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PV Radiometrics Workshop Proceedings

D. Myers, Chairman

July 24–25, 1995
Vail, Colorado

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Foreword

This report documents presentations and discussions held at the Photovoltaics Radiometric Measurements Workshop conducted at Vail, Colorado, on July 24 and 25, 1995. The workshop was sponsored and financed by the Photovoltaic Module and Systems Performance and Engineering Project managed by Richard DeBlasio, Principal Investigator. That project is a component of the National Renewable Energy Laboratory (NREL) Photovoltaic Research and Development Program, conducted by NREL for the U.S. Department of Energy, through the NREL Photovoltaic Engineering and Applications Branch, managed by Roland Hulstrom.

The workshop provided a forum for technical presentation and discussion of the state-of-the-art and immediate and long-term needs for solar and optical radiometric measurements and data as applied to improving photovoltaic engineering, testing, performance evaluation, and performance prediction. Twenty-six attendees from industry (6), utilities (2), national laboratories (14), and universities (4) provided expertise and insight during discussions of current and future radiometric needs and issues regarding photovoltaic applications.

The needs and issues discussed are summarized in the final paper of these proceedings and will serve as the foundation for setting goals and objectives in operations and for planning future work within the Photovoltaic Solar Radiometric Measurements and Evaluation Team which supports the Photovoltaic Module and Systems Performance and Engineering Project.

Approved for

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DEDICATION

Dr. Mark Koltun, on sabbatical at the Jacob Blaunstein Institute for Desert Research at Sede-Boker, Israel, from the Moscow, Russia, Institute of New Technologies, suffered an untimely death after the preparation of his paper for this workshop. Dr. Koltun was an instrumental player in developing photovoltaic systems for the space exploration program of the former Soviet Union, and a world-recognized expert on surface and material science. His premature passing has cut short the opportunity to work on an open basis with a dynamic and innovative individual. We dedicate this volume, which contains his last scientific paper, to his memory.

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Photovoltaic Radiometric Measurements Workshop Introduction and Overview

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Abstract. The National Renewable Energy Laboratory supports the U.S. Department of Energy's photovoltaic (PV) program through research in basic and engineering sciences related to improving the performance and commercial viability of PV energy conversion as an alternative energy source. Since 1975, much progress and technological evolution has taken place, chronicled in part by periodic scientific and engineering conferences, program reviews, and workshops involving manufacturers, universities, and private and government research laboratories. The growth of the PV program resulted in more specialized and topical workshops sponsored in part by the NREL Photovoltaic Module and Systems Performance and Engineering Project to address specific program issues. Solar and optical radiometric measurements and data are crucial in quantifying PV research progress, available solar resources, and predicted and installed PV array performance. This workshop is an effort to focus on the state-of-the-art, needs, future research directions, and NREL action items for radiometric instrumentation, data, and research to maintain the momentum of progress toward the fundamental understanding of, improvement in, and sustainability of PV technology as an alternative energy source.

INTRODUCTION

Since the mid 1970s, steady progress has been made in the basic understanding, performance, commercial diversification, manufacturing, and deployment of photovoltaic technology. The U.S. Department of Energy, Jet Propulsion Laboratory, National Renewable Energy Laboratory, Sandia National Laboratories, and numerous other government, university, and private research laboratories have worked to sustain this progress. The national PV program has grown in size, building upon technical and scientific success, to work toward the goal of PV serving as an effective alternative energy source. This growth has been assisted and chronicled by scientific and engineering conferences and workshops allowing technical interaction and information exchange between government-supported basic research and engineering and the commercial and industrial world.

Exchange of scientific information, and particularly technical information related to the PV community, generally takes place in large conferences of PV specialists covering a broad range of topics—such as in the periodic IEEE PV specialist conferences and periodic PV Program Reviews or in highly specialized single-technology settings (for example, an Amorphous Silicon Task Group)—and, of course, in scientific publications, journal articles, and technical reports. Periodically, specialized workshops dealing with crosscutting issues in the PV community are held.

The focus of workshops in the early 1970s and 1980s, such as the Terrestrial Photovoltaic Measurements Workshop[1] (March 19-21, 1975), Commercial

Photovoltaics Measurements Workshop[2] (July 27-29 1981), and the Photovoltaic Insolation and Measurements Workshop[3,4] (June 30-July 3 1985), was rather broad. Topics covered included measurement needs, PV product/customer interaction, quality assurance, consensus standards, materials characterization, module certification, device performance, array performance, and solar radiation instrumentation, measurements, and data.

Since 1986, periodic Photovoltaic Performance and Reliability Workshops developed by the NREL Photovoltaic Module and Systems Performance and Engineering Project have provided a venue for exchanging information about theoretical and measured PV module and system performance and reliability issues at the cell, module, and array level. Similarly, since 1990, periodic Standards and Codes Forums are conducted to keep government and industry engineers up to date and involved in developing the standards infrastructure to support commercial industrial needs related to PV. Table 1 illustrates the relationship and focus of the present PV workshop calendar sponsored by NREL. Although there is some overlap in focus and topics as one moves from column to column in the table, note the reduction in the number of topics and increased focus as one moves from left to right across the table.

The 1985 Photovoltaics and Insolation Measurements Workshop was the last concerted attention to the state of the art and discussion of needs related mainly to solar and optical radiometry in concert with the PV community. As the DOE PV program has grown since 1985, so have both the radiometric capability and needs within the program and in the commercial world. Many of the action items developed at the 1985 Conference have been addressed to some degree. After discussing this state of affairs within the NREL Photovoltaic Module and Systems Performance and Engineering Project, it was agreed that the PV Solar Radiometric Measurements and Evaluation Team should develop a workshop to focus on the interaction between radiometric measurements, instrumentation, data, models, and data bases to update the commercial and research PV community on progress since 1985.

Most importantly, the workshop must serve as a forum for defining critical issues, needs, and action items in the area of solar and optical radiometry that the PV community are aware of—or realize during the course of the workshop—that presently are not being addressed. These needs, issues, and action items can then be addressed (within the constraints of the resources available) through DOE/NREL project annual operating plans, task objectives, and interactions with other national labs, the National Institute of Standards and Technology, World Meteorological Organization, National Weather Service, etc.

In the following sections we present a brief overview of the status of 23 action items and recommendations identified in the 1985 PV and Insolation Measurements Workshop, and the strategy used during this workshop for soliciting and addressing radiometric needs of the PV community.

Table 1. NREL-Sponsored Photovoltaic Workshops and Focus

	PV Program Review	PV Performance & Reliability	PV Standards & Codes Forum	PV Radiometric Measurements
Cells	Device Physics Material Properties Reference Cells Champion Cells Mfr. Technique Efficiency Economics	Reference Cells Mfr. Technique Reliability Stability Calibration & Use Artifacts	Reference Cells Calibration and Use Standards Development ASTM, IEEE, ANSI, ISO	Reference Cells Source Calibration Spectral Response Spectral Mismatch Safety (Dose) Calibration Indoor vs Outdoor
Modules	Mfr. Improvement Design Performance Qualification Testing Reliability Durability Stability Rating Methods Diagnostics Applications Economics	Qual & Perf. Test Test Validation Std Test Cond Perf. Indoor/Outdoor Test Stability Rating Methods Diagnostics Artifacts	Draft Procedures ASTM, IEEE, ANSI Standards Development International Standards (ISO) Ratings Methods Accelerated Testing	Prevailing Cond. Spectral/Broadband Instruments Safety Indoor vs Outdoor Correlations Radiometer Characterization Resource Data for Perf. Models
Arrays	Perf. Prediction, Deployment, and Measurement Standards and Codes Safety Balance-of-Systems Economics	System Monitoring Stability BOS Standards & Codes Safety Reliability Performance Prediction	Safety (UL) Ratings Methods National Electric Code	Instrumentation Solar Monitoring for Performance Resource Data for Design & Prediction Performance & Radiation Modelling and Data Sets
Audience	Research Scientists Physicists Materials Scientists PV Engineers System Designers Manufacturers Universities Utilities DOE/NREL Program Management	Research Scientists Materials Scientists PV Engineers System Designers Manufacturers Universities Utilities	Industrial and Consensus Standards Organizations Research Scientists Materials Scientists PV Engineers System Designers Manufacturers Universities Utilities	Instrument Mfr. Atmospheric Physicists & Modelers PV Engineers System Designers & Modelers Manufacturers Universities Utilities

Note the above table is not all-inclusive, as many other very focused technical workshops, committees, teams, and ad-hoc groups work on technology specific problems under sponsorship of the DOE, NREL, and other interested parties, such as the Electric Power Research Institute, Utility PV Group, and consensus standards organizations.

STATUS OF 1985 WORKSHOP ACTION ITEMS

Over a period of three days, the 1985 PV and Insolation Measurements Workshop addressed solar radiation, device performance, and array performance. A panel of expert participants in each of the three areas came up with specific needs and recommendations, which were presented to the audience for discussion. A total of 22 "needs and issues" and 17 "recommendations" were identified by the PV research and development and manufacturing community, as areas of needed improvement to foster progress in the performance and acceptance of photovoltaic energy conversion.

Of the total of 39 separate items identified by the panels, 16 (or 41%) were essentially redundant or overlapping, resulting in 23 unique areas needing action. The topics were not prioritized, nor was there much difference in the wording of needs, issues, or recommendations. Therefore, I have identified the 23 unique topics identified as "action items" that needed addressing by the PV community in 1985. Table 2 lists the topics concisely, summarizing the results of research activity during the past 10 years and the current status of each item.

As the working groups and individuals involved in the 1985 workshop evolved in terms of changes in organization and responsibilities and in focus, some of the action items became objectives for newly evolved groups. However, the PV Radiometric Measurements and Evaluation Team has tried to remain aware of progress on as many fronts as possible, while focussing on radiometric engineering measurements, support, and calibrations for NREL and the PV community in general, and the PV Module and System Performance and Engineering Project in particular.

Significant progress has been made on items identified in ***bold italic*** text with a check mark ✓. Workshop speakers will address the progress made in these areas. See the notes at the end of the table for clarification of some items.

Table 2. 1985 PV & Insolation Measurements Workshop Action Items

NEED, ISSUE, or RECOMMENDATION	ACTION/RESOLUTION
✓Improved, well-defined radiation data sets	***New NSRDB [(a)] data base, insolation data manual, TMY, statistical summary***
✓Better attention to pyranometer calibration	***WMO/ASTM/NREL radiometer calibration data processing***
Access to international radiation data	Sol Rad Resource Assess Pgm (SRRAP)
Convert satellite data to radiation data	SRRAP group addressing
✓Spectral Solar Radiation Data Base	***3000 spectra available [(b)] (1989) 3 sites***
✓Spectral data to 3 microns	***Extended λ spectroradiometers GER, OL750***

NEED, ISSUE, or RECOMMENDATION	ACTION/RESOLUTION
Quantify microscale variations (1 mile, array field size)	NREL/SRRL/FETA [c] highly instrumented. Others?
Few, high-accuracy radiometric stations	RMIS? SRRL? CONFRRM [d] co-op sites
✓Resolve radiometer calibration issues	***Improved radiometers, characterization facilities, reporting, uncertainty [e]***
Improve the national radiometric monitoring network	Defunct; Co-op CONFRRM sites under SRRAP
✓Routine monitoring of atmospheric parameters, Tau, PWV, cloud cover	***Atmospheric Optical Cal. System [f] NSRDB data set Tau, PWV, CC***
✓Broadband-to-spectral data conversion	***Nann/Riordan Model SEDES2 conversion NSRDB->spectral (Tau, PWV) [g]***
✓Increased participation in international standards development	***TAG 82, Standards Codes Forum***
Standard methods for measuring multijunction spectral response	ASTM? NREL? Multisource methods?
✓Energy ratings related to various climatic conditions for modules	***Tech Review Committee, energy ratings [h]***
✓Multijunction performance prediction methods for range of climates	***NSRDB + Coefficients, Annual; statistical summaries [i]***
Standard testing methods for concentrator collectors	Sandia Labs experience?
Low-cost automatic solar tackers	Little progress(?)
Inexpensive large-area solar simulators	Little progress(?)
✓Consensus on performance ratings for PV arrays	***PVUSA, Energy TRC***
Array temperature prediction models need verification	Sunset Technology Model [j]
✓Improve solar radiation estimation models—climate specific Perez Coeff.	***Improved versions of Perez Model widely used***
✓Hold workshops every 2 years	***Periodic Perf. & Rel.; Stds & Codes***

Notes to Table 2:

(a) The National Solar Radiation Data Base (NSRDB) contains 30 years of hourly solar radiation and meteorological parameters for 223 sites for the period from 1961-1990. It was developed to update the existing Solar Meteorological (SOLMET) data base (covering 1952-1975) based on the regular 10-year updates of meteorological climatic means and normals. The NSRDB uses the latest (1990) solar radiation models and quality assessed and systematically corrected measured radiation data and a larger number of meteorological parameters (21 in all), including aerosol optical depth and precipitable water-vapor estimates. It is available from the National Climatic Data Center, Ashville, NC (customer service, 704-271-4800), as the Solar And Meteorological Surface Observation Network (SAMSON) on three CD-ROM disks, for about $100 per disk. See the papers by E.L. Maxwell and B. Marion on the data base, models, and products such as Solar Radiation Data Manuals and Typical Meteorological Years (TMY).

(b) The SERI (now NREL) Solar Spectral Data Base[5] contains 3000 spectra collected in conjunction with broadband and meteorological data at three sites (Cape Canaveral, FL; San Ramon, CA; and Denver, CO, over a period of 18 months from October 1986 to April 1988.

(c) The NREL PV Module and Systems Performance and Engineering Project operates and monitors a wide variety of module and system test beds at the NREL Field Experiment Test Area (FETA). Each of these systems or testbeds is instrumented with individual radiometric instrumentation that can be compared with 1-minute, time-averaged data collected by a Reference Meteorological and Irradiance Station (RMIS) located at one edge of the array field.

(d) The Cooperative Network For Renewable Resource Monitoring (CONFRRM) is a proposed network of regional centers managing and archiving radiometric data from a number of local monitoring sites, under NREL auspices. As of June, 1995, requests for proposals have been mailed to 466 prospective proposers to manage the regional networks. See the discussion of radiometric networks by T. Stoffel.

(e) New pyranometer and pyrheliometer radiometer designs are available from several manufacturers. Characterization of radiometers has been extensively studied by the International Energy Agency (IEA), the State University of New York (SUNY) at Albany, Department of Atmospheric Sciences, and NREL. See the radiometric instrumentation paper by T. Stoffel.

(f) The Atmospheric Optical Calibration System (AOCS) is an automated sunphotometer for monitoring atmospheric parameters needed to compute model spectral distributions and mismatch factors for various PV technologies on a near-real-time basis. See the paper on spectral radiometric instrumentation by T. Cannon.

(g) Nann and Riordan[6] developed empirical cloud cover modifiers to apply to the SPCTRL2 clear-sky spectral model of R. Bird, and it is being considered as one component of the Module Energy Rating activities under the PV Module and Systems performance and Engineering Project.

(h) The energy-ratings activity is conducted under guidance from a Technical Review Committee, established by Laxmi Mrig and Benjamin Kroposki of the NREL Photovoltaic Module and Systems Performance team, to address approaches, methodology, and validation of the approach taken, including choices of models.

(i) The paper by J. Burdick presents one approach to evaluate the performance of various technologies, including thin-film and multijunction devices, by playing empirically determined module coefficients (in co-operation with K. Emery and Steve Rummel of the NREL PV Measurements Team) against hourly radiation and temperature data in the NSRDB. Others have taken an approach based on statistical cumulative frequency distributions representative of the 30 years in the NSRDB for selected sites.

(j) J. Anderson of Sunset Technologies has developed extensively modified translation equations and new methods of estimating module temperatures, again in co-operation with K. Emery and Steve Rummel of the NREL PV Measurements Team, which are also incorporated into the work of J. Burdick.

With this report of the status of current and past activities concerning radiometric data and instrumentation in mind, we turn our attention in the next section to the strategy employed in this workshop to identify current and future needs and issues.

STRATEGY FOR IDENTIFYING 1995 WORKSHOP ACTION ITEMS

From the program and the topics presented, it is clear that the speakers will be presenting primarily the current status and view of radiometric issues from the NREL perspective. Our goal is to inform participants of the current PV Solar Radiometric Measurements and Evaluation Team knowledge regarding the state of the art. **We then will actively solicit the participants to identify and articulate issues, needs, and concerns for future direction and actions.**

Each speaker has been requested to provide adequate time for discussion of the topics or related subject as the talks are presented. In addition, at the end of each day's activities, the wrap-up sessions of about 30 minutes to an hour will be devoted to "brainstorming" sessions in which issues, ideas, and needs are noted without criticism. The final wrap-up session will be used to filter and identify the most pressing issues. These will be summarized in the final paper in these workshop proceedings, along with rationale and strategies, goals, and objectives associated with the identified issues.

Finally, we thank the workshop participants for their hard work in preparing the papers, and especially for the discussions and contributions provided to achieve the workshop goals.

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OPTICAL AND SOLAR RADIOMETRY

STANDARDS AND TRACEABILITY

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ABSTRACT

This paper presents an overview of the concept of traceability for optical and solar radiometry measurements, current measurement standards and consensus standards, and measurement uncertainty analysis. The inter-relationships between traceability, standards and uncertainty will be shown. This overview will provide some foundations for other papers in this Workshop.

