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Progress Report for Annex II – Assessment of Solar Radiation Resources In Saudi Arabia 1993 – 1997

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Prepared under Task No. WW021000

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Notice

Preface

The *Progress Report For Annex II–Assessment Of Solar Radiation Resources In Saudi Arabia* provides a record of work performed, results achieved, and products produced under Annex II, a project established under an Agreement for Cooperation in the field of Renewable Energy Research and Development (R&D) between the Kingdom of Saudi Arabia and the United States. This report covers work and accomplishments for the period from October 1993 through December 1997. The work was performed at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, at the King Abdulaziz City for Science and Technology (KACST) in Riyadh, Saudi Arabia, and at selected weather stations of the Saudi Meteorological and Environmental Protection Administration (MEPA). The primary objectives of Annex II were to upgrade the assessment of solar radiation resources in Saudi Arabia, to produce an improved atlas of solar radiation resources in Saudi Arabia, and to transfer NREL's solar radiation resource assessment technology to KACST in the form of hardware, software, and staff training. These objectives were substantially achieved.

Direct financial support for Annex II came from KACST through the Joint Economic Commission Office in Riyadh (JECOR), and the United States Department of Energy (DOE). Substantial indirect support was received from MEPA and from several R&D projects at NREL. In particular, MEPA performed maintenance of the solar radiation equipment at 11 of the 12 stations in the Saudi solar radiation network and transferred requested meteorological and satellite data to KACST, all at no cost to Annex II. In addition to direct support for software development, Annex II benefited from technology developments achieved under several NREL projects, including the technology to produce high-resolution solar radiation data grids, which was vital to the production of the Solar Radiation Atlas for Saudi Arabia. Special thanks are extended to Abdullah Fayez, Saleh Al-Doaiji, George Matter, and Dorothy Mazaka (JECOR), Alan Jelacic and Robert Martin (DOE), Fahad Huraib (KACST), all staff of MEPA who have been involved in the project activities, and Dave Renné (NREL) for their personal interest and support. We also acknowledge support received from Elizabeth Brady, Ray George, Daryl Myers, Ibrahim Reda, Martin Rymes, Tom Stoffel, Jim Treadwell, and Chester Wells during the preparation and presentation of various training courses and in support of other Annex II activities. And special recognition is given to Art Medrano, Abdulaziz Moammer, Abdullah Al-Rubaiq, and Moawiah Al-Khaldi, for their dedication to the maintenance and operation of the solar radiation network and the solar radiometer calibration facility at the Solar Village.

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1.0 Overview

In 1987, the United States Department of Energy (DOE) and the King Abdulaziz City for Science and Technology (KACST) signed a five-year Agreement for Cooperation in the Field of Renewable Energy Research and Development (R&D). This agreement has now been extended to the year 2000. Under this agreement, a four-year (1994-1997) project (Annex II) to improve the assessment of solar radiation resources in Saudi Arabia was initiated in 1993. Annex II is a joint effort carried out by KACST and DOE's National Renewable Energy Laboratory (NREL). This report summarizes the activities and accomplishments of Annex II through 1997.

The original plans for Annex II, prepared in 1992, included statements of the tasks/objectives to be accomplished. They are repeated here much as they were given in the original document:

Task 1 To upgrade solar radiation measurements in Saudi Arabia.

Task 2 To assemble a database of concurrent solar radiation, satellite (METEOSAT), and meteorological data (over a 10-year period, to the extent possible).

Task 3 To adapt NREL models and other software for use in Saudi Arabia.

Task 4 To develop procedures, algorithms, and software to estimate solar irradiance at locations and times for which measured solar radiation data are not available.

Task 5 To prepare a uniformly spaced grid of solar radiation data for use in the preparation of maps and atlases and to estimate solar radiation resources and solar energy system performances at any location in Saudi Arabia.

Summaries of the status of each of these tasks/objectives as of the end of 1997 are given here. In addition to satisfying most of the original objectives, Annex II has contributed to significant advances in the field of solar radiometry. If the work begun under this annex is continued during the coming decades, Saudi Arabia will have one of the best assessments of solar radiation resources in the world.

Task 1 Task 1 was fully accomplished. This includes the establishment of a 12-station solar radiation network at sites having different surface albedos, climates, elevations, and terrain characteristics. Each station in the network measures direct normal, diffuse horizontal, and global horizontal irradiances with first-class thermopile radiometers. The 12-station network is collecting good-quality data for an unusually high percentage of all possible data. An excellent radiometer calibration facility was established at the Solar Village (a solar research facility near Riyadh) and direct traceability to the World Radiation Reference at Davos, Switzerland, was accomplished in 1995.

Task 2 Concurrent solar radiation, satellite, and meteorological data are being assembled. However, the assembly of a database covering a 10-year period was not accomplished. The difficulties that prevented the accomplishment of this objective include: 1) Plans to supplement data collected by the 12-station network with historical bi-metallic actinograph data were not realized. The methodology to convert the actinograph chart records of radiation to equivalent hourly values was developed and transferred to KACST. However, resources were not adequate to acquire and process the historical data. (2) Several technical difficulties limited the collection of METEOSAT data. These include shortcomings in data-processing hardware, difficulties in obtaining the correct image-processing software, and recent encrypting of the data stream. Routine, monthly transfer of adequate METEOSAT images to KACST and NREL has yet to be accomplished. (3) The Saudi Meteorological and Environmental Protection Administration (MEPA) did not begin digitizing meteorological data until 1995. Therefore, it was impossible to obtain the required input data for NREL's meteorological/statistical (METSTAT) model.

Although a 10-year solar radiation database was not produced in 1997, this might be accomplished under a planned three-to five-year continuation of Annex II.

Task 3 Two major software packages, the Data Quality Management System (DQMS) and the Radiometer Calibration and Characterization (RCC) software, were transferred to KACST in 1994 and are routinely in use. These software packages represent important advances in solar radiometry that will continue to benefit solar resource assessment activities for many years. Upgrades of this software have been transferred to KACST annually. Furthermore, two NREL solar radiation models METSTAT and Climatological Solar Radiation (CSR) were transferred to KACST. These models were developed under other projects at NREL (Maxwell 1998; Maxwell, George, and Wilcox 1998).

Task 4 A two-week course, *The Estimation of Monthly Mean Daily-Total Solar Radiation on a Uniform Grid,* was given at NREL during the first part of March 1997. This technology transfer, which continued throughout 1997, encompassed all techniques (including modeling and geostatistics) for estimating solar radiation at locations and times for which measured solar radiation data are not available. These techniques were developed over a period of several years under several projects, including a multiyear International Energy Agency task (Zelenka et al. 1993).

Task 5 A uniformly spaced grid of monthly mean daily-total solar radiation completed in 1997 provided the data for maps and a Saudi Arabia Solar Radiation Atlas that were printed in 1999. However, the methods used to generate the grid were not those envisioned during the initial planning in 1992. During 1995 and 1996, NREL explored several options for producing solar radiation data grids, using DOE funding for resource assessment research. A major result of this work was the location of worldwide surface- and satellite-derived data that provide the inputs to the CSR model developed specifically to create climatological solar radiation data grids. Eventually, the continued collection of solar radiation data by the Saudi 12-station network will prove invaluable to the validation of the model and its associated input data.

The synergism afforded by combining Annex II and other NREL projects produced superior products for Saudi Arabia and has benefited all solar energy interests (see Section 11.0).

2.0 Establishing a Saudi Solar Radiation Network

Prior to Annex II, the measurement of solar radiation in Saudi Arabia had been carried out by an uncoordinated effort of several organizations. MEPA and the Saudi Ministry of Agriculture and Water had collected as many as 20 years of global horizontal solar radiation data at more than 20 sites. These measurements were made with bi-metallic actinographs, an electro-mechanical instrument that produces a continuous record of solar radiation on a strip chart. Bimetallic actinographs, when properly calibrated and maintained, are recognized as a reliable source of daily-total solar radiation. Less accurate values of hourly radiation can also be extracted from the strip charts. However, the uncertainty of these data was increased by the uncertainty of calibration and maintenance procedures.

Solar radiation data had also been collected for a number of years by several universities and by KACST. These measurements of global horizontal and direct normal radiation were made with thermopile instruments (pyranometers and pyrheliometers), which are capable of greater accuracy, especially for hourly and shorter integration periods. Again, however, uncertain calibration and maintenance procedures left doubts about the quality of much of the data.

The quality of historical data can be assessed, of course, by comparing measured values with physical limits, with empirical limits, or with model estimates. However, when only one element of solar radiation has been measured, most commonly global horizontal, the quality assessment tools are quite limited in their ability to detect measurement errors. Using physical limits, for instance, any measurement falling between zero and the value for extraterrestrial (top-of-the-atmosphere) radiation must be judged to be acceptable. In actuality, of course, such measurements could be greatly in error. The use of empirical limits (NREL 1993) will reduce the maximum threshold of acceptability; however, the range of acceptability is still too wide.

When two solar radiation elements have been measured (e.g., global horizontal and direct normal), the use of NREL's Solar Energy Research Institute (SERI) quality control (QC) software (NREL 1993) significantly reduces the range of acceptable values and allows a reasonable assessment of data quality. Nevertheless, measurement errors as great as 20% can go undetected. In order to reliably detect errors as small as 5%, one should simultaneously measure all three fundamental elements of solar radiation (global horizontal, direct normal, and diffuse horizontal). Because of the redundancy inherent in such measurements, any one of these elements can be calculated from the other two. Therefore, errors of just a few percent can be detected. Because individual radiometers are used for measuring each element, errors resulting from just about any cause (e.g., calibrations, dirty globes, improper installations), will be detected (NREL 1993).

2.1 Instrumenting the Saudi Solar Radiation Network

Because of the enhanced quality assessment potential, a decision was made to equip each of the Saudi network stations to measure all three solar radiation elements. Eppley Precision Spectral Pyranometer (PSP) pyranometers were selected for measuring global horizontal and diffuse horizontal radiation and Eppley Normal Incidence Pyrheliometer (NIP) pyrheliometers mounted on Eppley ST-1 solar trackers were selected to measure direct normal radiation.

The measurement of diffuse radiation is usually accomplished by using a shadowband to block the direct-beam radiation from the solar disk. This introduces a significant uncertainty in the measurements, however, because the shadowband blocks approximately 10% of the sky dome. If the radiation from the sky were homogeneous, the effect of the shadowband could be precisely and accurately corrected. The sky radiation is not homogeneous, however, even under cloudless conditions. When clouds are present, the amount of diffuse radiation blocked by the shadowband can vary greatly, depending on the location and type of clouds.

For these reasons, Eppley and other manufacturers developed tracking disk mechanisms to reduce the uncertainty of diffuse measurements. NREL's experience with Eppley's disk tracker, however, had revealed a tendency for failure to track, especially under windy conditions, because of the imbalance of the arm supporting the disk. To correct this problem, NREL recommended the design of a balanced tracking mechanism as shown in Figure 2-1. This figure shows the new tracking disk mechanism (Eppley Model RSD-2) and the other instruments mounted on the platform designed and constructed specifically for the Saudi solar radiation network.

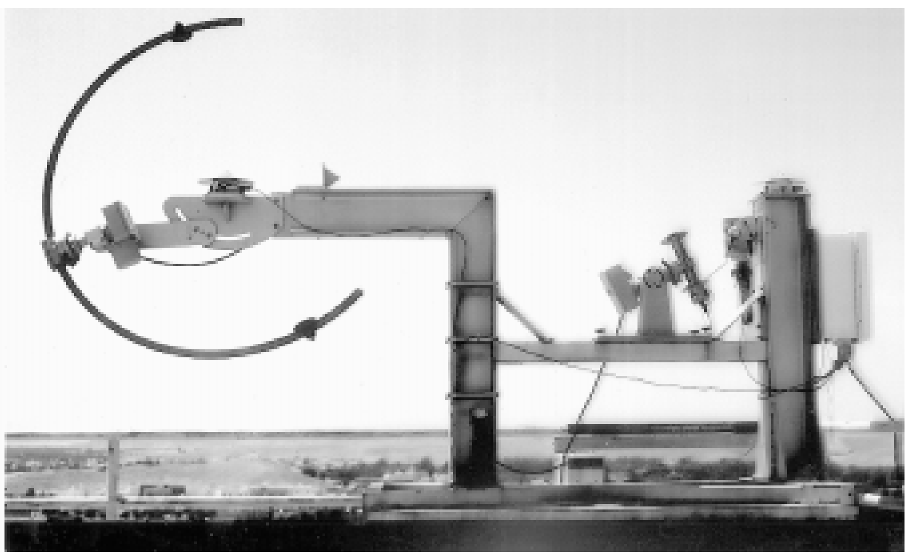

Figure 2-1. Eppley RSD-2 rotating tracking disk with PSP

The Eppley ST-1 and RSD-2 are simple equatorial trackers that depend on the alignment of the drive axis with true north and the precise speed of the motors (determined by the power line frequency) to maintain tracking. Both of these trackers operate continuously, 24 hours a day. Because of the continuous operation, the cable to the NIP will become so twisted after two or three days of operation that the tracker clutch mechanism will slip; the operator will then lose track of the sun. If the clutch is maladjusted and does not slip, the signal cable for the NIP will be damaged. This problem is normally overcome by disconnecting the NIP cable every two or three days, unwinding it, and reconnecting it to the NIP. However, if this procedure is forgotten for any reason, the result is loss of data and/or damaged equipment. Furthermore, the tracker alignment may be disturbed during the disconnection and reconnection of the cable, requiring readjustment of the tracker.

A better solution to this problem was accomplished for the Saudi network instrumentation by constructing a slip-ring assembly to which the NIP and data logger cables were connected (see Figure 2-2). The gold-plated slip-ring connectors are essentially noise free and very reliable, eliminating loss of data and cable damage.

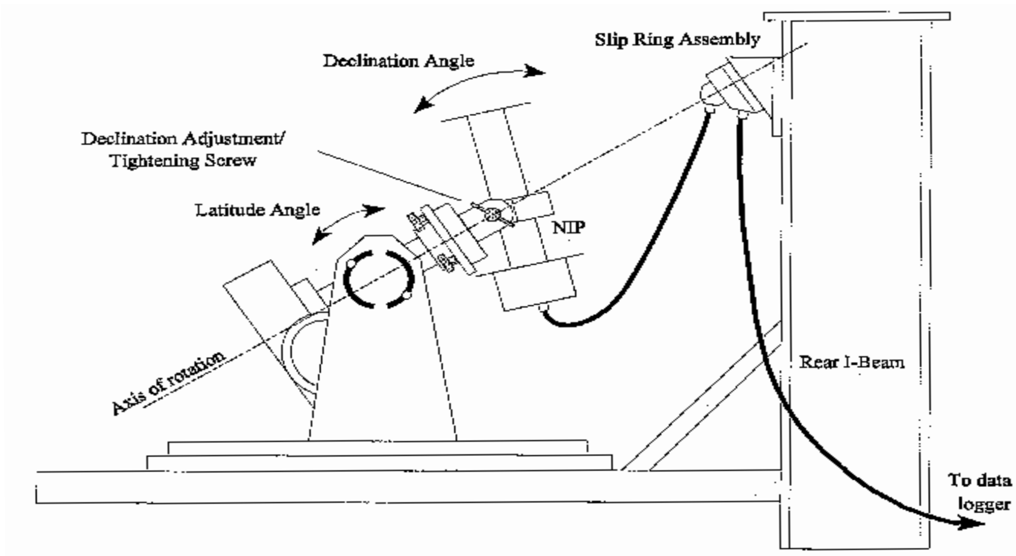

Figure 2-2. Eppley ST-1 and NIP with slip-ring assembly

Most pyranometers are leveled by centering a bubble in a level attached to the base. This method assumes that the sensing surface of the instrument is parallel to the base, which often is not true. The result is an instrument response that varies with the azimuthal position of the sun. Test results have shown that without radiometric leveling, measurement errors of several percent or more will occur at different hours of the day and different seasons of the year. To correct this problem, procedures for radiometrically leveling the pyranometers were developed. The first step in this procedure took place when the pyranometers were ordered, by specifying the instruments be built with adjustable bubble levels. The specifications also required precise centering of the sensor under the glass domes, because any displacement of the sensor produces an anomalous azimuthal response.

Both indoor and outdoor methods for radiometrically leveling the pyranometers were investigated. The indoor methods showed promise but the available artificial light sources lacked the intensity required. However, the collection of outdoor data under cloudless skies consistently indicated the azimuthal response characteristics of the instruments. When the instruments were radiometrically level, the mounting screws for the bubble levels were adjusted to center the bubble. Thereafter, field installation of the pyranometers could be accomplished by the standard procedure of centering the bubble. Approximately half of the Saudi pyranometers required radiometric leveling before being put into service.

2.2 Selecting the Network Sites

The first step toward the selection of the sites for the 12 network stations involved the designation of the following criteria for site selection:

1) Availability of people to maintain the equipment
2) Availability of reliable power and telephone service
3) Uniform spatial coverage of the Saudi Arabian Kingdom
4) Representation of major climates in the kingdom
5) Representation of surface albedo differences
6) An equipment location providing an unobstructed view of the horizon.

The combination of the first two siting criteria led to the selection of MEPA stations for all of the sites except for the station at KACST's Solar Village laboratory near Riyadh. Maps and satellite images were then used to identify regions in Saudi Arabia with similar climates and surface albedos. MEPA stations within these regions were then selected as potential sites. Finally, each of the prospective MEPA stations was visited by a team of KACST engineers to assess the availability of suitable locations for installing the equipment. Photographs of the environs around the locations selected for installing equipment were used in the final selection of the 12 MEPA stations shown on Figure 2-3.

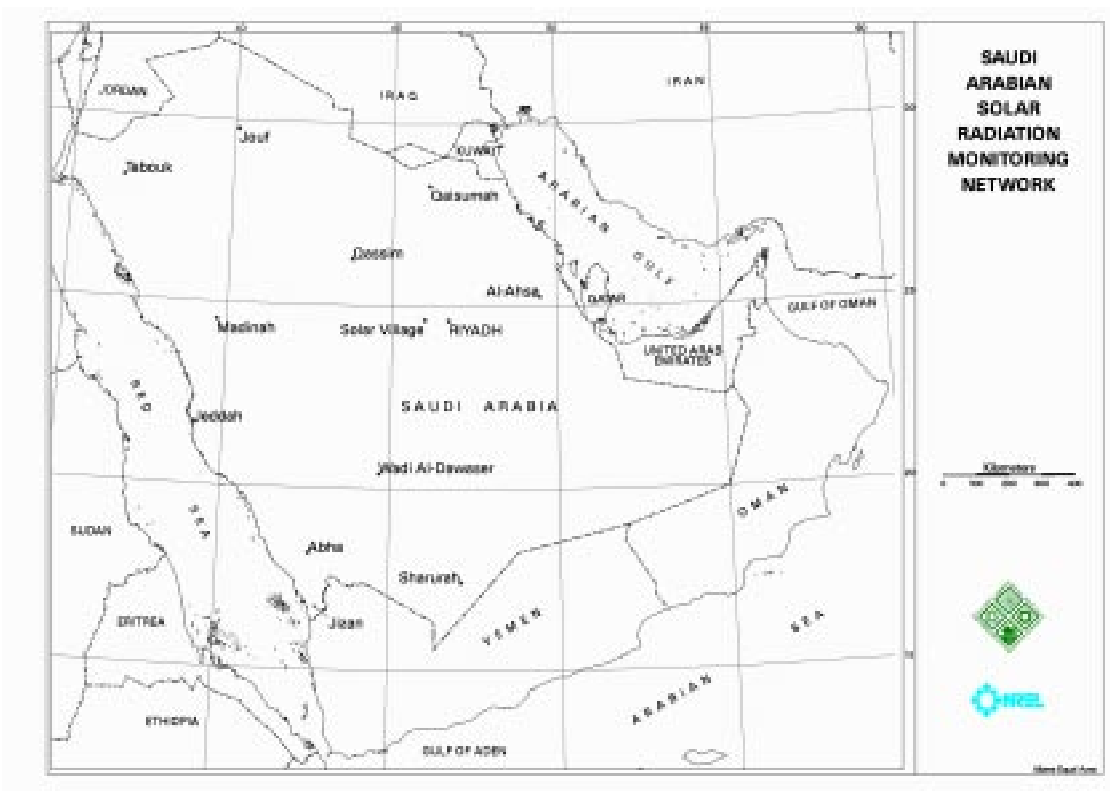

Figure 2-3. The 12-station Saudi Solar Radiation Network

2.3 Tracker Alignment

As noted above, the proper operation of these trackers requires the alignment of the drive axis of the trackers with true north. During the installation of the equipment at each station, the instrument platform was aligned north-south as accurately as possible. Then the base of the NIP tracker was leveled and aligned north-south. Finally, the latitude adjustment on each tracker was set to the latitude of the station. This accomplished an approximate alignment of the drive axis; however, the platforms and the trackers were not constructed with sufficient precision to provide a precise alignment. Therefore, it was left to the station operators to adjust the positioning of the trackers and the latitude setting to achieve reliable tracking. This “trial-and-error” procedure is time consuming and frustrating; as a result, some of the station operators were unable to properly align the trackers.

At those stations that could not achieve proper alignment of the tracker drive axes, the trackers had to be frequently realigned with the sun, sometimes daily. This resulted in a loss of data and frustration for the station operators. NREL installed a duplicate Saudi platform at the Solar Radiation Research Laboratory (SRRL) and investigated a number of potential solutions to the tracker alignment problem. After a number of failures, a tracker alignment tool was designed that allows the alignment of the tracker axes with the north star (Polaris). Although Polaris is not precisely congruent with the geographic North Pole, it is close enough to achieve acceptable tracking.

The tracker alignment tool (see Figure 2-4) is installed in the position of the mechanisms that support the NIP and disk support structures. On a relatively cloudless night, the north-south alignment of the platform and the NIP tracker and the latitude settings of both trackers are adjusted until the North Star is centered in the “bulls eye” of the Telrad Reflex Sight. With careful use of this tool, the trackers provide adequate tracking of the sun for two weeks or longer. This is a great improvement over the previous performance at some locations. The alignment tool was not available until 1997, so most of the direct normal and diffuse data were collected without the improved tracking it is capable of achieving.
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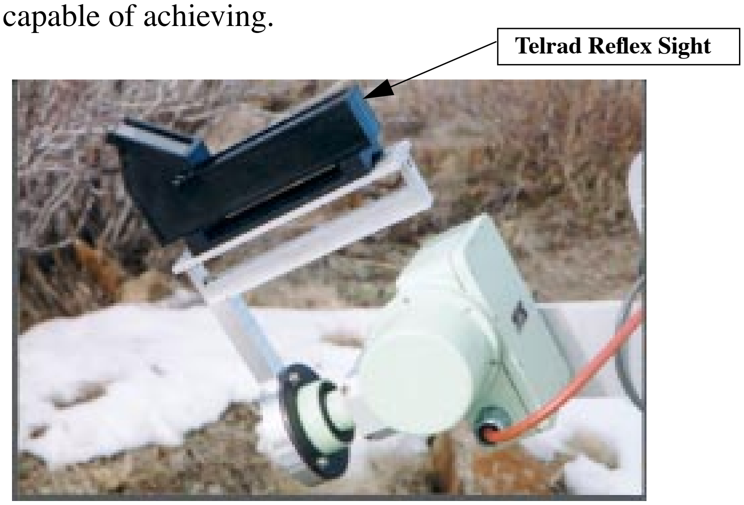


Figure 2-4. Tracker alignment tool on RSD-2 tracker

2.4 Bringing the Network On-Line

A three-man team from NREL spent most of October 1994 working with Saudi scientists and engineers at KACST. During that time, a facility for calibrating and characterizing solar radiometers was established at the Solar Village. All of the radiometers for the Saudi network were recalibrated. The first two stations of the Saudi network, at the Solar Village and Al-Qassim (see Figure 2-3), were established and network data acquisition was initiated at KACST. KACST completed the installation of equipment at all but one of the other locations during the first nine months of 1995. The final station in the network (Jeddah) began operations in April 1996.

The most time-consuming aspect of this work was the preparation of facilities at the MEPA stations. Power lines and telephone lines had to be brought to the location selected for equipment installation and for those stations where the equipment was to be installed on the ground, a concrete pad supported on pillars had to be constructed (see Figure 2-5). The pads were required to provide a stable support for the equipment platforms in the sandy soils present at most of the sites. Table 2-1 lists the location information and operational dates for each station.

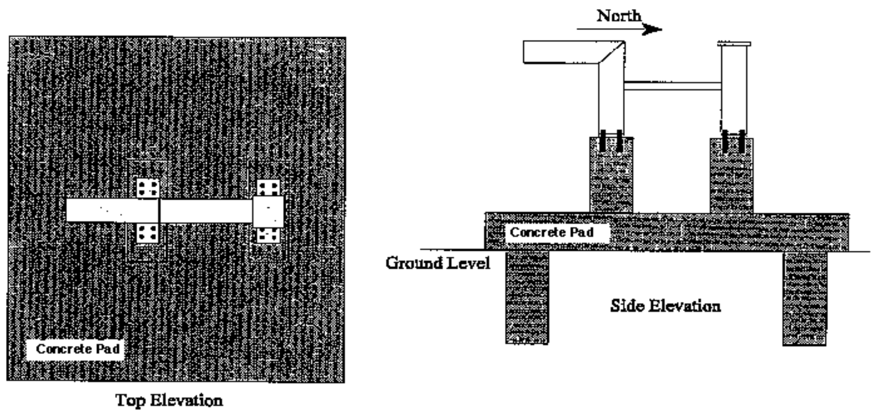


Figure 2-5. Single-pad concrete base with instrument platform

Table 2-1. Station Locations and Operational Dates

Stations	Latitude	Longitude	Elevation (meters)	Dates of Initial Operations
Solar Village	24.91	46.41	650	November 1994
Al-Qassim	26.31	43.77	647	November 1994
Al-Ahsa	25.3	49.48	178	January 1995
Wadi Al-Dawaser	20.44	44.68	701	April 1995
Abha	18.23	42.66	2039	June 1995
Gizan	16.9	42.58	7	June 1995
Sharurah	17.47	47.11	725	June 1995
Al-Jouf	29.79	40.1	669	August 1995
Al-Qaisumah	28.32	46.13	358	August 1995
Tabouk	28.38	36.61	768	August 1995
Al-Madinah	24.55	39.7	66	September 1995
Jeddah	21.68	39.15	4	May 1996

3.0 Achieving Traceability to the World Radiation Reference

There are many activities required to maintain reliable operation and the collection of high quality data by the stations in a solar radiation network. The first step toward this end is to calibrate the network radiometers against a standard or reference radiometer. There is no standard light source (equivalent to standard lengths and masses) for calibrating solar radiometers. Rather, the World Radiation Reference (WRR), consisting of a group of several cavity pyrheliometers, is maintained by the World Meteorological Organization (WMO) at Davos, Switzerland.

A cavity pyrheliometer is an instrument that compares energy received from the solar disk through a circular aperture of known area with energy generated by an electric current flowing through a resistor. The ultimate traceability to physical standards is achieved by measuring the diameter of the aperture, the current, and the resistor with instruments calibrated against national and international standards of length, voltage, and resistance. The name of the instrument is derived from the internal cavity within which the energy from the sun is absorbed.

