at the SRRL was measured at 7.75 in. We photographed the snow-covered instruments from 09:00 h to 11:30 h at about 30-min intervals (see examples shown in Figure 4-5). The RSRs and BMS instruments were *not cleaned* of snow and ice in order to observe the performance differences between the systems throughout the day.

A routine maintenance record for the day indicates the sensors for all instruments were clean at 14:31 h. Our cloud observations at the time indicated total cloud cover was 4-tenths and opaque cloud cover was 3-tenths of the sky dome, with cumulus formations to the west, north, and northeast. We also noted unlimited horizontal visibility in the four cardinal directions and an ambient air temperature above freezing (5.6°C or 42°F). The overnight low temperature reached -1.7°C (29°F).

The diurnal profiles of the RSRs and BMS irradiance data for day 120 are shown in Figures 4-6a and 4-6b. From the photographs on this day, the snow had completely melted from the pyranometers in both RSRs by 09:30 h. By about 10:00 h, the BMS pyrheliometer was free of snow and ice. The pyranometer under the fixed shadowband was clear by 11:30 h. By 11:45 h, the BMS pyranometer used for monitoring global irradiance was the last instrument to become free of snow.

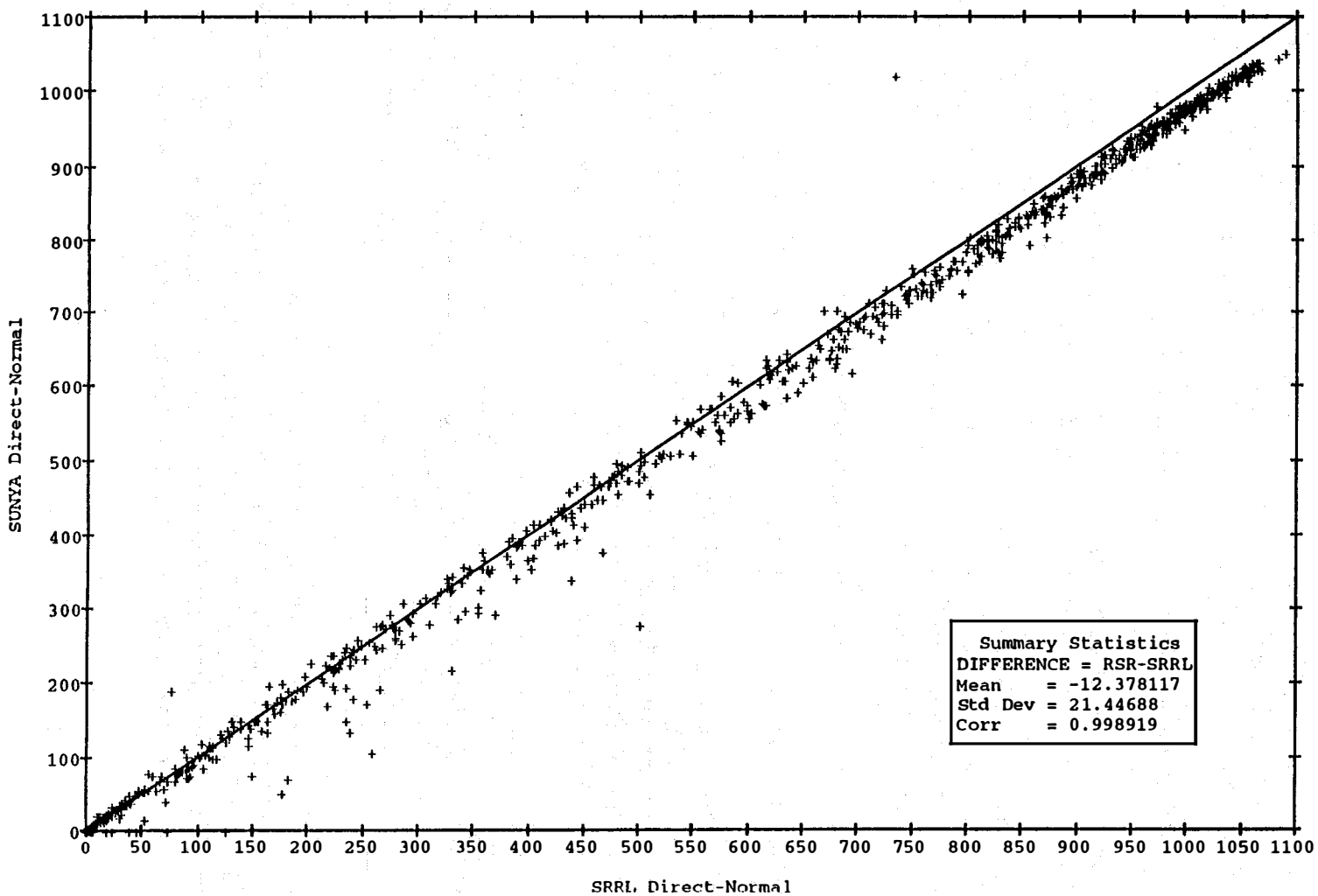


Figure 4-3a. Monthly comparison of 15-min data for March 1991 (units: watts/sq meter)