In the late 1970's, the solar energy research community encountered difficulties when comparing efficiency measurements of flat-plate solar thermal collectors—the efficiency measurements and tests made at participating laboratories revealed differences that were larger than would be expected from the errors believed to be present in the measurement processes used then. The differences were found to be largely due to the solar radiation measurements. There are lessons to be learned from that situation for PV radiometry activities.

The concept of traceability and its impact on PV radiometry, is explained and related to standards and calibration, measurement uncertainty analysis, measurement standards, consensus standards, and measurement quality assurance.

The measurement reference standards that support the PV optical and solar radiometry will be described. Basic concepts of measurement uncertainty analysis will be highlighted, and extensive references to the literature are given. Consensus standards applicable to PV radiometry work will be noted.

AN HISTORICAL PERSPECTIVE

In the time period between about 1978 and 1980, there was lack of agreement in results of testing the efficiency of solar thermal flat plate collectors. This occurred between laboratories in the U.S. and between laboratories in western Europe, and between laboratories on the two continents.

The principal measurements required to measure the efficiency of such a collector (efficiency being power output/power input) were temperature rise in the liquid flowing through the collector together with the heat capacity of that liquid; the liquid flow rate; and the input solar power. An examination of the temperature rise measurement indicated that this measurement was sufficiently accurate that it should not be responsible for such a large difference in efficiency measurements. The liquid flow rate measurement, though less accurate than the differential temperature measurement, was likely not to be the cause of the large differences. The heat capacity of the liquids in use (often it was water) seemed not to be an issue. This left the measurement of the solar power—the solar irradiance in units of watts/square meter impinging upon the solar collector during the test—as the likely source of the lack of agreement in the efficiency measurements.

The Performance Testing of Solar Collectors research task (Task 3) of the International Energy Agency's (IEA) Solar Heating and Cooling Programme (SHCP) sponsored a meeting of collector test and solar radiometry experts. It was hosted at the World Radiation Center (WRC), Davos, Switzerland (March 1980) during which the pyranometers used for the collector testing were compared[1]. Analysis of the comparison of the 23 instruments showed that there was a spread of 10.23% in the measurements (average of the ratios to the WRC reference pyranometer), centered 6.0% below the WRC reference. The comparison showed that "all calibration factors given by the manufacturers yield readings which are 6-7% lower than those referred to the World Radiometric Reference (WRR). Only about 2% can be explained by the difference between the IPS[2] and WRR. The remaining 5% seem to be due either to the method of calibration or to the reference instrument used."[3] Irradiance readings on the WRR are 2.2% higher than on the IPC-56 scale. That is, IPC-56 understated the solar irradiance by 2.2%. In a subsequent report[4], Claus Fröhlich reported that a +2.5% systematic error in irradiance readings of the reference pyranometer resulted from calibrating the reference instrument using the classical shade-unshade technique. This conclusion was reached after recalibrating the reference pyranometer using the component summation technique: for this calibration technique, the reference value of the global irradiance on a horizontal surface was taken as the sum of the vertical component of the direct beam plus the diffuse component of the global irradiance (measured using a pyranometer under a shading disk).

As a result, a round robin test program was initiated to have some of the pyranometers, which were compared at Davos, calibrated at various labs around the world. Then a meeting[5] of 21 experts from 8 nations was held in Boulder, Colorado (March 1981) to review the results of the round robin plus preliminary results from a subsequent second round robin of pyranometer tests still underway at the time, and to plan the next steps in solving the pyranometer measurement problem.

It was apparent that a new IEA research task was needed to specifically address the need for assessing the state of the art of pyranometry present at that time and to develop improvements for solar research and engineering work. So IEA Task 9, Solar Radiation and Pyranometry, was formed in 1982 to address these issues.

One of the goals resulted from that Boulder meeting is directly applicable to this PV Radiometric Measurements Workshop: "The state of the art of pyranometry will be improved to produce measurements of global solar radiation on any defined plane surface, oriented from the horizontal to the vertical with a total uncertainty acceptable for use in solar collector testing and other solar engineering applications." The April 1995 draft of the final report of that IEA Task IX work in pyranometry is being reviewed, with publication of the report expected later this summer[6].

Two results reported in this IEA document[7] are of importance to us at our meeting today:

- The best measure of the global solar irradiance using only a pyranometer requires a characterized Secondary Standard or 1st Class Pyranometer (as defined by WMO), used with a ventilator, and can be expected to produce measurement results with ±30 to 35 watts uncertainty (2σ).

- The best possible measure (that is, the measurement with the smallest total uncertainty) of global radiation will be achieved using the component summation technique, by measuring the direct beam component through continuous operation of an absolute cavity radiometer without a window and to measure the diffuse component with a ventilated Secondary Standard Pyranometer under a tracking shading disk and using zero correction provided by a pyrgeometer or the night-time pyranometer signal. The uncertainty is believed to be ±20 watts (2σ).

These results are generally in line with the conclusions of the state of the art in 1990 drawn in the work of experts in the Baseline Surface Radiation Network (BSRN) project of WMO. The ultimate goals of the BSRN are to be able to achieve ±1% of the direct beam and 4% of the diffuse radiation, and ±2% of the global horizontal, using the component summation technique with windowed or fully weatherproof housing for a cavity radiometer.[8]

LESSONS LEARNED

Referring to the pyranometry results discovered in the 1980-81 IEA work: how could this have happened? Reflecting back on that work, and what we learned in the ensuing years, there are possibly five reasons that led to the lack of agreement in pyranometry then, and these factors are important to us today in doing and improving solar radiometry for PV research, testing, and applications:

1. In solar radiometry, rigorous measurement traceability was not well understood and practiced, nationally or internationally. (There appears to be some more knowledge and practice of traceability in radiometry today, but that is not true in all cases.)

2. Consensus standards for calibration of instruments were not well developed at the time. (Basically, the standards are in place today, with some needing updating or replacement, and others needing development, which efforts are now going on.)

3. Measurement uncertainty was not (and is still not) widely understood and practiced in radiometry.

4. Rigorous measurement uncertainty requires characterization of radiometers. (We need to practice the characterization techniques we know how to do for the instruments we have today, and help hasten the introduction of more perfect instruments.)

5. Quality assurance measures were not (and usually still are not) practiced regularly, in both calibration and field radiometry measurements.

Concerning measurement traceability in the 1978-80 time frame, many labs were still using the IPS-56 measurement scale which had been found to produce low readings. In that time period, only a few absolute cavity radiometers were in use, and the WRR was just being finalized and promulgated. The rigor of traceability developed for general purpose measuring and test equipment in the metrology field had not (and still has not adequately) permeated the solar radiation and auxiliary measuring instruments used in meteorology or solar energy research and engineering.

The IEA results became a strong impetus for the development of consensus standards for calibration of solar radiometers, first in the U.S. through the American Society for Testing and Materials (ASTM), and later through the International Organization for Standardization (ISO). These consensus standards will be addressed later.

Measurement uncertainty analysis techniques, growing out of earlier "error analysis" techniques, were being refined. The first effective U.S. standard for measurement uncertainty analysis was not approved until 1985[9]. It was in 1985 that SERI (the Solar Energy Research Institute), now NREL, began to apply these techniques in a some of its research programs. The early work of Emery, Myers, Wells, and others in radiometry and PV reference cell calibration areas document some of that work.[10,11,12,13,14,15] At SERI, ANSI/ASME PTC 19.1 soon became the commonly referenced standard by those groups performing rigorous uncertainty analysis.

The characterization of pyranometers began in some earnestness in IEA Task 9, involving characterization and comparison of results at about 13 or more laboratories, internationally. The development of the ASTM and ISO standards, and now the BSRN project, have supported interest in improved pyranometer characterization and calibration capability, and produced greater awareness of the need for improved instruments.

What is needed now are: improved instruments with improved characterization and understanding of their uncertainties; more rigorous traceability in solar radiometry and radiometry that affects PV; with improved consensus standards for calibration, characterization, and field measurements; measurement quality assurance applied on a regular basis in instrument calibration and PV testing; and continued cooperation and exchange of results between laboratories.

TRACEABILITY OF MEASUREMENTS

The concept of traceability has philosophical, technical, and legal origins and implications that are discussed in some detail in two papers and the references contained therein.[16,17] They are worth reading.

From this background and from experience, the concept of traceability can be seen to rest on three legs. And, like the traditional farmer's milking stool, if one leg is missing, the result is something upon which it is hard to confidently place any weight! The three legs are calibration hierarchy, uncertainty analysis, and quality assurance:

1. If measurements are to possess the quality of traceability, then the measuring and test equipment used to acquire those measurements are calibrated utilizing reference standards whose calibrations can be followed (traced) back up a documented and unbroken pathway to the source of the highest accuracy (smallest uncertainty) national and/or international reference standards for the units of measure involved.

2. In the calibration and use processes, measurement uncertainty analysis is performed according to a well-proven approach, and reported at each step in the measurement chain.

3. The ultimate test of the traceability of a measurement is achieved through a measurement quality assurance system or process that ensures that the accuracy of any particular measurement result is within stated limits of uncertainty.

Traceability requires standards—both physical measurement standards and defined measurement scales, as well as procedural consensus standards, that are agreed to and used. The consensus standards define the measurement process through specifying procedures and measurement and analysis/data processing techniques and the equipment to be used. As we will see in the discussion of measurement uncertainty analysis, a specifically derived uncertainty value and statement applies only to the specifically defined measurement process that is analyzed. Any change in the measurement process (whether in equipment, technique, or environment, etc.) must be examined to see if the uncertainty value has changed.

"Direct" traceability to a particular standard means that a measuring instrument employed for a particular measurement has itself been calibrated or compared directly to that standard. For example, an absolute cavity solar radiometer has direct traceability to the World Radiometric Reference (WRR) if it has participated in the last International Pyrheliometer Comparison (IPC) in Davos, Switzerland.

NREL provides direct traceability to WRR, for itself and for other DOE labs and programs, through the two absolute cavity radiometers that participated in the last IPC. We have participated in all of the IPCs held since SERI was formed in 1977: IPC-V in 1980, IPC-VI in 1985, and IPC-VII in 1990. We have requested to participate in IPC-VIII in September-October 1995.

To provide some measurement assurance in our absolute cavity radiometry, we in the U.S. formerly (1978 through 1985) held 7 radiometer intercomparisons at the facilities of DSET Laboratories in New River, AZ (40 miles north of downtown Phoenix). These were called the New River Intercomparisons of Pyrheliometers (NRIPs). Now we are conducting cavity radiometer intercomparisons at NREL's Solar Radiation Research Laboratory (SRRL), on top of South Table Mountain here in Golden. These outdoor experiments help assure us that the cavity radiometers are performing properly. It is through this activity that we propagate the WRR to other DOE labs and provide them indirect traceability to WRR.

"Indirect" traceability is a path of measurement traceability that includes intermediate standards or calibration steps between the measurement in question and the ultimate highest standards. Indirect traceability for a measurement incurs larger uncertainty than if direct traceability existed, for there is a buildup of uncertainty at each step in a measurement chain.

Figure 1 shows a simple diagram developed several years illustrating how SERI (now NREL) established direct traceability for standards for broadband shortwave solar radiation and for solar spectral measurements.

MEASUREMENT STANDARDS FOR OPTICAL AND SOLAR RADIOMETRY

Measurement standards for solar spectral measurements are obtained in the form of calibrated lamps from the National Institute of Standards and Technology (NIST, formerly NBS, the National Bureau of Standards) in Gaithersburg, MD. These lamp standards are 1,000-watt quartz-halogen lamps, for which the spectral irradiance distribution and intensity have been determined through an extensive series of measurements, starting with the High Accuracy Cryogenic Radiometer as the primary standard and a gold point blackbody as the reference standard, to develop the spectral radiance scale. The average spectral radiance of the aperture of an integrating sphere source is determined, which becomes a spectral irradiance source by applying a geometric factor. The spectral irradiance of a group of working standard lamps is determined by comparison to the integrating sphere source.[18,19]

Customers lamp standards are calibrated against this group of working standards. The NIST FASCAL (Facility for Automated Spectroradiometric CALibrations) is being upgraded by further automation, to reduce the uncertainties and to reduce the man-hours involved in these calibration processes. Techniques have been improved to reduce the total uncertainty for spectral irradiance lamp standards.[20]

NREL purchases these lamp standards, with their calibration characterizations, to calibrate the spectroradiometers used in PV spectral measurements. Daryl Myers documented the

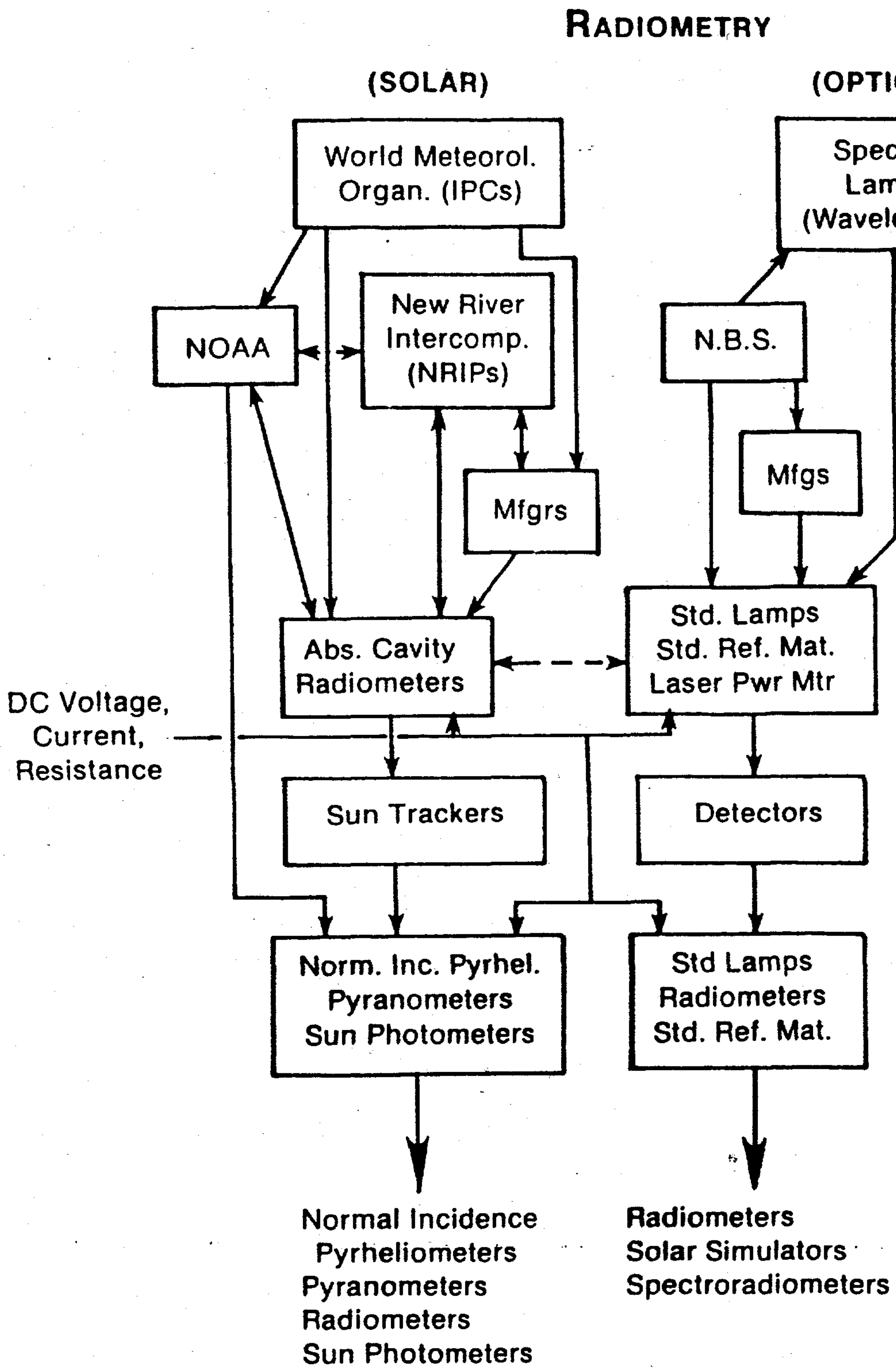

Figure 1. A diagram of traceability of solar and optical radiometry developed early in the metrology program at the Solar Energy Research Institute (SERI, now NREL)

uncertainty achieved in the calibration of the spectroradiometers[21] used in acquiring the spectral data base measurements.

The standard instruments for making shortwave solar irradiance measurements are absolute cavity radiometers. These absolute radiometers depend primarily on the dimensions of the precision aperture in front of a black cavity that absorbs all the solar radiation from in the UV, through the visible, into the near-IR. The solar power absorbed is compared to electrical power in a substitution measurement. Automated operation of the popular Hickey-Frieden absolute cavity radiometer (Eppley Laboratory Model AHF) has led to ease of use of these very accurate radiometers.[22]

In field application measurements, the direct beam is often measured using either cavity radiometers or normal incidence pyrheliometers (such as the Eppley model NIP). These instruments are calibrated by comparison against one or more cavity radiometers that participated in the International Pyrheliometer Comparison in Davos, or more usually, compared to cavity radiometers that have direct traceability to the radiometers through participation in the IPC in Davos.