Each cavity pyrheliometer has a response uncertainty of approximately 0.3%. By averaging the responses of all six instruments in the WRR group, a combined uncertainty of about 0.1% is achieved, which is quite adequate as a reference for solar radiation measurements (WMO OMM No. 8 1983). Traceability to the WRR for the Saudi network was accomplished by calibrating field radiometers using KACST's cavity pyrheliometer, whose response had been compared with the group of cavities at Davos (Swiss Meteorological Institute 1996).

3.1 Calibration Concepts

The calibration of a measurement instrument serves two fundamental requirements: to find deviations from a manufacturing average and to correct for changes in instrument response due to aging or environmental factors. In the calibration process, a measurement instrument is standardized or calibrated through comparison with a standard (reference) instrument. This comparison yields a correction factor that can be subsequently used to modify the output of the instrument under test to match that of the standard instrument.

Reference standards, instruments, and the definition of scales for temperature, length, or voltage measurements are generally established by the International Bureau of Weights and Measures (BIPM) in conjunction with national standardizing laboratories. Unlike other measurement disciplines, broadband optical solar radiation measurements necessary for solar resource assessment have no uniquely defined BIPM-sanctioned standard against which instruments can be calibrated. In the absence of a primary calibration reference, the solar radiation measurement scale and standard are both defined by a precision absolute cavity radiometer operated such that the solar energy falling on a sensor can be related to electrical energy.

3.2 The Solar Standard

The solar standard in use today is by consensus derived from a group of absolute cavity radiometers that are carefully maintained and operated by the WMO at the World Radiation Center (WRC) in Davos, Switzerland. A cavity radiometer absorbs the sun's energy in a small cavity in thermal contact with a thermopile, which converts the solar energy to an electrical potential. By substituting electrical heating in the absence of solar heating, the same electrical potential is achieved in the thermopile. The electrical power is computed by measuring the voltage, current, and resistance in the heating circuit. By knowing the area of the aperture to the cavity, it is then possible to relate the electrical energy to the solar energy captured by the cavity. These measurements of area and electrical parameters, which can be traced to defined standards, are the basis for a reference measurement of solar radiation.

3.2.1 The World Radiometric Reference

The World Radiometric Reference is defined by the weighted mean of a group of seven absolute cavity radiometers. These instruments were chosen because of their well-characterized history, stability, and consistent performance, as well as being representative of several methods of manufacturing. The instruments are operated simultaneously and a long-term data set is analyzed for a mean value and variability among instruments. From the group, one instrument is selected as representative of the whole based on low variability and proximity to the mean. During calibration events (called cavity intercomparisons), the representative instrument is assigned a factor to bring it into compliance with the mean of the group.

3.2.2 Comparison with the World Radiometric Reference

The International Pyrheliometer Comparison (IPC) is an event, sanctioned by the WMO, held every five years at the WRC in Davos. During this event, simultaneous data are collected by the WRR reference group and other participating cavity radiometers over a period of two or more weeks, weather permitting (clear skies are required). From this data set, a WRR factor is computed and assigned to each cavity under test. These instruments then become directly traceable to the WRR.

The IPC participating instruments are later compared with other cavity radiometers designated as working standards, which then achieve secondary traceability to the WRR. This transfer occurs during regional intercomparisons or other events that allow comparison with a directly traceable IPC instrument. Ultimately, research and field instruments are compared (calibrated) with the working standards.

3.2.3 Intercomparisons with the KACST Cavity

The KACST cavity, an Eppley Hickey-Frieden manual unit (serial number 30110), has been intercompared with other cavities three times: first with Eppley's IPC cavity, then at NREL (against NREL IPC cavity, serial number 28968), immediately after the instrument was delivered by the manufacturer. In 1995, KACST personnel took the cavity to Davos, Switzerland, where it participated in the eighth IPC. Thus, this cavity is both a directly traceable national standard for Saudi Arabia and, in practice, the working standard for the KACST radiometer calibration facility.

3.3 Calibrating the Saudi Network Radiometers

With the installation of the 12-station Saudi network, there was a need to recalibrate the radiometers on a regular schedule and thereby provide traceability to the WRR for all network measurements.

3.3.1 The Calibration Facility

In 1994, a calibration facility (Figure 3-1) was established at the KACST Solar Village near Riyadh to provide for regular calibrations of network radiometers. This installation was modeled after a calibration facility at NREL.

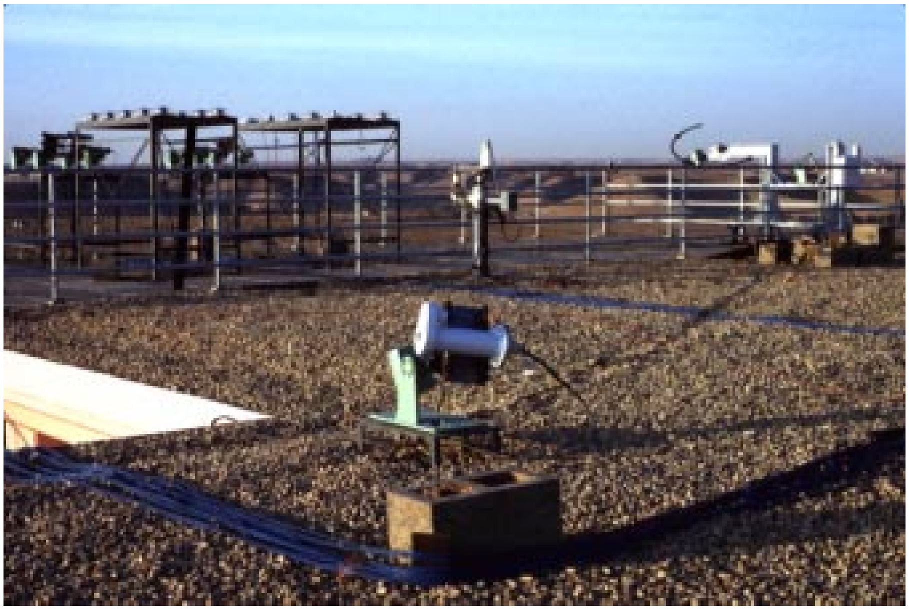


Figure 3-1. Solar radiation calibration facility at the KACST Solar Village

3.3.2 Calibration Software

As part of the project, Radiometer Calibration and Characterization (RCC) software was developed as an outgrowth of several years of testing and implementing such procedures at NREL. RCC combines all functions of the calibration event into a single software package that runs on a personal computer. In addition to the data acquisition and reporting functions of previous software, RCC provides these enhancements:

- Generation of calibration vectors (based on zenith angle) for pyranometers, including a report of their uncertainty
- Real-time data error checking that alerts the operator to find and correct data acquisition problems when they occur
- Monitoring of atmospheric and meteorological conditions that affect the results of a calibration event, allowing the filtering of data for optimal conditions
- A supporting instrument and calibration database that stores information about each instrument under calibration, including a history of calibration events.

3.3.3 Calibration Methodology

The calibration technique used (the Component Summation Method) is a modified version of the shading method described in the American Society for Testing and Materials Standard E913-82, "Standard Method for Calibration of Reference Pyranometers with Axis Vertical by the Shading Method." The direct normal irradiance is measured with the cavity radiometer, and the diffuse (sky) irradiance is measured by a pyranometer shaded with a tracking disk. The output voltages of these standards and the radiometers under test are measured at 30-second intervals throughout each day (clear-sky weather permitting).

The responsivity for a pyrheliometer is calculated for each data point by dividing the value of the instrument's output signal (microvolts) by the value of the absolute cavity radiometer output (W/m^2). The reported responsivity is the mean of all calculated responsivities in the sample data set. The sample data set is typically a subset of all data collected, with outliers removed.

The responsivity for a pyranometer is calculated by dividing the value of the instrument's output signal (microvolts) by the computed (component summation) reference global horizontal irradiance (W/m^2). The computed reference irradiance is the sum of the diffuse radiation and the vertical component of the direct-beam irradiance. This assumes that the pyranometer does not respond to the horizontal component (i.e., it has a perfect cosine law response). The vertical component of the direct beam is calculated as the product of the measured direct-beam irradiance and the cosine of the zenith angle, corrected for atmospheric refraction effects.

The first reported calibration factor (CF) is a weighted composite responsivity based on responsivities computed for 10 zenith angle bins, each 9 degrees wide (0-9, 9-18... 81-90). The value is the mean of the morning and afternoon means to minimize the effect of unequal sample sizes in each part of the day. The composite responsivity is a weighted average of each of the 10 zenith angle bins weighted by the cosine of the bin midpoint zenith angle (i.e., the midpoint of the 0-9 degree bin is 4.5 degrees). The responsivity of each zenith angle bin is also reported. Finally, a value for a 45-55 degree operating range is reported, which has been used in the past as a number suitable for most pyranometer solar radiometric measurements. Figure 3-2 shows the results of a typical calibration of an Eppley PSP pyranometer.

3.3.4 Calibration Schedule

Network operation procedures require the recalibration of all radiometers on an annual basis. These calibration events are called Broadband Outdoor Radiometer Calibrations, or BORCALs. BORCALs typically last for a week or more, and to minimize the effect on network data acquisition, spare instruments representing 50% of the network inventory were purchased. Thus, half of the required number of network radiometers may be calibrated at one time without disrupting measurements, except for the few minutes required to exchange instruments at each site. To meet the requirements of annual calibration, two calibration events are scheduled each year, allowing for 100% of the network instrument positions to be filled with calibrated instruments.

3.4 Calibration Validation

As part of the calibration process, two process control radiometers are included in each BORCAL event. These radiometers, one PSP pyranometer and one NIP pyrheliometer, are only exposed to solar radiation during each BORCAL. Because they are otherwise kept in storage between calibrations, the performance of these radiometers is expected to be consistent over time, and the data they produce serves as a validation of the entire BORCAL process.

RCC Results for a Pyranometer	
Serial Number	30252F3
Sample Size	7383
Std Deviation	0.041
Uncertainty	3.00
CF/45-55	8.27
CF/Composite	8.30
CF/Zen 00-09	8.34
CF/Zen 09-18	8.34
CF/Zen 18-27	8.33
CF/Zen 27-36	8.32
CF/Zen 36-45	8.30
CF/Zen 45-54	8.27
CF/Zen 54-63	8.24
CF/Zen 63-72	8.26
CF/Zen 72-81	8.19
CF/Zen 81-90	8.13

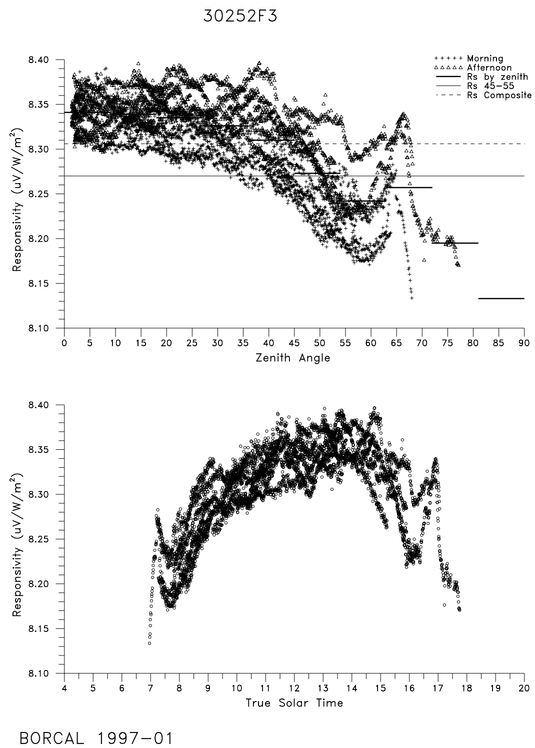
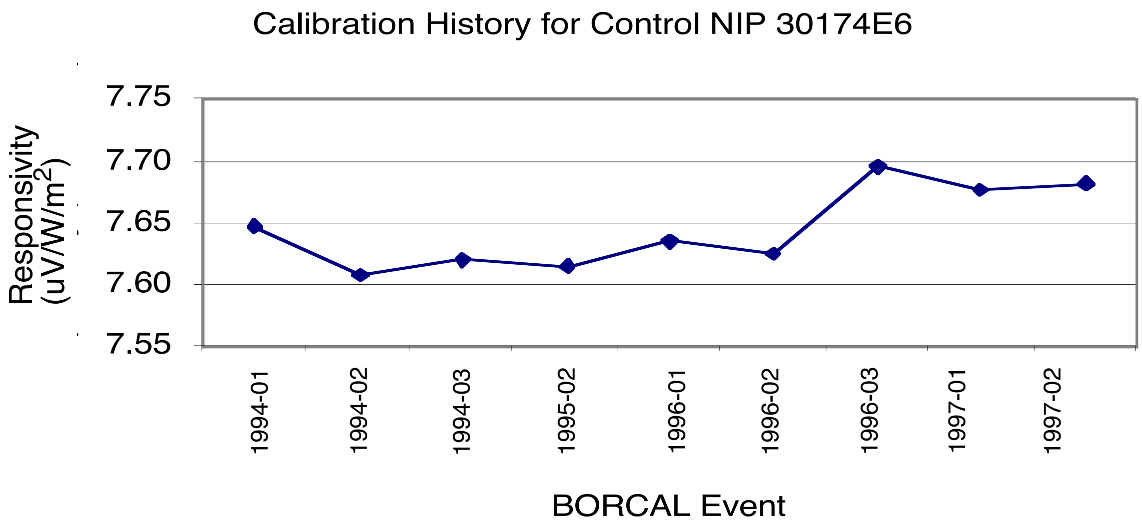


Figure 3-2. Calibration results for Eppley PSP pyranometer 30252F3

The responsivity history of the two control radiometers is shown in Figure 3-3. Although these graphs reveal a noticeable rise in responsivity for the last three calibration events, the magnitude of the change is no more than 1.25%, well within the expected uncertainty of the calibration process. Nevertheless, it is important to identify the cause of this apparent increase in responsivity of the control radiometers. The most likely causes are a reduction in the responsivity of the Hickey-Frieden cavity radiometer or a change in responsivity of diffuse measuring pyranometers. This will be checked during the next intercomparison in which this cavity participates.



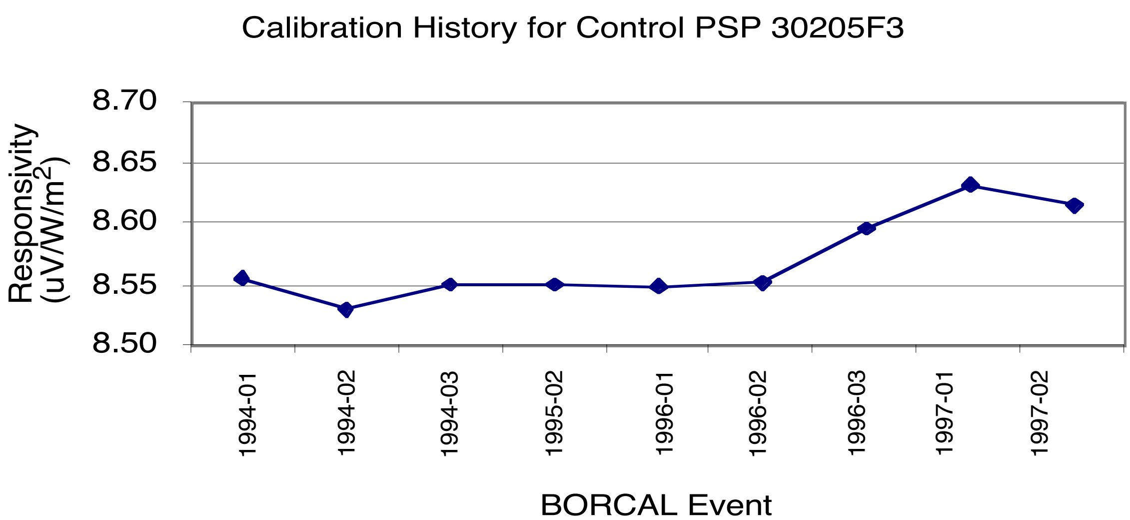


Figure 3-3. Calibration histories for the KACST control pyrheliometer (30174E6) and control pyranometer (30205F3)

4.0 Operating the Solar Radiation Network

This section describes the procedures that are in place to collect, process, and archive data from the solar radiation monitoring network. We developed these procedures with the goal of collecting the highest quality data possible. The almost daily data inspection and frequent feedback to personnel involved in all stages of the measurement process are critical to meeting that goal.

As described in greater detail in Section 2.0, the network consists of 12 stations, each measuring three components of solar radiation, temperature, and humidity. Observations are recorded at five-minute intervals and stored on site in data-logger memory. Once per day, data are downloaded from the data logger to the Network Operations Center at the Solar Village, where it is submitted to quality assessment (QA) and ultimately archived. A formal report is generated at the end of each calendar month. The report includes a summary of data quality, operational problems, and other noteworthy events.

Operation of a solar radiation network, or any multi-site scientific data collection endeavor, requires reliable field support to maintain each station and an operations center to manage the network. Without both of these elements, the data collected will be of questionable validity. The operations center supports the on-site personnel, provides the supplies and training necessary to keep the stations operational, collects and archives the data from each station, and performs QA tests on the incoming data to ensure proper station operation. If any of these responsibilities are overlooked, the quality of data collected from the network will be compromised.

Operations center activities are broken down into three major categories: data collection, data quality assessment, and data archiving. Data collection includes retrieving data from each individual station every night and making back-up copies of the raw data to prevent data loss. Quality assessment means examining the data, visually and with software, to check against expected values and consistency with other data. This also involves generating reports on the data quality. Archiving the data is more than just creating backups and storing them in a safe place; it also involves data dissemination and distribution of data products.

4.1 Data Retrieval

4.1.1 Hardware and Software

The data acquisition system is centered around the Campbell CR-10 data logger, manufactured by Campbell Scientific, Inc. The CR-10 incorporates adequate memory for storing several days of data and is attached to a dedicated modem for data transfer. At each site, the equipment is powered by conventional AC power, which charges an internal battery that bridges occasional power outages. At most sites, the modem is connected to a multi-user telephone line. To meet the needs of unattended data retrieval, an automatic telephone switch is installed, allowing remote switching of the incoming call to the data logger.

With Campbell CR-10 data loggers, several methods for downloading data are available. For the Saudi network, Campbell Scientific's DC112 telephone modems were chosen. These devices mount inside the CR-10 data-logger enclosure, connect to a telephone line, and allow a host computer to dial in to the logger and download data. Alternately, the modems may be used in a different mode, with the data logger calling out to the collection computer. However, with several stations in a network, it is easier to use Campbell's PC208 software to perform data collection from the host PC. The Campbell PC-208 software is used for remote programming of the data logger, maintenance procedures such as setting the data logger’s internal clock or changing instrument calibration factors, and for downloading data to the operations center. The software, which runs on a PC at the operations center, is configured for unattended operation.

4.1.2 Data Flow and Retrieval Schedule

Each night, the automated software at the operations center calls the 12 sites, one at a time, and attempts to download the previous day's data. The data are stored in files on the computer's hard drive, where they are available for processing and inspection when the staff arrives each morning. In practice, the staff frequently has to manually complete the downloading phase of the operation because of a variety of problems that occur during the nightly automated polling process. These problems include poor quality, long-distance phone lines or improperly connected phone lines at the site.

The raw data files are copied to floppy disks and stored in an on-site data archive at the Solar Village. In addition, the files are transferred to another computer at the KACST laboratory site in Riyadh. This serves to provide for both redundant off-site data storage and for more convenient access to the data by research staff in KACST. Each month, the data are consolidated into site files and transferred to NREL for parallel processing and analysis.

4.2 Data Analysis and Quality Assessment Software Development

4.2.1 DQMS Software

The Data Quality Management System software was developed initially by Augustyn + Company for its solar radiation network activities. Based on additional specifications from NREL, DQMS was designed to facilitate data collection from network sites and data quality analysis. Funding from KACST and the U.S. Department of Energy contributed to producing a Windows-based software package that satisfied the requirements of the Annex II project, including the SERI QC quality assessment software.

DQMS allows a network administrator to collect, analyze, report, and archive data on a daily basis. Many routines are automated or can be computer-initiated, minimizing operator involvement. Analysis is aided by visual graphing tools and summary reporting. In addition to archiving the data in a Paradox database, DQMS allows for exporting of data in commonly used data formats.

DQMS is a powerful tool for testing, flagging, and modifying data. It provides mass processing of data from individual stations, performing such functions as range checking, correcting, and reformatting data files. It can handle missing data in several different ways, including filling the blank data with an interpolation, or copying data from an earlier or later source. All changes made to the data files are logged for a complete record of the data processing steps taken on a data set.

DQMS appends a character to the end of each abbreviated site name in the table to create the file names for the station. This character comes from the Record Code in the record definition table. In this way, two data files may be collected from the same data logger. For example, on a Campbell CR-10, data could be collected from primary storage for a station with record code “1,” and secondary storage for record code “2.” This is what is done for the Saudi stations, with five-minute data appearing in record code 1 and hourly data in record code 2.

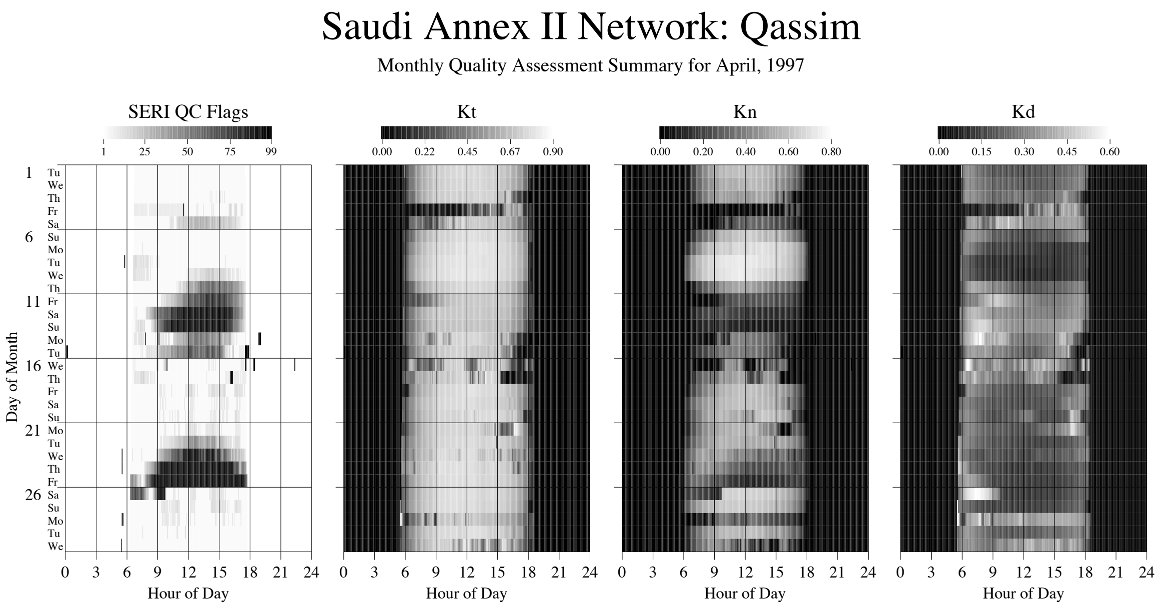
4.2.2 Quality Assessment Tools

Because of the large amount of data produced by a solar radiation network, software tools were developed to help the network administrator analyze the quality of the data on a daily, weekly, and monthly basis. By examining the network operations in these time frames, the administrator can spot data acquisition errors immediately, see trends of deteriorating data quality as they occur, and get an overview of a site's operations from a monthly perspective.

SERI QC and QCFIT are data quality assessment programs that were developed at NREL before the start of Annex II. NREL allowed Augustyn + Company to incorporate SERI QC into its DQMS program. QCFIT makes use of historical data collected at each station to establish boundaries within which good quality data are expected to lie. This allows new data from a specific site to be evaluated using guidelines derived from previous data for that same station. Once boundaries have been set using QCFIT, the SERI QC program is used to evaluate new data and to assign quality flags to such data.

The Shades Program developed for Annex II converts measured values and quality assessment flags to shades of gray and provides a visual Cylinder Plot representation of the data and its associated quality that is understandable at a glance, even when looking at tens of thousands of data points in a monthly data set. By organizing the shades of gray in a matrix of hours and days, trends in the data are highly conspicuous, alerting the data analyst to emerging problems and allowing for correction before the problem worsens. Figure 4.1 is a typical Cylinder Plot illustrating both good-quality operation of a station and the most common problems that occur.

In Figure 4.1, the irradiance values (in K space as a ratio with extraterrestrial irradiance) for global horizontal, direct normal, and diffuse horizontal are shown under the headings Kt, Kn, and Kd, respectively. The higher K values are displayed as lighter shades of gray. The quality flags for the data are displayed in the left-most plot under the heading SERI QC flags; the more severe flags are displayed as darker shades. This flag plot does not show the flags from all three components, but rather the most severe flag from among each flag of the three components for each measurement time. This method emphasizes the most significant problems in data acquisition.



Summary Statistics

Percent of data	Daytime Glo	Dir	Dif	Temp	RelHum	Nighttime Glo	Dir	Dif	Temp	RelHum
Present	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
*Flags <= 5%	76.9	76.8	76.8	100.0	100.0	100.0	99.9	99.8	100.0	100.0
*Flags > 10%	16.5	16.4	16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
*Below empirical limit	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
*Above empirical limit	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
*Strange but true	2.2	2.2	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Site Information

Identifier: GS1
Latitude: 26.31
Longitude: 43.77
Elevation: 647 meters
Time Zone: 3.0
Data Resolution: 5 min

* Flag statistics indicate percent of present data

Developed by the National Renewable Energy Laboratory

Figure 4-1. Cylinder plot of data for April 1997, Qassim, illustrating typical problems

In the example data, the analyst can immediately see two periods of serious data acquisition problems: one occurs between April 9th and April 15th, and the other between April 22nd and April 26th. In these cases, the problem is most likely due to failure of the station personnel to correct the tracker alignment for changes in the solar declination angle. This conclusion is based on several subtle observations in the plots. First, the errors grow progressively worse each day, starting out as minor flags (light shading) in a limited portion of the day, then expanding both in duration and severity with each progressive day. Then, as best seen on the morning of the 26th, the flags stop abruptly, indicating that the technician corrected the tracker settings. The effect of correcting the tracker alignment is also seen in the data for direct normal and diffuse horizontal as an unnatural discontinuity in the irradiance. Further, the global horizontal data, which does not rely on a tracker, shows no such discontinuity.

Based on this information (and, of course, corroborating evidence from station maintenance logs), the analyst could possibly deem the global horizontal data as salvageable. However, under these circumstances, even the global data would be suspect if indeed the instruments had been neglected for a period of a week or more.

These and other characteristic patterns in the cylinder plots have been identified, pointing to specific operational or equipment problems. Although these plots are a valuable tool for summarizing operational problems, a more proactive approach to data quality has been undertaken with software developed to produce similar plots with a shorter window of time. By producing plots of the previous week's data during routine daily processing, the analyst can identify problems as they develop and take immediate corrective action.

4.2.3 Monthly Network Processing Utilities

Several utilities were developed to aid in the generation of a monthly data and quality analysis report for the network. This group of programs and batch files aids the network operator in the repetitive tasks associated with producing summary reports for each station in the network.