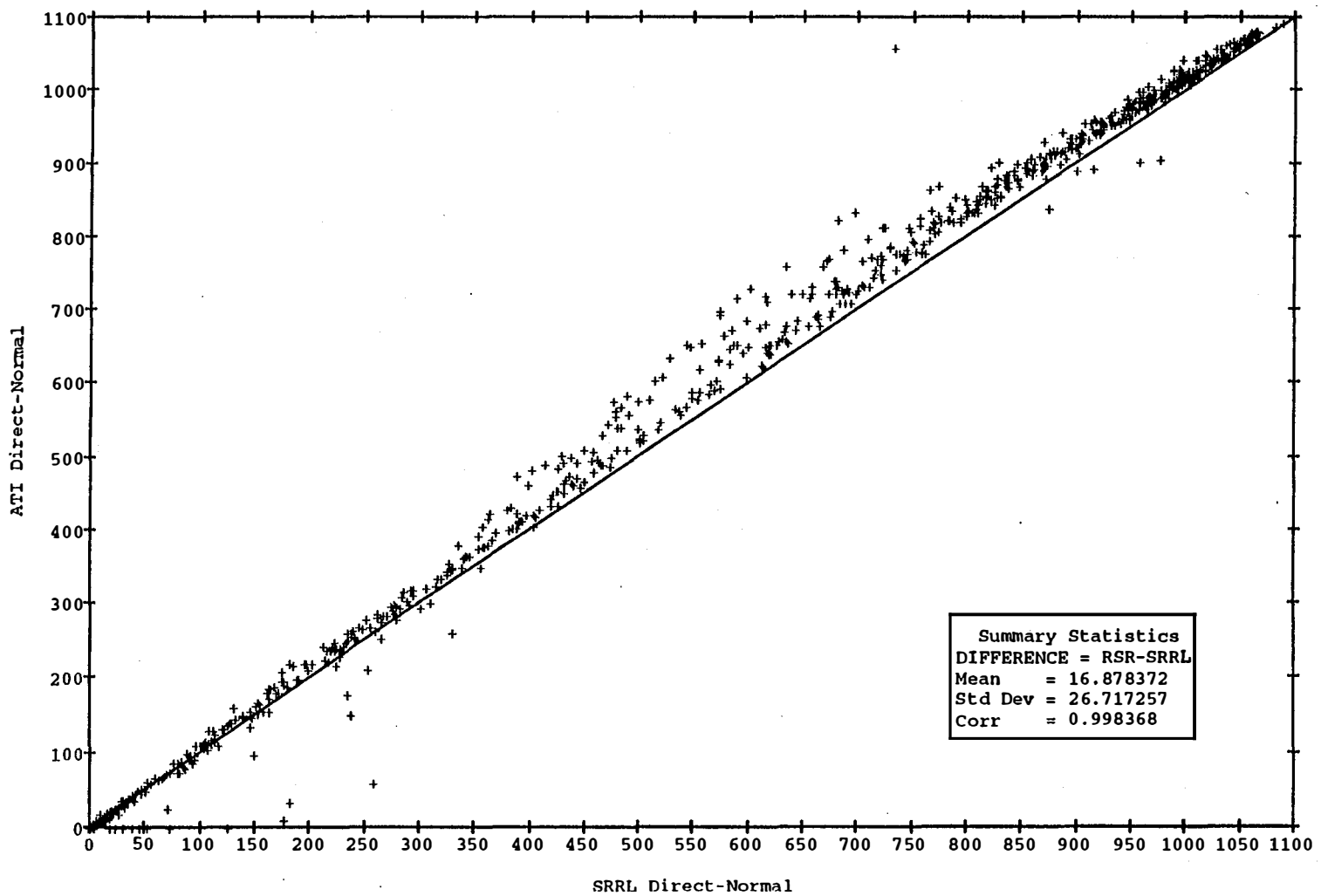


Figure 4-3b. Monthly comparison of 15-min data for March 1991 (units: watts/sq meter)