Global horizontal and hemispherical solar irradiance measurements are made using pyranometers (such as the Eppley model PSP), which measure the total solar radiation over a 2-pi solid angle. These are calibrated against absolute cavity radiometers or NIPs, using a shade-unshade or the component summation technique, as described in the consensus standards. A precaution sometimes overlooked is the fact that some pyranometers have a long second time constant (some have been measured at 180 to 240 seconds). This requires a shaded or unshaded period of approaching 10 minutes in order to reduce the error in the derived calibration factor due to this characteristic to less than 0.1%. At NREL, in our BORCAL calibrations (Broadband Outdoor Radiometer CALibrations), we use the component summation technique, with which we can calibrate even 30 or more pyranometers at one time. We are limited in number by table top area and data acquisition techniques.

MEASUREMENT UNCERTAINTY ANALYSIS

The value and worth of measurement uncertainty analysis is often overlooked: it is what gives real worth to our experimental results.

> "In NBS SP644, Eisenhart and Colle expressed how uncertainties should be considered: 'If there is one fundamental proposition for the expression of uncertainties, it is: The information content of the statement of uncertainty determines, to a large extent, the worth of the result.'
>
> "This information content can be maximized by following a few simple principles: 'BE EXPLICIT, PROVIDE DETAILS, DON'T OVERSIMPLIFY.'"[23]

This statement is equally true for any radiometric measurement or final PV component or system experimental result. The uncertainty information we can learn and state concerning a PV radiometric measurement or a module test result determines, to a significant extent, the worth and quality of that result. A result reported without a carefully worked out statement of uncertainty leaves the reader or user of that result with no clue as to how far the result can be trusted. It leaves him or her without the information necessary to propagate careful uncertainty analysis into their experimental work.

Measurement uncertainty analysis is an outgrowth of what has commonly been called error analysis, but uncertainty analysis, a more recent development, gives greater insight into measurement processes and tests, experiments, or calibration results. *Uncertainty analysis gives us an estimate of the interval about a measured value or an experiment's final result within which we believe the true value of that quantity will lie, with some degree of coverage (confidence level).* We will discuss *true value* in a moment.

The methodology for uncertainty analysis incorporated in the standard (ANSI/ASME PTC 19.1) in use today by a number of groups at NREL was developed largely in the fields of rocket and jet engine testing during the 1960s and 1970s. Two brief papers by Robert Abernethy and others[24,25] document the history of its development. Many details for this classical methodology can be obtained by using these documents: the Arnold Engineering Development Center report on uncertainty in gas turbine (jet engine) measurements[26]; the American Society of Mechanical Engineers standard on measurement uncertainty that is now an American National Standard[27] (note that this standard is undergoing major revision at this time and should be approved and issued before the end of 1996); the draft of the International Organization for Standardization (ISO) standard on Fluid Flow Measurement Uncertainty which is being prepared for official publication[28]. More recent documents reflect a change in nomenclature (i.e., calling random uncertainties "Type A" and systematic uncertainties "Type B") and some changes in computational methods.[29,30,31] Ron Dieck's book, in Appendix H, seeks to compare and harmonize these methods and nomenclature,[32] as will the revision of the ANSI/ASME PTC 19.1.

Uncertainty analysis addresses random error uncertainty, systematic error uncertainty, with signed bias limits, the defined measurement process, and uncertainty intervals and models.

In recent years, research work in refining uncertainty analysis has focused on calibration curve fitting and regression analysis, weighting competing answers, and outlier identification and rejection methods. Of particular concern today is the effect of errors in both X and Y on the uncertainty resulting from curve-fitting, and harmonizing the U.S. standard with the ISO *Guide*.

Uncertainty analysis establishes boundaries for how large the error in a measurement or experiment result might be, but not how large the error actually is. It does not determine what the bias errors are, or their sign or magnitude, but it helps us estimate within what limits they may fall. Uncertainty analysis provides a method for quantifying random errors. It provides a statistically correct method for combining random and systematic errors from many sources into a single expression of total uncertainty. It often helps us detect blunders and gross errors, which cannot otherwise be accounted for in our uncertainty analysis.

This analysis can be applied equally well to the measurement of a single physical quantity (such as the hemispherical solar irradiance in the plane of a PV array), the result of a simple lab experiment, and the intermediate and final results of complex experiments and engineering tests (such as the efficiency of a PV energy system connected to a power grid). It can be applied to the entire chain of traceable radiometric calibrations and measurements, starting from the WRR international standard and proceeding through intermediate calibrations to measurements made in a field experiment to test a PV module.

Why should we take the time to perform a rigorous uncertainty analysis? Such analysis (1) increases the credibility and value of research results; (2) enables valid comparisons of results from different experiments and even different labs; (3) helps improve experiment design and identifies where changes are needed to achieve stated accuracy objectives (through use of the pre-test analysis); (4) plays a significant role in validating measurements and experimental results, and in demonstrating (through the post-test analysis) that valid data have been acquired; (5) reduces the risk of making erroneous decisions; and (6) demonstrates quality assurance and quality control measures have been accomplished.

We generate and use data of many types and quality. Data is truly *Valid Data* if it has known and documented paths of origin, including associated theory, measurements and their traceability to measurement reference standards, computations, and statements of uncertainty of the results.

TRUE VALUE: DEFINITION AND IMPORTANCE

Robert Moffat, in an excellent paper entitled "Identifying the True Value - The First Step in Uncertainty Analysis,"[33], stated "...almost all situations where uncertainty analysis seems to fail arise because too little attention has been paid to identifying the intended true value of the measurement. Such an identification is always the first step in an uncertainty analysis, and lack of precision in that identification almost always causes serious trouble." I have also found this to be the case. The ability to define exactly what is being sought in a measurement process or a final result saves time, money, confusion, and frustration.

By true value, we mean the value of that quantity sought through the measurement and experimental process, whether it is a directly observable phenomenon (e.g., the dc power out of a specific PV array on a 20° south-facing tilt at solar noon on June 22, 1995, at NREL's Outdoor Test Facility into a specified resistive load) or one that exists only as a concept (e.g., the average efficiency of a certain model of PV array measured on June 22 at normal incidence over the range of air masses from 2.0 to 4.0).

The true value is the value of the quantity that would result if it could be measured perfectly; it can also be the final result of a "perfect" experiment, having no error in stating the true value sought, no measurement errors in carrying out the experiment, and no errors added in data reduction and interpretation processes. The true value is unknowable because of our finite measurement limitations and the fact that our measurement sensors frequently disturb that which we are trying to measure (even if we could define the true value without error). We can only approximate the true value, however close we may approach it. Therefore, there is uncertainty about our final result.

A significant source of error in measurements and tests may arise from lack of agreement on definitions, such as in the definition of "area" for a PV cell, module, or array. Even though the other measurements were performed with totally negligible error, disagreement on the definition and measurement of the area can lead to differences in results from lab to lab ranging from 1% to as great as even 200%.[34] I would classify this as an example of gross errors, arising from failure to adequately define (or agree on) the true value sought.

The ANSI/ASME standard (ANSI/ASME PTC 19.1-1985) partially covers defining the true value by stating that the assumptions inherent in performing a measurement uncertainty analysis include specifying the test objectives. In the ISO *Guide,* there is an extensive discussion in Annex D on "True" value, error, and uncertainty.

ERROR, UNCERTAINTY, AND THE TRUE VALUE

All measurements have errors - the differences between the measured values and the true value we are trying to achieve. But as discussed above, we don't really know the true value (it is really unknowable), so the actual amount of error in each measurement is uncertain. The purpose of measurement uncertainty analysis is to achieve a good quantitative estimate of the limit of those errors and thereby be reasonably confident that we can define the interval about our measurement result within which we expect the true value to lie.

In order to analyze the uncertainties, we must understand the nature of measurement errors and how to assess the errors in our measurements and experimental results. Errors encountered in a measurement process are frequently categorized into three types: random errors, systematic errors, and gross errors.

Random (also called precision) errors are the most commonly recognized and analyzed type of errors. Their effects are observed as varying results (scatter) in repeated measurements of the same unvarying quantity (if our measurement system has sufficient resolution). We are not talking about varying measurement results caused by variations in the quantity we are measuring (e.g., constantly changing values of the solar irradiance). A truly random measurement process will produce a distribution of results that will yield a frequency distribution that has a Gaussian, or so-called normal, distribution. The random error component is characterized by the shape of the distribution function, and the standard deviation that describes the dispersion of the measurements about the mean value. The mean value of those measurements is usually given as the result of a measurement process. A number of sources can contribute random errors to an experiment's result. Widely known statistical techniques are used to arrive at the random error component in an uncertainty analysis of a final result. How to combine all of the random errors is part of the methodology of uncertainty analysis.

However, the mean value is almost surely offset by some unknown amount from the true value—we won't know how much, or maybe even which direction. The difference between the mean value and the true value is called the systematic (bias, fixed, or offset) error. Systematic errors do not produce scatter in the final result, so they are not detected through the common statistical techniques. The exact values of systematic errors are unknowable, but we must still attempt to assess how large they might be. To do so requires considerable knowledge about the experiment, the measurement processes and instrumentation used, plus making some educated and seasoned engineering judgments. That is what makes systematic errors so difficult to identify and quantify. They are often ignored, or it is even said they don't exist. Some authors believe they are caused only by mistakes or equipment failure, or that they have been totally removed by calibration,[35] so that they are either overlooked or believed to be negligible. There are likely quite a few sources of systematic error in any but the most simple and trivial measurement. Combining the various systematic errors is another portion of the methodology of uncertainty analysis, as are the methods of combining both random and system errors into a final total uncertainty statement.

Often, the systematic component of the total uncertainty is larger than the random component. Five types of systematic or bias errors are identified in Table 1.

The systematic errors having a known sign and large magnitude (type 1) are reduced to a size limited by our measurement processes. We reduce these through the calibration process. However, even in the best calibration processes, including those at the National Institute of Standards and Technology, there are still some residual uncertainties remaining. These need to be identified and accounted for in our uncertainty analysis, even if they can be shown to be small enough to have a truly negligible effect on the final result.

The small systematic errors are also to be identified and accounted for in the uncertainty analysis, as appropriate. Those with known sign and magnitude (type 2) are used as correction factors; or, if very small, may be negligible. Those other small systematic errors having unknown (but estimated magnitudes) with either unknown or known sign (types 4 and 5) are considered when ascertaining the Bias Limit—the outer limit of how big bias errors might be.

<table>
<tr><th colspan="4">Five Types of Systematic or Bias Error</th></tr>
<tr><td></td><td>Known Sign and Magnitude</td><td colspan="2">Unknown Magnitude</td></tr>
<tr><td>Large</td><td>(1) Calibrated Out</td><td colspan="2">(3) Assumed to be Eliminated</td></tr>
<tr><td rowspan="2">Small</td><td rowspan="2">(2) Small Corrections; or Negligible Contributions to Bias Limit</td><td>(4) Unknown Sign</td><td>(5) Known Sign</td></tr>
<tr><td colspan="2">Contribute to Bias Limit</td></tr>
</table>

Table 1. Types of Systematic or Bias Errors [Ref. 26, p. 2]

A bias limit is defined as an estimate of the maximum possible systematic or bias error that is believed might exist for a particular measurement. The bias error, ß, of a particular measurement should lie between the two bias limits, ±**B**, if the limit is well understood:

$$-\mathbf{B} \leq \beta \leq +\mathbf{B}$$

Gross errors are the large errors of unknown magnitude that have been assumed to be eliminated but, in fact, have not (type 3). These errors invalidate the experimental result and its uncertainty analysis. Some common sources are operator mistakes, errors in experimental method, errors in calibration, equipment failure, installation problems, outside interference (such as EMI—electromagnetic interference from radio, TV, or radar transmitters). Outlier analysis techniques may find some of them but will not necessarily always detect them, especially when they never change (are truly systematic). How to find them or prove that they do not exist is a topic that Peter Stein addresses in detail in his courses on measurement system engineering.[36]

THE MEASUREMENT UNCERTAINTY MODELS AND STANDARDS

The following sections will present only a brief overview of the methodology of uncertainty analysis that is the basis of the ANSI/ASME PTC 19.1-1985 standard. For more complete discussions, refer especially to references 24 to 28.

The uncertainty of a measurement is a function of the specific measurement process used to obtain the measurement result, whether it is a simple or a complex process. Measurement uncertainty analysis provides an estimate of the largest error that may reasonably be expected for that specific measurement process. If the measurement process is changed, then the uncertainty analysis must be re-examined and changed as appropriate. Errors larger than the stated uncertainty should rarely occur in actual laboratory or field measurements, if the uncertainty analysis has been performed correctly. That is, the true value sought in the measurement or experiment process should rarely lie outside the stated uncertainty interval.

The random component of uncertainty for an individual measurement is taken as ±2**S** (or $\pm t_{95}$**S** for small samples of data, 30 or fewer measurements) where **S** is the standard deviation of the individual measurements and t_{95} is the two-tailed "Student's t" value for a 95% confidence level. The individual random error components are added in quadrature to develop the overall random uncertainty component.

The individual systematic error components are added in quadrature to obtain the systematic uncertainty component, the bias limit, **B**.

The ASTM PTC 19.1 standard presents two models of uncertainty to be used to combine the random and systematic uncertainties to develop the quantitative estimate of the uncertainty interval about the final result within which the true value is believed to lie. The interval is formed from the combination of the two components (random and systematic), added linearly or in quadrature. The two models follow:

- $\mathbf{U_{ADD}} = \mathbf{U_{99}}$ - This uncertainty model should encompass 99% of all measurement or experiment results if the test or experiment is repeated many times.

$$U_{99} = B + 2 \cdot S \quad or\ U_{99} = B + t_{95} \cdot S$$

- $\mathbf{U_{RSS}} = \mathbf{U_{95}}$ - This uncertainty model should encompass 95% of all measurement or experiment results if the test or experiment is repeated many times.

$$U_{95} = \sqrt{B^2 + (2 \cdot S)^2}$$

where t_{95} is the two-tailed "Student's t" for 95% confidence limits (use 2 if the number of measurements averaged is 30 or more),

$\mathbf{U_{99}}$ is a more conservative estimate of the uncertainty interval and will always describe a larger interval than $\mathbf{U_{95}}$. However, even $\mathbf{U_{99}}$ underestimates the uncertainty interval (that is, the coverage is less than 99%) if either the systematic or the random components is much larger than the other.

STEP BY STEP: HOW TO DO UNCERTAINTY ANALYSIS

We will now outline the steps for performing a measurement uncertainty analysis. For the details, consult references 24 to 28. Reference 27 is the U.S. national standard we use at NREL for uncertainty analysis.

Step 1: Clearly define the "true value" sought, in writing. It is well worth the time to do this in writing, for it will keep before you what you are trying to measure and will help clarify the measurement process and the experiment goal.[37]

Step 2: Define the measurement process, utilizing the statement of the true value and the research or calibration objectives. List all of the independent physical parameters to be measured and their nominal values or ranges. List all of the instruments and setups and their calibrations and characterizations that will be used to measure each parameter. Write the equations that define the functional relationships between the independent physical parameters (with their measurements) and the final result.

Step 3: List every possible elemental source of measurement error that can be thought of, no matter what the source or how large or small the error may be thought to be. An excellent method for listing elemental error sources is presented in the discussion and associated Tables 5 and 11 in reference 28.

Step 4: Group the error into these three categories, by source: (1) calibration errors; (2) installation and data acquisition errors; and (3) data reduction errors. It is not an absolute necessity to do this grouping, but the advantage is that you can see where the errors arise and where to concentrate to reduce the total uncertainty.

Calibration errors are those associated with the calibration of each measuring instrument, sensor, transducer, etc.

Installation errors are those errors that arise from how and where the sensors are installed in the experimental apparatus. Be particularly alert here for systematic errors. Data acquisition errors are those associated with the performance of the data acquisition system and sensors in the environment in which they are used. Use manufacturer's specifications if you have no better data and you have reason to believe you can trust those specifications. Gross errors more frequently arise in the installation and data acquisition processes.

Data reduction errors are errors associated with the computer's algorithms and numerical handling routines (remember the Pentium chip's floating point unit bug!), round-off errors, errors encountered in curve-fitting and regression analysis results. Data reduction errors can arise from how the data sets are chosen out of all the data taken, because you may choose data that doesn't pertain to the true value being sought, or you omit data you should have used.

Despite what some of the references suggest or neglect to discuss, I prefer to assign calibration curve fitting errors to the calibration category, not the data reduction category. That way, I know how much uncertainty originates in the calibration process and can deal with it there as necessary.

Step 5: Classify the errors into systematic and random errors. If data exist from which a standard deviation can be calculated, consider it a random error. Random errors produce scatter in the final result. Otherwise, consider the errors to be systematic errors. Systematic errors do not change for a given instrument, measurement process, and set of environmental conditions. Manufacturer's specifications can give useful information for the pre-test analysis.

Step 6: Calculate the systematic and random errors for each physical parameter. Sometimes this information can be obtained from previous tests, calibrations, or experiments.