4.3 Data Analysis and Quality Assessment Procedures

Using the software described above, staff at the network operations center carry out several daily and monthly procedures to help assure the quality and accessibility of the data.

4.3.1 DQMS Procedures

Each day after the data have been successfully transferred from all network sites, the data are transferred into Paradox data tables managed by the DQMS program. During this procedure, the data are transferred into a rigid time-series table; in the process, problems with incomplete or missing records, duplicate records, or other format errors are corrected. These tables are then the source of data for all other processing steps.

Quality assessment is performed using the SERI QC protocol, which is built into the DQMS software. Data are assessed and SERI QC flags are assigned and stored with each data point in the table. The data and flags are sent to the Shades Program, which gives the operator a temporal view of the data for a given site, spanning about one week. By viewing the quality flags in this week-long context, the analyst can spot immediate or persistent data acquisition problems and trend conditions that are likely to lead to more severe problems. The data are also examined in DQMS as a diurnal time-series plot.

4.3.2 Troubleshooting and Maintenance

If problems are discovered during the data examination and analysis phase, an effort is made to deduce the cause through characteristic effects of known malfunctions and the results of quality assessment. When the cause has been detected, the most common response is to contact the site operator and seek further information or recommend corrective action. With more serious problems beyond the expertise of the site operators, a specialist may be dispatched from KACST to visit the site and correct the problem.

The most persistent problems with maintaining high-quality data acquisition have been tracker misalignments. The causes of tracker problems generally fall into three categories: lack of attention by station personnel, improper tracker setup, or equipment failure. The two latter causes can also contribute to the former (reduced attentiveness) if attempts to maintain equipment are thwarted by conditions beyond the control of the on-site staff. To a lesser degree, power failures have contributed to improper measurements, a problem that is sometimes exacerbated by the lack of immediate follow-up and correction by station personnel.

The procedures also encourage contacting site personnel to relay positive reaction to data collection. This serves several purposes, including communicating the sense of a job well done and fostering an environment based in a spirit of scientific discovery. It is always important to impart a sense of purpose that otherwise might be lost on staff far removed from the end results of network data collection.

4.4 Current Status of Network Operations

As of the end of 1997, network operations as described here continued at the 12 observation sites. Daily data processing and data analysis continue at the network operations center at the Solar Village, with follow-up analysis at KACST and NREL. To date, all monthly analysis reports have been generated at NREL; however, beginning in 1998, KACST took responsibility for this function, with NREL participating as a consultant. Current procedures mandate that all network radiometers be calibrated on an annual basis. Each site is visited at least once per year to deploy calibrated instruments, and some sites are visited more frequently as the need for equipment repair or maintenance arises.

The value of these procedures is reflected in the overall quality of data produced by the network. As detailed in Section 5.0, statistics for 1995, 1996, and 1997 show data retrieval above 99% for the network, and data quality has been within instrument uncertainty for 85%-90% of all data collected. This represents outstanding individual station and network performance, far better than most other national networks, including those operated within the United States.

5.0 Summary of Network Data Acquisitions

This section gives an overview of data acquisition for the solar monitoring network from perspectives of both solar radiation values and data quality.

5.1 Data Analysis

The established procedures for assessing and reporting data quality involve computerized quality checks, expert examination by a data analyst, and keeping records of data acquisition problems. As detailed in Section 4.3.1, the network operations staff examines the data using the DQMS and SERI QC software packages. The SERI QC procedures compare the measured data with boundaries of expected values and assign quality flags that represent the magnitude of departure from expected values. These flags are then displayed on cylinder plots, allowing the analyst the opportunity to view the data in summary form.

The data analyst reviews quality flag summaries and then investigates known or suspected problems. With experience, the analyst can often make preliminary conclusions about equipment or maintenance problems by looking at the data or data summaries. These observations, when compiled over time, give the analyst a broad view of the effectiveness of the operations, equipment maintenance, and staff training for any particular station.

A useful statistic to characterize the quality of a solar radiation data set is the number of measurements that fall within a certain range of the expected values. Although various methods are incorporated in the software, the expected values for most of the Saudi Annex II network data are determined by measurement redundancy: the three measurements (global horizontal, direct normal, and diffuse horizontal) are related such that any one SERI QC uses a threshold of 5% disagreement between measured and calculated global horizontal solar radiation. This roughly translates into the uncertainty of the instrumentation and data acquisition process, given the nature of the operating environment. Thus, we routinely summarize data quality by reporting the percentage of data that falls within this 5% threshold of agreement, a level of quality that characterizes a well-run site. Conversely, we also report the percentage of data that exceeds a 10% threshold of agreement, which may suggest circumstances that cast suspicion on the usefulness of the data set for research or design purposes.

One commonly used solar radiation data product is monthly mean daily total solar radiation in kilowatt-hours (kWh) per meter squared. Although the network logs data with five-minute resolution in watts per square meter, these values can be converted to daily total radiation by integrating the five-minute values into a watt-hour value, then summing the watt-hours for the entire day (daily total), yielding the power potential for a collector device. These daily values can then be averaged over a period of a month to produce the monthly mean daily total. Over a period of several years, these values will represent the long-term potential for a site, and the standard deviation of the daily values represent the variability of the resource.

To produce a monthly mean daily total value, quality checks are made at several points, any one of which can thwart the attempt to produce a daily value. The first step involves integrating the five-minute values to an hourly value. Using some threshold of data quality, data are filtered during the integration step. Values with quality flags that exceed the threshold are eliminated from the calculation. But if too many measurements are eliminated during an hour, the resulting hourly value may not be representative of the true value. This may be especially true during times when the solar radiation is highly variable over the integration period, such as near sunrise or sunset, or under variable clouds.

We require a minimum of 10 of the 12 possible five-minute values within an hour to produce a valid hourly integration. If that criterion is not met, then an hourly value is not reported. But because the daily value is a summation of all hourly values, even one missing hourly value renders the daily total invalid. Hence, as few as three five-minute values outside the quality thresholds, if all occur in the same hour, can terminate the calculation of a daily total.

In the case of two stations (Al-Jouf and Al-Madinah), the required minimum number of valid five-minute values in an hour was reduced due to special circumstances. At these sites, the radiometers were briefly shaded by a nearby instrumentation tower each day for a period of several weeks. These events, which last about 15-20 minutes, could prevent the calculation of a daily total for every day of a month. Because of the good quality of data at these sites, this relaxed processing should have minimal effect on the overall statistics.

5.2 Data Reports

For each of the twelve network sites, Figures 5-1 through 5-12 provide a summary of station operations including:

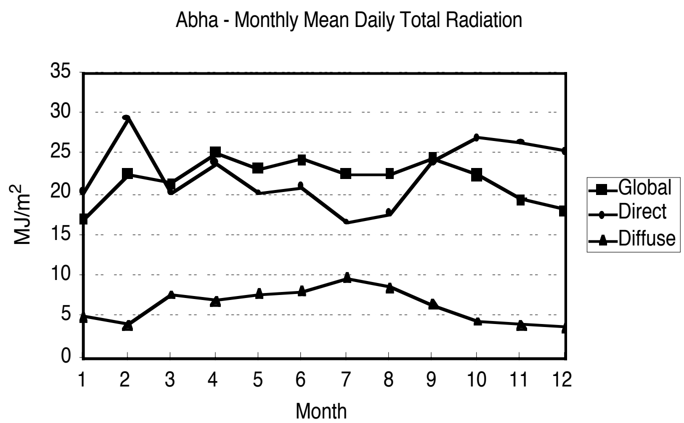
The period of record for the site
The percent of data that falls within the 5% threshold, by year
The percent of data that falls beyond the 10% threshold, by year
The percentage of possible data points collected, by year
A plot of monthly mean daily total radiation (global, direct, diffuse)
A table of monthly mean daily total radiation, standard deviations, and sample size
A narrative summary of the station operations.

In addition, Table 5-1 provides a summary of network operations for the percent of data that fall within the 5% threshold, by year; the percent of data that fall beyond the 10% threshold, by year; and the percent of possible data points collected, by year.

In the tables, the sample size N indicates the number of days within each month (over the period of several years), that met the quality assessment criteria and were used to compute the mean and standard deviations.

Abha Period of Record:
6/18/95 - 12/31/97

Abha–Data Quality			
Statistics	1995	1996	1997
<5%	93.9	89.8	92.1
>10%	3.2	5.9	4.0
% measured	91.7	99.7	99.9



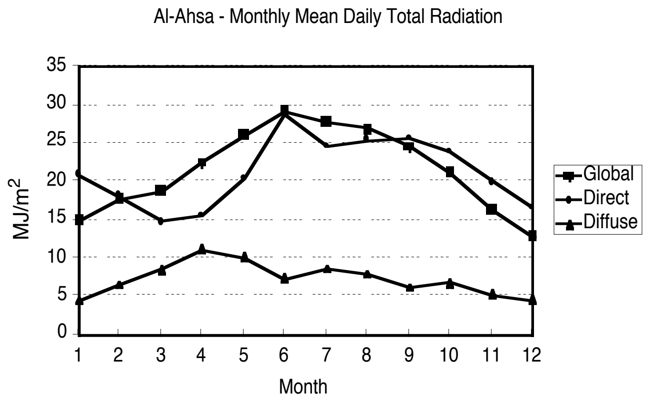
Abha–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size									
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	16.99	3.90	55	20.27	9.39	54	5.08	1.92	56
02	22.58	2.37	45	29.39	6.01	46	3.94	1.76	47
03	21.32	7.11	47	20.37	12.17	49	7.75	4.06	50
04	25.20	3.90	41	23.84	6.70	42	6.95	2.17	42
05	23.20	4.58	55	20.22	7.65	56	7.88	2.98	57
06	24.27	4.28	70	20.92	7.67	70	8.15	2.04	70
07	22.54	4.11	83	16.66	6.14	84	9.76	2.37	85
08	22.61	3.43	64	17.67	6.09	66	8.66	1.74	66
09	24.42	2.73	70	24.03	6.28	70	6.56	2.24	70
10	22.36	4.82	76	27.03	9.93	76	4.46	2.37	78
11	19.48	3.66	78	26.35	8.81	77	3.98	1.97	84
12	18.05	2.70	88	25.29	7.89	86	3.76	1.84	88

The statistics for this site are very good, indicating proper maintenance practices by site personnel. When data quality suffered, the cause was generally a short-lived occurrence and problems were detected and corrected by station personnel within a few hours or a day.

Figure 5-1. Summary of station operations at Abha

Al-Ahsa Period of Record:
1/23/95 - 12/31/97

Al-Ahsa–Data Quality			
Statistics	1995	1996	1997
<5%	92.1	88.3	90.3
>10%	4.4	6.8	2.8
% measured	92.8	100.0	97.4



Al-Ahsa–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

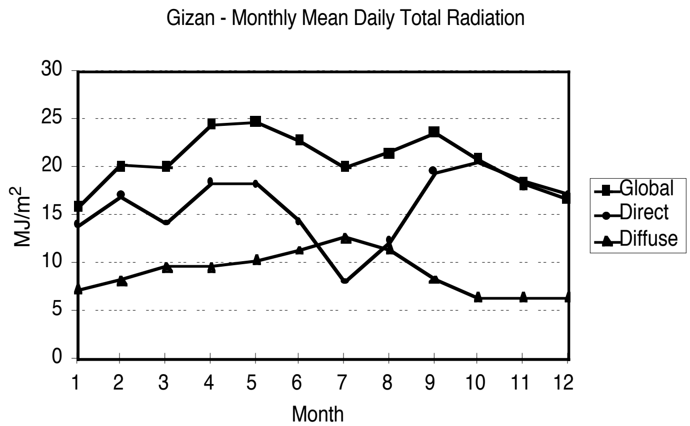
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	15.05	3.76	67	20.84	9.29	66	4.35	1.91	67
02	17.59	3.86	72	18.12	9.23	73	6.57	2.77	73
03	18.68	6.56	77	14.65	10.87	79	8.51	3.21	79
04	22.39	5.20	51	15.54	9.84	53	11.18	4.40	53
05	26.03	3.89	55	20.45	8.79	57	10.12	3.35	57
06	29.16	1.44	74	28.75	4.42	74	7.34	1.72	74
07	27.75	3.09	84	24.65	6.57	83	8.61	2.39	83
08	26.88	1.66	80	25.42	3.81	80	7.81	3.00	80
09	24.40	1.56	74	25.64	4.60	74	6.13	1.71	74
10	21.17	5.91	76	23.83	8.50	74	6.71	3.92	74
11	16.16	3.30	80	19.92	8.67	80	5.26	2.72	80
12	12.80	3.82	87	16.56	10.28	86	4.44	2.14	86

This site had tracker problems in 1996 that caused data degradation. And in 1997 the data logger malfunctioned for several weeks before a replacement could be deployed. Site maintenance has been consistently excellent through the period of record.

Figure 5-2. Summary of station operations at Al-Ahsa

Gizan Period of Record:
6/12/95 - 12/31/97

Gizan–Data Quality			
Statistics	1995	1996	1997
<5%	85.0	86.1	94.0
>10%	8.0	8.1	2.9
% measured	94.4	100.0	100.0



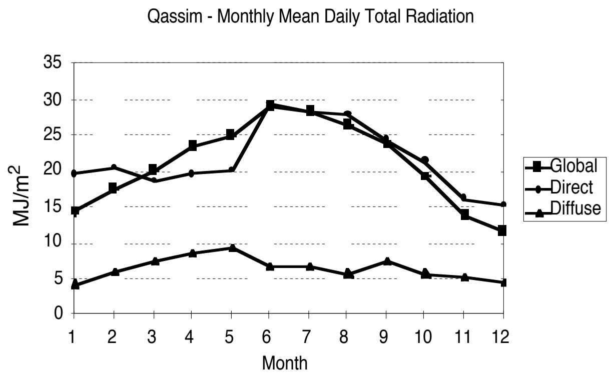
Gizan–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size									
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	16.05	2.69	57	13.93	6.11	57	7.34	1.58	57
02	20.16	1.82	49	17.01	3.94	50	8.25	1.52	50
03	20.13	3.64	38	14.22	7.65	40	9.67	2.33	41
04	24.52	2.02	32	18.44	4.31	31	9.70	1.59	31
05	24.76	3.28	25	18.25	5.79	26	10.45	2.50	26
06	22.94	3.44	37	14.32	5.83	36	11.40	2.67	37
07	20.14	3.48	66	8.13	4.12	64	12.76	1.91	64
08	21.57	3.57	61	12.36	5.20	62	11.55	3.05	63
09	23.70	1.07	75	19.52	3.23	74	8.41	1.63	76
10	20.97	3.28	75	20.59	5.45	75	6.52	1.46	76
11	18.35	2.82	65	18.53	6.13	66	6.43	1.86	68
12	16.77	1.63	87	17.20	4.37	87	6.43	1.22	87

Tracker malfunctions were a chronic problem at this site during 1995 and much of 1996. The problems were corrected in late 1996 and data quality improved significantly in 1997. The cause of the tracker malfunctions was improper alignment during setup and clutch failure. Despite these problems, site personnel have always been conscientious about detecting and compensating for the malfunctions in a timely manner.

Figure 5-3. Summary of station operations at Gizan

Qassim Period of Record:
11/8/94 - 12/31/97

Qassim–Data Quality			
Statistics	1995	1996	1997
<5%	85.3	91.7	93.0
>10%	8.5	4.6	3.8
% measured	98.6	100.0	100.0



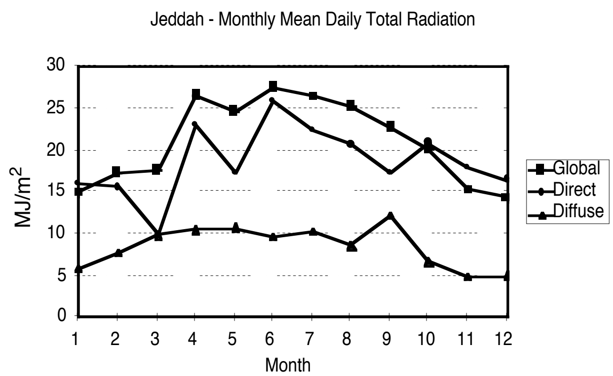
Qassim–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size									
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	14.54	2.50	73	19.77	8.29	75	4.48	1.82	75
02	17.86	4.41	58	20.69	10.42	59	6.20	3.75	62
03	20.28	5.71	69	18.69	10.73	71	7.68	3.18	71
04	23.54	4.95	59	19.67	9.42	60	8.73	2.85	60
05	25.26	4.61	76	20.35	9.43	78	9.51	2.98	78
06	29.14	1.47	75	29.52	5.01	80	6.75	2.11	80
07	28.44	1.78	90	28.27	5.60	90	7.02	2.71	90
08	26.71	1.23	89	28.02	3.49	89	5.97	1.46	89
09	23.82	1.84	71	24.50	5.28	72	7.52	4.58	77
10	19.49	2.58	79	21.53	7.21	79	5.98	2.03	80
11	14.04	4.38	75	16.32	9.97	75	5.30	2.07	75
12	11.78	4.19	82	15.48	10.28	82	4.53	2.22	83

Tracker problems plagued this site in 1995, and subsequently in 1996, the quality of the site maintenance appeared to decline. This decline manifested itself as repeated periods of a week or more when the trackers would not be adjusted for change in the solar declination angle. The quality of maintenance improved in 1997. Data from November and December 1994 are not included in this summary

Figure 5-4. Summary of station operations at Qassim

Jeddah Period of Record:
5/1/96 - 12/31/97

Jeddah–Data Quality			
Statistics	1995	1996	1997
<5%	NA	75.1	83.5
>10%	NA	20.2	10.2
% measured	NA	100.0	100.0



Jeddah–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

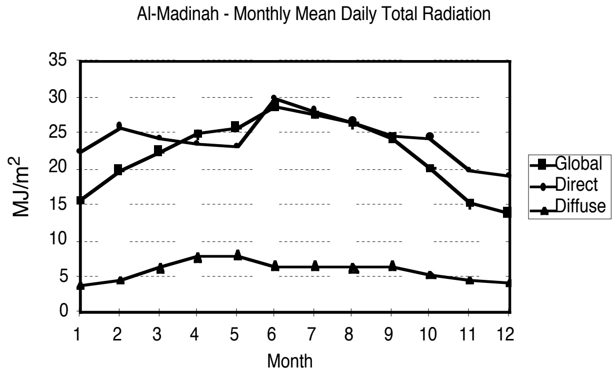
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	15.04	1.97	21	16.20	7.64	21	5.90	2.55	21
02	17.36	4.33	22	15.60	9.35	22	7.87	2.27	22
03	17.81	4.96	17	9.93	6.46	16	9.96	1.95	16
04	26.72	3.56	15	23.15	8.81	17	10.52	4.74	17
05	24.60	4.54	24	17.32	9.03	23	10.80	2.42	23
06	27.67	1.78	22	26.05	5.46	21	9.79	4.86	26
07	26.51	3.25	50	22.38	8.11	49	10.23	5.07	49
08	25.26	1.55	23	20.68	4.43	23	8.66	1.89	23
09	22.76	2.41	20	17.28	5.72	18	12.26	5.92	19
10	20.25	2.61	43	20.93	5.83	44	6.74	2.69	44
11	15.34	4.32	54	17.88	8.30	55	5.00	1.67	55
12	14.32	2.05	60	16.58	6.01	61	5.12	1.56	61

Jeddah was the last of the network sites to go online, and for the first year of operation data quality suffered from an improper platform installation that allowed the platform to tilt as it settled into the desert sand. Site personnel were also not performing maintenance regularly, a situation that persisted until the last quarter of 1997 when data quality improved significantly.

Figure 5-5. Summary of station operations at Jeddah

Al-Madinah Period of Record:
9/17/95 - 12/31/97

Al-Madinah–Data Quality			
Statistics	1995	1996	1997
<5%	76.8	94.1	91.5
>10%	19.2	3.8	5.2
% measured	85.1	99.7	99.8



Al-Madinah–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

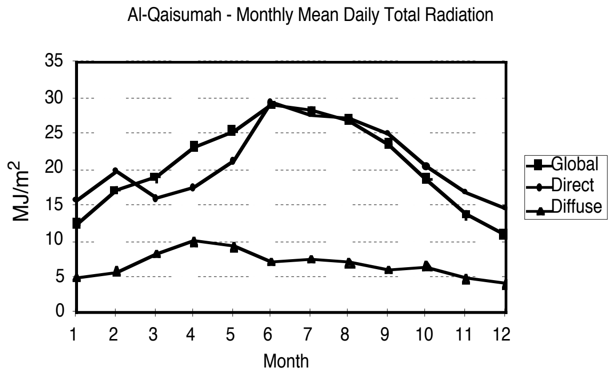
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	15.76	2.60	52	22.52	7.87	52	3.94	1.86	52
02	20.09	1.96	52	25.92	7.04	52	4.72	2.27	52
03	22.60	4.87	55	24.38	11.62	54	6.41	3.25	54
04	24.94	4.52	48	23.52	10.08	48	7.81	3.25	49
05	25.80	4.45	51	23.24	9.99	52	8.20	3.20	52
06	28.85	1.34	45	29.88	5.04	45	6.67	2.48	45
07	27.63	2.22	57	28.12	6.90	57	6.74	2.94	58
08	26.35	1.78	51	26.77	5.71	52	6.36	2.02	52
09	24.36	5.45	54	24.55	7.08	54	6.69	1.85	54
10	20.22	2.02	73	24.43	5.40	74	5.54	3.63	78
11	15.34	3.72	78	19.83	8.86	78	4.59	1.66	79
12	13.91	2.61	86	19.06	8.33	86	4.31	1.86	86

Serious problems with initial tracker setup degraded much of the data for this site in 1995. Maintenance has always been good at this site, and tracker problems were less significant after the trackers were set up correctly. A nearby instrumentation tower briefly shades the radiometers for a few minutes every day during several weeks in the summer.

Figure 5-6. Summary of station operations at Al-Madinah

Al-Qaisumah Period of Record:
8/27/95 - 12/31/97

Al-Qaisumah–Data Quality			
Statistics	1995	1996	1997
<5%	94.9	90.4	79.1
>10%	0.6	6.4	14.2
% measured	82.9	100.0	100.0



Al-Qaisumah–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

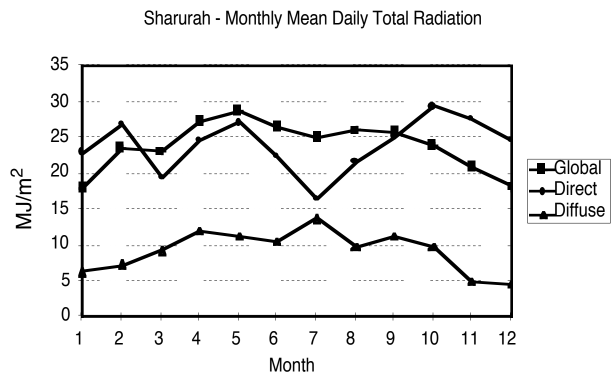
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	12.50	3.91	57	15.89	10.20	57	4.98	2.63	58
02	17.19	4.08	45	19.94	10.25	45	5.87	2.57	45
03	18.95	5.05	48	16.06	10.88	48	8.28	2.98	48
04	23.34	5.43	19	17.53	12.15	20	10.04	3.48	20
05	25.50	4.72	28	21.25	10.15	28	9.35	3.05	28
06	29.04	1.74	58	29.37	5.96	57	7.25	2.68	58
07	28.34	1.83	37	27.53	5.61	38	7.78	3.37	38
08	26.94	1.37	36	27.20	4.27	39	7.09	1.80	39
09	23.63	1.84	48	25.03	5.85	47	6.06	2.15	47
10	18.78	2.69	82	20.42	7.61	83	6.71	3.59	89
11	13.80	3.95	87	16.93	9.34	87	4.83	1.70	87
12	11.06	4.13	88	14.62	10.62	87	4.09	1.73	87

Consistently high-quality data with very few equipment problems distinguished this site for the first two years of operation. In 1997 it appears that site maintenance began to lapse and data quality suffered, as evidenced by periods of a week or more when no adjustments were made of the tracker declination settings.

Figure 5-7. Summary of station operations at Al-Qaisumah

Sharurah Period of Record:
6/6/95 - 12/31/97

Sharurah–Data Quality			
Statistics	1995	1996	1997
<5%	82.9	82.0	79.0
>10%	12.9	12.2	15.3
% measured	97.3	100.0	100.0

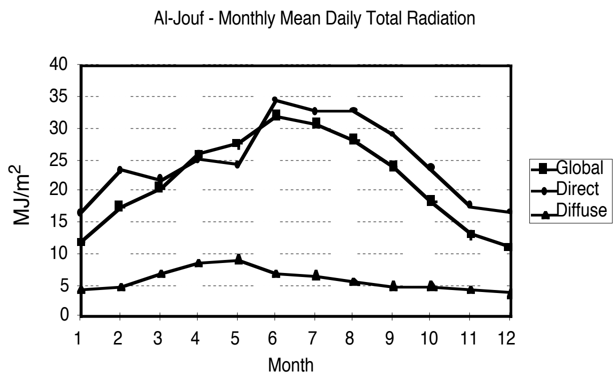


Sharurah - Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size									
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	18.06	4.07	43	23.00	9.13	43	6.35	5.12	48
02	23.56	2.39	31	27.01	6.96	31	7.36	5.03	32
03	23.08	3.77	46	19.39	9.14	46	9.39	3.83	46
04	27.26	2.25	32	24.59	7.79	31	12.18	6.98	40
05	28.89	2.88	37	27.12	7.45	36	11.22	5.48	37
06	26.75	4.25	50	22.40	7.96	48	10.52	4.75	51
07	25.23	2.84	56	16.51	6.24	55	13.75	5.76	66
08	26.10	1.59	63	21.72	4.77	59	9.84	4.69	67
09	25.96	1.69	53	25.14	5.76	53	11.45	8.41	68
10	23.98	2.06	52	29.31	5.11	51	9.95	8.40	69
11	21.00	2.56	61	27.68	6.97	62	5.08	3.88	65
12	18.27	2.14	53	24.61	8.75	54	4.77	3.27	56

Both equipment problems and a lack of consistent maintenance characterize the history for this site. The equipment problems were often exacerbated by the lack of attention, which resulted in minor and easily corrected malfunctions persisting for days at a time.