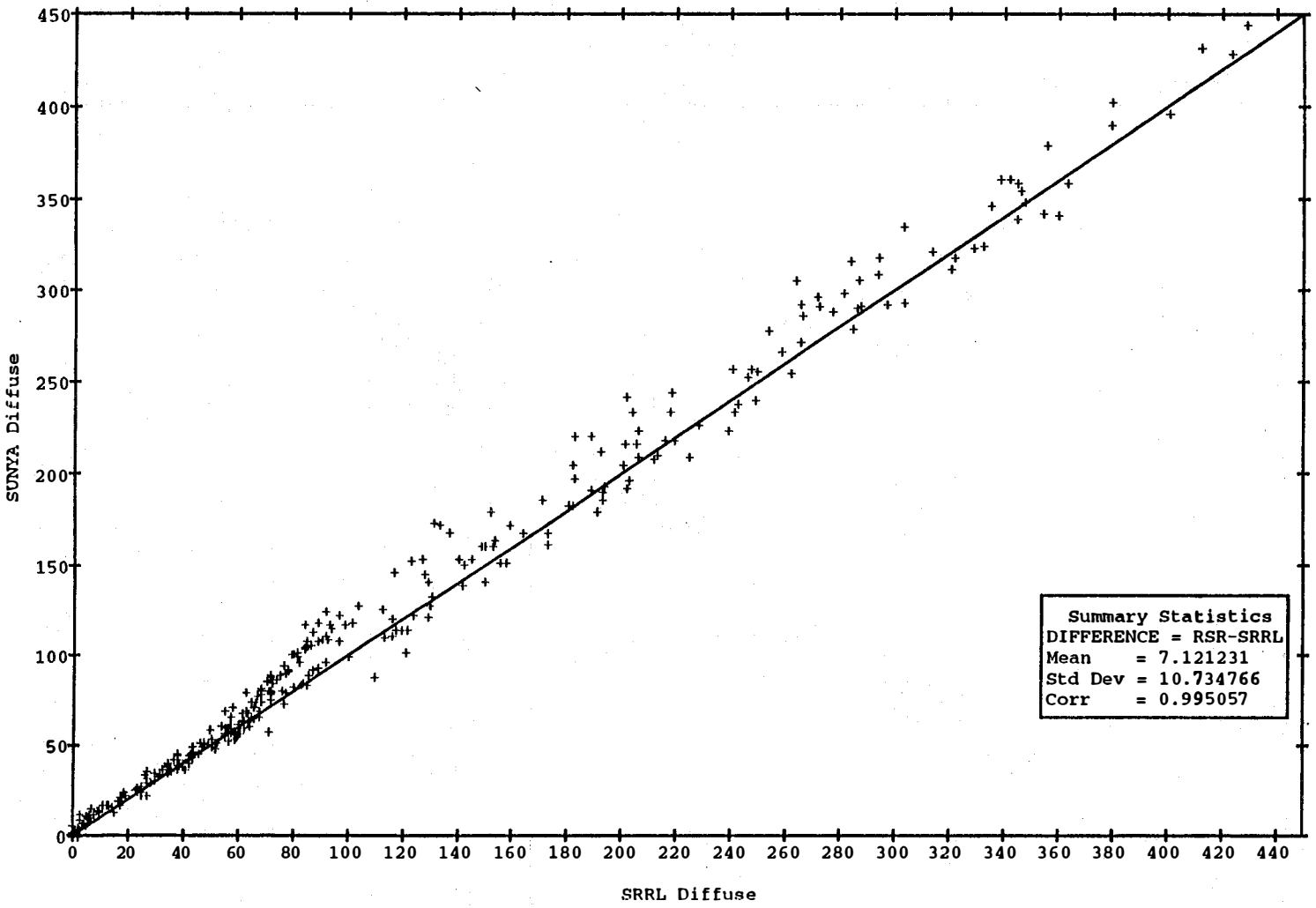


Figure 4-4a. Monthly comparison of hourly data for March 1991 (units: watts/sq meter)