Step 7: Separately propagate the random and systematic errors to the final result. Use the Taylor series or small deltas ("dithering") to determine the sensitivity of the final result to each individual source of error. Simply adding the errors may lead to an uncertainty estimate that is too large or too small, depending on the sensitivity coefficients for each error. This is discussed in detail in the references.

An important caution: be careful not to mix percentage and absolute errors (percent added to watts/meter^2, for example)!

For random errors, the uncertainty is:

$$S = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial F(X_1, X_2, ..X_n)}{\partial X_i}\cdot S_i\right)^2} \; ; \quad S_i = \frac{s_i}{\sqrt{N_i}}$$

where F is the function from which to compute the final result, the Xs are the independent variables, and $\partial F/\partial X_i$ is the sensitivity coefficient of S_i. If the value of X_i is the group mean of N measurements, S_i is the standard deviation of the mean of the group of measurements of the variable X_i, and s_i is the standard deviation of the individual measurements that form the mean of the N measurements.

The individual systematic error components are added in quadrature ("RSSed") to obtain the systematic error component, the total bias limit, **B**. For systematic errors, the uncertainty is

$$B = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial F(X_1, X_2, ..X_n)}{\partial X_i} \cdot B_i \right)^2}$$

where $\mathbf{B}_i$ is the bias limit for variable i, F is the function from which the final result is computed, $\partial F/\partial X_i$ is the sensitivity coefficient for $\mathbf{B}_i$, and the Xs are the independent variables. This is based on the probability that the individual fixed systematic errors will not all be at their maximum (limit) values; but, by the Central Limit Theorem, will be more nearly normally distributed over the entire bias limit region. So they are combined in quadrature.

Step 8: Calculate the uncertainty interval using either model (or both): $\mathbf{U}_{99}$ or $\mathbf{U}_{95}$.

Step 9: Use pre-test and post-test analyses. The use of both tests reduces the cost and risk of performing useless experiments, publishing invalid data, drawing wrong conclusions, or making wrong decisions. Uncertainty analysis should be factored into decisions, including those concerning awards for PV cell, module, or system performance.

Perform the pre-test analysis to predict the uncertainty before an experiment or test is performed. This can determine the appropriateness of measurement instruments and techniques before the investment is made to actually procure equipment and run the proposed experiment. If the predicted uncertainty is not small enough to obtain the needed result, redesign the experiment—don't go on and waste resources and time!

Perform the post-test analysis to examine the final results for validity, problems, and the necessity of having to repeat the experiment to achieve desired results. Uncertainty information for the final report is obtained in the post-test analysis.

Step 10: In the final report, show the final random error component of the uncertainty together with the associated degrees of freedom, the bias limit, and the uncertainty model used ($\mathbf{U}_{99}$ and/or $\mathbf{U}_{95}$, or even both).

The degrees of freedom, df, in the final result arising from the various random error sources are computed using the Welch-Satterthwaite equation. If df is more than 30, then use 2.0 instead of t_{95}. See the references.

It is very important that the final result reports the total systematic and total random components of uncertainty, along with degrees of freedom. This information will be needed by anyone taking the results of this experiment and wanting to conduct a good rigorous uncertainty analysis of their result. For they need to include in their analysis the random and systematic components of uncertainty from your final result and propagate them through their analysis. They will need the degrees of freedom as well. As long as each report in a series of measurements and/or calibrations contains this information, the uncertainty analysis can proceed on indefinitely, as long as the uncertainty hasn't grown so much as to unusable.

At NREL, we have begun to use rigorous uncertainty analysis to provide a measure of the uncertain in the factors that relate our absolute cavity radiometers to the WRR and provide similar information to our Saudi Arabian[38] and Dept. of Energy colleagues for their absolute cavity radiometers that participated in a cavity comparison held at SRRL.

Charles Babbage, inventor of the first calculating machine, is supposed to have said, "Errors using inadequate data are much less than those using no data." A similar comment might be made concerning uncertainty analysis: "An uncertainty analysis based on inadequate information is better than no uncertainty analysis at all." This is not intended to encourage superficial work, but we can start with a somewhat simplistic analysis to begin to gain the insight and rigor we need. Ron Dieck commented on my comment: This "may be too optimistic and get you into trouble!" Therefore, be careful!

MEASUREMENT QUALITY ASSURANCE METHODS AND TECHNIQUES

Conducting calibrations without a method of evaluating the final result might be compared to have an open-loop control system with no feedback mechanism. You know what you want, and you put an input into the system that you think will give you what you want, but you have no way of measuring accurately the result.

One way of monitoring and assessing the quality of a calibration process is to use "control standards." We do this at NREL by calibrating one or more control standard pyranometers and pyrheliometers each time we perform a BORCAL. Within some limits, we should obtain the same calibration factor for each control standard. The use of more that one control standard of each type of instrument permits observing whether one (control standard) radiometer is drifting, or is the calibration process itself changing?

Cavity radiometer comparisons has long been a method of assuring ourselves that our cavity sensors have not been contaminated and that these absolute radiometer systems are performing properly.

The use of control standards at a manufacturing facility is an excellent means of determining that the calibration process is under control. And the evaluation of the control standard's data will reveal some information about the repeatability of the calibration process and the control standard as a closed loop system.

Measurement assurance techniques in radiometer calibration and field test processes are important to controlling and evaluating the processes.

CONSENSUS STANDARDS IN PV RADIOMETRY AND MODULE CERTIFICATION

Traceability and measurement uncertainty analysis require that the techniques and measurement processes are well understood, analyzed and documented. Good consensus standards provide a good starting point for that documentation. Such standards may include an indication of measurement uncertainties to be expected from the technique and equipment specified.

Over the past 15 years or more, a number of consensus standards applicable to radiometry have been developed by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO). The following standards pertain to radiometric calibrations and measurements applicable to PV radiometry and module certification.

E 772 *Terminology Relating to Solar Energy Conversion*[39]

E 816 *Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers*

E 824 *Standard Method for Transfer of Calibration from Reference to Field Pyranometers* (This standard is being revised)

E 842 *Method for Transfer of Calibration from Reference to Field Radiometers*

E 891 *Terrestrial Direct Normal Solar Spectral Irradiance for Air Mass 1.5*

E 892 *Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface*

E 913 *Calibration of Reference Pyranometers with Axis Vertical by the Shading Method*

E 941 *Method for Calibration of a Pyranometer Using a Pyrheliometer* (E 913 and E 941 are being combined and harmonized with ISO 9846)

ISO 9059:1990(E) *Solar Energy — Calibration of field pyrheliometers by comparison to a reference pyrheliometer*[40]

ISO 9060:1990(E) *Solar Energy — Specification and classification of instruments for measuring hemispherical and direct solar radiation*

ISO 9845 *Solar Energy — Reference solar spectral irradiance*

ISO 9846:1993(E) *Solar Energy — Calibration of a pyranometer using a pyrheliometer*

ISO 9847 *Solar Energy — Calibration of field pyranometers by comparison to a reference pyranometer*

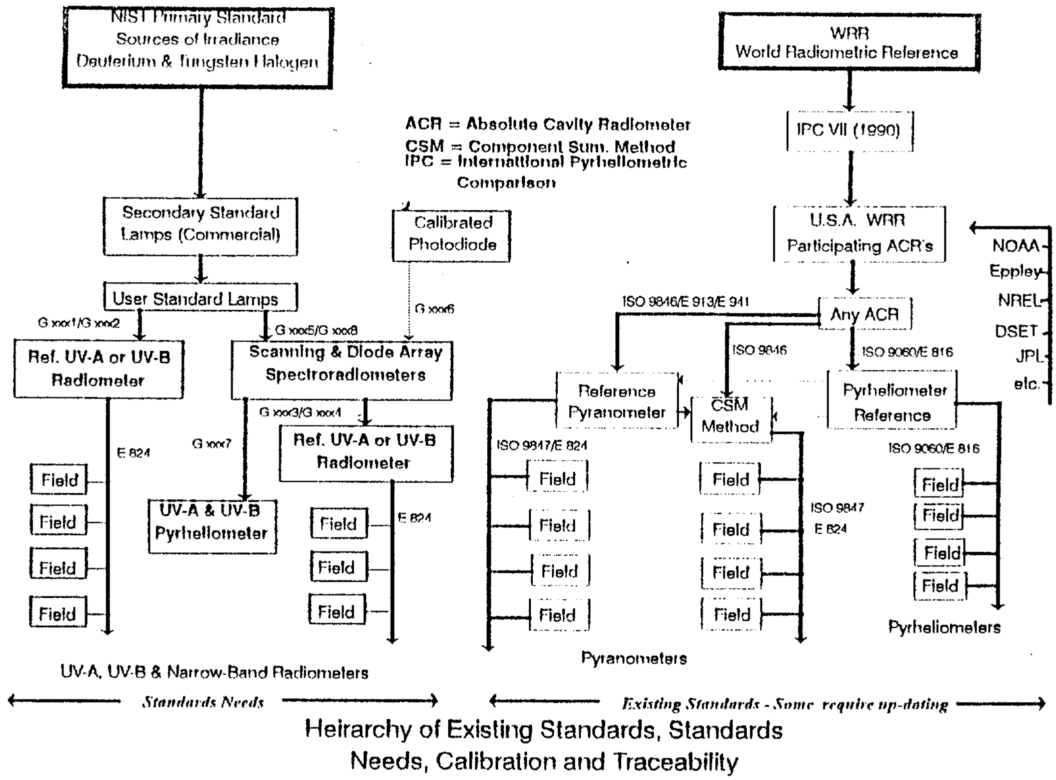

Figure 2. A radiometry traceability flow diagram and associated standards. From Reference No. 42.

ISO/TR 9901:1990:(E) *Solar Energy — Field Pyranometers—Recommended practice for use*

Another important document is the so-called CIMO Guide: *Guide to Meteorological Instruments and Methods of Observation,* from WMO.[41]

Gene Zerlaut recently discussed the development of existing standards and needs for new and revised standards. He developed a traceability diagram show how the existing and needed standards fit into the traceability flow.[42] Figure 2 reproduces this diagram. Traceability requirements for radiometric measurements in the context of testing photovoltaic modules are contained in PV-1, "Criteria for a Model Quality System for Laboratories Engaged in Testing Photovoltaic Modules."[43] This document was based on ASTM Standard E 548 and ISO/IEC Guides 25 and 38, and relevant sections of the ISO 9000-series and the ANSI/ASQC 90...94 series. The commonly used MIL-STD-45662A was rescinded in February 1995, and is being replaced in the Dept. of Energy and the Dept. of Defense, by the new American National Standard, ANSI/NCSL Z540-1-1994.[44] This standard applies to many other activities requiring standards and traceability beyond just radiometry within the DOE.

CONCLUSION

We have explored in some detail the three legs that support traceability and how they fit together: calibration hierarchy, uncertainty analysis, and measurement quality assurance. Calibration provides the smallest error in relation to the national or international standards. Uncertainty analysis estimates how small the error might be, and gives insight as to how and where one can further reduce the error. It is the uncertainty statement which accompanies the final result that gives the real worth of the value because it reveals the confidence that can be placed in its value. Measurement quality assurance activities can assure the user of the data that it is as good as it is said to be. This is probably the most overlooked and neglected of the three legs of traceability.

We have taken a fast trip through the subject of uncertainty analysis, looking briefly and the concepts and the steps to conduct an uncertainty analysis. When the random and systematic components of uncertainty are reported along with the degrees of freedom, the users of the reported information can then propagate the uncertainty through their own experiments in a rigorous fashion. The ANSI/ASME Measurement Uncertainty Standard, PTC 19.1-1985 provides a good starting point in performing such an analysis.

Consensus standards exist to help perform radiometric calibrations in such a fashion so as to have the least uncertainty. These standards address many issues that might otherwise be overlooked. They provide a starting point for the documentation needed for a traceable measurements program. The use of control standards during the calibration process or a module test provides a portion of the assurance the calibration or test process is under control and can be counted on to yield consistent results.

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PV Reference Cell - Construction, Calibration, and Use

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Summary

A reference cell is a sensor that produces a given response for a given total and spectral irradiance. A photovoltaic reference cell has a calibrated short-circuit current for a given total and spectral irradiance at a given operating temperature. A reference cell could be a thermal detector such as a cavity radiometer. A reference cell is typically chosen to minimize the spectral mismatch error between the reference cell and device under test. ASTM standard E1040 defines a reference cell "as a calibrated and finished product that consists of the photovoltaic cell, cell holder, cover and cabling." Primary AM0 reference cells calibrated by NASA Lewis on their high altitude jet are typically bare cells. Groups like NREL, Sandia, or the Fraunhofer Institute for Solar Energy Systems in Germany calibrate a wide range of PV cell technologies for the PV community as secondary reference cells.

A primary reference cell should be stable and packaged to prevent damage caused by repeated contacting, moisture, abrasion, being dropped. A reference cell package should include a temperature sensor accurate to ±1 °C, have separate wires for current and voltage contact to the PV device, be made on non-reflecting surfaces (<5% reflectance) and wires or suitable connector. For a reference cell to be useful it should have a degradation of less than 1% per year. Color glass filters that may be placed over a reference cell to more closely match the response of the test device can be expected to change their transmittance at the 1% per year level. A single-crystal or multi-crystal Si reference cell with a Schott KG5 color glass filter is often used to simulate the response of amorphous silicon which can change its calibration with light and temperature. Reference cells in a module package are popular for outdoor measurements because the package mounts and behaves thermally and optically like a module yet can be calibrated with the same accuracy as a cell. Many groups have a calibration traceability path to NREL for their unencapsulated research or production cell structures because every cell that the laboratory measures is treated as a secondary reference cell which requires an accurate primary reference cell, spectral mismatch correction and calibration at the reference temperature.

A single calibration procedure for primary reference cells has yet to be adopted. Primary AM0 reference cells have an estimated uncertainty of ±1% and have a proven long-term

repeatability of less than ±1% can be translated to primary terrestrial reference cells with minimal (0.5%) loss in accuracy. The method adopted by NREL has been published in a variety of places and is summarized in ASTM standard E1125. NREL's method involves measuring the short-circuit current of the reference cell, its temperature, the direct normal irradiance within a 5° field of view (primary absolute cavity radiometer), and the spectral irradiance within a 5° field of view. The data is then corrected for temperature and the spectral mismatch error to give the current with respect to standard reference conditions. The method has an estimated uncertainty of ±1%. The method's accuracy has been verified by numerous intercomparisons with primary AM0 reference cells, other terrestrial reference cells of comparable accuracy. The method favored by Sandia involves illuminating the reference cell with a standard lamp and correcting to standard reporting conditions. Other groups calibrate reference cells under global sunlight with pyranometers and spectral mismatch corrections.

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OUTLINE

Reference Cells
- Thermal *versus* Photovoltaic
- Secondary *versus* Primary
- Construction - Design Constraints
- Characterization - How , What
- Use - Simulated *vs.* Natural Light

Reference Cell Calibration Methods
- Absolute Spectral Responsivity
- Calibrated Source
- Calibrated Detector

NREL Primary Reference Cell Calibrations

Thermal *Versus* Photovoltaic

Total Power

Thermal detector

Constant response versus wavelength,
Zero spectral error

PV detector

Response increases with wavelength,
narrow response range, spectral error present

Power With Respect to a Reference

Spectral and Total Irradiance

Thermal detector

Large spectral error if PV test device,
Smaller spectral error if thermal test device

PV detector

Minimal Spectral error if test device PV
Larger spectral error if thermal test device

Construction of PV Reference Cell

Package Options - simulated or natural sunlight
primary or secondary reference

Cell

Unencapsulated - can be same size and technology as reference device, NASA AM0 primary references. Research lab secondary references for simulator use

ASTM E1040 Package - specific size
JPL Balloon style - fixed resistor, white, no temperature sensor, required for balloon flown primary reference
Custom block for specific test bed

Cell in Module Package

Mechanically, Optically and thermally like a module can be calibrated like a cell

Module

Useful as a secondary reference for setting or checking a module simulator

Reference Cell Package

Mechanical

Cell protected from physical damage
Warpage of the package possible
Scratching or damage to optical surfaces

Change in Optical Properties with time

Encapsulant transmittance
Filter transmittance
Window transmittance
Cosine Response

Cell Degradation

Temperature Sensor

Reference Cell Characterization

Spectral Response

At "one-sun" bias light level
At zero volts
At reference temperature

Temperature Coefficient

Required if used at other than calibration temperature

Angular Response

Difficult to interpret, triple integrals in general,
to a first order -
incident angle dependent correction factor

I-V curve at SRC

Useful to monitor Voc and FF for stability

Measure I_{sc}^{t} & Relative Spectral Response of Cell

Determine Absolute Spectral Irradiance of Light

Correct I_{sc}^{t} for spectral error and total irradiance

$$I_{sc} = I_{sc}^{t} * E_{tot} \frac{\int_a^b E_r(\lambda) QE(\lambda) \mathrm{d}\lambda}{\int_a^b E_r(\lambda) \mathrm{d}\lambda * \int_a^b E_s(\lambda) QE(\lambda) \mathrm{d}\lambda}$$

Measure Absolute Quantum Efficiency then Integrate with the reference Spectral and Total Irradiance to Get J_{sc}

$$J_{sc} = \frac{E_{tot} \int_a^b E_{ref}(\lambda) QE(\lambda) d\lambda}{\int_a^b E_{ref}(\lambda) d\lambda}$$