Figure 5-8. Summary of station operations at Sharurah

Al-Jouf Period of Record:
8/9/95 - 12/31/97



Al-Jouf–Data Quality			
Statistics	1995	1996	1997
<5%	94.1	93.4	93.4
>10%	2.0	3.7	3.6
% measured	94.3	100.0	100.0

Al-Jouf–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

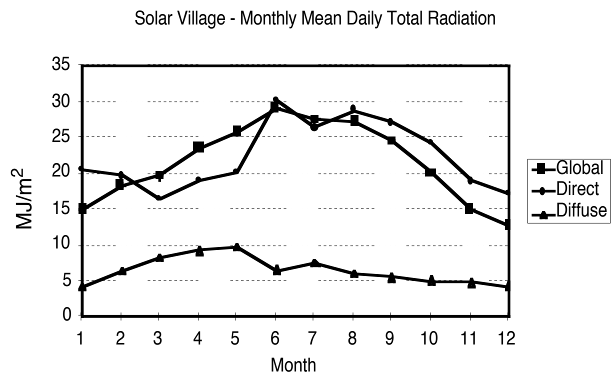
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	11.99	3.52	60	16.64	10.54	60	4.50	2.15	60
02	17.55	2.49	55	23.39	8.44	55	4.99	2.44	55
03	20.75	4.41	52	22.10	9.95	51	6.94	2.82	52
04	26.01	4.00	50	25.09	8.65	50	8.58	3.31	51
05	27.57	5.71	36	24.30	12.12	35	9.32	3.94	38
06	32.04	1.42	34	34.71	6.33	34	6.93	3.48	35
07	30.87	2.22	47	32.76	7.13	44	6.69	2.60	44
08	28.24	1.90	80	32.82	5.08	79	5.73	2.10	82
09	24.04	1.68	83	28.91	4.93	82	5.16	1.72	84
10	18.67	2.33	92	23.68	6.95	92	5.01	2.10	92
11	13.21	3.54	84	17.83	9.57	83	4.49	2.06	86
12	11.18	3.34	90	16.74	9.89	90	3.86	1.75	90

This site has an exemplary record of high-quality data, nearly unblemished by any evidence of improper maintenance. However, some persistent tracker problems were evident during early morning hours at certain times of the year. Data quality would undoubtedly be higher were it not for the necessity to install the radiometers where they are shadowed briefly everyday by a nearby instrumentation tower during the fall and winter. During the periods of radiometer shadowing, the quality assessment software imposes severe flags.

Figure 5-9. Summary of station operations at Al-Jouf

Solar Village Period of Record:
11/8/94 - 12/31/97

Solar Village–Data Quality			
Statistics	1995	1996	1997
<5%	94.2	98.7	98.6
>10%	1.8	0.3	0.2
% measured	100.0	100.0	100.0



Solar Village–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

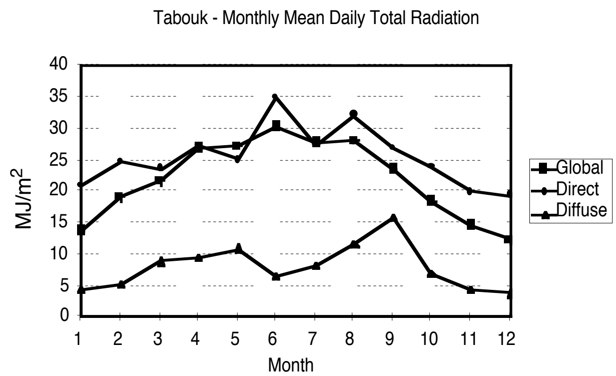
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	15.12	3.33	89	20.63	9.17	90	4.36	1.97	90
02	18.36	3.57	79	19.68	9.26	80	6.47	2.60	81
03	19.68	5.63	81	16.56	10.57	81	8.34	2.98	82
04	23.61	4.51	84	19.13	9.25	84	9.32	2.85	84
05	25.82	3.80	88	20.32	8.58	88	9.98	2.93	88
06	29.23	1.30	81	30.21	4.51	80	6.66	1.85	81
07	27.61	3.34	88	26.42	7.34	85	7.61	2.32	88
08	27.29	1.41	93	28.92	3.64	93	6.04	1.31	93
09	24.58	1.59	90	27.16	5.01	89	5.70	1.90	90
10	20.22	3.15	93	24.28	6.79	93	5.14	1.73	93
11	15.10	4.17	90	19.02	10.83	90	4.85	2.08	90
12	12.87	4.09	92	17.15	10.55	91	4.46	2.12	91

This site, which is home to the network operations center, retains the best data quality record among all network stations. Maintenance is consistent, routine, and expert, resulting in a data set of the highest caliber. Data from November and December 1994 are not included in this summary.

Figure 5-10. Summary of station operations at Solar Village

Tabouk Period of Record:
8/16/95 - 12/31/97

Tabouk–Data Quality			
Statistics	1995	1996	1997
<5%	62.8	87.6	86.8
>10%	31.9	9.1	9.7
% measured	89.7	100.0	100.0



Tabouk–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

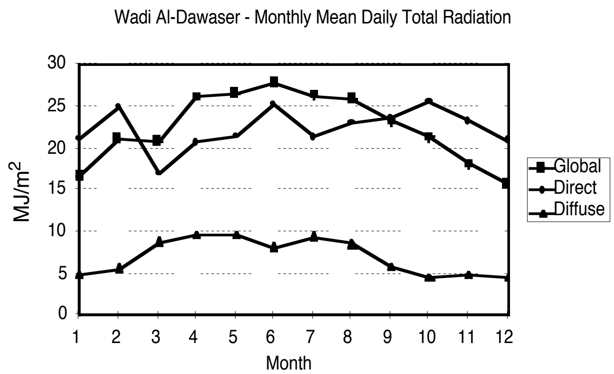
Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	13.97	2.44	36	21.08	8.88	35	4.37	2.44	37
02	19.10	2.48	38	24.91	9.43	37	5.35	3.37	37
03	21.69	4.93	32	23.76	9.49	30	9.06	6.86	32
04	26.95	2.43	27	27.23	8.61	26	9.44	5.34	27
05	27.32	4.85	37	25.04	11.06	37	11.00	5.65	38
06	30.44	1.59	20	34.83	3.53	20	6.66	2.82	20
07	27.85	3.32	25	27.48	9.71	25	8.39	5.26	25
08	28.15	1.81	42	32.21	2.54	41	11.67	9.90	55
09	23.65	2.00	26	27.02	5.48	25	15.97	9.25	58
10	18.68	2.34	45	23.91	7.35	46	6.88	5.51	52
11	14.78	2.97	55	19.95	9.00	54	4.53	2.41	54
12	12.44	3.13	61	19.42	10.01	62	3.94	2.58	64

The trackers at this site have been unreliable throughout nearly the entire period of record. Although site personnel appear to be conscientious about performing routine equipment adjustments, problems appear on nearly a daily basis during some months. Despite efforts to replace defective components, the problems recur, suggesting unsatisfactory tracker setup or improper training that results in equipment damage.

Figure 5-11. Summary of station operations at Tabouk

Wadi Al-Dawaser Period of Record:
4/24/95 - 12/31/97

Wadi Al-Dawaser–Data Quality			
Statistics	1995	1996	1997
<5%	91.2	92.6	94.7
>10%	5.1	2.4	2.8
% measured	88.1	100.0	100.0



Wadi Al-Dawaser–Monthly Mean Daily Total Radiation (MJ/m^2), Standard Deviation, Sample Size

Month	Global			Direct			Diffuse		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
01	16.73	3.58	59	21.22	8.64	59	4.90	1.87	59
02	21.29	1.39	44	24.97	5.64	44	5.68	2.39	44
03	20.89	4.93	60	17.00	9.60	60	8.92	3.34	61
04	26.19	1.86	53	20.70	5.94	54	9.79	2.89	54
05	26.72	2.52	67	21.52	6.80	70	9.65	2.77	70
06	27.94	2.55	71	25.26	6.62	72	8.27	2.63	72
07	26.47	2.69	85	21.34	5.95	85	9.51	2.20	85
08	26.12	1.80	71	23.14	5.10	71	8.66	2.94	73
09	23.32	6.71	82	23.82	7.94	83	6.03	2.50	83
10	21.29	5.04	84	25.71	8.61	85	4.68	2.22	85
11	18.24	3.08	84	23.20	8.80	84	4.99	2.52	85
12	15.91	3.28	91	20.94	9.08	90	4.70	1.97	90

This is an excellent data set despite some minor lapses in site maintenance. Some of these lapses may occur when the person responsible for maintenance is away from the site and there are no trained personnel to continue to work.

Figure 5-12. Summary of station operations at Wadi Al-Dawaser

Table 5-1. Network Rollup

Statistic	1995	1996	1997
<5%	86.6	88.8	89.7
>10%	8.9	6.9	6.2
% Measured	92.3	100.0	99.8

6.0 Acquiring Meteorological and Satellite Data

Task 2 of Annex II called for the assembly of a database of concurrent solar radiation, satellite (METEOSAT–Europe's geosynchronous weather satellite), and meteorological data (over a 10-year period, to the extent possible). This database was needed to support Tasks 3, 4, and 5. In particular, such a database could be used to: 1) evaluate and modify, if necessary, NREL models and other software for use under the climate conditions found in Saudi Arabia; 2) form a serially complete solar radiation database for Saudi Arabia, similar to the United States National Solar Radiation Data Base (NSRDB Vol. 1, 1992); 3) develop and evaluate methods to extract solar radiation data from METEOSAT images of Saudi Arabia; and 4) support the preparation of a uniformly spaced grid of solar radiation data for Saudi Arabia, for use in the preparation of maps and atlases and to estimate the performance of solar energy systems at any location in Saudi Arabia.

A significant effort was made to accomplish Task 2, and concurrent solar radiation, satellite, and meteorological data were assembled. However, the assembly of a database covering a 10-year period was not accomplished. Instead, sporadic data of various types were collected, primarily for the period from 1995 to 1997. The difficulties that prevented the accomplishment of the original objective include: 1) Plans to supplement data collected by the 12-station network with historical bi-metallic actinograph data have not been realized for reasons given in Section 7.0; 2) Several technical difficulties have limited the collection of METEOSAT data. These include shortcomings in data-processing hardware, difficulties in obtaining the correct image-processing software, and recent encrypting of the data stream; 3) MEPA did not begin digitizing meteorological data until 1995. The cost and time required to digitize historical data precluded the possibility of obtaining 10 years of meteorological data for all network stations.

The efforts made to accomplish Task 2, the problems encountered, and the results achieved are the subjects of this section. The first step toward the fulfillment of this task took place during a meeting at MEPA headquarters in Jeddah.

6.1 Acquisition of METEOSAT Images

On October 11 and 12, 1994, Dr. Saleh Alawaji, KACST project leader, and Dr. Maxwell, Annex II leader for NREL, traveled to MEPA headquarters at Jeddah. They met with key MEPA administrators and technical staff to discuss details of the installation, maintenance, and operation of the solar radiation equipment to be installed at MEPA facilities, including the procedures for transmitting the data to KACST and ultimately to NREL. They also discussed the acquisition, recording, and transmission of METEOSAT images, to be used in conjunction with network data to develop methods for estimating solar radiation resources using satellite data.

As a result of the meeting in Jeddah, MEPA began copying METEOSAT images to 8-mm tape early in 1995. However, problems were encountered because MEPA did not have adequate computer disk storage. Under their normal operations, they use the METEOSAT images for preparing weather forecasts and have no need to save them for more than two days. Therefore, KACST purchased and installed a large disk drive at MEPA headquarters, to facilitate the processing of METEOSAT images. Unfortunately, the disk drive failed after only one week of use. Overall, the time required to obtain a replacement disk drive consumed several months and by the end of 1995, only two tapes containing METEOSAT data had been received at NREL.

To make matters worse, NREL's initial attempts to extract data from the METEOSAT tapes were unsuccessful. The format of the data received could not be read by the software available to NREL. These problems were eventually resolved and it was determined that these images were essentially unprocessed raw images as received from the satellite.

During May 1996, two NREL scientists, Steve Wilcox and Chris Cornwall, traveled to Riyadh to assist KACST with the recalibration of solar radiometers. While there, they took the opportunity to visit MEPA headquarters with Dr. Alawaji and Mohammed Bin Mahfoodh to discuss the ongoing problems with the transfer of meteorological and METEOSAT data to NREL. These discussions were helpful and by the 4th quarter of 1996, METEOSAT data collected by MEPA and forwarded to NREL by KACST, were being processed and analyzed. However, routine, daily collection and transmission of data had not been accomplished. Furthermore, many of the images received from MEPA were still encrypted and NREL could not use them. The number of useful METEOSAT images received by the end of 1996 was inadequate to analyze the feasibility of extracting solar radiation data from them.

Late in 1996, MEPA installed a new downlink system for receiving METEOSAT images. The encryption problem was resolved and useful images were transmitted to NREL. Furthermore, the images received in 1997 were in a standard format [Tagged Image File Formats (TIFF)], error correction had already been performed, and they were geo-rectified such that image pixels corresponded with ground locations. These images were limited to the Saudi Arabian peninsula. All in all, these changes were highly desirable because they greatly reduced the data processing required of NREL. However, the two sets of images received were at different scales, one with 7-km pixels, the other with 11-km pixels. At the conclusion of the first four years of Annex II, useful METEOSAT images had been received, but not in sufficient quantity to support the research that had been planned. The potential for extracting useful information regarding solar resources is still there, but it will not be realized unless five images per day are routinely collected and processed for a period of five years or more.

6.2 Acquisition of Meteorological Data

In 1996, MEPA provided NREL with surface meteorological data for the period from January 1995 to June 1996. In 1997 these data were extended to June 1997. The data were supplied in the WMO Synoptic format (WMO 1995), but the file structure for the two transmissions of data were not the same. The first data were in monthly files; the second were in daily files. A format decoder was developed at NREL that allowed partial reading of the files; however, a complete and consistent decoding was not achieved. These data are being compared with a source of worldwide meteorological data to determine which will be most useful for solar resource applications.

Upper air, radiosonde data were received from MEPA for the period from January 1994 to November 1995. They were supplied in a format that provides temperature and humidity data at predetermined atmospheric pressure (altitude) levels. Such data can be processed to determine the distribution of water vapor in the atmosphere as well as the total precipitable water vapor from the surface to some specified upper limit. Data were also received for a later period of time, but these were in a different format and could not be combined with the previous data.

Format changes and intermittent deliveries are still limiting the usefulness of the data received from MEPA. Hopefully these difficulties will be resolved during the extension of Annex II such that a long-term solar radiation database for Saudi Arabia can be produced. If not, another source of meteorological data will be used.

6.3 DATSAV-2 Data

The United States Air Force and NCDC have cooperated to acquire and archive all of the worldwide surface meteorological data as it is transmitted to WMO. The DATSAV-2 data contain all of the WMO mandatory fields but may not include optional fields collected by the meteorological services of some of the countries. Using DOE funding, NREL has acquired tape copies of all of the worldwide DATSAV-2 data. Extensive computer code was written to extract those data from the tapes that are required for forming wind and solar radiation resource assessment databases.

The data extracted from the DATSAV-2 tapes for MEPA stations can and likely will be used to produce a solar radiation database for Saudi Arabia. Because of this extensive multi-year effort that was funded entirely by DOE, the difficulties encountered in collecting similar data under Annex II will be circumvented. Under an extension of Annex II, a solar radiation database for Saudi Arabia should be realized and should cover a period of 20 to 30 years rather than 10 years, as was originally planned.

7.0 Evaluating Bimetallic Actinograph Data

The bimetallic actinograph has been in use for decades throughout the world as an easily installed, low-maintenance method of measuring global solar radiation. Many models use a windup spring for power to run the strip chart data-logging system. The replaceable paper charts hold data for a week or more. These characteristics make the actinograph attractive for measuring data in remote locations where power is not available and daily attention is not possible.

A significant disadvantage of the actinograph is that the data are delivered in a hard-copy pen-and-ink graphical form; in the past, putting the data in electronic form has required digitization using a planimeter or other manual method.

The purpose of this project was twofold: 1) Determine the accuracy of measurements from the bimetallic actinograph, and 2) determine the feasibility of digitizing a large amount of bimetallic strip chart data. Having obtained positive results from both of these tests, the potential exists for significantly enlarging the historical archive of solar radiation measurements.

7.1 Principle of Operation

The operation of the actinograph is based on the properties of the bimetallic strip, which bends in response to temperature changes. By coating the strip with a black absorbent material and exposing it to the sun's energy, the strip bends in proportion to the change in temperature, which is proportional to the intensity of the solar radiation. Through a linkage to an ink pen, the bending of the bimetallic strip is translated to a strip chart graph of solar intensity. The unit is temperature compensated through the use of a second, shaded bimetallic strip that counters the effect of ambient temperature changes. The photographs in Figures 7-1 and 7-2 show the working mechanisms of the Belfort actinograph.

7.2 Project Design

To test the operation and accuracy of the device, an actinograph was purchased and set up at the Solar Village research facility, to be run in tandem with the state-of-the-art network system at that location. The unit purchased was a Pyranograph Model 5-3850A manufactured by the Belfort Instrument Company. The specifications for this unit claim accuracy within 5%. The global horizontal instrument at the Solar Village is an Eppley PSP radiometer, which was used for comparison with the actinograph. Data logging for the PSP was accomplished with a Campbell Scientific CR-10 data logger. During the test period, both instruments were scheduled to receive similar daily maintenance, which consisted primarily of cleaning instrument optics and checking data-logging operations.

7.3 Data Digitization

To convert the data logged on the actinograph strip charts to digital form, a system was developed at NREL that takes advantage of advances in image-scanning computer technology. By scanning the strip chart as a bit-mapped image, the image can be considered as a matrix; hence, the position of the graph line can be interpreted as changes in solar radiation as a function of time.

Figure 7-1. Bimetallic strips under dome of a Belfort actinograph (shaded strip toward the back)

Figure 7-2. Belfort actinograph with cover removed showing pen linkage to bimetallic strips at top

7.3.1 Scanning

The digitization process begins by making a high-resolution color scan of the strip chart. Figure 7-3 is a typical one-week record from the actinograph at the Solar Village. Because the strip-chart background is light yellow and the scale markings are red, the contrasting blue ink of the data trace is easily discernible as a separate information entity. Using capabilities of the PhotoShop image software sold by Adobe Systems, Inc., one may select for the blue spectrum, and all image information except for the blue ink portion may be filtered and discarded. Some minor editing is usually required to clean up other spurious image pixels. This leaves an image of only the data

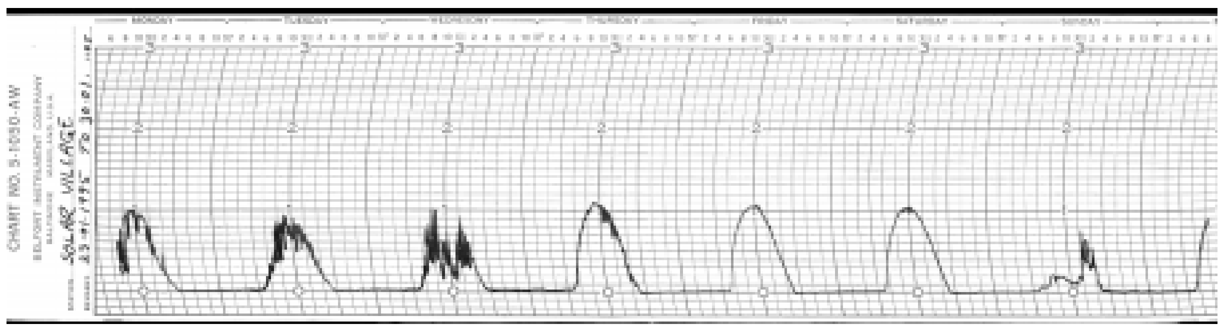


Figure 7-3. An actinograph chart from the Solar Village for January 23, 1995 to January 30, 1995

line in bit-mapped form. Again using the PhotoShop software, reference marks are placed on the image to index the image for time and the chart zero reference. The image is then saved in the Windows BMP format as a black and white one-bit image. By careful selection of the scanning resolution, each column of pixels represents a five-minute sample. Figure 7-4 is the image obtained from scanning the chart shown in Figure 7-3.

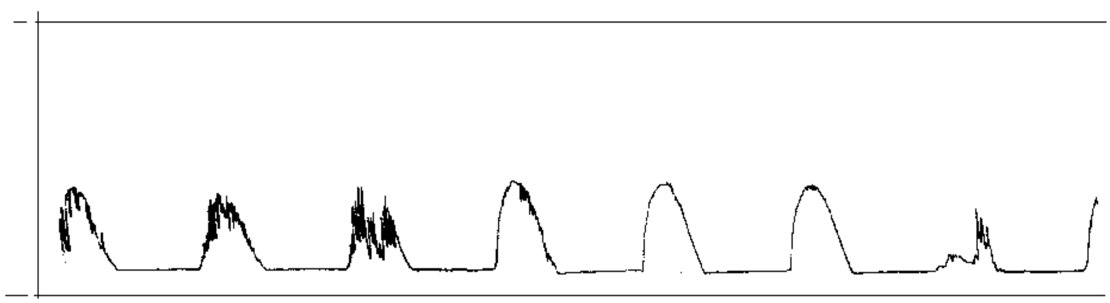


Figure 7-4. The bit-map image obtained by scanning the chart in Figure 7-3

7.3.2 Interpreting the Image

Software was developed to interpret the scanned image and translate it into an output file that is similar to the output of a data logger. The system seeks and identifies the index marks that were placed on the image during the scanning step, then moving across the image from left to right, it extracts information from each vertical column of pixels. This process also accounts for the curvature of the chart record imposed by the radius of the pen arm. Because the ink line is almost always more than one pixel in height, the system outputs two values for each five-minute sample, corresponding to the top and bottom pixels in the column. The resulting output file holds records of data that give the date and time and two values of solar radiation in watts per square meter (W/m^2). If no image information exists in the column, a marker value indicating missing data is output. This data file is considered to be an accurate representation of the pen-and-ink chart as produced by the actinograph. However, the data require further processing to extract hourly and daily values from the five-minute samples.

7.3.3 Deriving Hourly and Daily Values

Interpreting the two output values for each five-minute sample raises several issues:

1) Where in the line width does the actual recorded value lie?

2) During periods of rapidly changing solar values (passing clouds), the pen may retrace itself many times forming a wide area of ink; how can accurate hourly solar radiation values be extracted from these areas?

3) How should chart-positioning errors be handled?

The simplest approach to deriving a single value from the width of the line is to take the half-way point between the top and bottom as representative of the line. This undoubtedly works well under many conditions since the mid-point presumably represents the center of the pen as the line was drawn. This is the method used by the current version of the software. However, data logging during partly cloudy periods often produces an inked area many times wider than the width of the line. This is illustrated in data for January 25, 1995, the third daily profile shown in Figure 7-3. The portion of the actinograph chart for that date is enlarged in Figure 7-5a and clearly shows a day with highly variable solar radiation due to passing clouds. Figure 7-5b shows the upper and lower bounds as digitized by the system, which represents the area traced by the pen. As portrayed in Figure 7-5c, picking the midpoint under these circumstances can represent a significant departure from both the high and low solar radiation values observed during the period. Further research is required to determine if a characteristic bias is introduced into hourly values by taking the mean of the extremes of a highly variable data set.

Chart positioning and other bias errors, such as a poorly calibrated zero mark during actinograph setup, are dealt with by examining the night time data. Because we assume solar radiation to be zero when the sun is down, the data can be normalized to zero at night and the line throughout the rest of the day adjusted appropriately. However, because the bias observed at night typically varies from night to night, the system examines the data at midnight both before and after a given day. At each midnight, the data are independently adjusted to zero, then the remaining day's data are adjusted by an amount determined by a linear interpolation between the two midnight offsets. After adjusting for offsets, the five-minute samples are integrated into hourly and daily total values of Wh/m^2 and written to output data files.

7.4 Comparison of Actinograph and Thermopile Data

To compare the data from the two types of instruments, four months of data from 1995 (January, April, July, and October) were selected. Data from the Eppley PSP pyranometer were integrated into hourly and daily values to match the output of the actinograph digitization system. Comparing the five-minute data was not attempted because the width of the pen line is equivalent to a 10-minute interval. Therefore, for each month, hourly values, daily totals, and monthly average daily total values were compared.

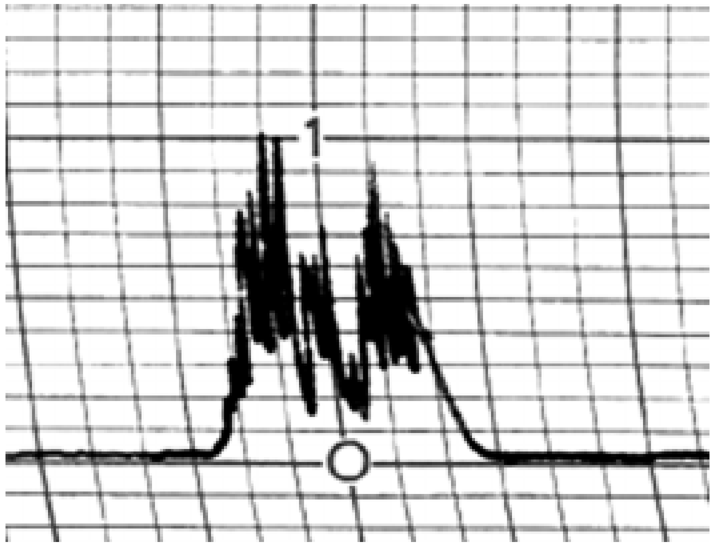


Figure 7-5a. Detail of actinograph chart shown in Figure 7-3

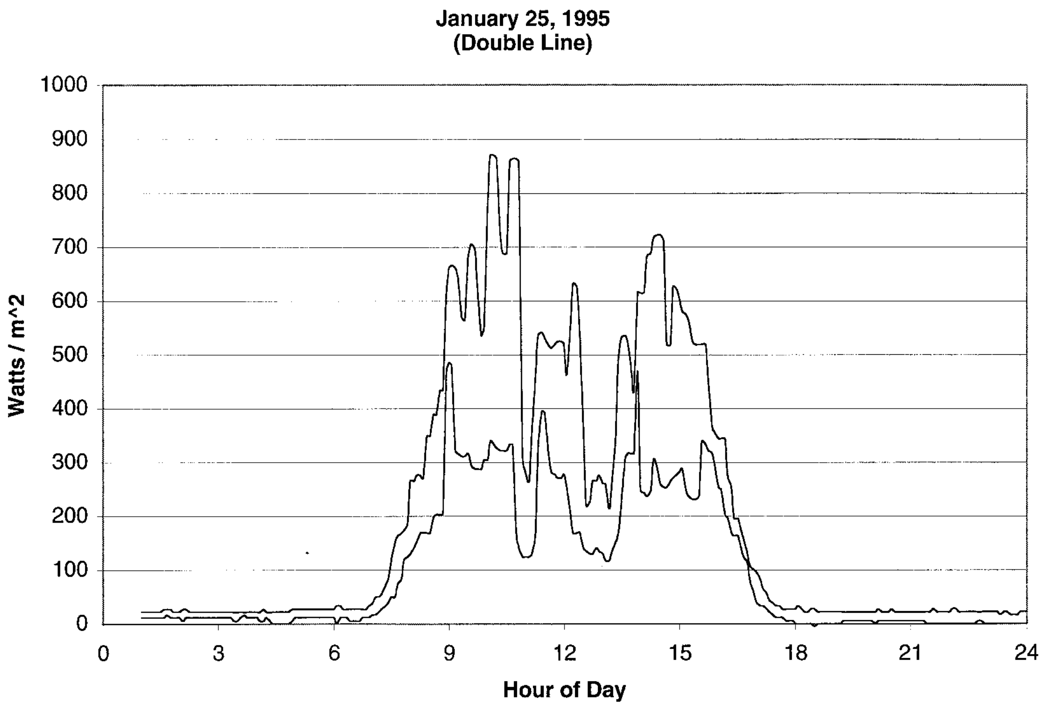


Figure 7-5b. The upper and lower bounds as digitized by the system, which represents the area traced by the pen

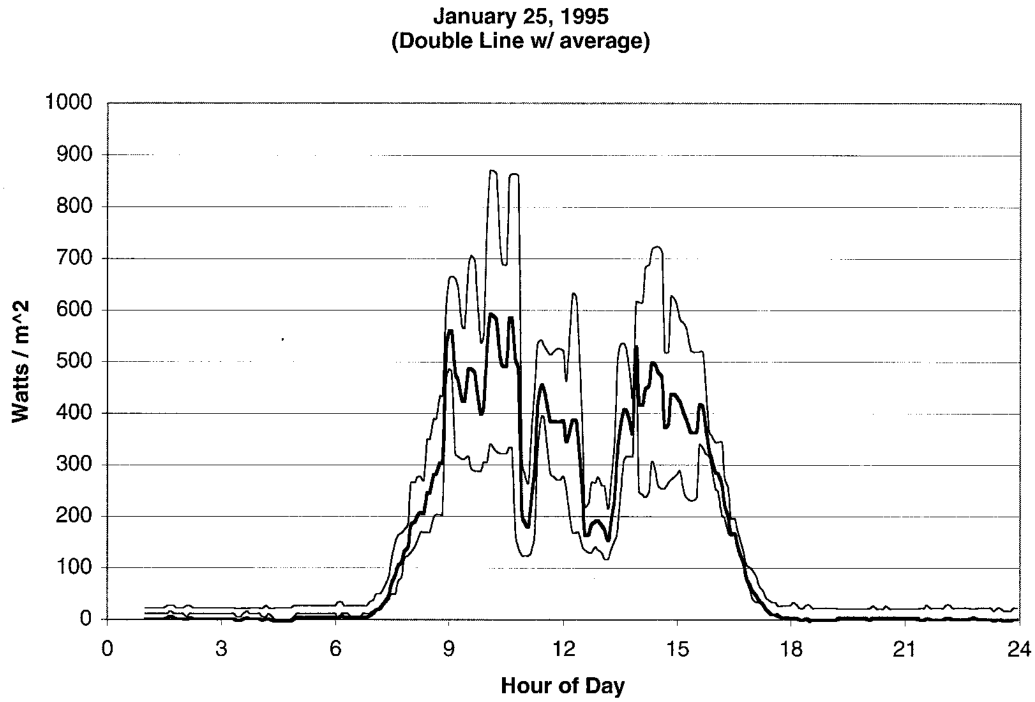


Figure 7-5c. Upper and lower bounds with average line

Figures 7-6 through 7-9 show daily total global radiation values for the four months using those days for which data were available from both instruments. Overall, the agreement of the two instruments is reasonably good. Under cloudless skies the data are almost identical, but significant differences are noted for individual days during the cloudier months of January and April. The differences noted for cloudy days could be caused by the difficulty in identifying the average radiation during partly cloudy conditions.