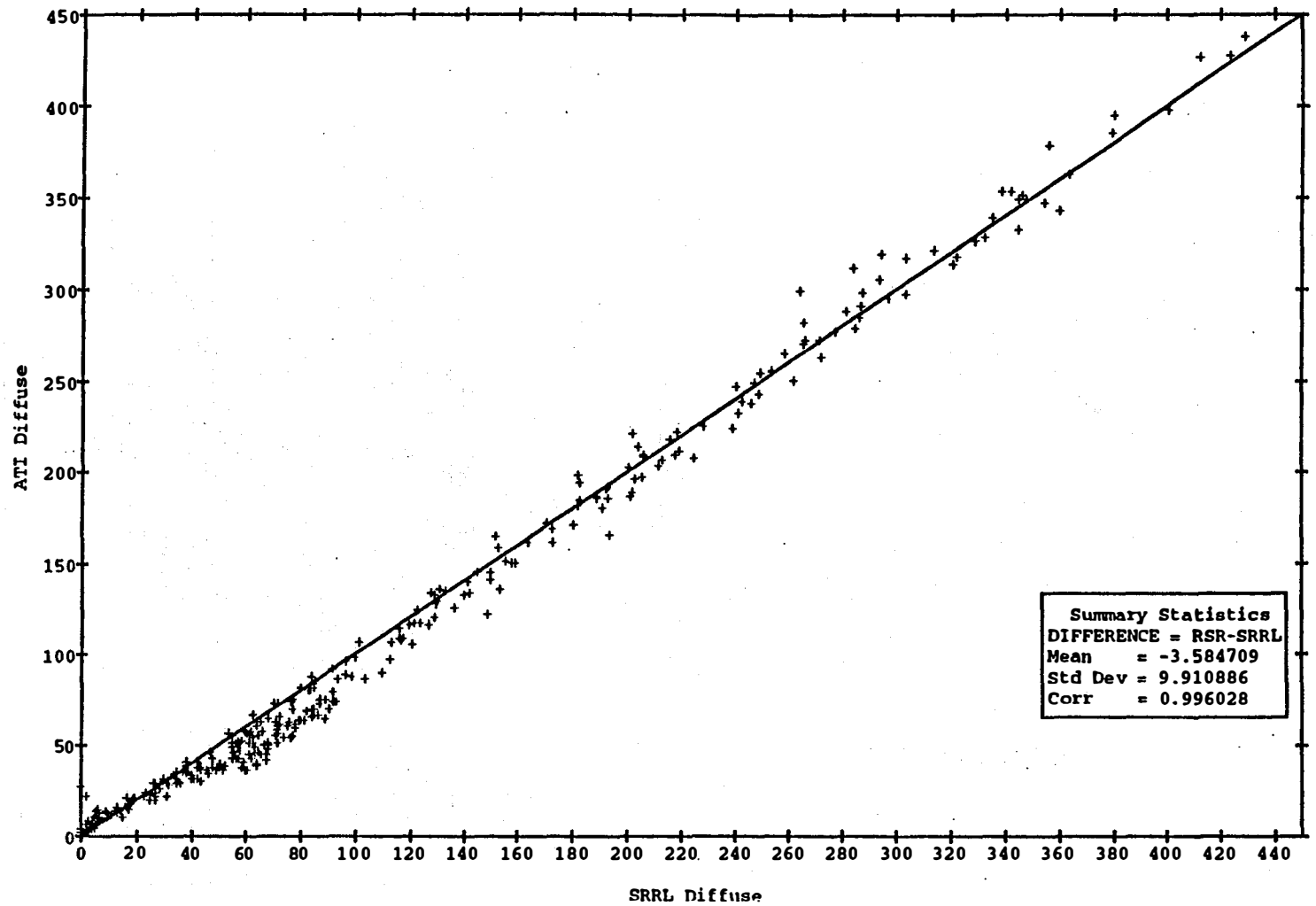
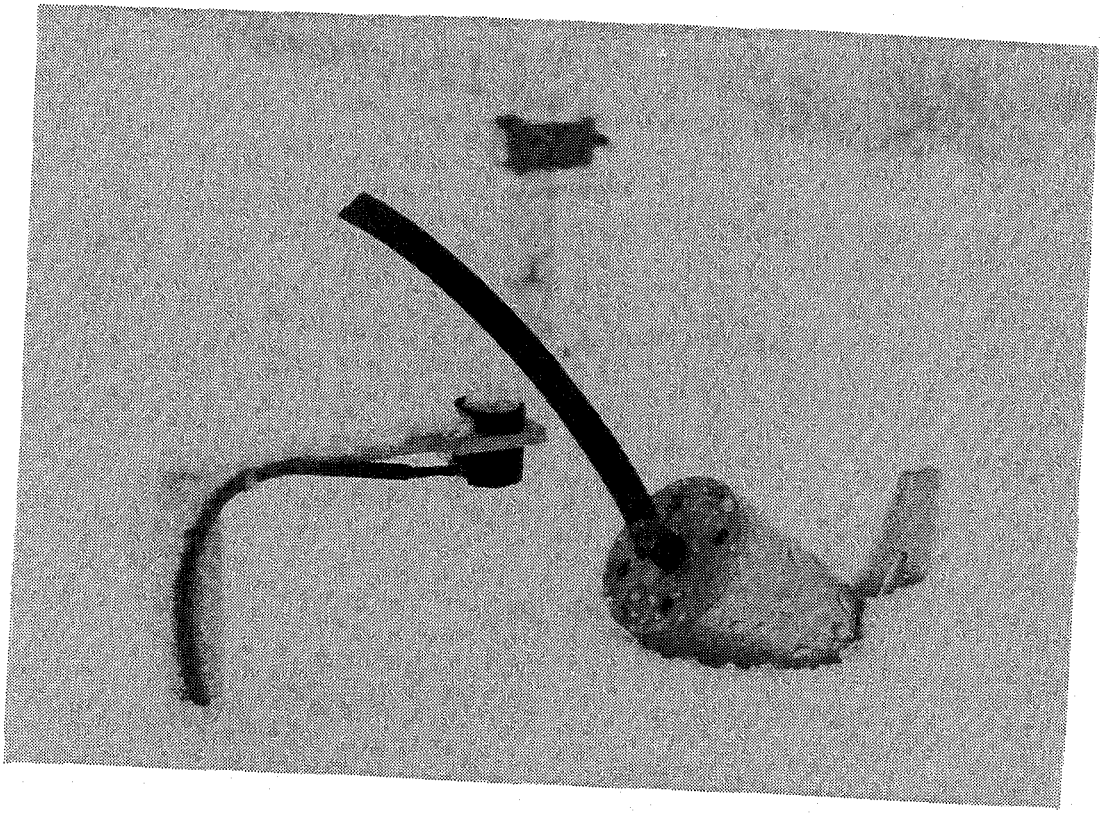


Figure 4-4b. Monthly comparison of hourly data for March 1991 (units: watts/sq meter)