Global and Direct-Normal Calibrations

$$CV = \frac{I^{R,S}}{E_{tot}} * \frac{\int_{\lambda_1}^{\lambda_2}\int_{\theta_1}^{\theta_2}\int_{\phi_1}^{\phi_2} E_{ref}(\lambda,\theta,\phi) * S_r(\lambda,\theta,\phi)\, d\lambda d\theta d\phi}{\int_{\lambda_1}^{\lambda_2}\int_{\theta_1}^{\theta_2}\int_{\phi_1}^{\phi_2} E_{ref}(\lambda,\theta,\phi)\, d\lambda d\theta d\phi} * \frac{\int_{\lambda_1}^{\lambda_2}\int_{\theta_1}^{\theta_2}\int_{\phi_1}^{\phi_2} E_s(\lambda,\theta,\phi)\, d\lambda d\theta d\phi}{\int_{\lambda_1}^{\lambda_2}\int_{\theta_1}^{\theta_2}\int_{\phi_1}^{\phi_2} E_s(\lambda,\theta,\phi) * S_r(\lambda,\theta,\phi)\, d\lambda d\theta d\phi}$$

CV ≡ reference cell calibration value ($mAW^{-1}m^{-2}$)

E_{tot} ≡ total irradiance incident on the PV sample

E_s ≡ source spectral irradiance

E_r ≡ reference spectral irradiance

S_r ≡ spectral response of the reference cell

$I^{R,S}$ ≡ short-circuit current of the reference cell corrected for temperature to the reference temperature and measured at the same time as E_s and E_{tot}

Simulator Based Calibrations

$$C = \frac{CV * E_{ref}}{M * I^{R,S}}$$

Adjust simulator irradiance until C ≈ 1

E_{ref} ≡ reference total irradiance

CV ≡ calibration value of the reference cell

$I^{R,S}$ ≡ reference cell short-circuit current corrected to the reference temperature

$$M = \frac{\int_{\lambda 1}^{\lambda 2} E_s(\lambda) * S_t(\lambda) d\lambda}{\int_{\lambda 3}^{\lambda 4} E_s(\lambda) * S_r(\lambda) d\lambda} * \frac{\int_{\lambda 3}^{\lambda 4} E_{ref}(\lambda) * S_r(\lambda) d\lambda}{\int_{\lambda 1}^{\lambda 2} E_{ref}(\lambda) * S_t(\lambda) d\lambda}$$

E_s ≡ source spectral irradiance

E_r ≡ reference spectral irradiance

S_r ≡ spectral response of the reference cell

S_t ≡ spectral response of the test cell

$$I^{T,R} = I^{T,S} * C$$

$I^{T,S}$ ≡ test cell short-circuit current corrected to the reference temperature

$I^{T,R}$ ≡ **test cell short-circuit current under standard reporting conditions**

PV REFERENCE CELLS: CALIBRATION AND STABILITY PROBLEMS

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Abstract

The PV reference cells described in this paper were made and calibrated in Russia. Their parameters have also been measured in Italy, Germany and Israel, in recent years.

Different calibration methods are discussed, as well as stability data of PV reference cell parameters, as measured from 1962 to date.

Introduction

The development and standardization of accurate methods of measuring the characteristics of solar cells and modules have attracted considerable attention. General interest in this field has been stimulated by considerable advances in the performance of silicon solar cells [1] and gallium arsenide heterojunction cells [2]. This means that solar modules can already be widely used not only in space, but also under terrestrial conditions, and we now have a basis for developing photovoltaic power stations capable of delivering appreciable amounts of power [3]. Problems relating to the stability of the parameters of modern solar cells and modules under prolonged operation can now be regarded as essentially solved [4,5].

The electrical parameters of solar cells have to be measured for a number of reasons. This, for example, is essential when standardized parameters have to be determined in quality control, when technological processes have to be monitored, when efficiency sorting is carried out, prior to selection of individual cells and groups for assembly with minimum switching losses, when the electrical parameters have to be predicted for different nonstationary conditions of operation, and in the optimization of parameters, whenever new types of solar cell are developed. Such measurements must be strictly standardized, and accurate enough, so that reliable and reproducible results can be obtained. Standardization of measurements is essential for the accurate prediction and determination of the characteristics of modules when these are designed, developed and fabricated.

Benefits of reference solar cells

Since the spectral energy distribution of even high-grade simulators is not identical with the standard solar distribution, and the sensitivity of solar cells is selective, the simulator intensity cannot be adjusted with the aid of nonselective radiation detectors (radiometers). Specially calibrated reference cells must be used for this purpose. These reference or standard cells, often referred to as photometer devices, are actually radiometers with selective sensitivity.

Calibrations of reference solar cells involve measurements of the short-circuit current under standard illumination. A reference solar cell is used to adjust the simulator, i.e., its radiation flux is adjusted until the short-circuit current of the reference cell is the same as under standard conditions.

When a reference solar cell is employed, satisfactory precision of measurement can be achieved even with poorly corrected simulators or sources with arbitrary spectral energy distribution. The uncertainty in the measured electrical parameters of a tested solar cell will then depend on the extent to which its spectral sensitivity differs from that of the reference cell. It is thus clear that the basic requirement imposed on reference solar cells is that their optical and, especially, spectral characteristics must be identical to the characteristics of the solar cells with which they are compared. When reference cells are employed under simulators producing a wide beam of radiation, it is also necessary to take into account the angular distribution of sensitivity. This is largely determined by the surface microtopology of the solar cell, which influences the reflection coefficient as a function of the angle of incidence [4, p.p. 98-102]. Even the most advanced technological process will not result in identical optical and spectral characteristics among all the cells of a given type. Reference cells must, therefore, be chosen so that their characteristics are as close as possible to the average characteristic for particular series.

Reference cells design

The PS-9 reference cell, which has a typically sophisticated structure, was developed in the USSR in 1980-1982 as a standard for the countries in the Socialist Economic Community. It comes with a rectangular, photosensitive, area of 30 x 35 mm, or a circular area with a diameter of 50 mm, for measuring the paramenters of cells and modules, for space and terrestrial applications, respectively.

This reference cell has a built-in cooling system, incorporating a radiator which can be cooled with water from a thermostat, and a sensitive temperature sensor. The PS-9 uses silicon solar cells with a shallow p-n junction, and heterojunction cells consisting of a solid solution (aluminium in gallium arsenide) and gallium arsenide. The large body of the PS-9 ensures a field of view in excess of 166°, which means that it can be used for measurements on solar cells and modules in both total flux and directly collimated flux.

Constant improvements in fabrication technology and the development of new types of solar cell mean that the parameters of solar cells with nonstandard spectral sensitivity have to be measured. This demands the availability of reference solar cells with different spectral characteristics. Solar cells for these standards are produced by altering the depth of the p-n junction, by varying the properties of the antireflective coatings, and by bombarding the cells with protons and electrons of different dose and energy. A quick test can be based on the comparison of the blue-red ratios of the reference cell and that of the cell to be examined, using filters to isolate the blue and the near-infrared radiation, respectively. The reference cell with the nearest value of the blue-red ratio is then selected. This approach can also be used to select reference cells when the parameters of solar modules, consisting of nonstandard solar cells, are measured. A set of reference cells, with nonstandard spectral sensitivity distributions, has been developed on the basis of the PS-9.

Reference solar cell fabrication and tests

Reference cells are selected from mass-produced cells, or are fabricated especially. When selecting them, particular attention is paid to the quality of the end surfaces, the shunt resistance, and the series resistance. The cells must have uniform properties (especially the spectral and integral sensitivities) over their working area. It is desirable that they have the minimum possible temperature coefficient of short-circuit current. Cells selected in this way are mounted on frames and subjected to natural or accelerated ageing.

The stability of cell sensitivity is determined by measuring the short-circuit current, after the cells have been fully assembled. Since 1962, such measurements have been routinely carried out in Russia, at the minimum rate of twice per annum. A total of 75 reference cells was prepared in 1967, and work began on the determination of the stability of their sensitivity. Cells that cease to work satisfactorily, or those that are found to have unstable senstivity, are periodically discarded, and new sets of standards, consisting of improved silicon cells, gallium arsenide homojunction cells, and AlGaAs-GaAs and Cu_2S-CdS heterostructures, have been added to this set. Reference solar cells whose properties were found to be stable over a period of one year or more (short-circuit current remained constant to within ±0.5%) were then chosen as primary standards. These cells were calibrated either directly, in solar radiation, or by comparing them with primary standards of flux density.

Out of the 75 reference cells assembled in 1967, seven retained their sensitivity to within ±1.5% by 1981, despite the fact that none had glass shields. The reference solar cells were kept in a laboratory with no special precautions, and were used daily, for one or two weeks, during the periodic checks, which were performed two or three times a year.

Prolonged use of the improved PS-9 cells, from 1980 to date, has shown that more than 90% of them have retained their sensitivity to within ±1.5%, and several cells to within ±0.5%, over a period in excess of fifteen years.

Calibration methods

Reference cells are operated under short-circuit conditions, and their calibration involves determining the short-circuit current under exposure to normalized solar spectrum and flux density (extra-atmospheric or terrestrial). Two basically different types of calibration are possible, i.e., calibration in natural solar radiation, or laboratory calibration. The former consists of a variety of methods used to calibrate reference cells for simulators of extra-atmospheric solar radiation. These include high-altitude measurements from spacecraft, rockets, sounding balloons and from high-fly aircraft, as well as measurements on the ground.

The high-altitude method most frequently used in calibration measurements, under natural solar illumination on the ground, involves extrapolation to zero air mass. Calibration involves successive measurement of the short-circuit current delivered by reference solar cells, for different values of the air mass (different positions of the sun above the horizon). Since the experiments are performed under stationary conditions, it is sufficient to determine the short-circuit current as a function of the relative air mass. The extra-atmospheric value of the short-circuit current is obtained by linear extrapolation of the logarithm of the current, as a function of relative air mass, to its zero value.

This method was found to produce calibration short-circuit currents of terrestrial reference solar cells that were in good agreement with values obtained by other methods. In 1994, these results were checked by the author against the calibration data of reference cells in Israel (The Ben-Gurion National Solar Energy Center, Sede-Boker), Italy (EC - Joint Research Centre, Ispra and ENEA, Portici) and Germany (Fraunhofer Institute for Solar Energy Systems, Freiburg), and were found to be in very close agreement, to within 1-3%.

Determining the short-circuit current of reference cells under standard, extra-atmospheric and terrestrial solar spectra, can also be achieved from the measurement of their spectral sensitivity.

It is quite clear that measurements of the spectral sensitivity of reference solar cells (with a view to subsequent conversion to the standard spectral energy distribution and determination of the calibration photocurrent) must be performed for levels of illumination that are close to the conditions encountered when standard cells are used in practice.

One such system for measuring spectral sensitivity, with simultaneous simulated solar illumination, was developed in Russia and has been used there since the mid-seventies. It has been instrumental in calibrationg of reference solar cells [5].

The particular feature of this system is the presence of the headlight-type lamps, in which the reflector and the transmitting window carry multilayer interference filters, that correct the spectrum of the halogen lamp to bring it closer to the solar spectrum. An irradiance of 1360 W/m^2 is produced on the surface of the cell and is monitored by a thermoelectric radiometer with a large field of view. The radiometer is carefully calibrated in a broad spectral range. The illuminating lamps are supplied by stabilized sources with minimum high-harmonic content.

Monochromatic radiation of sufficient intensity is produced by using a diffraction grating monochromator. The short-circuit current under modulated monochromatic illumination is measured at different points on the photoactive surface of the reference solar cell, and is then averaged over the entire working area.

It should be noted that the temperature of standard cells must be fixed, because the spectral sensitivity is a temperature-dependent cell parameter.

Stability

It is worth considering the stability of standard cells. This may become a problem, as light degradation is brought about by prolonged cell use. It had long been considered that the only damage produced by the solar radiation itself was the darkening of the optical coating of the solar cells. However, the development of optically stable multilayer coatings, in which the uppermost layer is a glass slide containing cerium dioxide, that absorbs the entire ultraviolet radiation below 0.36mm has reduced the light degradation of the cell, due to the deterioration in the optical properties of the coating, down to a very low level (0.5 - 2.5%), even under continuous operation on board spacecraft remaining in orbit for several years [4, 5].

It was, therefore, surprising to many researchers to find that the properties of solar cells deteriorated under exposure to solar radiation (the so-called photon degradation). This phenomenon was investigated in the early experiments, along with the damaging effect of corpuscular radiation and temperature [6,7]. These studies and subsequent ones have not only revealed the importance of the simultaneous effect of several damaging factors on the properties of semiconducting materials and solar cells but also reflected the real, practical situation, in both space and laboratory. For example, solar cells, containing low levels of oxygen in the original silicon wafers produced by zone-melting, exhibit high levels of photon degradation, i.e., the reduction in current due to high-intensity may amount to 10-12%. On the other hand, experiments performed without illumination have shown that these cells were more radiation-resistant than cells containing silicon grown by the Czochralski method, and containing relatively high levels of oxygen. It is possible that the deterioration in the properties of solar cells made from oxygen-free silicon is due to the higher density of dislocations in such crystals. Strong illumination leads to the freeing and activation of boron-containing point defects trapped by dislocations. However, there is no doubt that the additional introduction of oxygen and carbon does stabilize the behaviour of solar cells under illumination, especially if the overall concentration of carbon and oxygen in silicon exceeds 10^{17} cm^{-3}.

Photon degradation can be substantially reduced by preventing silver atoms from reaching the silicon base layer, by mechanically removing the damaged silicon surface, prior to diffusion, as well as by diffusing the dopant at a temperature of 875°C or less. Photon degradation must be taken into account, in designing reference solar cells used for monitoring sun simulators, because these cells must be highly stable. In addition to the above technological measures, photon degradation can be reduced, in future reference cells, by having the base layers in the form of thin silicon wafers, with a large minority-carrier diffusion length L. Large L/l_b (where l_b - base layer thickness) ratios ensure effective carrier collection from the base region, even under strong illumunation.

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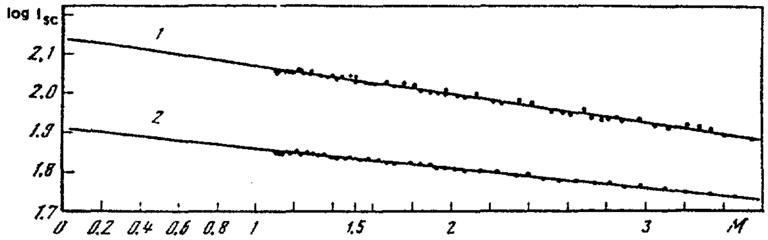

FIG. 1. Measured short-circuit current of standard solar cells plotted against the air mass on a semilogarithmic scale. The experimental data were obtained as a result of high-altitude measurements on 26 June 1982, near Alma-Ata: 1) silicon; 2) AlGaAs–GaAs cell.

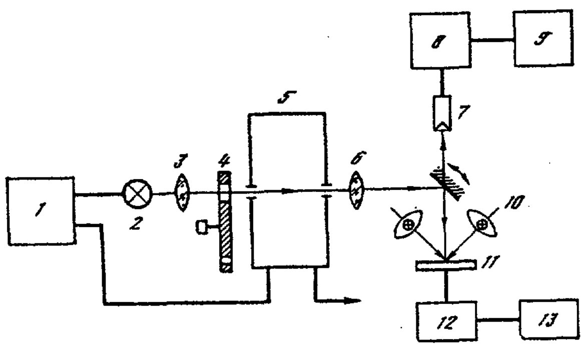

FIG. 2. Apparatus used to measure the spectral sensitivity of standard solar cells: 1) supplies for lamp and monochromator; 2) lamp used to illuminate the entrance slit of the monochromator; 3) condenser; 4) modulator; 5) monochromator; 6) focusing lens; 7) thermoelectric radiometer; 8) amplifier for the output voltage of the thermoelectric radiometer; 9) graph-plotter; 10) lamps simulating solar radiation; 11) thermostated standard solar cells; 12) tuned amplifier for the current produced by the standard solar cell; 13) recording equipment.

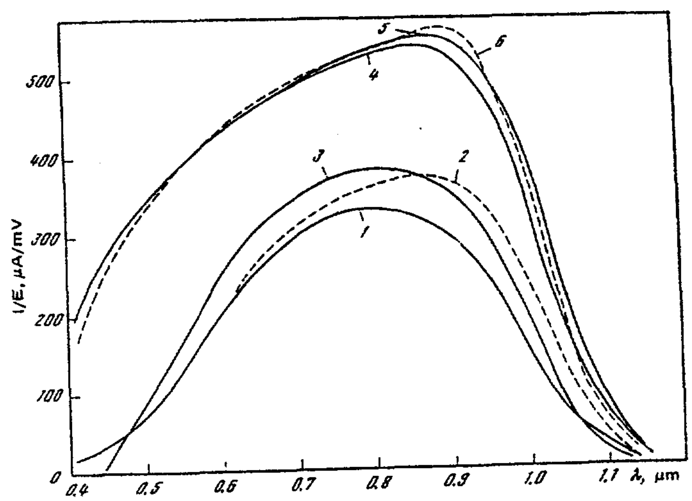

FIG. 3. Absolute spectral sensitivity of silicon solar cells with a deep p–n junction and without an antireflective coating (doped

Radiometric & Other Requirements for Accreditation of PV Testing Laboratories

The Photovoltaic Module Testing, Certification and Labeling Program

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Introduction

It is intended that the requirements for calibration, traceability of calibration and statistical representation of calibration and test data represent additional requirement of the Laboratory Quality System developed in support of the photovoltaic module certification and labeling program. The elements of this program, which are listed in Chart 1 in the form of major program documentation, have been developed in a contract at Arizona State University under Subcontract from NREL.[1] Documents PV-1 through PV-2, as well as technical issues and deliberations of the Criteria Development Committee (CDC), represent the Phase I results and are presented in NREL Report TP-412-7680.[2] Phase II of the program is currently underway and certain of the results of this work are the subject of this paper.