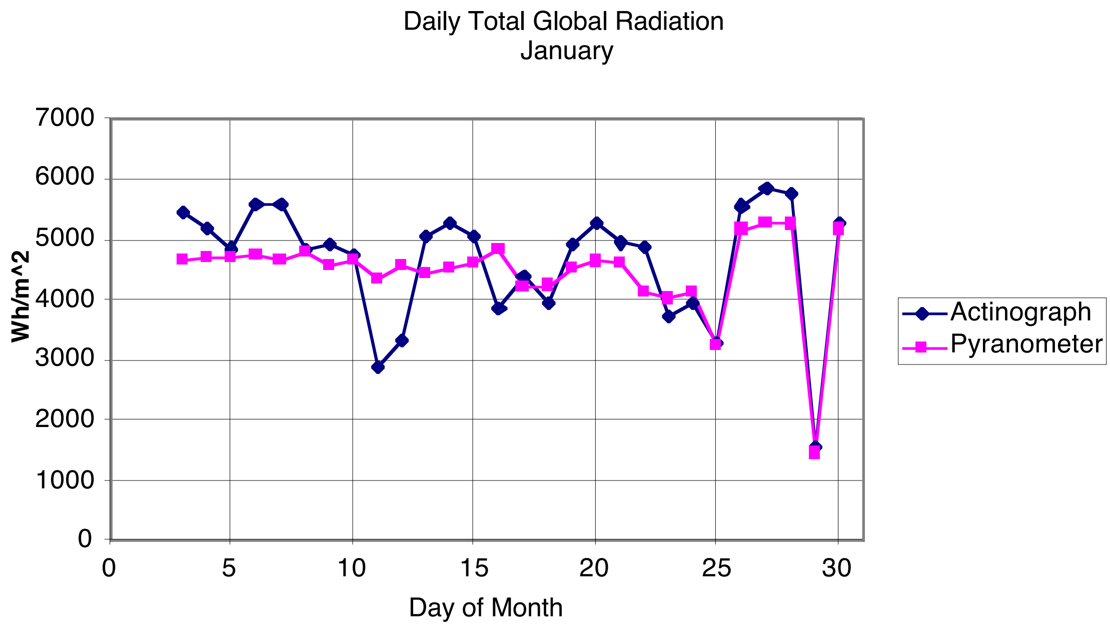


Figure 7-6. Daily total global radiation at the Solar Village for January 1995 as recorded by the actinograph and the PSP pyranometer

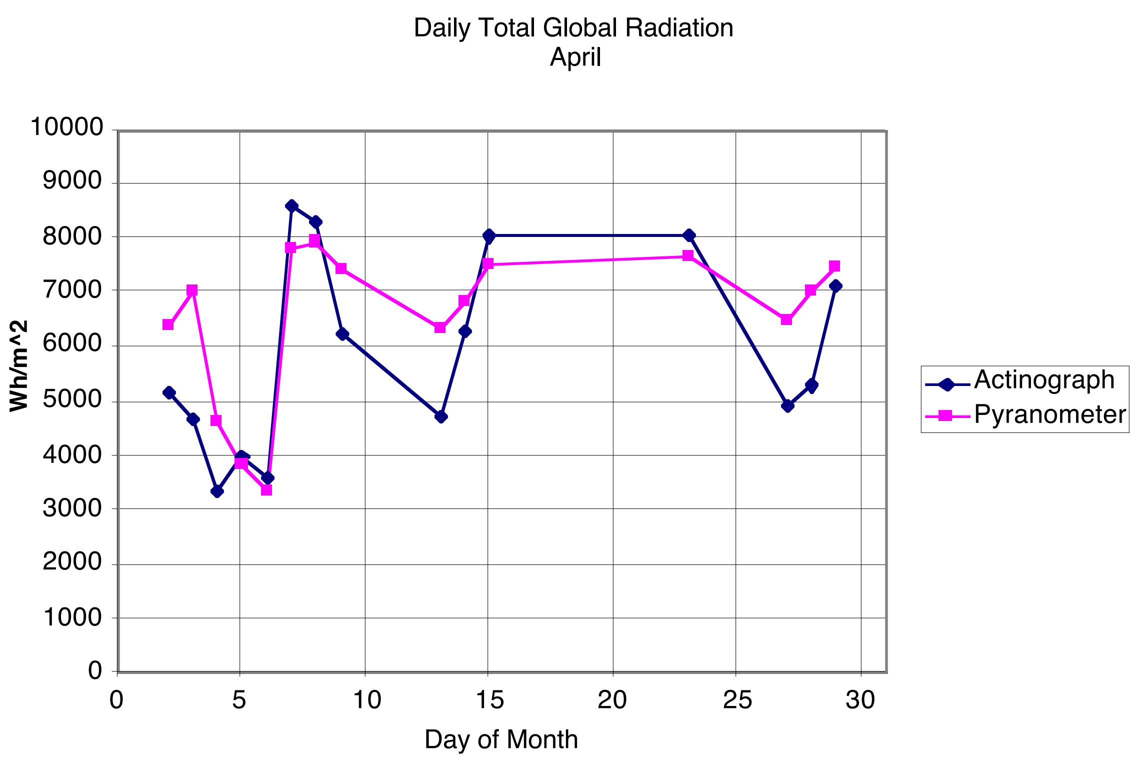


Figure 7-7. Daily total global radiation at the Solar Village for April 1995 as recorded by the actinograph and the PSP pyranometer

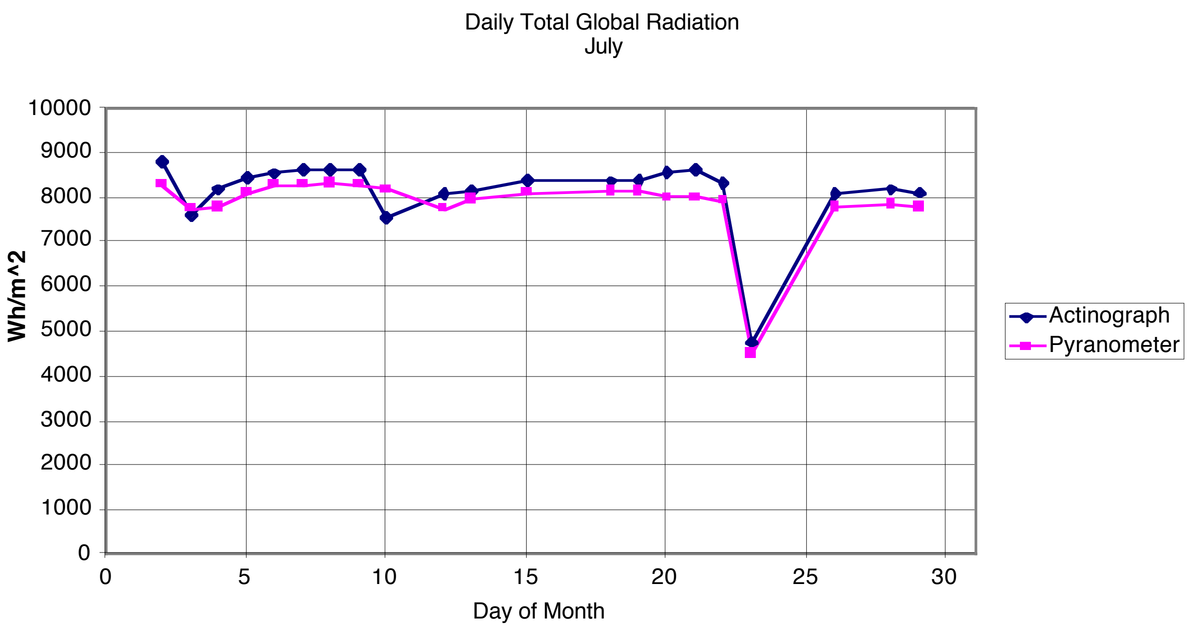


Figure 7-8. Daily total global radiation at the Solar Village for July 1995 as recorded by the actinograph and the PSP pyranometer

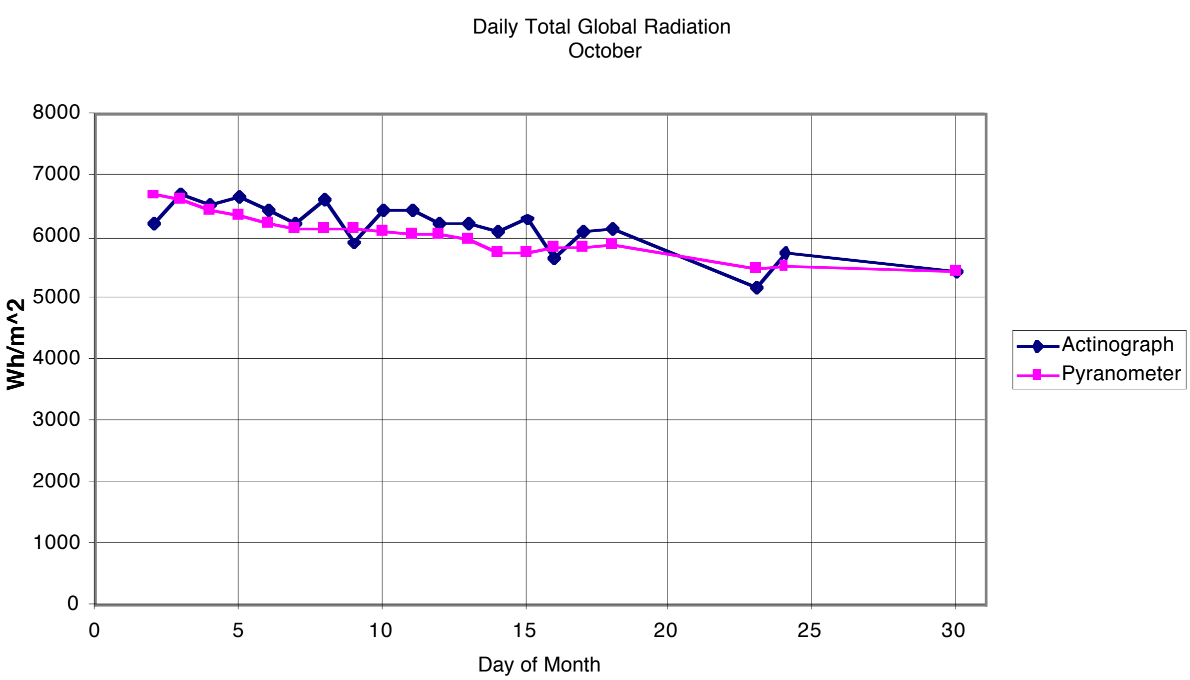


Figure 7-9. Daily total global radiation at the Solar Village for October 1995 as recorded by the actinograph and the PSP pyranometer

Figures 7-10 to 7-13 provide a comparison of hourly data for the four months by plotting the actinograph data against the pyranometer data. These results show some very interesting differences from month to month. The best agreements are found for the generally cloudless skies of July and October and the largest differences are noted during the cloudier month of April. The polynomial fit to the data for April shows that the processed actinograph data were generally lower than the PSP data for the same times.

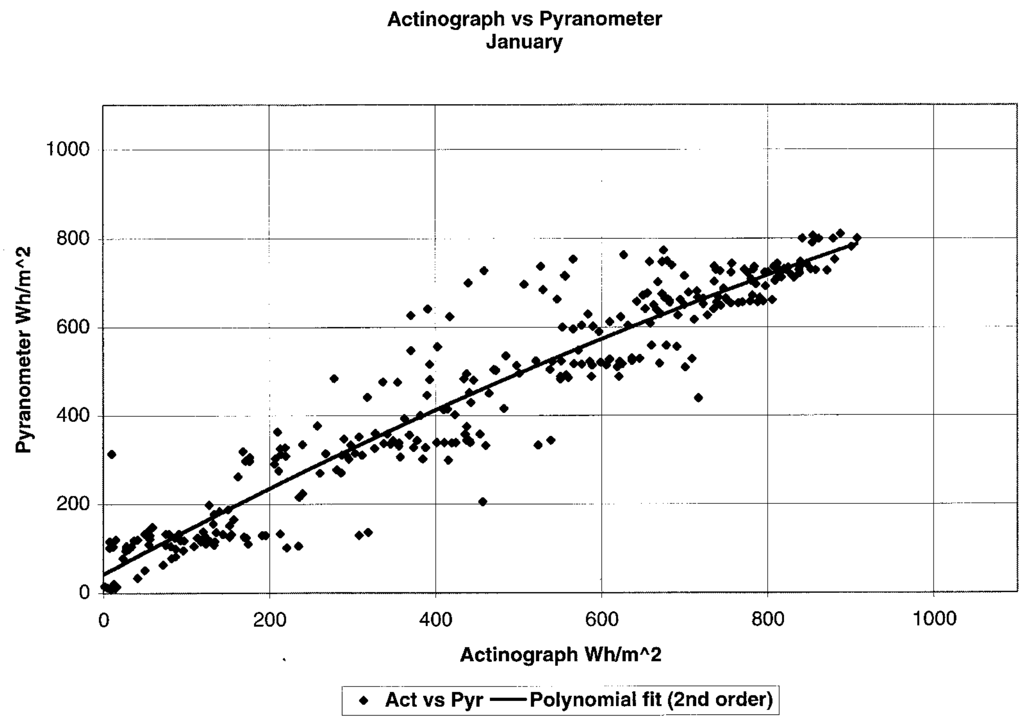


Figure 7-10. Scatter plot of hourly actinograph vs. PSP pyranometer data for January 1995

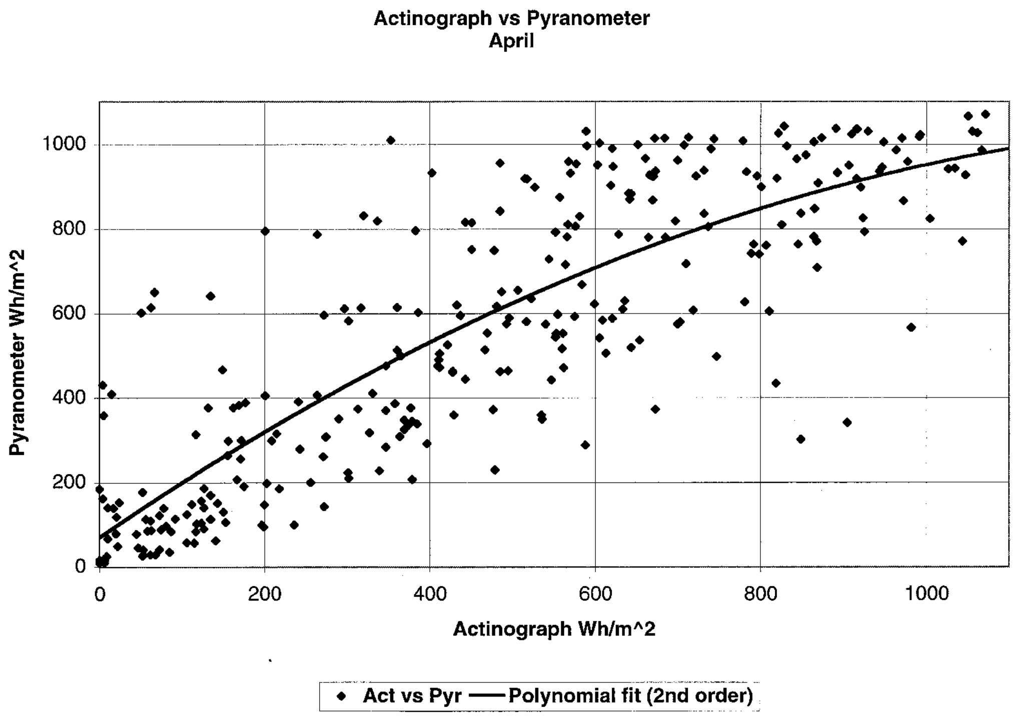


Figure 7-11. Scatter plot of hourly actinograph vs. PSP pyranometer data for April 1995

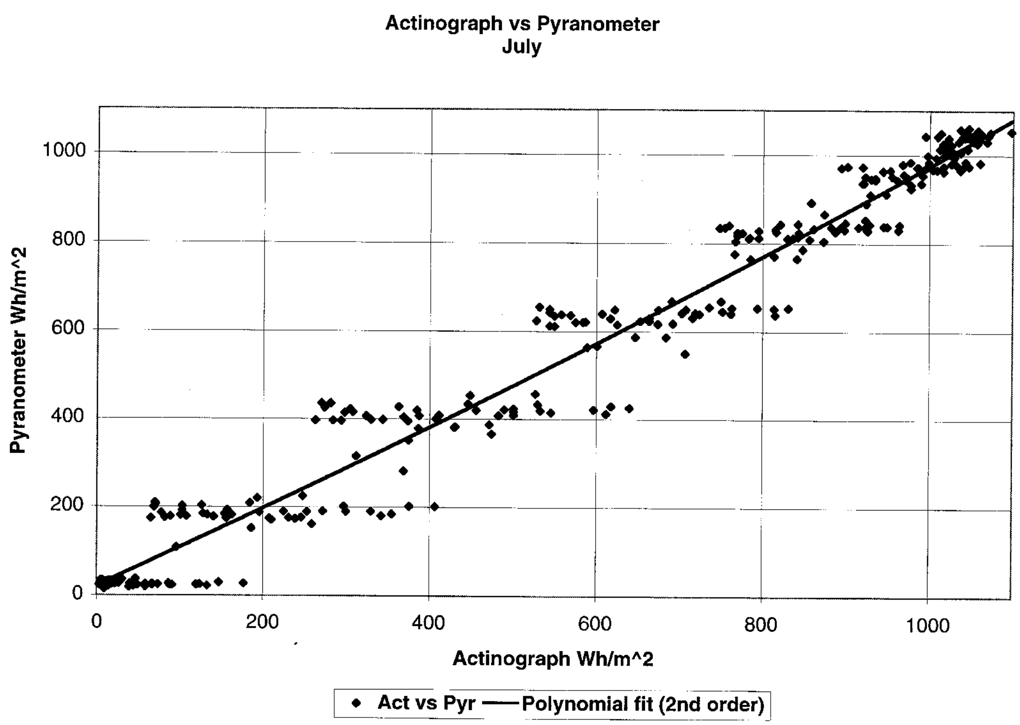


Figure 7-12. Scatter plot of hourly actinograph vs. PSP pyranometer data for July 1995

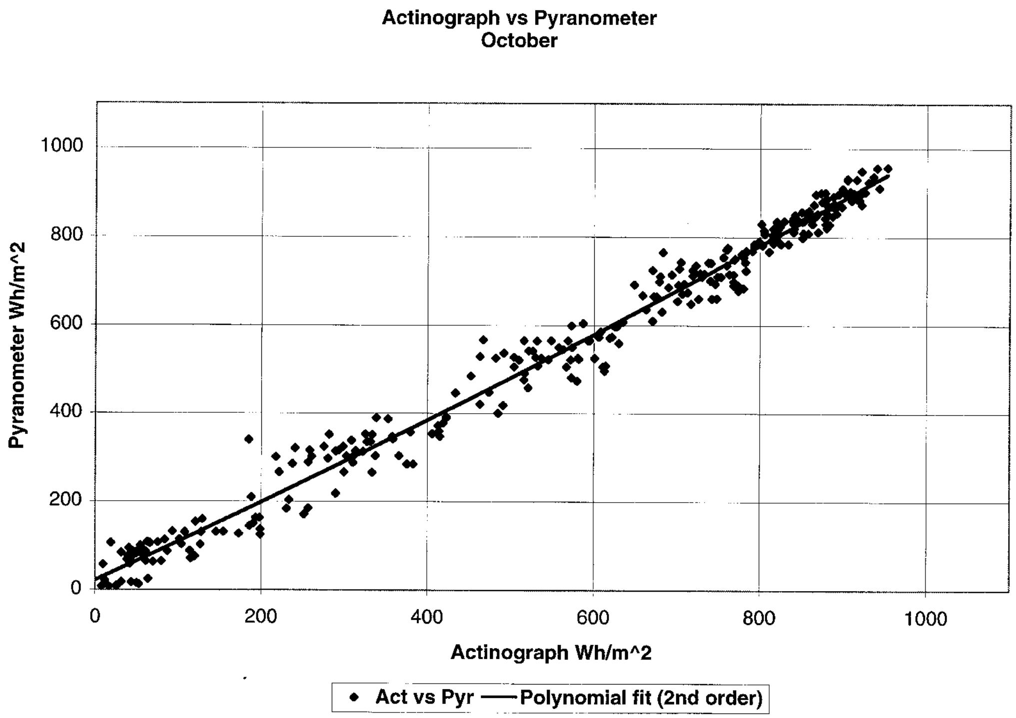


Figure 7-13. Scatter plot of hourly actinograph vs. PSP pyranometer data for October 1995

The results for July are particularly revealing. Because of the slow change in the solar declination immediately following the summer solstice and because of the constantly cloudless skies, the solar radiation recorded by the PSP pyranometer for each hour is almost the same day after day. However, the actinograph records for the same hours show large differences from day to day, particularly for values of 200, 400, and 600 Wh/m^2. These values are registered during the morning and afternoon hours when the solar radiation is changing rapidly, as shown in Figure 7-14 (a typical cloudless day in July at the Solar Village). These differences are the results of errors in the time scale on the strip chart. In the future, this can be improved by comparing sunrise and sunset times taken from the chart recordings with sunrise and sunset computations. The differences in times can then be used to correct the time scales on the charts.

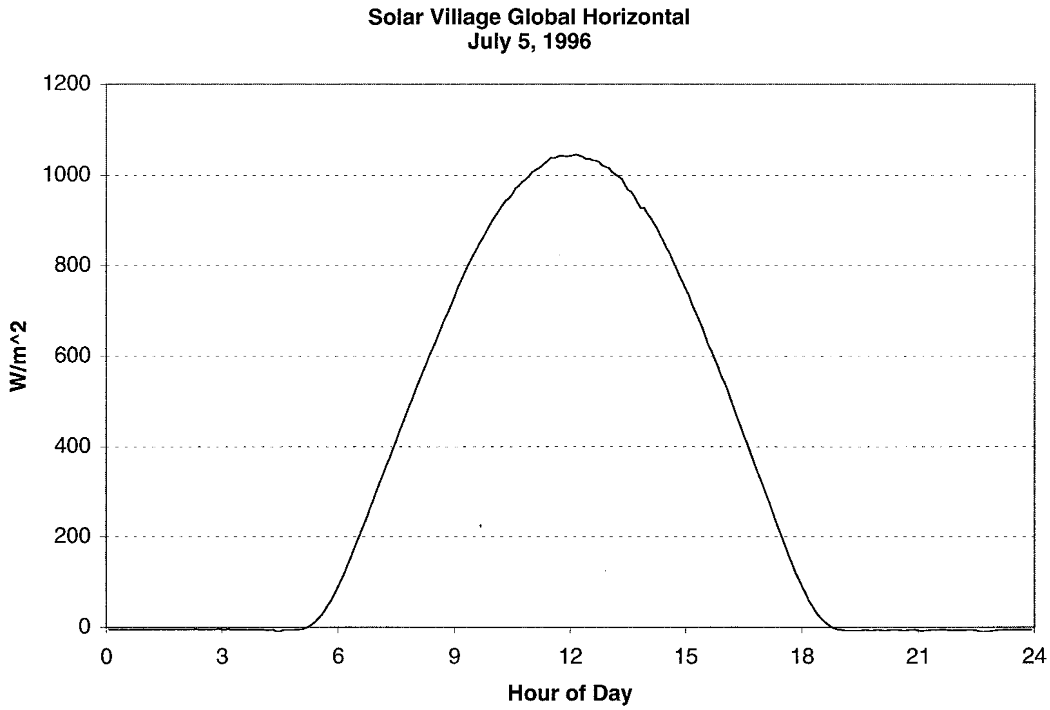


Figure 7-14. Five-minute PSP data from the Solar Village for a clear day in July

Figures 7-15 and 7-16 show normalized actinograph and pyranometer differences for April, plotted as functions of solar azimuth and solar zenith angles, respectively. The differences displayed as a function of azimuth angle show a morning and afternoon bias that could be the result of either clock error or an eastward tilt of the blackened bimetallic strip. However, if the differences were due to the tilt of the bimetallic strip, one would expect to see the morning and afternoon differences for July (see Figure 7-12) displayed as two clusters of data, one on each side of the polynomial fit, for each hour of the day. In other words, the more or less uniform distribution of the differences around the line is more indicative of random clock differences from week to week and day to day than a fixed tilt of the bimetallic strip.

Normalized differences between daily total irradiance measured by the two instruments were also examined. The four plots in Figures 7-17 through 7-20 show that on a monthly basis, the mean differences range from 2% in October to 10% in April.