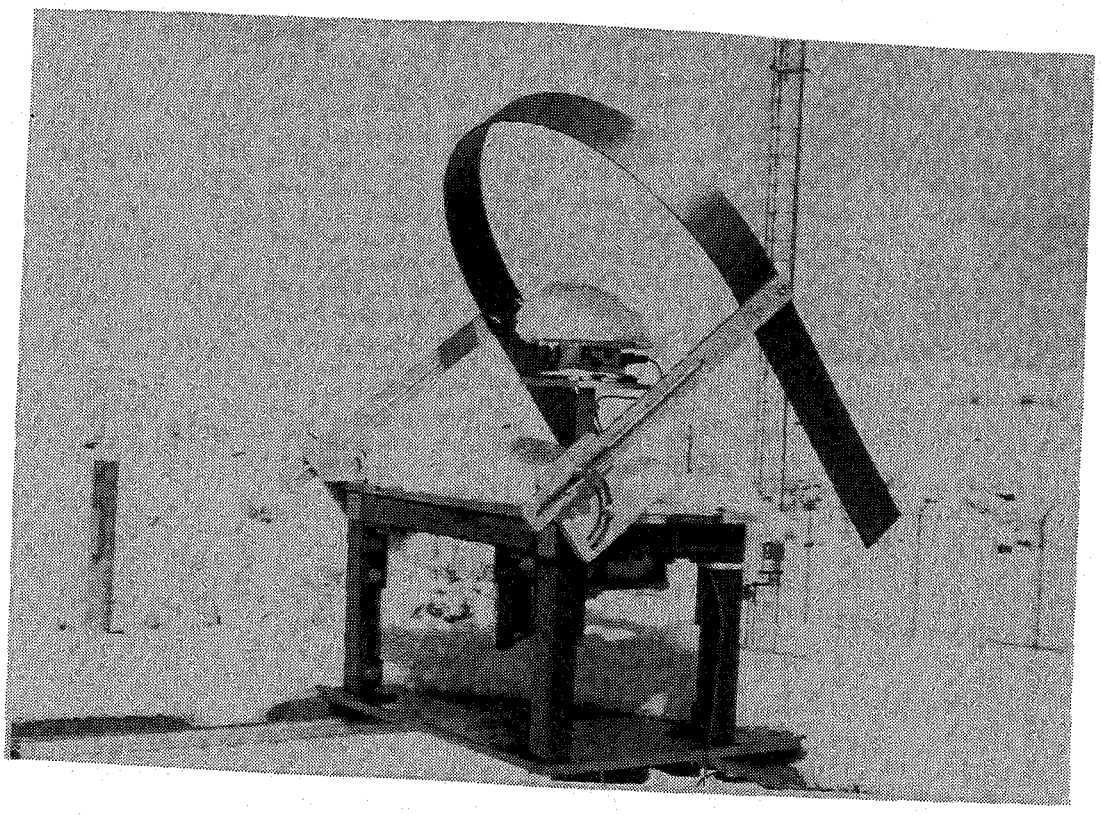


Figure 4-5a-b. Snow-covered instruments on 30 April 1991

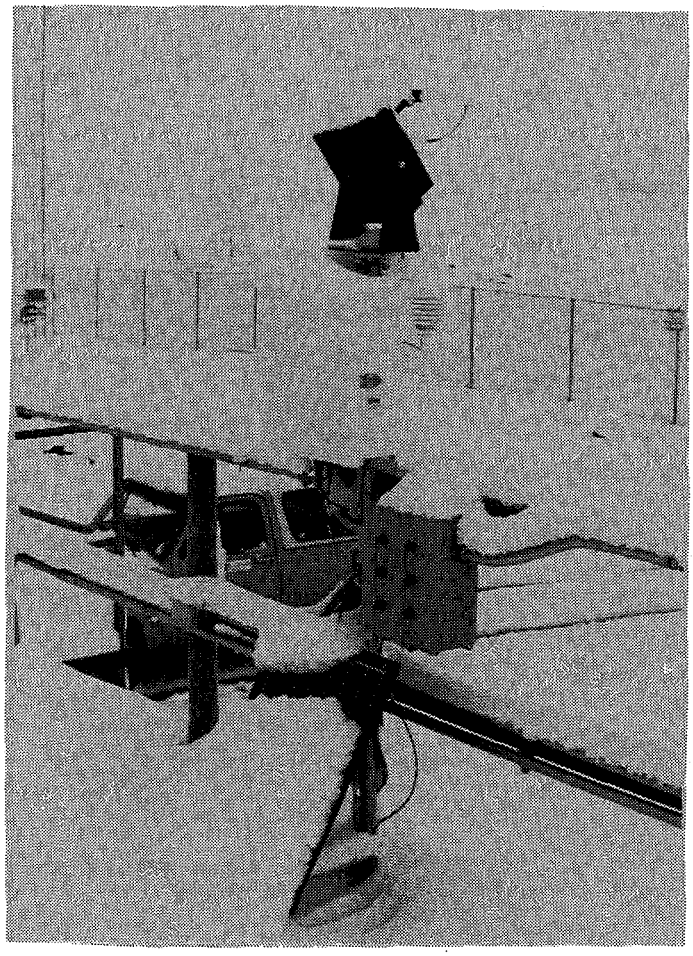


Figure 4-5c. Snow-covered instruments on 30 April 1991

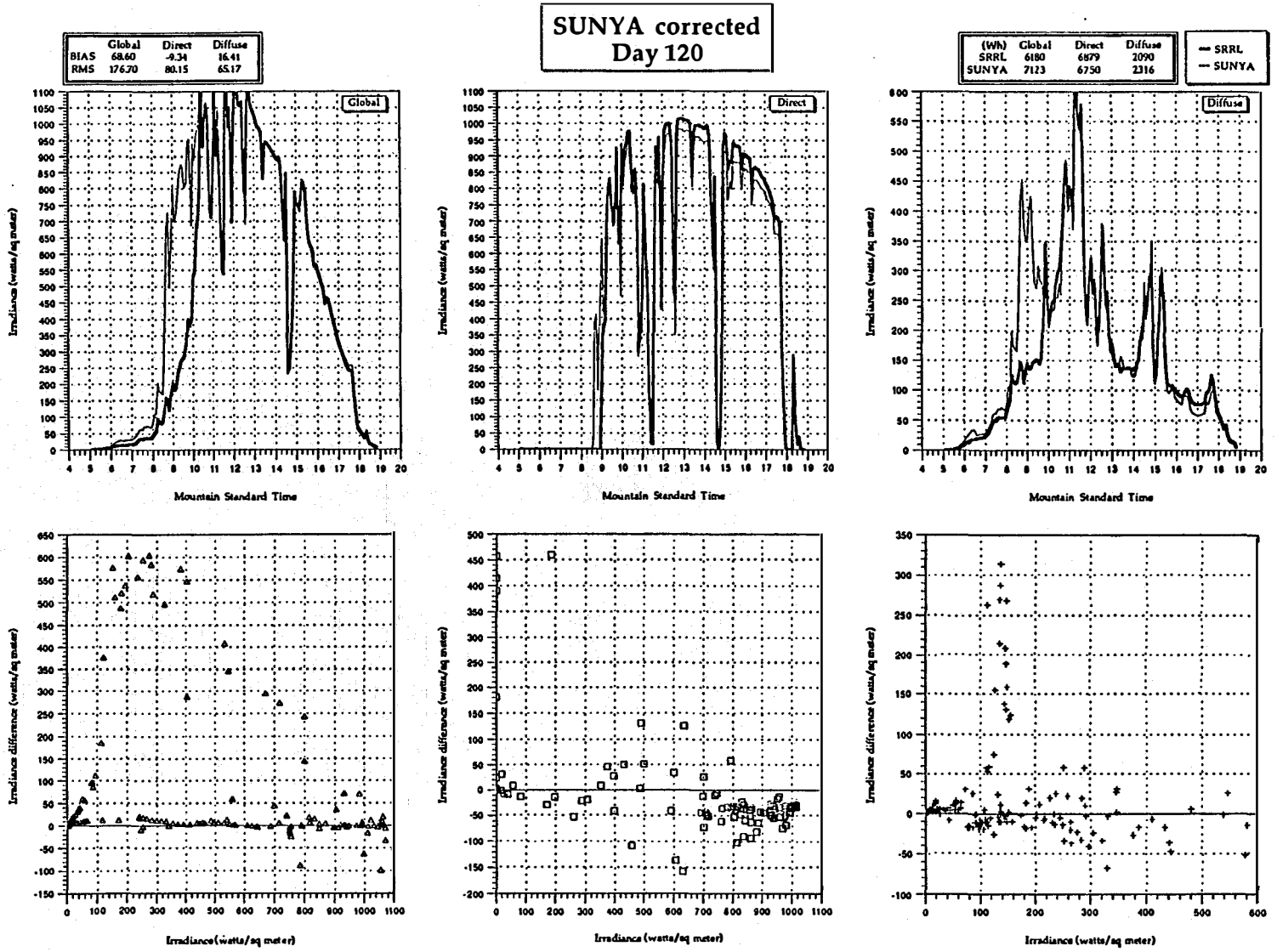


Figure 4-6a. Five-min averaged data for 30 April 1991

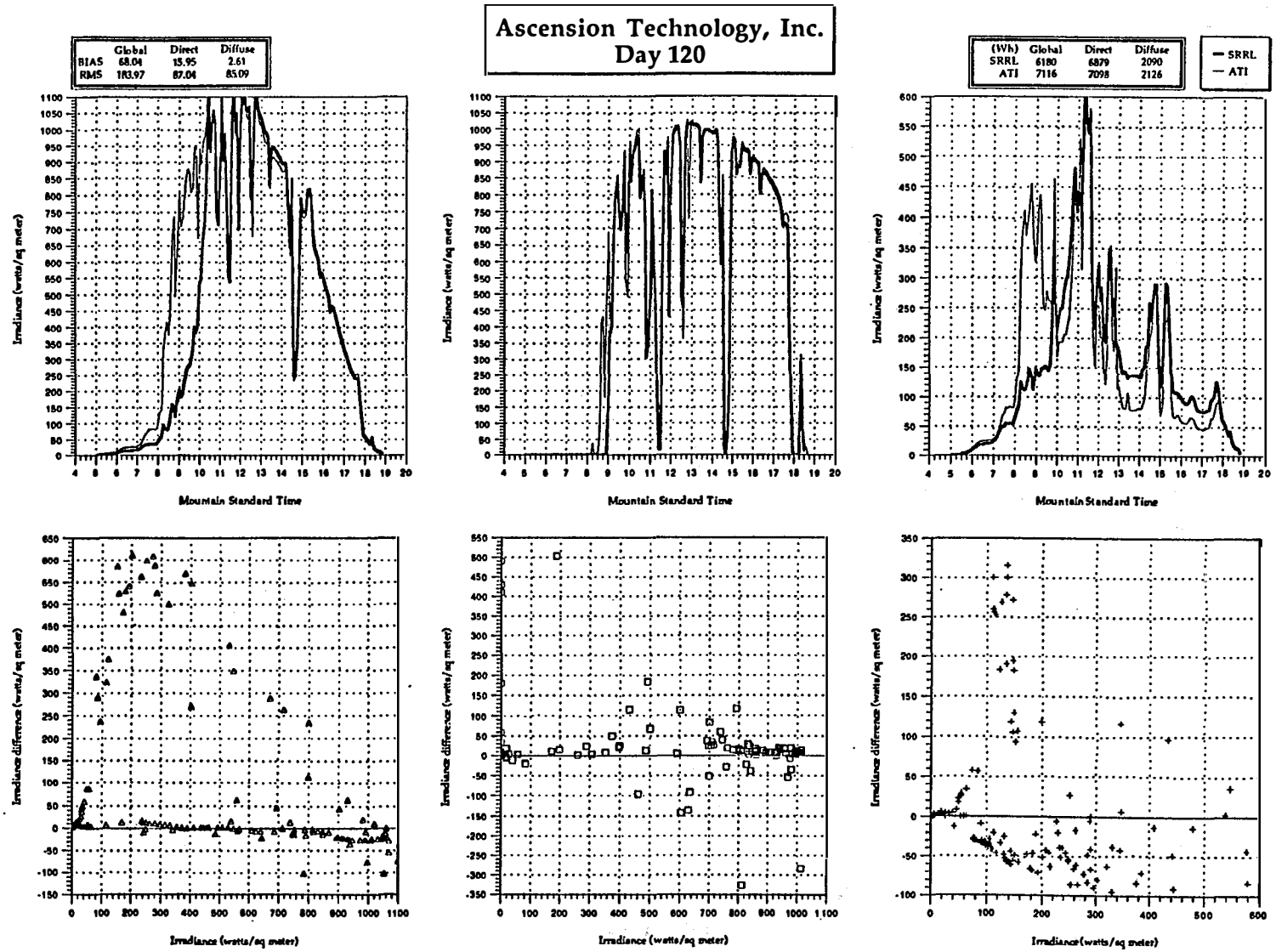


Figure 4-6b. Five-min averaged data for 30 April 1991

The daily total irradiance values on day 120 for each component are shown in Table 4-2. The BMS data are lower than those from the RSRs (global down 13%, direct down about 3%, and diffuse down about 5%). These values are consistent with our inspection records for the day. The BMS instruments were covered by snow and ice for up to 2 h longer than the RSRs on the morning of day 120. Irradiance differences between the RSRs and the BMS can be attributed primarily to the effects of the snow and ice that remained on the BMS radiometers. These data offer the opportunity to quantify the effects of unattended operation under these conditions.

Similar information is available, from the daily plots and maintenance logs in Appendix C of Volume 2, for other days with precipitation, high winds, and dust.

Table 4-2. Daily Total Radiation Values (Wh/m^2) for Day 120

System	Global	Direct	Diffuse