Much of the material presented in this paper were developed by the author as Document PV-1.1a (Addendum to Document PV-1), which is currently out for review by the CDC. These requirements are intended to be employed by [1] laboratories engaged in testing photovoltaic devices in support of the module certification program, and [2] assessment bodies, and their assessors (or auditors), as additional criteria against which laboratories are examined for the purposes of initial and continuing accreditation.

Scope of Requirements

All laboratories accredited, or otherwise approved, for the purpose of testing photovoltaic energy conversion devices shall be required to comply with these requirements. Document PV-1.1a sets forth the minimum requirements for calibration frequency, traceability of calibration, and for the development of information required for the statistical representation of calibration and test data. This document covers only those instruments used to measure parameters required in the testing and certification of photovoltaic modules.

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[1] Mr. Robert L. Hammond, Director of Alternative Energy Development at Arizona State University, is the ASU Project Director; Mr. Carl R. Osterwald, Solar Energy Research Facility, is the NREL Program Manager, and Gene A. Zerlaut is the chief consultant on the project.

[2] C. R. Osterwald et al, Photovoltaic Module Certification/Laboratory Accreditation Criteria Development, NREL/TP-412-7680, April 1995

Measurements covered by the requirements of Document PV-1.1a include both radiometric (Chart 2) and non-radiometric instrumentation (Chart 3). All equipment and instrumentation selected for the measurement of the test parameters required by Document PV-3[3] must be calibrated on a regular, periodic, basis at a frequency that depends on the specific measurement in question. Document PV-3 requirements are taken largely from IEEE 1262 and ASTM E 1036.

Traceability of Calibration

Matrices including the measurement of interest, instrument, reference instrument, traceability, re-calibration frequency and calibration-verification, or between-calibration check, are presented in Charts 4 and 5 for radiometric and non-radiometric instrumentation, respectively. The program requires that all calibration certificates, regardless of their hierarchy and source, contain a traceability statement and a statement of the total uncertainty of the transfer of calibration from either NIST or the World Radiometric Reference, WRR, whichever is applicable.

While the laboratory may select recognized National Laboratories, commercial vendor, or private calibration laboratories for its initial and re-calibration sources, it is required that the between-calibration checks and calibration verifications be performed by the PV Test Laboratory.

The hierarchy of NIST traceability for all instruments except *total* radiometers is presented in Figure 1. As indicated, the preferred calibration traceability scenario for the PV test laboratory would be for the laboratory to employ only Tier 1 traceability (i.e., with the test laboratory then having secondary traceability). If the test laboratory chooses to use a Tier 2 calibration laboratory (which is itself traceable to NIST through a Tier 1 laboratory), giving it tertiary traceability, the test laboratory shall be responsible for ensuring the competency of both the Tier 1 and Tier 2 laboratories.

Figure 2 presents the hierarchy of permissible traceabilities to the WMO World Radiometric Reference (WRR) for Type 1 PV Reference Cells. This first requires that the pyranometer used to calibrate the Type 1 reference cell shall be either a WMO First Class or a Secondary Standard Pyranometer and that it shall have been calibrated within the past 6 months in accordance with Clause 6 (Component Summation Method) of ISO 9846. If the PV terrestrial reference cell will be employed to measure the performance of modules at tilt, including vertical, the calibration of tilt requirements of ASTM E 941 (Rev) must be employed. These requirements are detailed in Chart 6.

> It should be noted that ASTM Standard E 1039 does not specify the WMO *class* required of the reference pyranometer. In addition, citation of ASTM E 1039 was inadvertently omitted in the Reference section of Document PV-3.

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[3]Testing Requirements for a Certification and Labeling Program for Photovoltaic Modules: Test Standards, Test Methods, and Instrumentation and Facilities

ASTM Standards E 913 and E 941 dealing with the shading disk calibration of pyranometers at horizontal and at tilt, respectively, are currently being merged into a single document and re-written to be in harmony with ISO 9846 (which covers both aspects).

If a WMO First Class pyrheliometer is employed in the PV-reference cell calibration, it shall have been calibrated within the previous 6 months against an Absolute Cavity Radiometer (ACR), also called known as a self-calibrating absolute cavity pyrheliometer.

It will be the PV test laboratory's responsibility to ensure that the requirements of Figure 2 are met regardless of whether [1] the test laboratory itself performs the calibration of PV reference cells, [2] obtains the PV reference cells from either the module manufacturer or a third party, or [3] performs selected portions of the calibration chain presented in Figure 2.

Other Radiometer Requirements

In the event that the PV module test laboratory either chooses to, or is required to, manufacture the PV terrestrial reference cells used to determine the effective irradiance for current-voltage (I-V) testing of modules, the cells shall be constructed in accordance with the requirements of ASTM E 1040. Dimensional requirements shall be traceable to NIST as shown in Chart 5.

If the test laboratory is required to determine the spectral response and spectral mismatch coefficient of PV terrestrial reference cells, the measurements shall be performed in accordance with ASTM Standards E 1021 and E 973, respectively.

Should the module test laboratory construct or otherwise acquire a solar simulator for testing in support of the PV module certification program, its characteristics shall meet the requirements of ASTM E 927. The technical requirements for uniformity of spectral energy distribution will necessitate the use of a spectroradiometer with its calibration traceable to NIST.

Source of Calibration

When an outside, independent calibration laboratory is selected to perform the laboratory's regular, periodic re-calibrations, the laboratory shall ensure that [1] the calibration facility, or laboratory, is accredited either by the American Association for Laboratory Accreditation (A2LA) or by the National Voluntary Laboratory Accreditation Program (NVLAP) for the exact measurements required, and shall obtain evidence to that effect[4], [2] the laboratory is certified to ANSI/NCSL Z540.1 (formerly MIL-STD-45662, which has been suspended), and obtain evidence to that effect, or it must [3] investigate the competency of the vendor calibration laboratory in accordance with the requirements of Criteria 17.1 of Document PV-1 Criteria for a Model Quality System for Laboratories Engaged in Testing Photovoltaic Modules.

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[4]The nation's two major umbrella laboratory accreditation programs

A U.S. Certification Body that does not seek reciprocity with other countries' through Mutual Recognition Agreements (MRA's) most likely will not require U.S. National Laboratories to have their calibration facilities accredited as providers of either PV reference cells, or reference cell calibrations.

When the original equipment, or instrument, manufacturer is selected for either the initial or re-calibration requirements, the laboratory shall ensure that all applicable traceability requirements are met, including the requirement that the original equipment vendor shall have direct traceability to NIST for those measurements for which NIST traceability is applicable, or to the WRR for those measurements for which traceability to the World Meteorological Organization is required. The PV test laboratory shall investigate the quality and competency of the manufacturer to provide accurate calibration values in accordance with the requirements of Criteria 17.1, 17.2 and 17.4 of Document PV-1.

The test laboratory will be required to use the checklist contained in Appendix 1 of Document PV-1.1a to evaluate the competency of any independent calibration facilities employed, as well as the quality and competency of original equipment and instrument manufacturers with respect to the initial calibrations provided, or to any re-calibrations obtained. A synopsis of the required checklist is presented in Chart 7.

Statistical Requirements

The PV module test laboratory shall ensure that all calibration certificates obtained from outside, independent calibration laboratories, or from original instrument manufacturers, are provided with an expression of uncertainty by the vendor laboratory.

For internal calibrations, measurements and the expression of test results, the laboratory must utilize [1] between-calibration checking of reference standards, [2] verification testing of whatever environmental conditions are maintained in chamber testing (e.g., temperature and relative humidity), [3] correlation analyzes, and [4] SPC charting of module measurements to the extent possible. Also, the laboratory must perform between-calibration checking of both measurement and reference standards for voltage, current, temperature and effective irradiance. This must include regression analysis of the correlation between different temperature probes, different current and voltage measuring devices, and different pyranometers and PV reference cells.

In the absence of an industry-developed proficiency test module, the laboratory must maintain not less than two internal reference photovoltaic modules whose short circuit current and open circuit voltages, and fill factors, are determined on a regular, periodic basis for the purpose of control charting using statistical quality control (SQC) charting.

Chart 1

The Photovoltaic Module Testing, Certification and Labeling Program

Major Documentation

- PV-1 Criteria for a Model Quality System for Laboratories Engaged in Testing Photovoltaic Modules
- PV-2 Model for a Third-Party Certification and Labeling Program for Photovoltaic Modules
- PV-3 Testing Requirements for a Certification and Labeling Program for Photovoltaic Modules: Test Standards, Test Methods, and Instrumentation and Facilities
- PV-4 Operational Procedures Manual for the Photovoltaic Module Testing, Certification and Labeling Program (in development)
- PV-5 Application and Certification Procedures for the Photovoltaic Module Testing, Certification and Labeling Program (in development)

Developed by Arizona State University under Subcontract from NREL, NREL/TP-412-7680

Chart 2

Radiometric Calibrations

Instrumentation

- Pyrheliometers, including Absolute Cavity Radiometers
- Pyranometers
- Reference Cells
- Illuminating Spectrometers
- Spectroradiometers

Chart 3

Non-Radiometric Calibrations

Electrical, Mechanical, Dimensional, etc.

- Current
- Voltage
- Electrical resistance, series
- Electrical power
- Temperature
- Wind velocity
- Linear dimensions

Chart 4
Traceability & Calibration Frequency Requirements
Radiometric Instrumentation

Measurement	Instrument	Reference Instrument	Traceable To	Re-Cal Frequency	Check Frequency
Direct Irradiance	Pyrhelio-meter,ACR*	ACR(s)	WRR	Annual	90 days
Global Irradiance	1st Class Pyranometer	Pyrhelio-meter, ACR	WRR	Annual	90 days
Effective Irradiance	PV Reference Cell	1st Class Pyrano-meter	WRR	Annual	60 days
Spectral Irradiance	Spectroradi-ometer	Standard Lamp	NIST	Annual	Each Use
Spectral Response	Monochro-mator	Mercury Vapor Lamp	NIST	Annual	Each Use

*ACR = Absolute Cavity Radiometer (Pyrheliometer)

Chart 5

Traceability & Calibration Frequency Requirements

<u>Non-Radiometric Instrumentation</u>

Measurement	Instrument	Reference Instrument	Traceable To	Re-Cal Frequency	Check Frequency
Current, amperes	Bi-Polar Power Supply or Multimeter	Multimeter or Calibrated Shunt	NIST	2 Years	90 days
Voltage, volts	Bi-Polar Power Supply or Multimeter	Multimeter or Calibrated Shunt	NIST	2 Years	90 days
Resistance, ohms	Multimeter	Calibrated Resistance	NIST	Annual	60 days
Temperature, C	Digital Thermometer	Long-stem Thermometer	NIST	Annual	30 days
Wind Velocity, mps	Anemometer	Standard Anemometer	NIST	Annual	90 days
Linear Dimensions	Calibrated Ruler	Caliper	NIST	2 Years	None

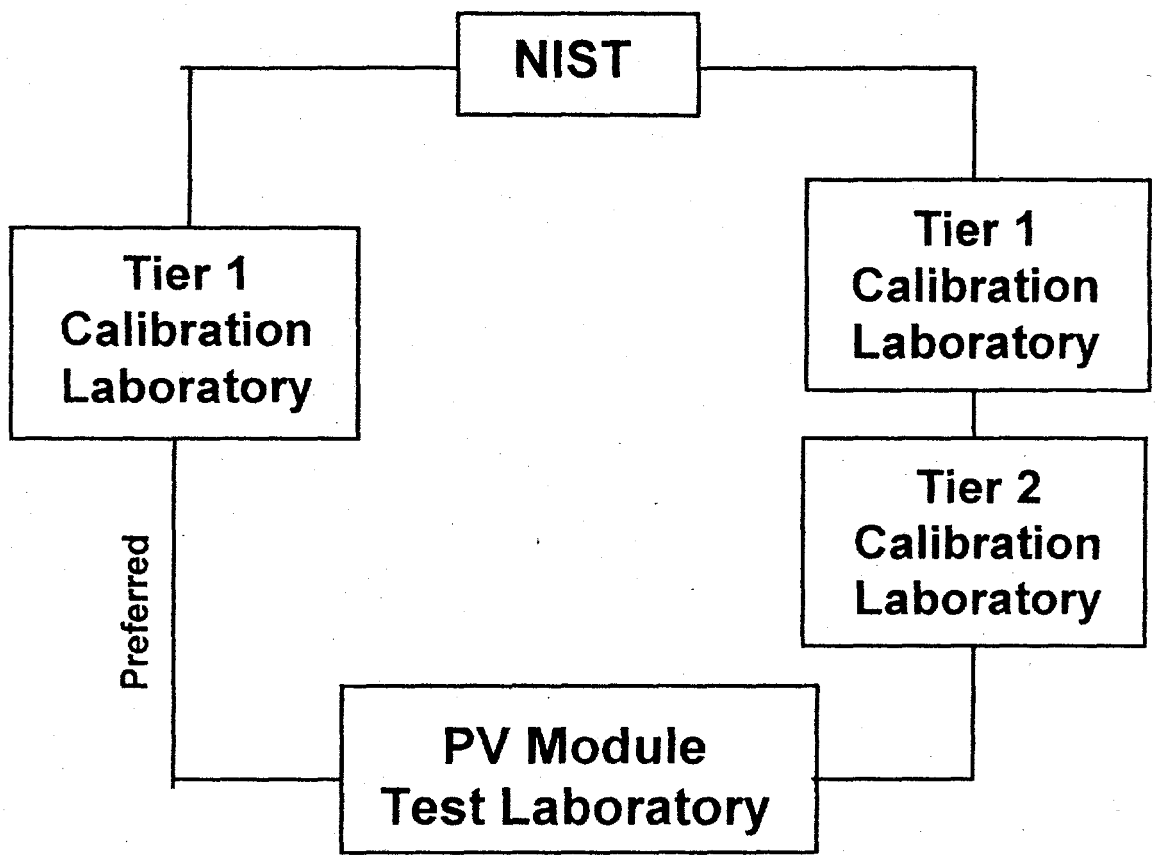

Figure 1: Hierarchy of Traceability to NIST

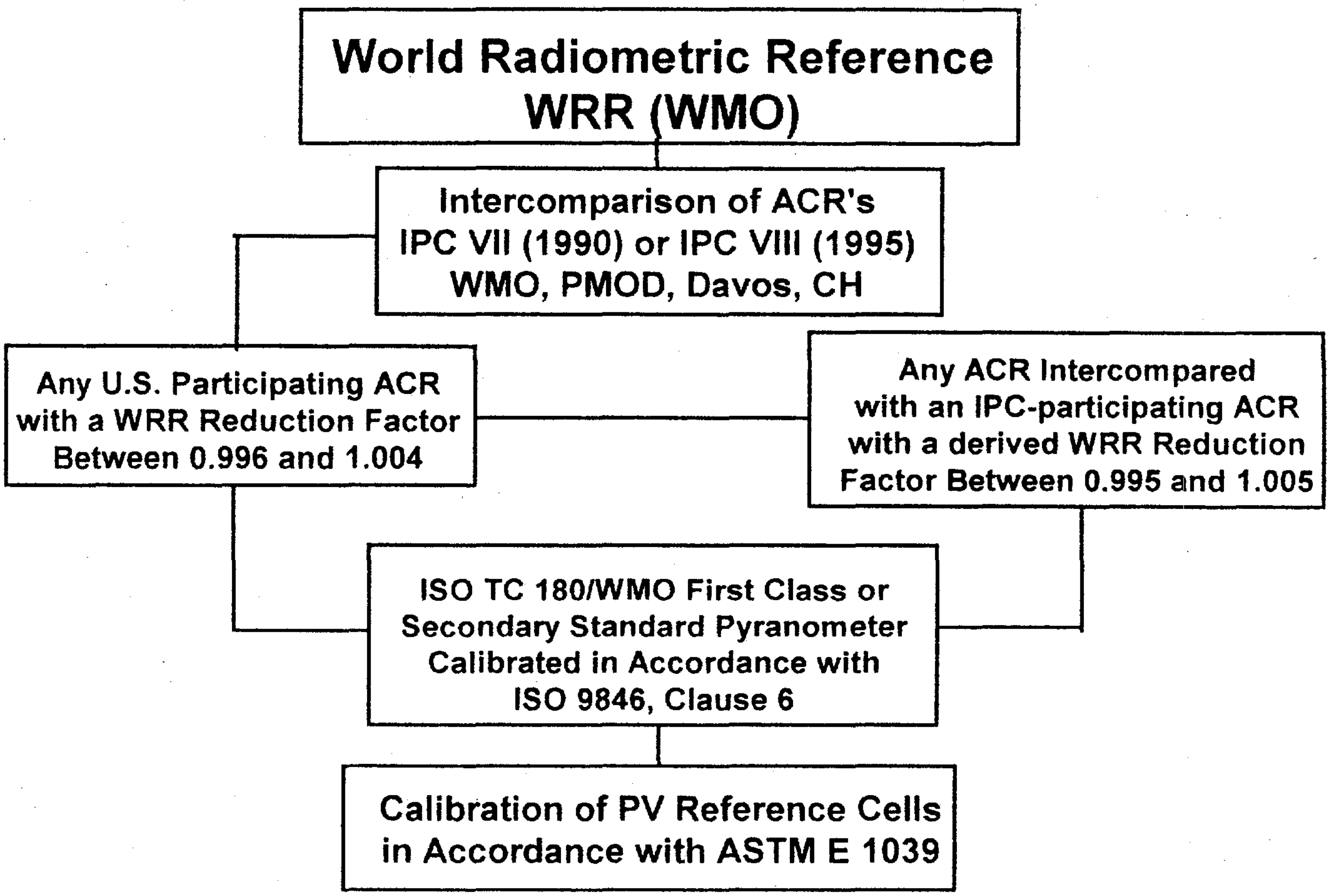

Figure 2: Hierarchy of Traceability to WMO's World Radiometric Reference (WRR) for PV Terrestrial Reference Cells