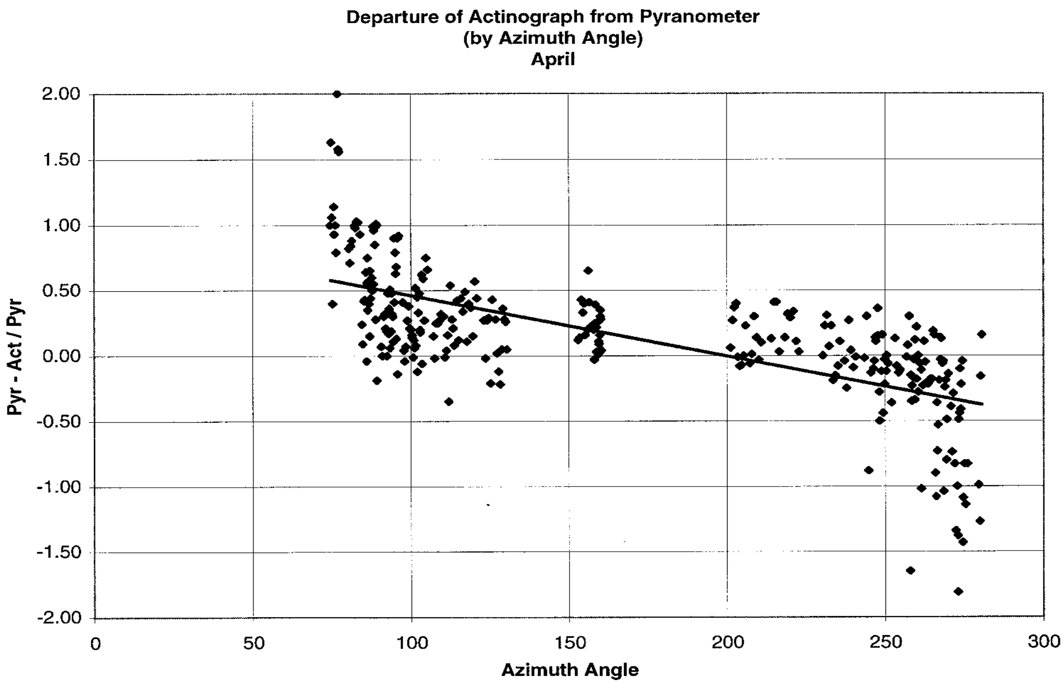


Figure 7-15. Proportional differences between hourly actinograph and pyranometer data as a function of solar azimuth angle

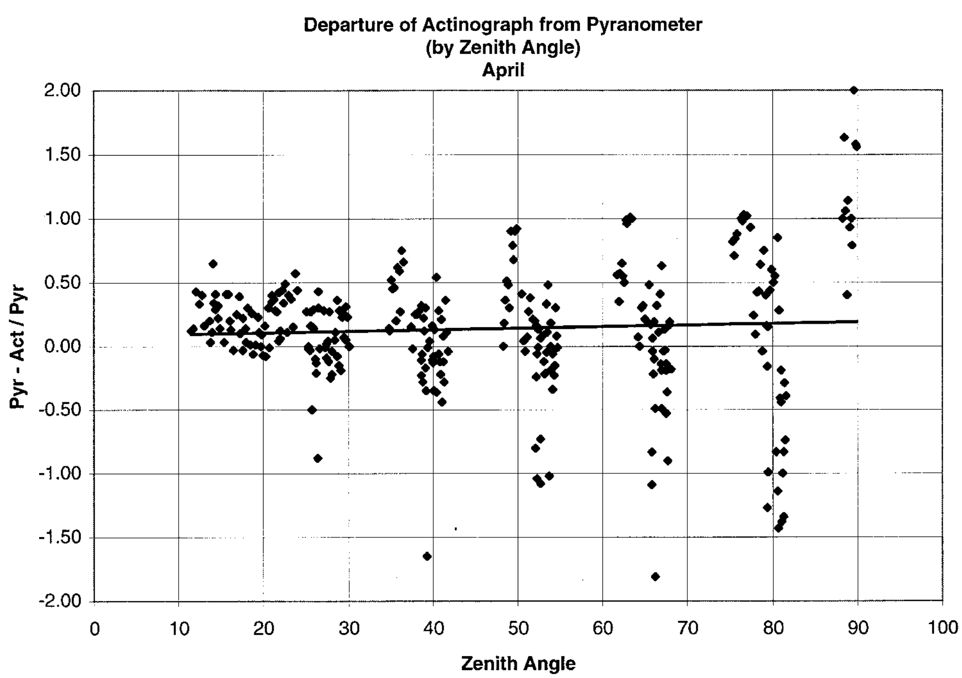


Figure 7-16. Proportional differences between hourly actinograph and pyranometer data as a function of solar zenith angle

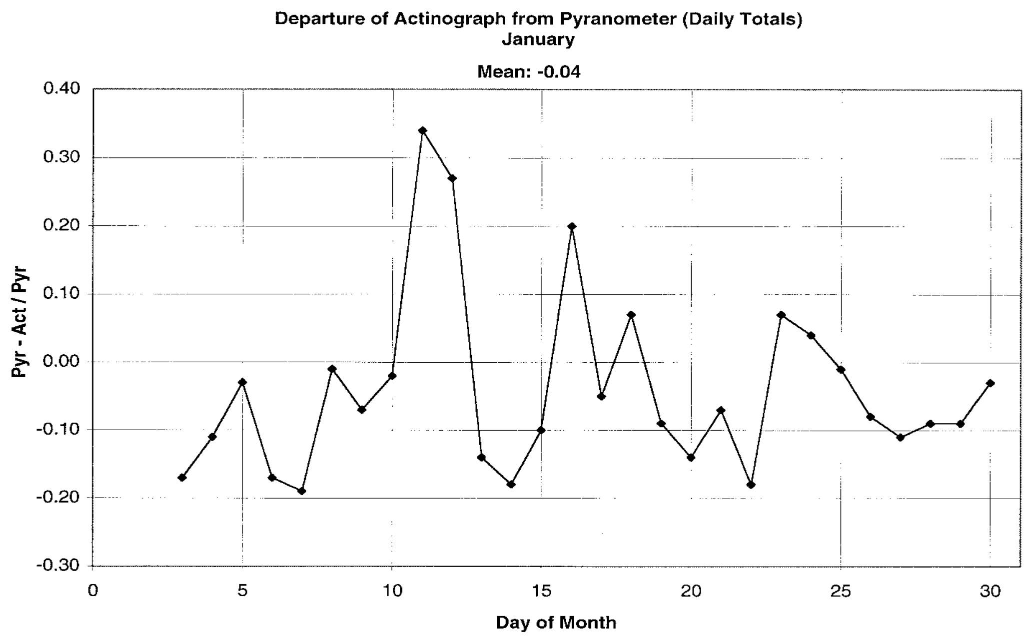


Figure 7-17. Proportional differences between daily actinograph and pyranometer data as a function of day of the month in January

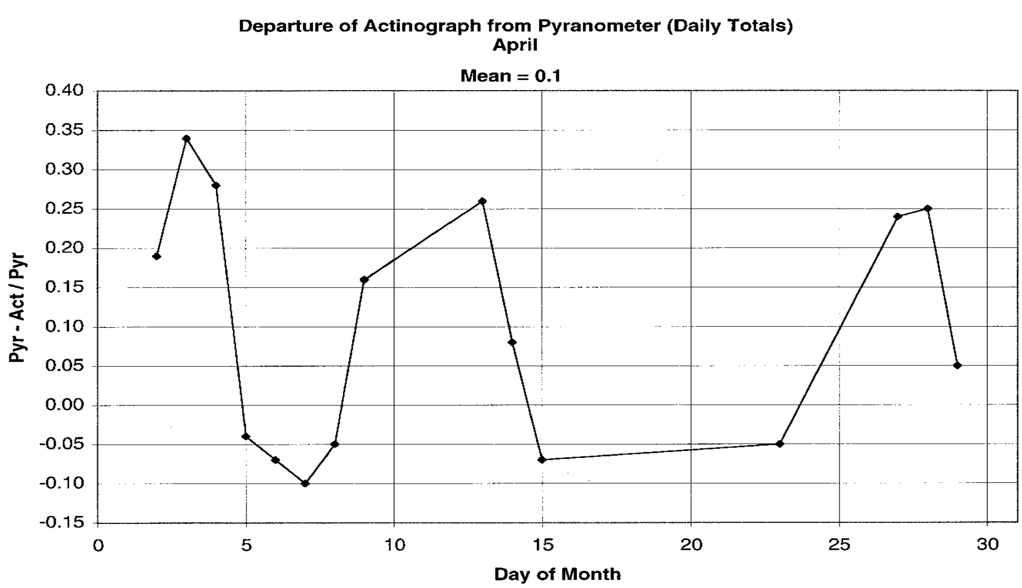


Figure 7-18. Proportional differences between daily actinograph and pyranometer data as a function of day of the month in April

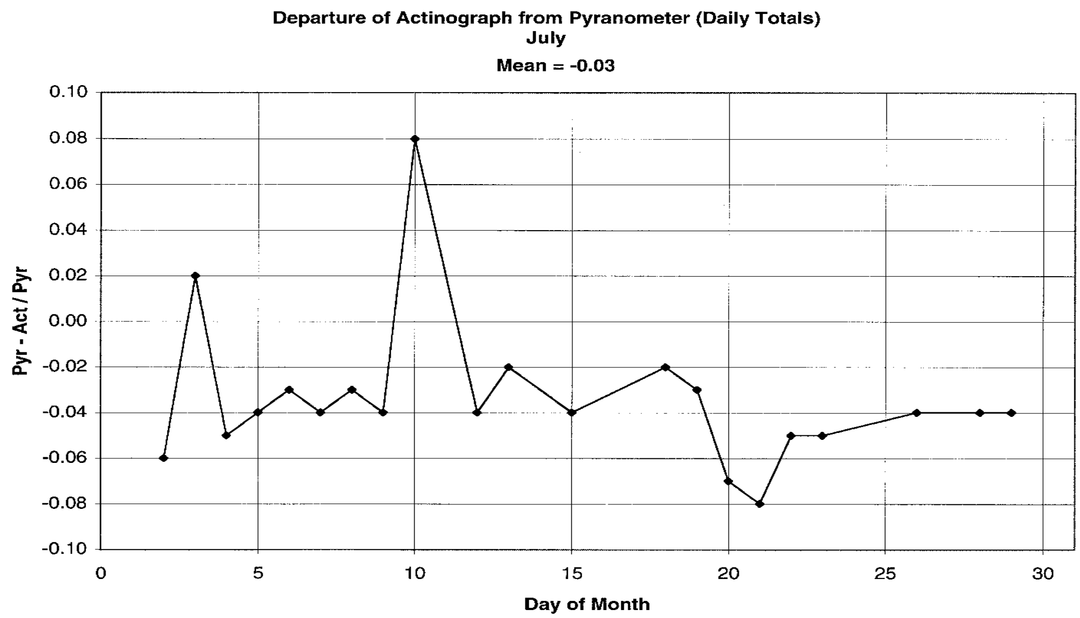


Figure 7-19. Proportional differences between daily actinograph and pyranometer data as a function of day of the month in July

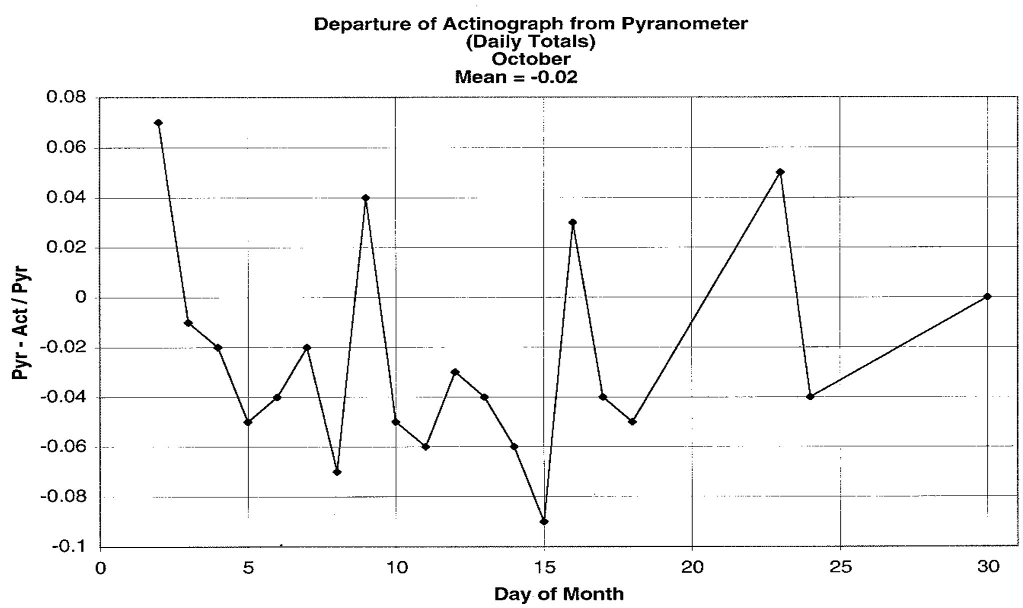


Figure 7-20. Proportional differences between daily actinograph and pyranometer data as a function of day of the month in October

Altogether, these analyses show that during clear skies or steady-state irradiance under overcast skies, data from the actinograph digitization system compare favorably with data from the pyranometers. However, during varying cloud conditions, the differences between the two systems increase significantly. It is not known if the increased differences are due to errors in the measurements by the actinograph, or to shortcomings in the method of digitizing highly variable data logged by the pen-and-ink recording system.

Figures 7-21a and 7-21b show the marked differences between the five-minute pyranometer data and the data produced by the double line and average actinograph digitization process described in Section 7.3.1. Both pyranometer and actinograph data sets were from the same day (January 25, 1995). In the case illustrated, the daily total irradiance for the pyranometer data is 3,240 Wh/m^2 compared with 3,277 Wh/m^2 for the averaged actinograph data, a difference of about 1%. However, as shown in Figures 7-17 through 7-20, such close agreement is an exception. Further research is required to determine if the differences can be characterized for a variety of sky conditions.

There are also differences that most likely result from timing errors in the chart recordings. Although such errors (when minor) would not affect daily total values, they should be corrected for other time-series analyses.

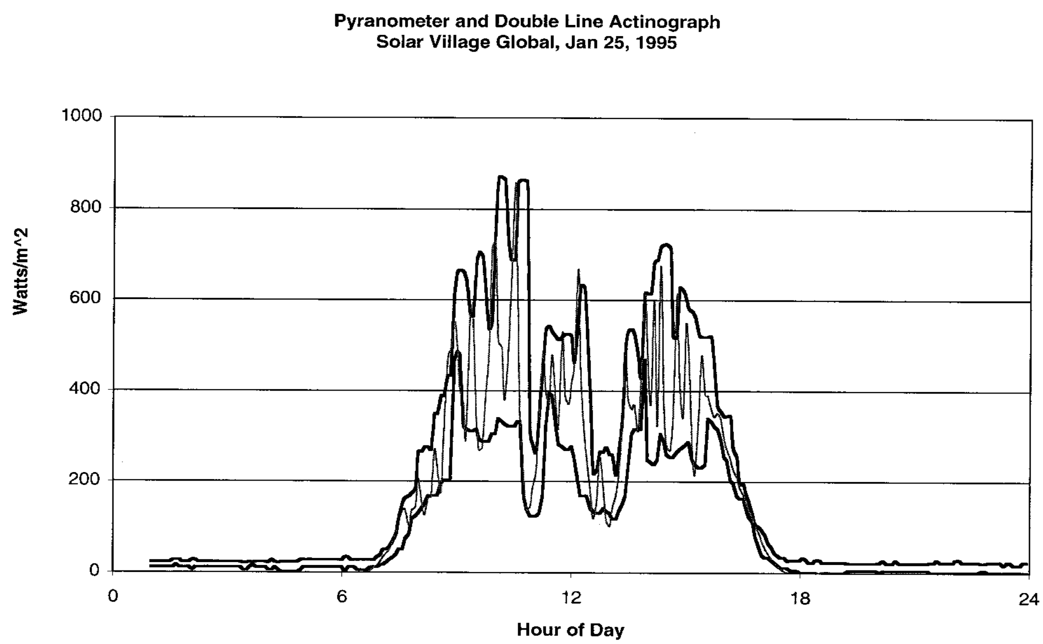


Figure 7-21a. Pyranometer data (light line) with the actinograph double line

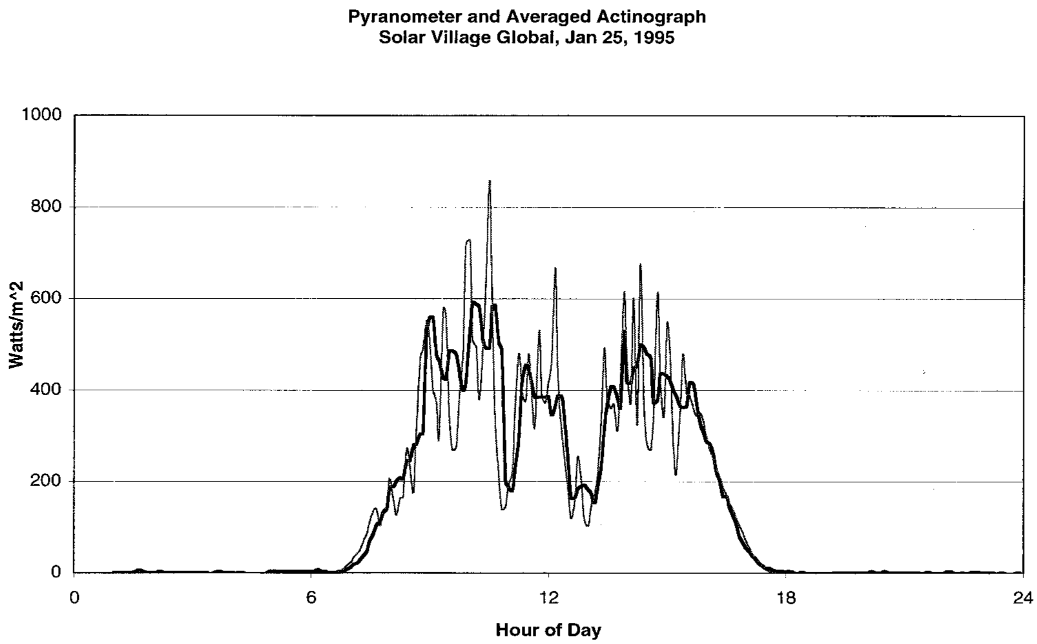


Figure 7-21b. Pyranometer data (light line) with the actinograph averaged digitization

8.0 Evaluating a Multi-Pyranometer Array Radiometer

8.1 Background

The use of a multi-pyranometer array (MPA) to measure solar radiation is an alternative to using individual pyranometers and a pyrheliometer with their associated trackers and shading disks or shadowbands to measure global horizontal, diffuse horizontal, and direct normal solar radiation. The MPA consists of three or four pyranometers with different azimuthal, zenith, and tilt orientations providing different views of the sun and sky. As shown in Figure 8-1, an artificial horizon prevents any of the pyranometers from receiving reflected radiation from the surrounding terrain.

Figure 8-1. Photograph of an MPA radiometer

Iterative comparisons are made of the actual solar radiation received by each pyranometer, with model estimates of the radiation each would receive from varying amounts of direct normal and diffuse horizontal radiation. Those amounts of direct normal and diffuse horizontal radiation that yield the best agreement between measured and modeled radiation for all of the pyranometers are assumed to be the true values. These direct normal and diffuse horizontal amounts are then used to calculate global horizontal radiation.

The results obtained from an MPA instrument are not expected to be as accurate as the values obtained from individual measurements of the direct normal, diffuse horizontal, and global horizontal elements. This expectation is based on the known limitations of both the model estimates and the measurements. In reality, because an MPA instrument has no moving parts and because trackers are notoriously unreliable, the day after day, month after month, and year after year data received from an MPA could be more reliable than data received from individual pyranometers and pyrheliometers.

However, there are other factors that affect the relative performance of an MPA and more conventional solar radiometers. First-class radiometers (such as the Eppley PSP pyranometers and NIP pyrheliometers in the Saudi 12-station network) use thermopile sensors. Thermopile radiometers respond to that part of the solar spectrum (0.3 μm to 3.0 μm) within which 98% of the sun's radiation is found. Typical MPA instruments, however, use silicon photodiode sensors (e.g., LI-COR 200B pyranometers) because of their small size and low cost (about one-tenth the cost of a PSP). Silicon is only responsive to that part of the spectrum between 0.4 μm and 1.0 μm. Therefore, because the spectrum of the radiation reaching the earth's surface is a function of the solar zenith angle and atmospheric conditions, silicon and thermopile instruments do not always yield the same results. This introduces another variable that must be considered when comparing data collected by MPA and individual thermopile radiometers.

NREL's investigation of MPA radiometers was preceded by developmental work by Faiman et al. (1993), who obtained monthly direct normal estimates for Sede Boqer, Israel, within 4% of pyrheliometer measurements and with a root mean square error (RMSE) of about 50 W/m^2 for 10-minute averages. Faiman, however, used Eppley PSP instruments for his MPA rather than LI-COR 200 B pyranometers. His results, therefore, were expected to be somewhat better than NREL's.

Data collection for the MPAs at NREL's Solar Radiation Research Laboratory (SRRL) began in July 1994 and continued through August 1995. Software was developed for the routine processing of the MPA data and for iterating the solution of direct normal and diffuse horizontal radiation from five-minute MPA data. Results for the MPAs at SRRL were equivalent to those obtained by Faiman.

In addition to the advantages offered by the lack of moving parts, the use of LI-COR pyranometers was expected to reduce the need for frequent maintenance to clean the optical surfaces. PSP and NIP instruments require daily cleaning to avoid soiling of their quartz domes and windows. Because the LI-COR pyranometer uses a plastic diffusing disk as its outer optical surface, it was thought that small amounts of dust would have a minimal effect on its responsivity.

8.2 Operation of MPAs at the Solar Village

The dusty desert environment at the Solar Village offered an ideal opportunity to test this hypothesis, so two identical LI-COR MPAs were installed there along with an additional PSP pyranometer. In order that soiling effects could be determined, the pyranometers for one of the MPAs were cleaned regularly, whereas those for the other MPA and the new PSP were only cleaned at specified times. The MPAs were installed in June 1996 and data collection continued through July 1997.

The azimuth angle from north and the tilt angle from horizontal for the MPA pyranometers installed at the Solar Village are given in Table 8-1. This arrangement, which is for a site latitude of 24.9 degrees, permits normal incident direct beam radiation to occur for each pyranometer during the vernal and autumnal equinoxes. For the vernal and autumnal equinoxes, the incident angle of direct beam radiation will be zero for the following pyranometers and solar times: pyranometer 1 = 6:00 (sunrise), pyranometer 2 = 10:00, pyranometer 3 = 14:00, and pyranometer 4 = 18:00 (sunset).

For other latitudes, the azimuth and tilt angles of pyranometers 2 and 3 can be adjusted appropriately by changing the tilt angle of the mounting block to which they are fastened. When the tilt angle of the mounting block equals the site latitude, pyranometers 2 and 3 are properly positioned. For all latitudes, pyranometers 1 and 4 face due east and west, respectively. Throughout the day, this arrangement permits one of the pyranometers to receive near maximum available direct beam radiation and one of the pyranometers (either number 1 or 4) to receive only diffuse radiation. This is advantageous for iterating a solution for the direct normal and diffuse horizontal solar radiation.

Table 8-1. Azimuth and Tilt Angles for Solar Village MPA Pyranometers

Pyranometer No.	Azimuth(˚)	Tilt(˚)
1	90.0	90.0
2	126.2	38.3
3	233.8	38.3
4	270.0	90.0

Subsets of the Solar Village MPA data were used to evaluate MPA configurations using only three pyranometers. MPA configurations using pyranometer combinations 1, 2, and 4 and pyranometer combinations 1, 3, and 4 yielded equivalent results to the four-pyranometer MPA.

MPA estimates of direct normal radiation were compared with Eppley NIP measurements of direct normal radiation. Overall and monthly comparisons were made using mean bias error (MBE) and RMSE statistics. The use of the term "error" refers to differences between the MPA estimates and NIP measured values. As noted earlier, the NIP measured values of direct normal are not necessarily the true values. The results of these comparisons are shown in Figure 8-2.

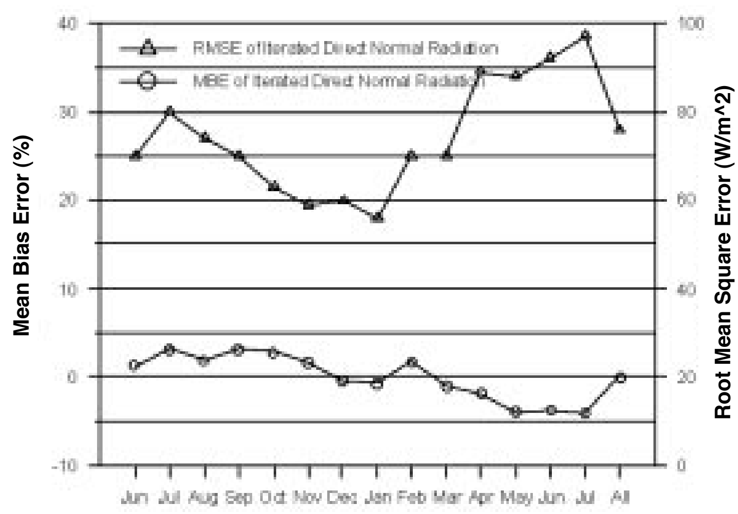


Figure 8-2. Mean bias and root-mean-square-errors for MPA estimated direct normal radiation for the Solar Village for June 1996 to July 1997

MBEs were 4% or less for all months and the overall error for the period studied was approximately zero. The RMSEs were based on five-minute averages and were greater than those found at NREL's SRRL, with some months having RMSE values of nearly 100 W/m^2. The root mean square error for the entire period was 76 W/m^2 (14% of the average direct normal measurement).

Differences between measured and MPA estimated values of direct normal radiation for five-minute data for the month of July 1996 are shown in the scatterplot in Figure 8-3. The diagonal has a slope of one and represents exact agreement between NIP measured and MPA estimated values. In general, the Solar Village MPA overestimated direct normal radiation in the early morning and late afternoon and underestimated direct normal radiation during midday.