ATI	7116	7098	2126
SUNYA	7123	6750	2316
BMS	6180	6879	2090

5.0 CONCLUSIONS AND RECOMMENDATIONS

In general, our evaluation indicates that BMS and RSR instrument options in this comparison can be considered for solar radiation resource assessment. We must recognize, however, that the RSRs are still under development, and there is limited field experience to date. The selection of a particular option, or group of options, depends on several application-dependent factors:

- Radiation component(s) of interest
- Installation requirements -
  space, supporting structure, labor, communications, and access
- Maintenance requirements -
  access, system complexity, and frequency/schedule
- Measurement accuracies (for each radiation component)
- System reliability
- System purchase price.

5.1 Operations and Maintenance Considerations

The RSRs offer a simplified design for establishing and maintaining a solar radiation monitoring capability compared to a multisensor collection of thermopile-based radiometers and potentially more complex support equipment (e.g., 2-axis solar tracker) to measure global, direct, and diffuse irradiance. However, RSRs have moving parts that could fail, and long-term data and experience (i.e., more than the 6-month test results presented here) are needed to document long-term reliability. The concept of using a single radiometer rather than two or three radiometers employed in alternate methods is less costly in terms of the calibration and the number of instrument spares needed to continuously operate a station. The smaller optical surfaces of the RSR pyranometer tend to require less maintenance than the glass domes and windows of the thermopile instruments (as far as ice and snow buildup and water/dust spots), although more field observations are needed to confirm and quantify this observation.

The simplest option for using thermopile-based radiometers for determining global, direct, and diffuse solar irradiance is to combine a pyranometer for measuring global irradiance with another pyranometer under a fixed shadowband for measuring diffuse irradiance and then compute direct irradiance. This option, however, requires regular shadowband adjustments one to five times per week and also requires the application of a shadowband correction factor to all diffuse data during postprocessing. Adding a solar tracker and pyrheliometer for measuring direct normal irradiance provides redundancy for quality assessment and reduces the uncertainty of the direct normal data, but also increases the complexity and expense of the measurement system.