Chart 6

Radiometric Calibration Requirements

Standards

Radiometer	ASTM Standard	ISO Standard*
WMO First Class Pyrheliometer	E 816	ISO 9059
WMO First Class Pyranometer	E 913 & E 941 in revision	ISO 9846
Type I Reference Cell	E 1039	-

***Use of ISO Standard required in absence of ASTM Standard**

Chart 7

Tier 1 and Tier 2 Calibration Laboratories (Vendor)

Elements of Second Party Assessment

- A documented Quality Policy
- A documented measurements verification program
- An established reference instrument maintenance program
- Established written calibration procedures
- Participate in:
  - Collaborative reference programs,
  - Proficiency test programs, or
  - Interlaboratory comparisons
- Utilize SPC Charting, x-y correlation measurements, etc.
- Documented Corrective Action Program
- Have policy and history of performing internal audits

NOTE: Most likely will be insufficient if Certification Body seeks reciprocity with the EC & EFTA Countries, or Japan

Radiometric Instrumentation for PV System Performance Monitoring

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ABSTRACT

This paper provides an overview of existing instrumentation options and solicits user needs for improving outdoor solar radiation measurements for determining PV system performance. The following topics are discussed:

- Historical overview and terminology
- Radiometer calibration and characterization methods used by NREL
- Sample calibration results for various commercial instruments
- Current research topics
- User needs for improved PV performance monitoring.

Emphasis is placed on the need for the user to understand the measurement capabilities of commercially available radiometers and interpret the measurement results accordingly. A list of radiometer manufacturers is also provided.

1. Introduction

Regular measurements of solar radiation began in the late 1800's with the advent of the Campbell-Stokes *Burning Sunshine Recorder*. Mechanically a very simple device, this instrument was widely used, and continues to be used in developing countries, to measure the duration of bright sunshine (direct or beam irradiance). A 76 mm diameter glass sphere focuses the direct rays of the sun on a piece of chemically treated paper printed with the hours of the day. The paper is placed in a holder to fix its location in the focal plane of the sphere. The paper burns when the direct irradiance is greater than 210 Watts per square meter . At the end of each day, a technician replaces the used paper and measures the total burn length comparing the length to the total number of daylight for the date. The ratio of burn-length (mm) to day-length (mm) multiplied by 100 yields the daily percent possible sunshine (%SS). Until the energy crisis of the 1970's and the resulting interest in measuring solar radiation, the majority of solar data for the world was based on the measurements of %SS. Models were developed to estimate the total hemispherical (or global) solar irradiance from %SS. The amount of energy available on a solar collector was then further estimated by models providing direct normal (beam) and diffuse (sky) irradiance based on the amount of global irradiance. The modelling continued by recombining the direct and diffuse irradiance elements onto a surface of arbitrary orientation (e.g., a south-facing flatplate collector).

Also during the turn of the century, physicists were interested in measuring the solar constant. Several designs for pyrheliometers to measure the direct normal irradiance were used for this purpose. These calorimetric instruments were designed to equate solar intensities with the changes in temperature of water, silver, or other media. Improved instruments were produced based on the thermoelectric and photoelectric effects.

By the 1950's, the U.S. Weather Bureau established a network of weatherized pyranometers used to measure global solar radiation in support of agricultural interests. Continuous direct normal solar irradiance measurements would come much later with the development of automatic solar trackers used to maintain proper alignment of the pyrheliometer with the solar disc. Table 1 summarizes some of the significant historical developments of radiometry and the associated instrumentation needs.

Table 1. History of Radiometry Development

Period	Need/Application	Instrument
1870's	Sunshine Duration	Campbell-Stokes Burning Sunshine Recorder (Still in use)
1900's	Determining the Solar Constant	Pyrheliometers: Smithsonian Silver Disk Abbott's Water-flow Pyranometer
1930's	Agricultural	180° Pyrheliometer for total hemispherical irradiance (global)
1950's	U.S. Weather Bureau	Lightbulb Pyranometer
1960's	Meteorological Monitoring	Model 2 Pyranometer Precision Spectral Pyranometer
1970's	NASA Satellite Design Solar Simulator Output World Radiometric Reference	Absolute Cavity Radiometer (Defines International Measurement Scale)
1980's	Renewable Energy	Improved data acquisition systems Automatic Solar Trackers (need 5% accuracy)
1990's	Climate Change	Windowed Absolute Cavity Radiometer Pyranometer under Tracking Shading Disk Pyrgeometer for infrared Ultraviolet Photometer Rotating Shadowband Radiometers Improved Pyranometers (need 1% accuracy)

The present instruments for measuring solar radiation continue to rely on the measurement of temperature or the photoelectric effect of semiconductors (see Zerlaut, 1989 for a complete description of instrument developments). It is important to note the absolute cavity radiometer (a pyrheliometer) provides the best measurement capability and is the basis for the internationally recognized scale of solar radiation measurement, the World Radiometric Reference (WRR). The WRR is maintained by the World Radiation Center and has a stated uncertainty of ±0.3%. The PV designer should keep this limitation in mind when developing a measurement program or analyzing experimental results.

2. Radiometer Calibration & Characterization

There are several accepted methods for calibrating pyranometers and pyrheliometers for PV system performance monitoring. The component summation and shade-unshade methods are used at NREL for the outdoor calibration of broadband radiometers.

2.1 Reference Instruments

All methods of radiometer calibration require either reference sources (lamps) or reference radiometers. At NREL, the basis for all outdoor broadband radiometer calibrations is a group of absolute cavity radiometers. These radiometers are electrically self-calibrated and are individually characterized by the manufacturer. The measurement principal is based on our abilities to measure voltage, resistance, and area from first principles (traceable to the National Institute of Standards and Technology - NIST). These cavity radiometers are identical in construction to those "passive" instruments maintained by the World Radiation Center as the World Reference Group (WRG). The six radiometers in the WRG form the basis of the World Radiometric Reference (WRR) scale of measurement. Commercially available absolute cavity radiometers have a stated measurement uncertainty of ±0.5% and have demonstrated a precision of better than ±0.05%. NREL maintains three cavity radiometers for the purpose of calibration transfer:

- Primary Reference Standard - directly traceable to the WRR
- Secondary Reference Standard - calibration traceable to the Primary Reference
- Working Reference Standard - calibration traceable to the Primary Reference and used for routine calibration of field radiometers.

The Primary Reference Standard is compared with the six instruments in the WRG on a 5-year cycle at the International Pyrheliometer Comparisons held at the World Radiation Center. The Secondary Reference and Working Reference Standards are compared at least annually with the Primary Reference. All NREL outdoor radiometer calibrations are performed with the Working Standard.

A pyranometer designated for measuring the diffuse irradiance is calibrated using the shade technique and the Working Standard Reference cavity radiometer. In this method, the difference in output of the pyranometer while alternately shaded and unshaded is compared to the vertical component of the direct normal irradiance. The pyranometer calibration factor (mV / W / sq m) is the average ratio of the unshaded minus shaded signal (mV) to the direct normal irradiance (W / sq m) measured by the cavity which has been multiplied by the cosine of the appropriate solar zenith angle. The calibrated pyranometer is then installed under an automatic solar tracker to position an occulting disc over the pyranometer sensing surface for continuous measurement of the reference diffuse solar irradiance.

2.2 Pyrheliometers

Pyrheliometers are calibrated outdoors by comparing nearly simultaneous 1-minute measurements of the instrument under test with the output of the Working Reference Standard absolute cavity radiometer. Data are collected under clear sky conditions (short-term irradiance variations less than ±2%) when the direct irradiance is between 400 and 1080 Watts per square meter. Typically 300 to 600 data points collected over a 3-day period are used to determine the calibration factor of the pyrheliometer under test.

2.3 Pyranometers

Groups of pyranometers (SRRL can accommodate up to 90 instruments) are calibrated using the component summation technique. Here, the reference total hemispherical (global) irradiance is computed for each 1-minute measurement of the reference direct normal irradiance and the coincident reference diffuse horizontal irradiance (G = Direct x Cos(Zenith) + Diffuse). Figure 1 illustrates the instrumentation elements used for NREL's Broadband Outdoor Radiometer CALibration (BORCAL) process. Typical BORCAL irradiance data are shown in Figure 2 for two days of data collection. All calibration factors are determined from the average of 1-minute data collected during the period defined by the solar zenith angle range of 45° to 50° for each day of data.

2.4 Measurement Uncertainty

Results typical of the calibrations performed for about 150 radiometers each year are shown in Figures 3 through 17. As shown by these time-series and solar zenith angle plots, the calibration factor of an instrument can vary with solar position and air temperature (typically results in families of curves for the same instrument). The following elements contribute to the measurement uncertainty associated with the BORCAL process and the radiometer response:

- Calibration traceability to the WRR
- Performance of the Reference Cavity Radiometer
- Performance of the Reference Diffuse Pyranometer
- Tracker alignments (effects of varying amounts of circumsolar)
- Angular response of the radiometer under test
- Temperature response of the radiometer under test
- Linearity of the radiometer under test
- Spectral response
- Thermal EMFs at electrical connections
- Thermal gradients in the instrument
- Data acquisition system measurement performance
- Data reduction (computation of solar position).

A careful analysis of the impacts of the above elements results in the measurement (calibration) uncertainties shown in Figure 18 for pyrheliometers and pyranometers using the BORCAL procedures (Myers, 1988; Myers, 1989; Myers, et al, 1989). The measurement uncertainties (U_{95}) are combinations of bias (B) and random (sigma) components.

3. Calibration Stability

Each BORCAL event includes the calibration of three control radiometers. The repeated use of these instruments provides an indication of the process consistency. The seven-year calibration records for the control pyrheliometer (s/n 17836E6) and the control pyranometer (s/n 25825F3) are shown in Figures 19 and 20 respectively. The stability of these calibration with time indicates, with some exception, the BORCAL process has been repeatable and/or the radiometer measurement responses have been consistent to within the World Meteorological Organization's specifications for Class 1 radiometers (less than 1% change in overall response per year). The results for other instruments are shown in Figures 21 through 25.

4. Current Research & Development Activities

As funding permits, the following research and development activities are in progress and/or planned for the near future:

- Automated radiometer calibration and characterization system - an upgrade to the BORCAL process resulting in a "calibration factor vector" describing the pyranometer response as a function of solar zenith angle in addition to the classical single-value data.

- Automated pyranometer characterization system - hardware and software for evaluating the cosine response of pyranometers under controlled conditions.

- Rotating Shadowband Radiometer - continue the evaluation of this device using data from the thermopile instruments in the SRRL Baseline Measurement System from 1992 to present (T. Stoffel, et al, 1992).

- Multiple Pyranometer Array (MPA) - evaluation of low-cost pyranometers mounted in fixed orientations from the horizontal to provide data for estimating the amounts of direct normal and diffuse horizontal irradiance components without the need for automatic solar trackers.

- Evaluation of commercially available radiometers - acquire at least one sample of each manufacturer for outdoor comparisons over one to five years.

- Development of standard practices for radiation measurement system operation and maintenance - document(s) describing options for selecting, siting, operating, and maintaining radiometers in support of renewable energy research and development.

5. User Needs

The author solicits reader feedback for quantifying the following radiometer performance issues:

- Accuracy - Is the present measurement capability adequate? [Pyranometers @ ±5% and pyrheliometers @ ±2%]

- Precision - Same as above, but about one-half the uncertainties.

- Stability - WMO Class 1 adequate?

- Size & Weight - Suitable for PV design installations?

- Time Response vs Spectral Response - Thermoelectrics are 1 sec for 1/e but spectrally flat, photoelectrics are quick (micro-seconds) but spectrally selective (silicon response).

- Cost / Performance - Thermoelectrics are $2,000 for WMO Class 1 specifications, photoelectrics are $200 for Class 2 and Class 3 specifications.

- Other - What other considerations are important to PV?

Contact any of the manufacturers listed in Table 2 for more information and/or suggestions for your measurement applications.

6. Conclusions

Solar irradiance measurements for determining PV performance place greater demands on radiometer performance than does the meteorological monitoring for which they were designed. Characterize the radiometer measurement responses of your specific instrument to improve your measurement certainty. Know the changes in "calibration factor" as a function of solar incidence angle and ambient air temperature before reducing your experimental data. Radiometer manufacturers can provide improved instruments if you let them know your needs. Always specify radiometer calibrations that are traceable to the World Radiometric Reference scale of measurement to improve the comparability of the measurements with those from other experimentors or designers.

7. References

Myers, D. 1989: "Application of a Standard Method of Uncertainty Analysis to Solar Radiometer Calibrations", *Proceedings of the 1989 Annual Conference, American Solar Energy Society, Denver, Colorado, June 19 - 22, 1989.* M.J. Coleman (editor).

Myers, D., K. Emery, and T. Stoffel 1989: "Uncertain Estimates for Global Solar Irradiance Measurements Use to Evaluate PV Device Performance", *Solar Cells, 27*. pp. 455 - 464.

Stoffel, T., C. Riordan, and J. Bigger 1992: *Evaluation of Solar Radiation Measurement Systems: EPRI/NREL Final Test Report, Volume 1.* NREL/TP-463-4771. National Renewable Energy Laboratory, Golden, CO 80401-3393. 63 pp.

Zerlaut, G. 1989: "Solar Radiation Instrumentation", Chapter 5. pp.173-307, *Solar Resources*, Hulstrom, Roland L. (editor). The MIT Press, Cambridge, Massachusetts. ISBN 0-262-08184-9. 408 pp.