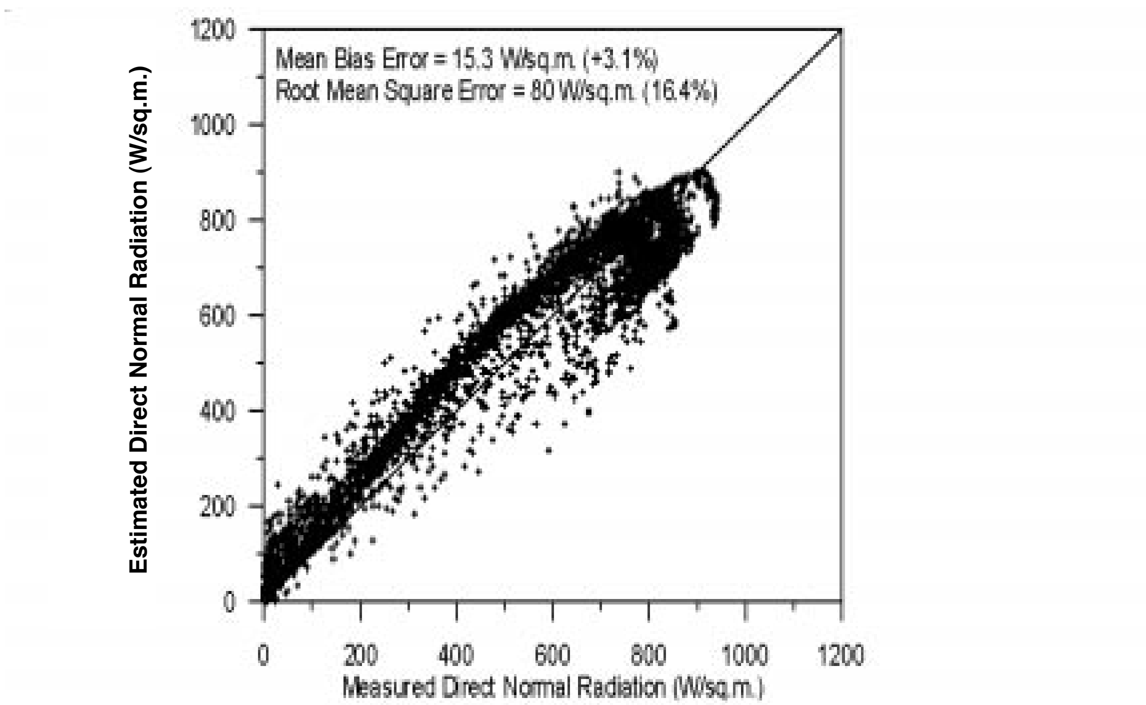


Figure 8-3. Comparison of NIP measured and MPA estimated direct normal radiation for July 1996 at the Solar Village

The overestimates are probably a consequence of the increased response of the LI-COR pyranometer to the shift in the solar spectrum toward longer wavelengths as the zenith angle increases. The underestimates were probably caused by the Perez model (Perez et al. 1990), which is used to estimate diffuse radiation on tilted surfaces.

8.3 The Effects of Pyranometer Soiling

The reduction in pyranometer output from soiling was evaluated at the Solar Village for two time periods: August 1, 1996, to October 26, 1996 (86 days,) and May 13, 1997, to July 22, 1997 (70 days). During these periods, the pyranometers for one of the MPAs were not cleaned whereas the pyranometers for the other MPA were cleaned each work day. A similar effort was performed for pairs of Li-COR pyranometers and Eppley PSPs measuring global horizontal radiation.

At the end of the periods, all sensors were cleaned and the relative increase in sensor output (based on daily totals) of the sensors that were not cleaned during the period was attributed to the effects of soiling. These results are given in Table 8-2. which also includes the results of the effect of soiling of the MPA sensors on the iterated values of direct normal radiation.

Table 8-2. Loss in Output from Soiling at the End of the Time Period

Instrument/Parameter	Loss in Output (%) 8/1/96 - 10/26/96 (86 days)	Loss in Output (%) 5/13/97 - 7/22/97 (70 days)
MPA LI-COR #1	0.5	0.5
MPA LI-COR #2	2.0	2.5
MPA LI-COR #3	2.5	2.5
MPA LI-COR #4	1.0	1.0
Global Horizontal LI-COR	2.5	2.0
Global Horizontal PSP	3.5	2.5
Iterated Direct Normal	1.5	2.0

The MPA LI-CORs 1 and 4 showed the most resistance to soiling, with only 0.5% to 1.0% degradation in output at the end of both periods. These LI-CORs are tilted at 90˚, facing east and west, and provide less favorable surfaces for dust accumulation. The MPA LI-CORs 2 and 3, with tilt angles of 38.3˚, and the horizontal LI-COR experienced larger soiling losses, but less than that for the horizontal PSP. The effect of soiling on iterated values of direct normal radiation was in the range of 1.5% to 2.0%, a composite value of the effects experienced by the individual LI-CORs of the MPA.

Scheduling maintenance for the MPA depends on the loss of accuracy that is tolerable. Assuming that soiling conditions are similar to those of the evaluation periods, cleaning Solar Village pyranometers once every two months should prevent soiling reductions in estimates of daily direct normal radiation from being greater than 2%. Variations of the soiling rate were observed throughout the evaluation periods, as a likely consequence of dust storms and other weather events. Weekly cleanings may be required to prevent soiling losses for estimates of daily direct normal radiation from being greater than 1%. Other maintenance strategies could also be used, such as monthly cleaning with additional cleaning after the occurrence of dust storms. These results may not be universally applied due to wide variations in soiling environments.

8.4 Calibration Histories of the MPA LI-COR Pyranometers

The MPA LI-COR pyranometers were calibrated before and after the data collection periods. The pyranometers installed on the MPAs were removed immediately after the data collection period and stored indoors except for the post-calibration periods. A control pyranometer was also calibrated.

Table 8-3 shows calibration results and changes in calibration responsivity for the LI-COR pyranometers at the Solar Village. Total outdoor exposure for the Solar Village pyranometers was about 15 months between the before-and-after calibrations. Over this period, the before-and-after calibrations show an average decrease in responsivity of 0.5%; however, individual changes ranged from -6.5% to +4.2%. These individual changes could also be observed in the data collected over the test period by comparing measurements between the #1 MPA and the #2 MPA. Judging by their serial number, these pyranometers are of early manufacture. We do not have any information on their history of use before their MPA application.

Table 8-3. Calibration Responsivity (V/W/m^2) of Solar Village MPA Test LI-COR Pyranometers Using Outdoor (BORCAL) Methods for Solar Zenith Angles Between 45° and 55°

Location	Pyranometer	Serial Number	Before 5/96	After 9/97	% Change
#1 MPA	1 (East Vertical)	1723	15.270	15.097	-1.1
#1 MPA	2 (Southeast Tilt)	1724	13.860	12.960	-6.5
#1 MPA	3 (Southwest Tilt)	1726	15.650	15.323	-2.1
#1 MPA	4 (West Vertical)	1729	15.750	15.931	+1.1
#2 MPA	1 (East Vertical)	1730	15.100	15.735	+4.2
#2 MPA	2 (Southeast Tilt)	1732	15.100	14.690	-2.7
#2 MPA	3 (Southwest Tilt)	1734	15.820	15.610	-1.3
#2 MPA	4 (West Vertical)	1744	14.960	15.481	+3.5
Instrument Stand	#1 Global Horizontal	1750	15.440	15.276	-1.1
Instrument Stand	#2 Global Horizontal	1757	13.820	14.024	+1.5

8.5 Summary of MPA Performance

MPAs evaluated at the Solar Village yielded monthly direct normal estimates within 4% of measurements and with an RMSE for five-minute averages of about 76 W/m^2 (14%). Our results are in agreement with Faiman's previous MPA results for Sede Boqer, Israel, except that the overall RMSE for the Solar Village was greater. The RMSEs are believed to be higher for the Solar Village because of the sensitivity of the LI-COR pyranometer to a more widely varying spectral distribution and because the Perez model underestimated the diffuse radiation for the east-and-west facing pyranometers for summer months and small zenith angles.

Compared to resource assessment for concentrator applications depending strictly on the MPA direct normal estimates, resource assessment using MPA data for technologies using flat-plate collectors has increased in accuracy because of the potential for cancellation of errors between the

MPA estimates of direct normal and diffuse horizontal radiation and the Perez model estimates of incident radiation for a collector surface of arbitrary orientation.

Furthermore, if the renewable technology being assessed matches the spectral response and other characteristics of the MPA LI-COR pyranometers, the MPA data will provide a more accurate estimate of a flat-plate technology's performance than would measurements made using thermopile instruments such as Eppley NIPs and PSPs. This was demonstrated by the minimal error associated with using the MPA estimates of direct normal and diffuse horizontal radiation to model the output of global horizontal LI-COR pyranometers at the Solar Village.

The extent of the reduction in pyranometer output from soiling was evaluated at the Solar Village for two time periods: August 1, 1996, to October 26, 1996 (86 days) and May 13, 1997, to July 22, 1997 (70 days). Depending on pyranometer orientation, the loss in output at the end of the soiling periods ranged from 0.5% to 2.5% for the MPA pyranometers, with a resulting decrease in the iterated values of direct normal of 1.5% to 2%. A horizontal PSP evaluated for the same period showed slightly higher soiling losses (2.5%-3.5%). Although these results do show that the LI-COR pyranometers are less susceptible to loss in responsivity due to soiling, the advantage over the PSP pyranometers would not be a decisive factor in choosing one over the other.

Analysis performed using SRRL and Solar Village MPA data showed that the MPA could be optimized with respect to performance and cost by reducing the number of pyranometers from four to three. This reduces the pyranometer and calibration costs, as well as the complexity and cost of the machined pyranometer mounting bases, and allows for the use of a lower-cost data logger with fewer input channels. The total cost of an optimized MPA measurement system is estimated to be $2,400, which is about one-tenth the cost of a solar radiation measurement station using conventional thermopile pyranometers and a pyrheliometer mounted on a computer-controlled tracker.

Corrective procedures developed and applied to the LI-COR measurements so they better represent thermopile instruments have the potential to improve MPA estimates of direct normal and diffuse horizontal radiation. These procedures would correct the LI-COR pyranometer data for cosine response, temperature, and solar spectrum. Efforts to modify the Perez model to prevent underestimating the amount of diffuse radiation for the vertical east- and west-facing pyranometers for summer months and low zenith angles would also be beneficial.

The design of calibration techniques specifically for the LI-COR pyranometers would lower calibration uncertainties and the costs of network operations. If techniques were implemented to characterize the cosine response of each pyranometer, the resulting information could be used to minimize the effects of measurement error due to cosine response.

Although not as inherently accurate as a pyrheliometer for measuring direct normal radiation, in practice the MPA may provide better estimates of the solar resource for sites with limited manpower for maintaining and operating the measurement equipment. Equipment that is not maintained or repaired promptly after failure increases the uncertainty of the measurements results. The MPA requires little expertise to use and maintain. Its pyranometers are fixed and it requires no periodic adjustment such as that required by some trackers and shadowbands.

Further, it has increased reliability because there are no moving parts. The pyranometers are less expensive and they exhibit good resistance to soiling, permitting cleaning intervals to be extended.

9.0 Creating a Solar Radiation Data Grid and Atlas for Saudi Arabia

The primary objective of Annex II was to update and upgrade the Solar Radiation Atlas for Saudi Arabia. Initially, it was expected that satellite (METEOSAT) data would play an important part in satisfying that objective by providing estimates of solar radiation at locations between the 12 stations of the surface network. For the reasons discussed in Section 6.0, the use of METEOSAT data was not realized. Nevertheless, satellite data did play an important role in creating a data grid and atlas for Saudi Arabia. In fact, several satellites provided input to a model that was used to estimate monthly mean solar radiation values at each point on a uniformly spaced grid covering the Saudi Arabian. This methodology was developed by NREL using funding provided by DOE.

9.1 Introduction to Data Grids

During 1995, the National Renewable Energy Laboratory initiated the Data Grid Task under DOE's Resource Assessment Program. A data grid is a framework of uniformly spaced locations (grid points) for which data are available, such as elevation data at the intersection of latitude and longitude lines. A solar radiation data grid contains information on solar radiation resources at each grid point. The inherent value in elevation and solar radiation data grids is quite similar. Elevation data are used by engineers to select optimum routes for highways, determine excavation and fill requirements, and design structures such as dams and buildings to conform to the shape of the land. Similarly, solar radiation data grids can be used to select optimum sites for large solar energy applications such as power plants, to estimate the performance of any solar energy system at any location, to design optimum solar energy systems for specific sites, and to estimate probable returns on investments.

A climatological solar radiation (CSR) data grid contains long-term (multiple-year) information on solar radiation resources at each grid point. CSR data grids can be used to select likely sites for large solar energy applications such as power plants and to generate estimates of performance for any solar energy system at any location.

There are several options for producing a CSR data grid. As noted previously, the initial plan for Saudi Arabia called for extracting CSR data from a long-term collection of satellite images. However, because of problems encountered in collecting the required satellite images of Saudi Arabia (see Section 6.1), the use of a parametric CSR model to estimate direct normal, diffuse horizontal, and global horizontal solar radiation became the most viable option. The CSR model uses climatological input data obtained from both surface observations and satellite images. The model and its sources of input data are described in the next section.

9.2 The CSR Model

The digital data grid used to prepare the maps for the Solar Radiation Atlas of Saudi Arabia was produced with NREL's CSR model, which uses inputs of monthly mean values of total and opaque cloud cover, aerosol optical depth, precipitable water vapor, atmospheric pressure, ozone, and surface albedo. The CSR model is a modified version of the METSTAT model (Maxwell 1998), which was used to calculate hourly solar radiation values for the National Solar Radiation Data Base (NSRDB Vol. 1, 1992) for the United States. Both models first calculate unitless transmittance values for the direct beam and diffuse sky solar radiation elements for each atmospheric parameter that absorbs or scatters radiation. The transmittance values are then multiplied by appropriate extraterrestrial (top-of-the-atmosphere) solar radiation values to yield surface solar radiation in Wh/m^2. These calculations are performed only for that day of each month for which the daily total extraterrestrial radiation (ETR) most nearly equals the monthly mean daily total ETR. The ETR value used is the solar constant, 1367 w/m^2, corrected for the earth-to-sun radius vector, which varies by $\pm$13% throughout the year.

For each month, the CSR model calculations proceed through the following steps:

Step 1–Solar Geometry
Starting at midnight, the date and the latitude and longitude of a cell are used to calculate the solar elevation. These calculations are repeated every five minutes until the sun comes up, at which time the algorithms to calculate solar radiation are implemented and used until the sun sets. Logic statements handle the high latitude situations when the sun never comes up or when it never sets.

Step 2–Direct Beam and Diffuse Transmittances
Direct-beam transmittance algorithms include the effects of Rayleigh scattering (T_R), ozone absorption (T_O), uniformly mixed gas absorption (T_{UM}), water vapor absorption (T_W), aerosol absorption and scattering (T_A), opaque cloud absorption (T_{OPQ}), and translucent cloud absorption (T_{TRN}). Diffuse sky transmittance algorithms include contributions from Rayleigh scattering (Ks_R), aerosol scattering (Ks_A), opaque cloud scattering (Ks_{OPQ}), translucent cloud scattering (Ks_{TRN}), and multiple ground-to-atmosphere/cloud reflectances (Ks_{GRFL}).

Step 3–Combining Transmittances
The algorithms to combine direct-beam and diffuse transmittances are,

$$Kn = T_R\, T_O\, T_{UM}\, T_W\, T_A\, T_{OPQ}\, T_{TRN}$$

$$Ks = (Ks_R + Ks_A)\, f_m$$

$$Kd = (Ks + Ks_{OPQ} + Ks_{TRN}) + Ks_{GRFL}$$

$$Kt = Kn + Kd$$

where Kt, Kn, and Kd are transmittances for global horizontal, direct normal, and diffuse horizontal solar radiation, respectively, and f_m is an empirical air mass function. Corrections are made for sunrise and sunset periods shorter than five minutes in length.

Step 4–Calculating Solar Radiation Intensity
Calculating solar radiation intensity for each five-minute period is accomplished by multiplying transmittances by ETR and ETRN (extraterrestrial solar radiation on a surface normal to the sun),

$$In = ETRN\, Kn$$

$$Id = ETR\, Kd$$

$$It = ETR\ Kt$$

where ETRN, ETR, In, Id, and It are in W/m^2.

Step 5–Calculating Daily-Total Energy
For the final step, the daily total solar radiation energy in Wh/m^2 is calculated by summing five-minute values and dividing by 12 (there are 12 five-minute periods per hour),

$$In_{TOT} = \left(\sum_{n=1}^{12} In\right)/12$$

$$Id_{TOT} = \left(\sum_{n=1}^{12} Id\right)/12$$

$$It_{TOT} = \left(\sum_{n=1}^{12} It\right)/12$$

9.3 Model Input Data

The feasibility of a CSR model was dependent on the availability of climatological input data. The parameters having the greatest effect on the transmission of solar radiation through the atmosphere include (listed in order of importance): total and opaque cloud cover, aerosol optical depth (AOD), the uniformly mixed gases (oxygen, nitrogen, and carbon dioxide), precipitable water vapor, atmospheric pressure, surface albedo, and ozone. Because they are uniformly distributed around the globe, the effects of the uniformly mixed gases are assumed to be unvarying in space and time.

Climatological cloud cover data are found in the Real Time Nephanalysis (RTNEPH) Data Base. The RTNEPH originates at the U.S. Air Force Global Weather Center (AFGWC) at Offutt Air Force Base, Nebraska. On August 1, 1983, AFGWC started a global cloud analysis project that produces cloud information every three hours for grid points separated by a nominal 40 km. These ongoing analyses use all available information, including surface observations, upper air (radiosonde) data, and polar orbiting satellite data to produce cloud data for polar stereographic projections of the Northern and Southern Hemispheres. Although not as reliable as hourly surface observations, the 40-km resolution makes these data ideal for data grid production. RTNEPH data base products are available from the National Climatic Data Center in Asheville, North Carolina.

The RTNEPH product of particular importance to the production of data grids is the histogram database formed from three-hourly data for the seven-year period from 1985 through 1991. This database includes a histogram of the number of occurrences of low, middle, high, and total cloud amounts in increments of 5% for sky cover amounts from 0% to 100% for each month and each three-hour observation time. The histograms of total sky cover amounts for hours between sunrise and sunset are used to determine monthly mean total cloud cover during daylight hours. Opaque cloud cover amounts are estimated from analyses of the low, middle, and high cloud amounts.

After cloud cover, aerosol optical depth has the next greatest effect on surface radiation, especially direct-beam and diffuse sky radiation. AOD provides a measure of the attenuation of direct-beam radiation from the solar disk due to aerosols (dust, smoke, pollen, and liquid droplets). Climatological AOD data are not readily available for any location in the world. Actually, the availability of reliable AOD data of any kind is quite limited. Although AOD measurements have been made at selected wavelengths using sunphotometers, such data are only available for a limited number of locations for limited periods of time.

For Saudi Arabia, AOD values were calculated from the direct normal solar radiation data collected by the 12-station solar radiation network. Algorithms from the Bird Clear Sky model (Bird and Hulstrom 1981) were used to calculate direct normal transmittances for Rayleigh scattering (T_R), ozone absorption (T_O), absorption of uniformly mixed gases (T_{UM}), and water vapor absorption (T_W). Standard algorithms found in the literature were used to calculate the solar position and the relative length of the path (air mass) traversed through the atmosphere by the solar beam. The individual transmittances were combined to obtain a value for molecular transmittance, T_M,

$$T_M = T_O \, T_R \, T_{UM} \, T_W. \qquad (9\text{-}1)$$

Aerosol transmittance is then calculated as

$$T_A = I_N / I_o \, T_M \qquad (9\text{-}2)$$

where I_N is the measured direct normal irradiance and
I_o is the extraterrestrial direct normal irradiance.

Finally, an inversion of Beer's Law was used to compute broadband aerosol optical depth, τ_A,

$$\tau_A = - (\ln T_A) / m \qquad (9\text{-}3)$$

where m is relative air mass.

The two meteorological inputs required for the calculation of molecular transmittance are the effective vertical thicknesses of ozone and precipitable water vapor in the atmosphere. An average ozone value of 0.30 cm was used for these calculations. Hourly values for precipitable water vapor were obtained by interpolating between 12-hour radiosonde soundings or from hourly surface measurements of temperature and relative humidity, when radiosonde data were unavailable (Garrison and Adler 1990; Myers and Maxwell 1992).

AOD calculations were performed for the period from January 1995 through June 1996. These were the months for which we had radiosonde and/or surface meteorological data from MEPA to calculate precipitable water vapor. Although the measurements were performed using well-calibrated pyrheliometers, SERI QC, a solar radiation quality assessment software package (NREL 1993) was used to identify and delete questionable data. Also, only data for hours with zenith angles less than 75° were used, because of the increased uncertainty associated with measurements at lower solar elevations.

Of equal importance was the selection of cloudless sky hours. This was accomplished using concurrent sky cover observations to identify hours for which zero sky cover was indicated. This last requirement reduced the possibility of clouds affecting the measurements during the hour over which the solar radiation measurements had been averaged.

This procedure produced broadband aerosol optical depths for 10 of the network stations for which measured direct normal data were available. The data available for Jeddah were too few in number to obtain accurate estimates of aerosol optical depth. The data at the Solar Village could not be used because we had not received concurrent meteorological data for Riyadh. We also needed a means of estimating optical depths for times and locations without measured direct normal data. To accomplish this, seasonal functions were developed to extrapolate data for the 10 stations to any other location in Saudi Arabia.

Monthly mean values of aerosol optical depth were plotted and used to obtain coefficients for a sine function of the form

$$t_A = a \sin((360^\circ X/365) - b) + c \tag{9-4}$$

where X is the day of the year (1-365) and
b was assigned a value of 90˚.

The annual average, c, was calculated for each station and the amplitude, a, of the variations around the annual average was estimated from the plots. These coefficients were then plotted on a map of Saudi Arabia. Using educated estimates based on elevation, distance to population centers, and other factors, coefficients were assigned to 2.5˚ intervals of latitude and longitude for the entire region. These coefficients were then used to calculate aerosol optical depths for the day of the month used by the CSR model to calculate solar radiation.

Although the available data for calculating aerosol optical depths were few in number, the data were of high quality. Furthermore, the results were quite consistent for the 10 stations and showed reasonable geographical patterns. Nevertheless, these calculations should be updated when more solar radiation and meteorological data become available. Much better estimates of AODs over Saudi Arabia will be possible after 5 to 10 years of data have been collected.

Monthly mean precipitable water vapor CSR input data were obtained on a global 1˚ grid from the NASA Water Vapor Project Data Set (NVAP). This data set was prepared from high-quality radiosonde (upper-air) data combined with data from the Total Ozone Vertical Sounder (TOVS) and the Special Sensor Microwave/Imager on the TIROS satellite. These data cover the period from 1988 to 1992. The NVAP data set has undergone extensive quality control and provides uniform worldwide coverage. Because water vapor absorbs (rather than scatters) solar energy, it affects all three elements (direct, diffuse, and global) by similar amounts.

Atmospheric pressure data were calculated from five-minute (9-km grid) elevation data that are available for the entire world. Atmospheric pressure is an input to the algorithms that calculate the Rayleigh scattering and quantum absorption processes associated with uniformly mixed atmospheric gases (nitrogen, oxygen, and carbon dioxide). The absorption of oxygen and carbon dioxide has a rather minor effect on surface radiation, but the effect of Rayleigh scattering is exceeded only by the effects of aerosols and clouds.

Ozone data for the world were obtained from the Total Ozone Mapping Spectrometer, available on a CD-ROM produced by the National Oceanic and Atmospheric Administration (NOAA). The absorption of solar energy by ozone provides a vital shield to limit the intensity of ultraviolet (UV) radiation, which is damaging to both plants and animals. However, UV radiation comprises only a small percentage of the total radiation from the sun. Hence, the effect of ozone on solar radiation energy is not of great importance.

Worldwide surface albedo data are available from a number of sources, including the Canadian Center for Remote Sensing (CCRS). The satellite-derived 2.5˚ CCRS data were used to estimate monthly mean surface albedo for Saudi Arabia and the surrounding region. Surface albedo affects multiple scattering of solar radiation between the surface of the earth and the atmosphere (especially clouds). This affects the diffuse and global elements of solar radiation, but has no effect on the direct beam element.

The various model input data come with resolutions varying from 9 km (elevation/pressure) to 280 km (albedo). Because cloud cover plays a dominant role in determining solar radiation at the earth's surface, the polar projection 40-km grid of the RTNEPH database was selected for both the input and output grids of the CSR model. Therefore, all of the non-cloud cover data inputs were resampled such that input values for all variables were available for each of the RTNEPH 40-km cells. The resampling process used standard interpolation and geostatistical procedures including weighted averaging of input grid values within a prescribed distance of the cell of interest. Maps prepared for each of the resampled data input grids were examined as part of the overall quality control procedures.

9.4 The Performance of the CSR Model

The performance of the CSR model was initially evaluated by comparing CSR calculations with monthly mean daily totals extracted from the NSRDB for 213 sites in the contiguous United States. More than 95% of the solar radiation data in the NSRDB were calculated using the METSTAT model. Hence, this evaluation amounts to a comparison between monthly mean daily totals obtained from 30 years of hourly values generated by the METSTAT model (using hourly surface observations of cloud cover and other atmospheric parameters) with monthly mean daily totals calculated with the CSR model using monthly climatological averages for the model inputs. The first comparison (see Table 9-1) used monthly average cloud cover values from the NSRDB. These results represent a comparison of the different model methodologies. The second comparison (see Table 9-2) used monthly average cloud cover values derived from the RTNEPH histogram database. These results represent a comparison of the models and the RTNEPH cloud cover values.

In general, these monthly mean bias differences are less than 3% of typical monthly mean daily totals and the standard deviation differences are less than half of typical interannual variations (standard deviations of monthly means).

Table 9-1. CSR Model Minus NSRDB Differences (Wh/m²/day)
(Using NSRDB Monthly Average Cloud Cover Values)

	Mean Bias			Standard Deviations		
Month	Global	Direct	Diffuse	Global	Direct	Diffuse
January	21	-35	9	87	95	78
February	34	-10	8	118	84	105
March	30	50	-51	119	82	114
April	82	62	-26	140	98	100
May	86	33	-6	161	92	99
June	18	-17	-32	134	103	111
July	-18	-51	-40	131	133	109
August	-12	-4	-67	110	111	111
September	88	51	-2	127	103	73
October	30	30	-16	70	92	53
November	26	2	-2	63	86	42
December	24	-49	19	60	96	53
Annual Average	34	5	-17	110	98	87

Table 9-2. CSR Model Minus NSRDB Differences (Wh/m²/day)
(Using RTNEPH Monthly Average Cloud Cover Values)

	Mean Bias			Standard Deviations		
Month	Global	Direct	Diffuse	Global	Direct	Diffuse
January	29	-9	5	111	277	85
February	-11	-148	32	147	354	121
March	76	163	-71	197	373	131
April	129	159	-42	246	400	117
May	24	-108	27	197	325	114
June	50	37	-38	201	296	118
July	-42	-113	-25	200	328	111
August	-56	-98	-51	185	331	121
September	51	-47	15	144	279	88
October	21	7	-14	98	262	69
November	-12	-135	13	85	309	63
December	44	57	6	90	264	58
Annual Average	25	-20	-12	158	316	100

The use of the RTNEPH cloud cover input data resulted in very little change in the mean bias differences. The increase in standard deviation differences is significant and expected because the RTNEPH data cover only a seven-year period compared to the NSRDB 30-year period. The large direct normal standard deviation differences are a reflection of some large differences found for individual stations. For example, direct normal differences for a few individual station-months exceeded 1,000 Wh/m^2/day when using RTNEPH cloud cover values. These and other large differences (> ± 400 Wh/m^2) were always associated with large differences in NSRDB and RTNEPH opaque cloud cover values. It is worth noting that the differences between 30-year NSRDB monthly mean daily totals and values for any seven-year period from the NSRDB are of the same order of magnitude as those given in Table 9-2. All together, these results indicate very good performance for the CSR model and support the use of the RTNEPH database as a source of mean monthly cloud cover data.