Our test site in Golden, Colorado, offered a variety of extreme operating conditions needed to evaluate the durability of the systems (ice and cold), but the effects of urban air pollution on sensor contamination should be explored further. With the exception of a possible wind-induced failure of the ATI PV panel, there were no environmentally caused hardware failures. We noticed the system clock in the SUNYA RSR required daily adjustments to maintain our 3 s timing difference limit when the daily air temperature was below freezing for more than 2 days.

Most of the data lost during this project were lost because of operator errors during routine maintenance of the systems. Written procedures for setting the SUNYA RSR clock were not followed correctly. Data were lost when the technician reset the clock *before* retrieving all data from the RSR's memory. As described in Appendix J of Volume 2, data from this RSR must be retrieved before resetting the system's clock. The ATI RSR was the easiest system to install and operate. The SUNYA RSR system is now available with a Macintosh PC interface. This could reduce the opportunities for operator error and may provide better data handling and display options than those available from the personal computer system used during this project.

Initial and periodic (at least annual) radiometer calibrations, traceable to the World Radiometric References (WRR) are essential to assure high-quality data and to perform measurement uncertainty analysis.

5.2 Performance Comparisons

The analyses of the RSRs' performance relative to thermopile-based radiometers used in the BMS for 6 months in Golden, Colorado, indicate 5-min average differences in global horizontal and direct normal solar irradiance within the total measurement uncertainty estimates associated with the BMS (±4.03% and ±2.07%, respectively, assuming nominal irradiance values of 500 W/m^2 global and 750 W/m^2 direct normal). Using the BMS instruments as a reference, the typical monthly coefficients of determination were greater than 0.98 for 5-, 15-, and 60-min averaged data.

The estimated measurement uncertainty for measuring diffuse irradiance using a thermopile-based pyranometer is ±4.80% under a fixed shadowband and ±4.32% under a tracking disk. Comparisons of the RSRs' diffuse horizontal irradiance values with the BMS or the RIS indicate larger differences (up to 35% at 100 W/m^2), but the 5-min average differences over the 6 months are within the measurement uncertainty of 4.80% for the fixed shadowband option (assuming a nominal irradiance of 300 W/m^2). Monthly coefficients of determination are greater than 0.97.

Data analyses of 11 days of data collected during the project under clear sky conditions confirm the above findings and also illustrate the different response characteristics of the pyranometers being compared. Thermopile-based and silicon-based radiometers exhibit different spectral and cosine (incidence angle modifier) responses.

5.3 Recommedations

Based on the results of this 6-month study in Golden, Colorado, the BMS instruments and RSRs can be considered as options for collecting reliable solar irradiance data needed for assessing the solar irradiance energy options for electric utilities. By design, the RSRs offer the potential advantages of lower maintenance and calibration costs because they use a single instrument with a diffuser for determining the direct, diffuse, and global solar irradiance rather than up to three radiometers with larger optical surfaces, more complex support equipment (if using a pyrheliometer in an automatic sun-following tracker), or more maintenance-intensive support equipment (in the case of a manually adjusted, fixed shadowband). Their potential disadvantage is the higher estimated measurement uncertainty because of factors such as the restricted spectral response of the silicon-based detector used in the RSR pyranometer. The SUNYA RSR includes software for postmeasurement adjustments to compensate for this spectral mismatch. (For silicon PV applications, the raw data from an RSR may better reflect the energy available for conversion.) Postprocessing software to account for the limited spectral response of the silicon detector could also be developed and applied to the ATI RSR data. Because the RSRs have moving parts, their long-term reliability (longer than 6 months) should be documented (in the same way that a tracker for direct normal measurements using an Eppley NIP would be documented).

Initial and periodic (at least annual) calibration, traceable to WRR, of the instruments is essential to assure high-quality data and to perform measurement uncertainty analyses before applying the data. Improvements can be made to the instrument calibration methods and data postprocessing methods to reduce the measurement uncertainty; these improvements require additional research efforts. Quality assessment methods are available (Maxwell et al. 1989) to flag data that violate physical principles or fall outside of expected ranges. The expected ranges can be better defined using the relationships among global, direct, and diffuse solar radiation (and sun position and atmospheric conditions) if more than one of these solar radiation measurements is made. If three instruments are used in a measurement system, information from the separately calibrated instruments (such as calculating direct normal from measured global and diffuse, and comparing it to measured direct normal) can also provide quality assessment information.

At least daily access to the data from the measurement system is an important part of quality assurance. This helps prevent significant data loss resulting from system failures or operator error. Instrument and operating conditions (e.g., sky conditions) should be noted during field inspections.

More experience is needed to evaluate the maintenance requirements of the two RSRs. We suggest placing two units at a site and comparing the data over time (months) with regular cleaning of only the "control" sensor. After determining postexperiment calibration differences, the data may be reviewed to determine the maximum time between maintenance visits that will not significantly affect the measurement.

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