9.5 Evaluating the Saudi Data Grid

Measured solar radiation data from the Saudi 12-station network were used to evaluate the Saudi data grid produced by the CSR model. The monthly average daily-total solar radiation measured at each station was compared with the modeled value for the 40-km cell within which the station is located. Because the network was put into operation in 1995, the quantity of data available for these stations is limited. Fewer than 90 days of good quality data were available for each station-month. A minimum of 10 days was the limit set for including comparisons in the analyses. The composite results of these comparisons are shown in Table 9-3. The effect of the small quantity of data is particularly noticeable in the high standard deviations and the variability from month to month. Also, most of the input data for the CSR model are for the period from 1985 to 1991, whereas the measured data for the network were collected from January 1995 through June 1997. If March is excluded, the average mean difference for the other 11 months is 4.1%. With March, the average mean difference is 5.7%. Both of these values are within the 6% –9% uncertainty assigned to annual and monthly mean daily-total direct normal solar radiation for the United States NSRDB. And with the exception of March and May, all of the monthly differences also fall within this uncertainty. Given the limited quantity of data and the differences in the time periods of measured and modeled data, these results are as good as can be expected.

By extending the CSR calculations some 5° in longitude to the west, it was possible to make comparisons between CSR model-generated data and data obtained from the World Radiation Data Center (WRDC) for 10 stations in Egypt and Sudan. The WRDC, located in St. Petersburg, Russia, had not received any data from Saudi Arabia. Although the WRDC data include only the global horizontal element and are not of the same high quality as the Saudi network data, they cover a longer period of record and are, therefore, more representative of climatological conditions for this Mideast region. The mean bias and standard deviation differences between CSR-modeled and WRDC-measured data for these 10 stations are given in Table 9-4. These results indicate that the CSR data grid and atlas for Saudi Arabia should be representative of the Saudi climate.

Table 9-3. CSR Model Minus Saudi Network Differences (Wh/m^2/day)

Month	Mean Bias Global	Mean Bias Direct	Mean Bias Diffuse	Standard Deviation Global	Standard Deviation Direct	Standard Deviation Diffuse
January	335	387	47	180	736	276
February	35	112	-21	392	1116	346
March	691	1409	-237	411	1022	358
April	-41	173	-77	296	718	381
May	352	753	-109	218	624	359
June	-47	-128	90	265	706	306
July	120	491	-149	312	801	390
August	-10	203	-75	130	685	314
September	50	370	-221	293	479	329
October	7	-432	162	270	572	189
November	284	336	58	272	686	187
December	386	402	69	253	529	217
Annual Average	180	339	-39	274	723	304

Table 9-4. CSR Model Minus WRDC Global Horizontal Differences (10 Stations in Egypt and Sudan)

Month	Mean Bias Wh/m^2/day	Mean Bias %	Standard Deviations Wh/m^2/day	Standard Deviations %
January	35	0.7	360	7.3
February	-5	-0.1	378	6.6
March	36	0.5	404	6.2
April	58	0.8	429	6.0
May	108	1.5	418	5.9
June	109	1.5	647	9.2
July	-30	-0.4	694	10.1
August	-8	-0.1	642	9.5
September	116	1.8	565	8.9
October	148	2.5	432	7.4
November	90	1.7	404	7.9
December	-6	-0.1	339	7.2

The maps generated from the digital data grid for Saudi Arabia were used to produce a Solar Radiation Atlas for Saudi Arabia. The atlas also contains tables of monthly mean daily totals from each of the 12 network stations. Copies of the atlas can be obtained from KACST.

10.0 Technology Transfer and Training

Transferring NREL technology to KACST through training programs and direct transfer of software and hardware was a major objective of Annex II. In this way, the continuation of the work that was initiated during the first four years is assured. This is extremely important because true climatological measures of Saudi Arabia's solar radiation resources requires the collection of at least 30 years of high quality solar radiation data. Actually, technology transfer and training activities were conducted continuously throughout the entire four years of this project.

10.1 Initial Six-Week Training in Solar Radiometry

Two KACST staff (Mohammed Bin Mahfoodh and Ahmed Al-Amoudi) and a Saudi graduate student studying in the United States arrived at NREL on June 6, 1994. During their first week at NREL, they received classroom training on the following subjects:

- Solar Radiometry–An Overview
- Pyranometers and Pyrheliometers
- Solar Tracker and Radiometer Repair
- Radiometer Calibrations
- Cavity Pyrheliometers
- Quality Assessment of Solar Radiation Data.

During the weeks of June 13 and 20, the classroom training was put into practice as the Saudis participated in an intercomparison of the Saudi cavity pyrheliometer with two NREL cavities. This provided traceability to the World Radiometric Reference and prepared the Saudis to participate in similar international intercomparisons. The hands-on training continued as Saudi pyranometers and pyrheliometers were installed at NREL's Solar Radiation Research Laboratory, where calibration and characterization data were collected using the Radiometer Calibration and Characterization software that was developed under this project.

During the week of June 27, the Saudis attended the annual American Solar Energy Society (ASES) conference held at San Jose, California. This was also part of their training since they were exposed to a wide range of renewable energy topics during the conference. Upon their return to NREL, they received training on the installation of radiometers on the special instrument platform (designed at NREL) to be used in the Saudi network. They were also trained to program the Campbell Scientific CR-10 data logger and to operate the equipment for collecting solar radiation data.

Dr. Saleh Alawaji, the Saudi Coordinator for the Joint Renewable Energy Project, attended the ASES conference and from there proceeded to NREL, where he participated in the final two weeks of training. During the first week in July, Dr. Alawaji and his three associates participated in a two-day course in uncertainty analysis. Several other scientists and engineers from NREL and the NOAA Laboratory in Boulder also participated in this training. During the next week, Jim Augustyn and Rob Nelson from Augustyn & Co. presented three days of training on the Data Quality Management System software that they were developing for KACST and NREL. DQMS is the software used to collect, process, and archive data collected by the Saudi 12-station network. A preliminary version of the software and a draft of the user's manual were taken back to KACST, where the Saudi staff had the opportunity to become familiar with its use.

10.2 On-site Radiometry Training at KACST

A three-man team from NREL (Dr. Eugene Maxwell, Task Leader; Christopher Cornwall, Staff Engineer; and Steve Wilcox, Computer Scientist) spent most of October and part of November 1994 at Riyadh, working side by side with scientists and engineers at KACST. This constituted a continuation of the training begun at NREL four months earlier. An interim facility for calibrating and characterizing solar radiometers was established at the Solar Village, a KACST research facility located approximately 50 km northwest of Riyadh. Figure 10-1 shows Dr. Maxwell and Ahmed Al-Amoudi checking the installation of solar trackers used in the calibration of the network pyrheliometers. All of the radiometers for the Saudi 12-station solar radiation network were recalibrated. Although this recalibration was not technically necessary, it provided an important training opportunity for several KACST staff, who were not able to participate in the training conducted at NREL. The recalibration, which followed the NREL calibration, also provided a validation of the calibration facility installed at the Solar Village.

The practical hands-on training at KACST also included the installation of the first two stations of the Saudi network, at the Solar Village and Qassim. Figure 10-2 shows the instrument platform, radiometers, and solar trackers as installed at the Solar Village. During the final week at KACST, data flow from the stations at the Solar Village and Qassim was initiated, which offered the opportunity for practical training on the use of the DQMS software package. Although not carried out with the formality of classroom lectures and laboratory exercises, the hands-on, side-by-side training accomplished while setting up the KACST calibration facility and the first two stations of the Saudi network resulted in very effective technology transfer, as evidenced by the excellent operation of the network and the good quality of the data collected.

Figure 10-1. Dr. Eugene L. Maxwell and Ahmed Al-Amoudi inspecting the alignment of solar trackers at the Solar Village calibration facility

Figure 10-2. Instrumentation platform with Abdullah Al-Rubeq and Chris Cornwall at the Solar Village station

10.3 Advanced Radiometry Training at NREL

NREL presented training (at NREL) in Advanced Solar Radiometry to two Saudi staff (Saleh Al-Zahrani and Abdullah Al-Rubeq) during March 1996. The course addressed calibration, installation, and maintenance of instruments and the detection, diagnosis, and resolution of instrument problems. The presentation of this course after the Saudi network had been in operation for over a year provided an opportunity to further develop subjects that had been introduced during previous training activities. Actual problems found in the data collected by the Saudi network were used as examples. Good weather during the course provided opportunities for radiometer calibrations, including two instruments brought from KACST.

Three scientists from other organizations (NREL, University of Oregon, and NOAA) also attended. Their different experiences in solar radiometry led to discussions of topics from several perspectives, which added to the value of the course. The topics presented during the course included:

- Radiometry and Instrumentation
- Network Design
- Station Installation
- On-Site Maintenance
- Training of Field [Station] Operators
- Network Operation
- Instrument Calibration
- Tracker Problems.

A notebook containing lecture handouts and other materials was provided to each of the attendees.

10.4 Data Grid Short Course

A two-week course, “The Estimation of Monthly Mean Daily-Total Solar Radiation on a Uniform Grid,” was given at NREL during the first two weeks of March 1997. The course was designed to train KACST staff to produce a solar radiation data grid and a solar radiation atlas for Saudi Arabia, using solar radiation data from the Saudi 12-station network, cloud cover data derived from satellite and surface observations, and meteorological data obtained from MEPA. Seven NREL scientists and engineers participated in the presentation of the course material. The KACST staff taking the course (Mohammed Bin Mahfoodh and Abdullah Al-Boiez) were also trained to use a new solar tracker alignment tool while they were at NREL (see Section 2.4).

The topics addressed during the data grid short course included:

- Extraterrestrial Solar Radiation and Solar Geometry
- Atmospheric Interactions with Solar Radiation
- Cloud Interactions with Solar Radiation
- Solar Climate Effects
- Resource Requirements
- Solar Radiation Measurements
- Solar Radiation Models
- Supplementing Solar Radiation Measurements with Satellite Data
- Supplementing Solar Radiation Measurements with Models
- Daily Estimates of Aerosol Optical Depths
- Worldwide Data Sources for Models
- NREL Data Gridding Procedures
- Data Gridding Hardware and Software
- Geographic Information Systems
- Model Input Data Processing
- Model Input Data Interpretation
- Data Grid Production Procedures
- Data Grid Evaluations.

The course consisted of lectures and laboratory exercises intended to give the students the opportunity to exercise the software, including models and geographic information systems routines. Because many of the data-gridding procedures and software packages were undergoing development and modifications at the time of the course, the laboratory work could better be described as demonstrations rather than exercises. Nevertheless, the attendees were given a comprehensive introduction to this complex methodology. It was planned that they would purchase the required hardware and software upon their return to Riyadh, so they could begin exercising the procedures at KACST. Unfortunately, difficulties encountered in obtaining the software in Riyadh prevented the realization of this plan.

10.5 Annex II Summary Course

The Annex II Summary Course presented at KACST from September 13, 1997, through October 1, 1997, consisted of five parts that were designed to accomplish three distinctly different objectives. Part I–”Summary of Annex II Activities and Accomplishments” and Part II–

"Applications of Annex II Products" took place during the first two days of the course and were designed to address an audience of administrators, scientists, and engineers from various Saudi government, academic, and industrial organizations with an interest in renewable energy. During these two days, KACST and NREL project participants summarized the activities undertaken under Annex II and described the products forthcoming from Annex II and the potential applications of those products. The individual presentations given during Parts I and II are listed below:

Part I ---- **Summary of Annex II Activities & Accomplishments**
- Agreement for Cooperation in the Field of Renewable Energy R&D
- Initial & Annual Planning for Annex II
- Creating Traceability to the World Radiation Reference
- Establishing a Saudi Solar Radiation Network
- Operating the Solar Radiation Network
- Processing & Quality Assessing Network Data
- Acquiring Meteorological & Satellite Data
- Evaluating Bimetallic Actinograph Data
- Evaluating a Multiple Pyranometer Array Radiometer
- Creating a Solar Radiation Data Grid & Atlas for Saudi Arabia
- Summary of Software Development
- Technology Transfer
- Publishing Results
- Future Activities & Products

Part II ---- **Applications of Annex II Products**
- Hourly Solar Radiation Database
- Typical Meteorological Year (TMY) Data Sets
- Application Specific Data Manuals
- Solar Radiation Data Grid & Atlas

Part III–*Solar Radiation Resource Assessment Fundamentals* took place during the last three days of the first week and was also meant to address an audience from a wide range of Saudi organizations. It was also expected that a number of individuals from KACST would be interested in the presentations on the fundamentals of solar radiation resource assessment. The individual presentations given during Part III are listed below:

Part III ---- **Solar Radiation Resource Assessment Fundamentals**
- *Solar Radiation Fundamentals*
  - Solar Radiation Outside the Earth's Atmosphere
  - Atmospheric Interactions
  - Cloud Interactions
  - Solar Climate Effects
  - Solar Radiation Resource Requirements
- *Solar Radiation Measurements*
  - Radiometers
  - Standards
  - Sources of Error
  - Uncertainty Analyses

Solar Radiation Modeling
- Model Types
- Input Data
- Sources of Error
- Uncertainty Analyses

Techniques for Supplementing Solar Radiation Measurements
- Geostatistical Methods
- Satellite Methods
- Modeling Methods

Producing a Solar Radiation Data Grid
- Geographic Information Systems
- Worldwide Data Sources
- NREL Process

As it turned out, the audiences for Parts I, II, and III were essentially the same. The list of attendees during the first week of the Summary Course is presented below. There was a good representation from Saudi universities and government agencies. In addition, the Saudi Arabian-United States Joint Economic Commission was represented by Dorothy Mazaka, the Program Officer for the Renewable Energy Research and Development Project, of which Annex II is a part.

List of attendees during the first week of the Summary Course:

<u>Universities</u>

Mohammed A. Bin Afeef, Assistant Professor
King Abdulaziz University, Jeddah

Dr. Habib Abualhamayel, Dean
College of Engineering Science
King Fahd University of Petroleum & Minerals, Dhaharan

<u>Saudi Arabian-United States Joint Economic Commission, Riyadh</u>

Dorothy M. Mazaka, Program Officer

<u>Ministry of Agriculture and Water, Riyadh</u>

Saeed Safar Al-Suhrhi, Meteorological & Geophysics
Hydrology Division

Ghanem AB. Alghalnem, Hydrologist
Hydrology Division

Meteorological & Environmental Protection Administration, Jeddah

Saleh Omar Baazim, Acting Director
Regional Operations

Ahmed Saeed Almarbae, Electrical Engineer
Observations and Systems Department

Saudi Arabian Standards Organization, Riyadh

Ibrahim Mohammed Al-Nafeesah, Chemist
Radiation Department

King Abdulaziz City for Science and Technology

Saleh H. Alawaji, Associate.Research Professor
Assistant Director of Solar Program
Energy Research Institute

Mohammed Y. Bin Mahfoodh, Scientific Researcher
Energy Research Institute

Nunilo Eugenio, Research Engineer
Energy Research Institute

Abdullah Al-Kudsi, Research Engineer
Energy Research Institute

Saleh Al-Zahrani, Research Engineer
Energy Research Institute

Abdulaziz Al-Hazza, Research Physicist
Energy Research Institute

Naif M. Al-Abbadi, Assistant Research Professor
Energy Research Institute

Abdullah Al-Boeiz, Research Engineer
Energy Research Institute

Ayed Ali Algarni, Scientific Researcher
Energy Research Institute

Abdulrahman M. Al-Ibrahim, Assistant Research Professor
Energy Research Institute

Hassan Abaoud, HYSOLAR Program Manager
Energy Research Institute

Yaseen G. Al-Saedi, Solar Village Site Manager
Energy Research Institute
Ibrahim A. Al-Sagaby, Scientific Specialist
Institute of Natural Resources and Environment

Mohammed Saad Al-Farhan, Scientific Researcher
Institute of Natural Resources and Environment

Parts IV and V of the Summary Course were presented to a group of KACST staff. These sessions took up the final two weeks of the course. The objective of Parts IV and V was to train as many KACST staff as possible to carry on the work of Annex II. Critical to the success of any renewable energy resource assessment program is the maintenance of continuous measurements. Hence, Part IV addressed the operation of the Saudi 12-station solar radiation network. Part V provided instruction in the use of measured and modeled data to create resource assessment products that have been found to be useful for designing and siting solar energy systems. The subjects addressed during Parts IV and V are listed below:

Part IV ---- **Operating the Saudi Solar Radiation Network**
Maintaining Traceability to the WRR
Maintaining Network Operations
Data Processing & Quality Assessments
Upgrading the Network

Part V ---- **Producing Solar Radiation Resource Products**
Saudi Solar Radiation Database (SSRDB)
General Statistical Data Manual
Application Specific Data Manuals
Typical Meteorological Year Data Sets
Solar Radiation Data Grids

10.6 Summary of Technology Transfer

10.6.1 Formal and Informal Training

The transfer of technology from NREL to KACST was extensive and took many forms including formal classroom instruction and informal hands-on training at NREL and KACST laboratories. The formal courses described above:

Initial 6-Week Training in Solar Radiometry
Advanced Radiometry Training
Data Grid Short Course
Annex II Summary Course

encompassed a total of 13 weeks and were roughly equivalent to two 15-credit semesters of lecture and laboratory courses at a university.

Informal hands-on training took place almost continuously during the entire four years of the project. Intense side-by-side training occurred during three – five-week visits of NREL staff to KACST. These took place during October and November 1994, May 1996, and September 1997. In addition, NREL staff provided assistance to KACST and SASO personnel during the international intercomparison of cavity radiometers at Davos, Switzerland, in October 1995. Furthermore, each month from 1995 through 1997, NREL staff evaluated the solar radiation data collected by the 12-station network and provided feedback in the form of a monthly report on network operations. There were also many telephone, fax, and e-mail exchanges of information during the lifetime of the project, which are still taking place during the current extension of Annex II.

10.6.2 Hardware Transfers

Hardware designed and/or developed at NREL and transferred to KACST includes:

- Radiometer platforms
- Shading disk balanced arm
- Slip-ring assembly
- Tracker alignment tool.

The radiometer platform used at each of the 12 stations in the Saudi network was designed at NREL, based on experience gained from instrumenting stations within the United States. Engineering drawings and a prototype platform were shipped to KACST, and then transferred to a manufacturer in Riyadh to have 12 duplicate platforms constructed. NREL also provided drawings and specifications for the radiometer platforms used in constructing a calibration facility at the Solar Village.

The Eppley Laboratories prepared the engineering drawings for the balanced arm of the shading disc tracker and contracted for their construction. However, NREL initiated the idea for the arm and provided conceptual drawings for Eppley's use. These arms have provided more reliable shading disk measurements of diffuse horizontal radiation than previous hardware using an unbalanced arm or a shadowband.

The slip-ring assemblies used to connect the signal cable to the tracking pyrheliometer were designed and constructed in NREL's machine shop and then shipped to KACST. The slip-ring connections eliminated the need to disconnect and unwind the cable every two or three days. This improved the reliability of the tracker operations and eliminated the possibility of damage to the cables, trackers, or pyrheliometers.

Both of the solar trackers used at the Saudi stations are of the equatorial type. Proper operation of these trackers requires the alignment of the drive shaft, on which the pyrheliometer or shading disk arm is mounted, with the earth's north-south axis. An approximation to this alignment is accomplished by aligning the base of the tracker north-south and by setting the latitude adjustment on the tracker to the latitude of the site. (In the field, it is difficult to achieve the precision necessary on these two adjustments. The result is usually a tracker that requires further adjustments every few days.) This results in loss of data and frustrates the station operators, which can result in loss of even more data. After trying other methods to improve the tracker operations, NREL designed and constructed a tracker alignment tool that provides much more accurate alignment, resulting in greatly improved tracker operations.

The NREL tracker alignment tool consists of a precision-machined aluminum bracket on which a telescope sight (used to point telescopes at stars or planets) is mounted. The aluminum bracket is mounted on a tracker in place of the hardware that holds the pyrheliometer or tracking disk, thereby aligning the telescope sight with the drive shaft of the tracker. On a cloudless evening, this tool can be used to align the solar tracker with the earth's axis by adjusting the positioning of the tracker base and setting the latitude adjustment until the telescope sight is pointing precisely at the North Star (Polaris). Of course, the tool will not work in the Southern Hemisphere.

10.6.3 Software Transfers

Several software packages were transferred to KACST. These include the RCC and DQMS software packages described in Subsections 3.4.2 and 4.2, respectively. Both of these software packages were developed in conjunction with other projects at NREL, which reduced the cost to Annex II and permitted the development of more sophisticated software than would have been possible with Annex II funding. In addition to transferring the software to KACST, Saudi staff were trained in its use on several occasions. Furthermore, both of these packages have been upgraded several times to better meet the needs of other users. In each instance, the upgrades have been transferred to KACST at the earliest opportunity. The final result has been the provision of very sophisticated software of benefit to KACST and solar radiometry in general.

In addition to RCC and DQMS, KACST has received software for the METSTAT and CSR solar radiation models used for the production of solar radiation databases and data grids. Other related software has also been transferred to KACST. As this software is improved, KACST will receive upgrades.

11.0 Leveraging of Funds and Synergistic Benefits

When funds from more than one source can be combined to support the same or similar activities, each of the sources benefits from the expanded activities. This usually permits greater accomplishments than would have been possible with the funding available from any single source. In addition to this leveraging, synergism (the result of the combined activities is greater or improved in comparison to the sum of the individual activities if they had been undertaken independently) also occurred. During the first four years of Annex II, opportunities for leveraging and synergism were actively pursued. The benefits that accrued to KACST and Saudi Arabia's solar energy programs were substantial and are summarized here.

11.1 Advances in Solar Radiometry

Annex II and several other projects synergistically benefited from common needs to improve the state of the art of solar radiometry. In 1994, the first full year of Annex II, three sources of funds were used to initiate the development of the DQMS software package. The cost of developing DQMS was shared equally by three projects, Annex II and two DOE-funded projects. The Solar Radiation Resource Assessment Program (SRRAP) was planning to support multiple solar radiation networks across the United States and needed a sophisticated data quality management system to provide compatibility among the networks. In addition, a UV measurement network needed similar software to manage its data collection program. By meeting the needs of each of these projects, the funds for all three were leveraged and a more sophisticated software package with a broader range of capabilities was produced. Software developed to meet only the individual needs of each of these projects would not have been compatible and could not have been combined to achieve the capabilities of DQMS.

Since the development of the original DQMS, several upgrades have been made to meet the expanded needs of the original projects, as well as DOE's Atmospheric Radiation Measurement (ARM) program. In addition to DQMS, the ARM program has contributed significantly to the advanced development of the RCC software. The original RCC software was developed using a combination of Annex II, SRRAP, and NREL Metrology funding. For many years prior to the start of Annex II, NREL played a major role in the development of improved methods for the calibration and characterization of solar radiometers. In 1994, the combined funding allowed the development of a more sophisticated calibration and characterization software package than any of the individual projects could have afforded. Recently, the special requirements of the ARM program led to further upgrades of RCC. It is very unlikely that the independent efforts of these four projects would have achieved as much as was accomplished by combining their funds to address common needs. Certainly, the capability of the RCC software being used at the Solar Village far exceeds that which could have been developed with only Annex II funds.

The daily maintenance required to achieve reliable operation of solar trackers and thermopile radiometers led to the development of multiple pyranometer arrays (MPAs) (see Section 8.0). The MPA instrument being evaluated by NREL has no moving parts and uses LI-COR pyranometers with diffusing discs over the silicon sensors to achieve flat cosine response characteristics. It was expected that this instrument would be less sensitive to the accumulation of dust, and hence, would require less frequent maintenance.

This hypothesis was tested at the Solar Village, where dust builds up rapidly on outdoor equipment because of the high concentrations of dust in the atmosphere. Two MPA instruments were installed, one was left unattended and the other was cleaned daily. An Eppley PSP pyranometer was also left uncleaned and compared with the MPA instruments. The LI-COR pyranometers were not as affected by dust accumulations as was the Eppley thermopile pyranometers, but the difference was not as great as expected. This opportunity to evaluate the MPA radiometer under the Saudi atmospheric conditions could not have been duplicated in the United States.

11.2 Development of Data-Gridding Technology

As described in Section 9.0, NREL's data-gridding technology was initially developed under the DOE Solar Radiation Resource Assessment Project. During 1996, funding to support data gridding was also received from DOE's Solar Thermal and Photovoltaic Projects. These projects led to the production of cloud cover maps for South America, Africa, Australia, India, Borneo, and Egypt. Then, in 1997, funding from the Solar Thermal Project supported the production of solar radiation data grids for India and the surrounding region; funds from Annex II and the Solar Thermal Project were used to produce solar radiation data grids for a Mideast region centered on Saudi Arabia. The Saudi Arabian Atlas, of course, was produced only from Annex II funds.

SRRAP funding has been available to support the development of the data-gridding technology from 1995 to 1998, and was used to produce data grids and maps of North America. However, the availability of funding from the Solar Thermal, Photovoltaic, and Annex II projects has allowed the advancement of this technology much farther and much faster than could have been done using only SRRAP funds. Each of these sources of funds has benefited from the leveraging of funds from the other sources; the resulting data grid capability is far greater than could have been achieved by separate and independent projects.

11.3 Development of Training Materials

All of the courses presented to Saudi staff at NREL were, at times, attended by scientists and engineers from NREL and other organizations (e.g., NOAA and the University of Oregon). Furthermore, some of the training materials developed for Annex II courses have been used for other courses at other facilities. Because of the multiple needs for such training, the cost of the development of the training materials was shared by several NREL/DOE projects. This allowed the development of more extensive and higher quality materials than would have been possible under Annex II funding alone.

Of equal importance to the sharing of funds was the attendance of the courses by individuals from other organizations, which enhanced the learning experience. This synergistic benefit resulted from the different backgrounds brought to the classes by everyone in attendance. The comments and questions from each participant led to discussion and sharing of information that would not have taken place had the classes been attended by only the Saudi participants.

11.4 Expected Future Benefits

The opportunities for leveraging and synergism are continuing as this report is being written. Under a project to evaluate new satellite sensing systems, NASA has funded NREL to provide them with data from the Saudi 12-station network. This, plus the interest of the WMO-sponsored

BSRN program to add a Saudi station to the BSRN network, will result in upgrading the station at the Solar Village, and offers the opportunity for KACST scientists to attend NASA and BSRN meetings. This opportunity for KACST scientists to interact with and learn from solar radiation experts from around the world would not be possible without the continuation of Annex II. There is every reason to expect that both KACST and NREL will continue to benefit from leveraging and synergistic opportunities afforded by this joint project.

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In 1987, the United States Department of Energy (DOE) and the King Abdulaziz city for Science and Technology (KACST) signed a five-year Agreement for Cooperation in the Field of Renewable Energy Research and Development (R&D), which has been extended to 2000. Tasks include: 1) upgrade solar radiation measurements in Saudi Arabia; 2) assemble a database of concurrent solar radiation, satellite (METEOSAT), and meteorological data; 3) adapt NREL models and other software for Saudi Arabia; 4) develop procedures, algorithms, and software to estimate solar irradiance; and 5) prepare a grid of solar radiation data for preparing maps and atlases and estimating solar radiation resources and solar energy system performances at locations in Saudia Arabia.

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