Table 2. Solar Radiation Instrument Manufacturers

1. Ascension Technology, Inc.
   P.O. Box 314
   Lincoln Center, MA 01773
   Telephone: (617)890-8844
   Telefax: (617)890-2050

2. Brusag
   Chapfwiesenstrasse 14
   CH-8712 Stäfa
   Switzerland
   Telephone: 01-926 74 74
   Telefax: 01-926 73 34

3. Casella London Limited
   Regent House
   Britannia Walk
   London N1 7ND
   Telephone: 01-253-8581
   Telex: 26 16 41

4. KO Instruments Trading Co., LTD.
   21-8
   Hatagaya 1-chome
   Shibuyaku, Tokyo 151
   Japan
   Telephone: 81-3-3469-4511
   Telefax: 81-3-3469-4593
   Telex: J25364 EKOTRA
   U.S. Distributor:
   SC-International, Inc.
   346 W. Pine Valley Drive
   Phoenix, AZ 85023
   Telephone: (602) 993-7877
   Telefax: (602) 789-6616

5. The Eppley Laboratory, Inc.
   12 Sheffield Avenue
   Newport, RI 02840
   Telephone: (401) 847-1020
   Telefax: (401) 847-1031

6. Kipp & Zonen, Delft BV
   P.O. Box 507
   2600 AM Delft Holland
   Mercuriusweg 1
   2624 BC Delft Holland
   Telephone: 015-561 000
   Telfax: 015-620351
   Telex: 38137
   Division of:
   Enraf Nonoius Co.
   390 Central Avenue
   Bohemia, NY 11716
   Telephone: (516) 589-2885
   (800) 645-1025
   Telefax: (516) 589-2068

7. LI-COR, Inc.
   4421 Superior Street
   Lincoln, NE 68504
   Telephone: (402) 467-3576
   (800) 447-3576
   Telefax: (402) 467-2819
   TWX: 910-621-8116
   Bulletin board: (402) 467-3555

8. Matrix, Inc.
   537 S. 31st St.
   Mesa, AZ 85204
   Telephone: (602) 832-1380

9. Sci-Tec Instruments USA, Inc.
   4240 Bluebonnet Dr.
   Stafford, TX 77477
   Telephone: (713) 240-0404
   Telefax: (713) 240-0428
   Canadian HQ: (306) 934-0101

10. Solar Light Company
    721 Oak Lane
    Philadelphia, PA 19126-3342
    Telephone: (215) 927-4206

11. Yankee Environmental Systems, Inc.
    Montaque Industrial Park
    101 Industrial Road
    P.O. Box 746
    Turners Falls, MA 01376
    Telephone: (413) 863-0200
    Telefax: (413) 863-0255

BORCAL FUNCTIONAL SCHEMATIC

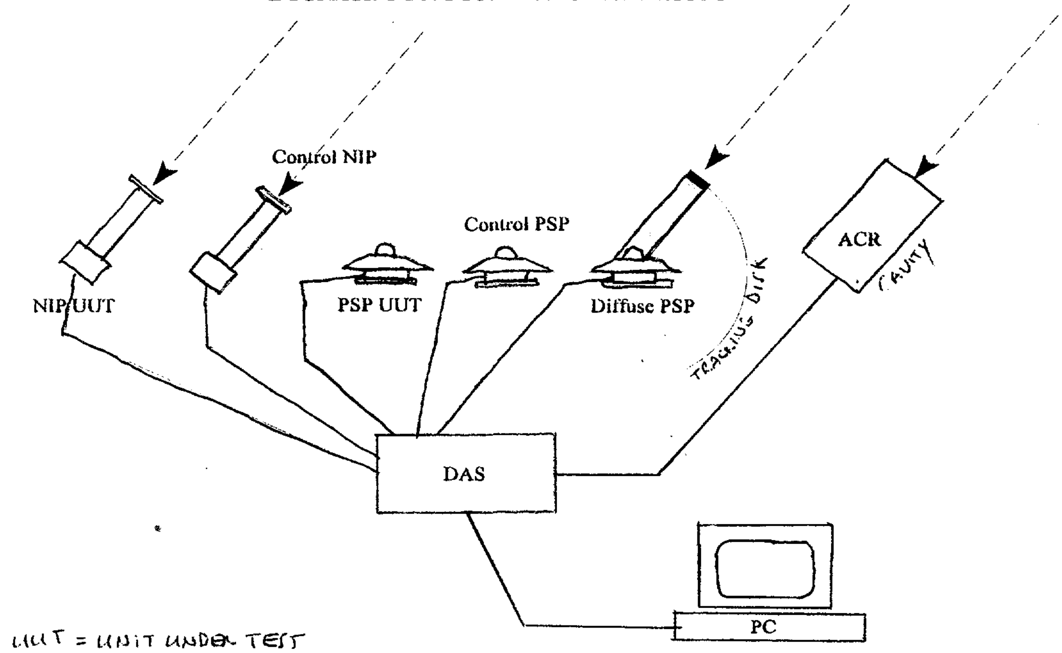


FIGURE 1. BROADBAND OUTDOOR RADIOMETER CALIBRATIONS (BORCAL)

RADIOMETER CALIBRATION REFERENCE IRRADIANCES
CALIBRATION EVENT: BORCAL95_01

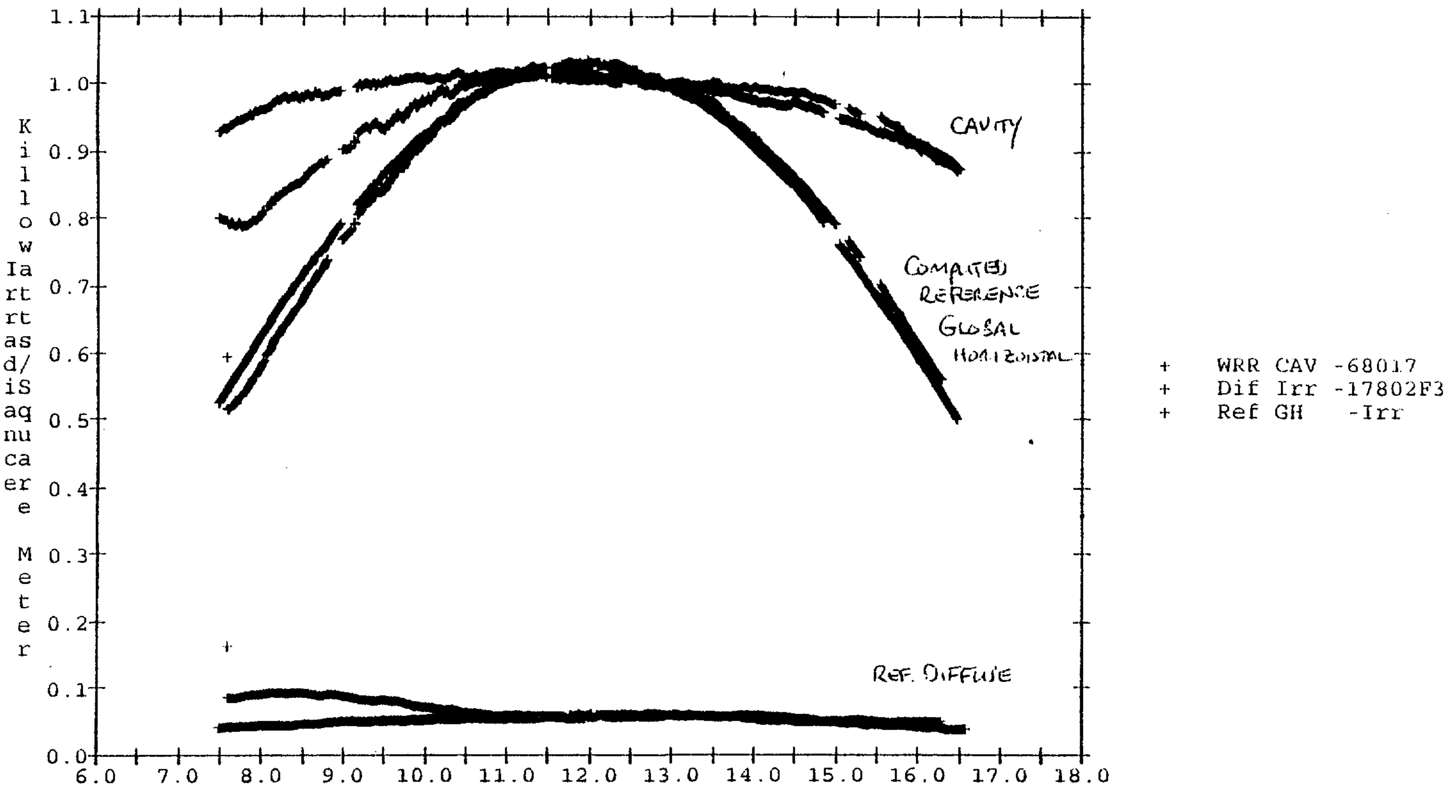
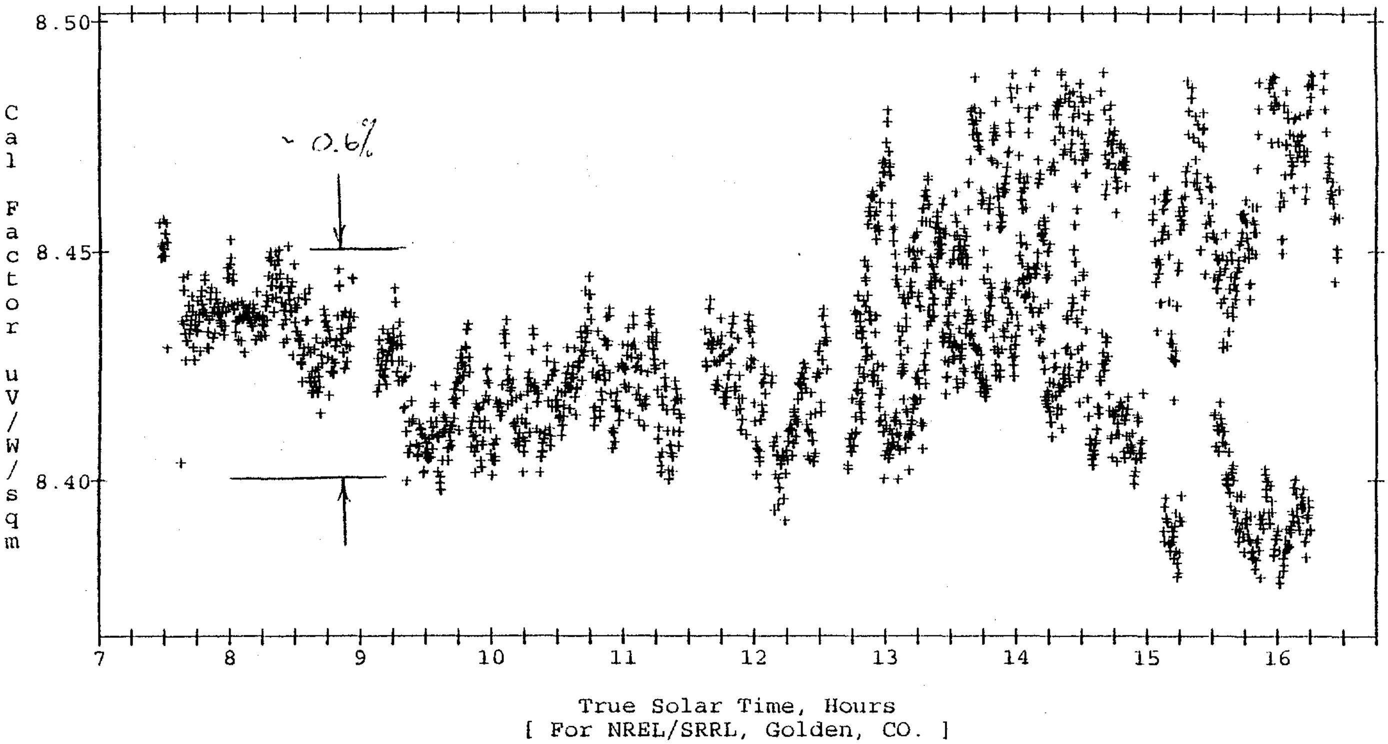


Figure A
Mountain Standard Time

[FIG. 2] TWO DAYS of MEASUREMENTS

Calibration Dates: JUN 11 JUN 18 1995
Zenith Angle Range: 16.2 to 59.3 Degrees
Reviewed by: Kevin Eldridge

Calibration Factor (Cf) for 17836E6 (NIP)
vs TRUE Solar Time



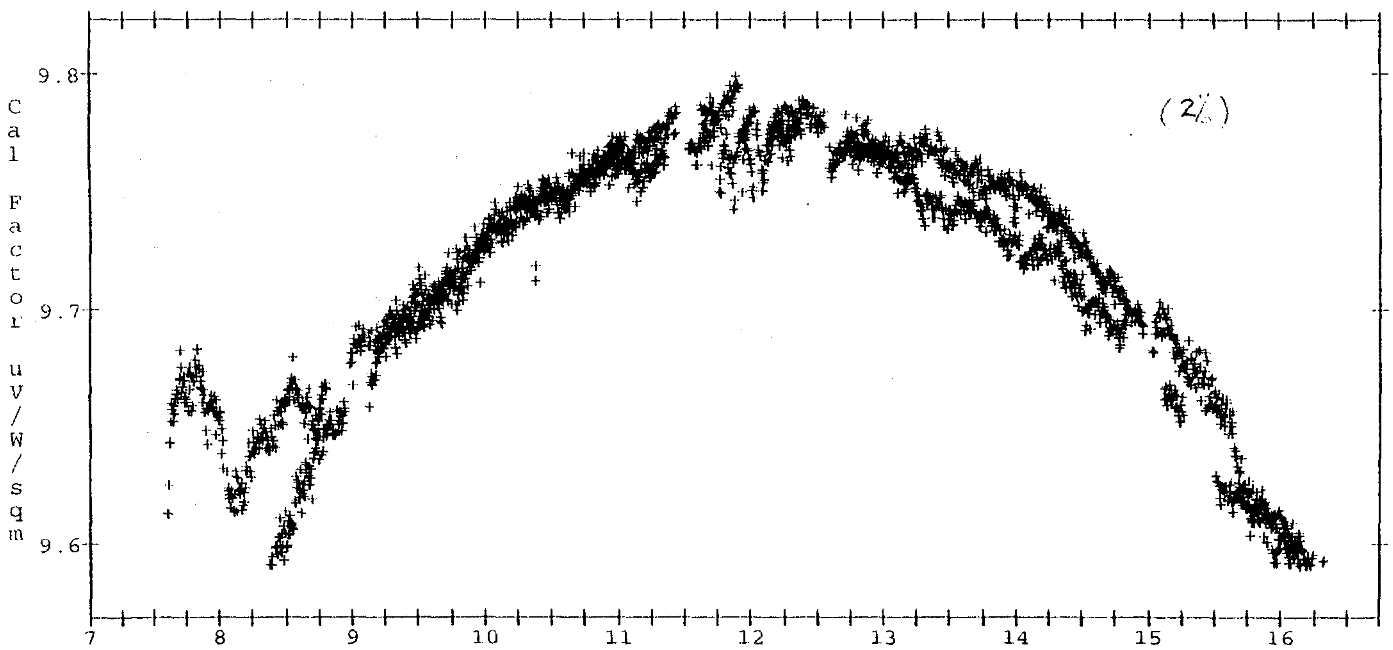
Reference Radiometer: TMI 68017, WRR correction = 1.000227
Dates of calibration: JUN 11 JUN 18 1995

NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure ~~1-A~~ 3

Calibration Factor (Cf) for 25825F3 (PSP)
vs TRUE Solar Time



True Solar Time, Hours
[For NREL/SRRL, Golden, CO.]

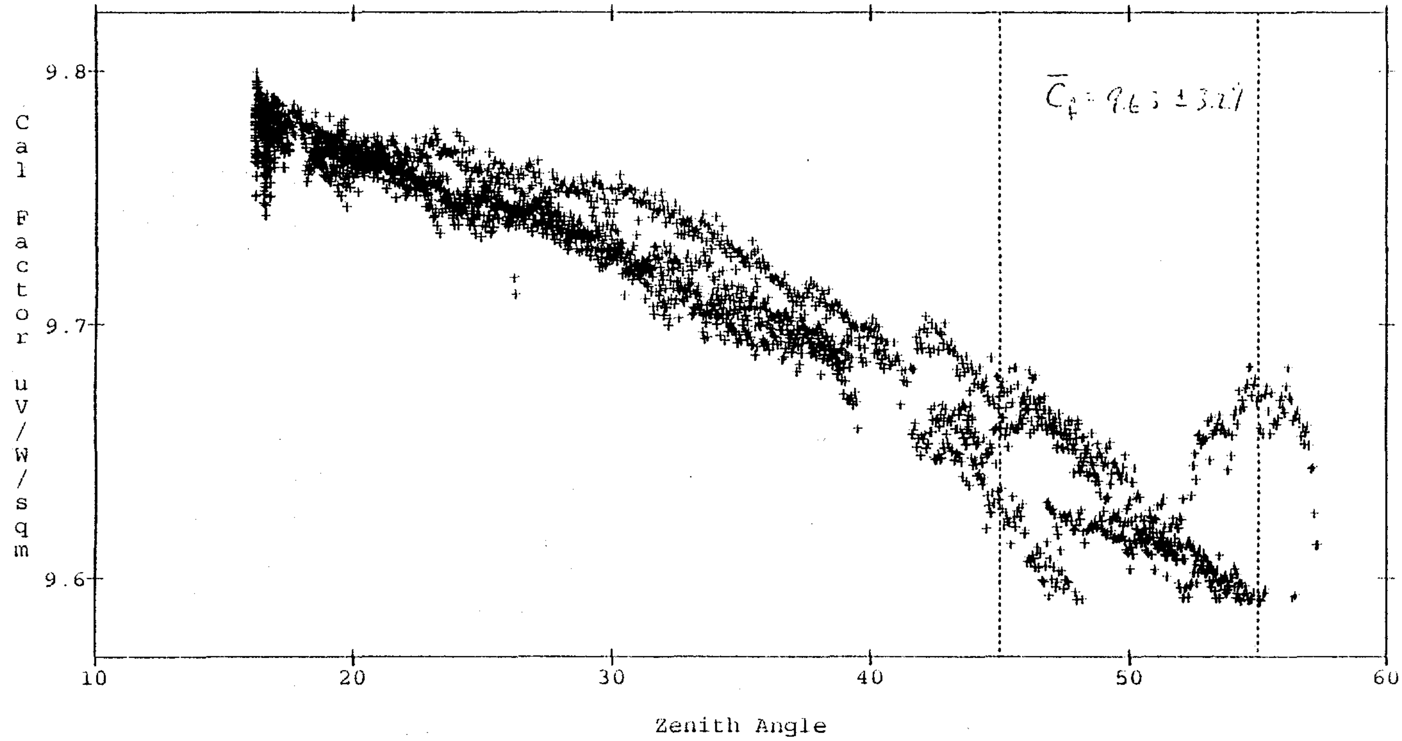
Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued
yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure ~~3~~ 4

Calibration Factor (Cf) for 25825F3 (PSP)
vs Refraction Corrected Zenith Angle



Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV
Dates of calibration: JUN 11 JUN 18 1995

NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Dotted lines bracket calibration zenith angle Range

Figure 5

COMPONENT SUMMATION CALIBRATION UNCERTAINTY
NREL CALIBRATION EVENT: BORCAL95_01

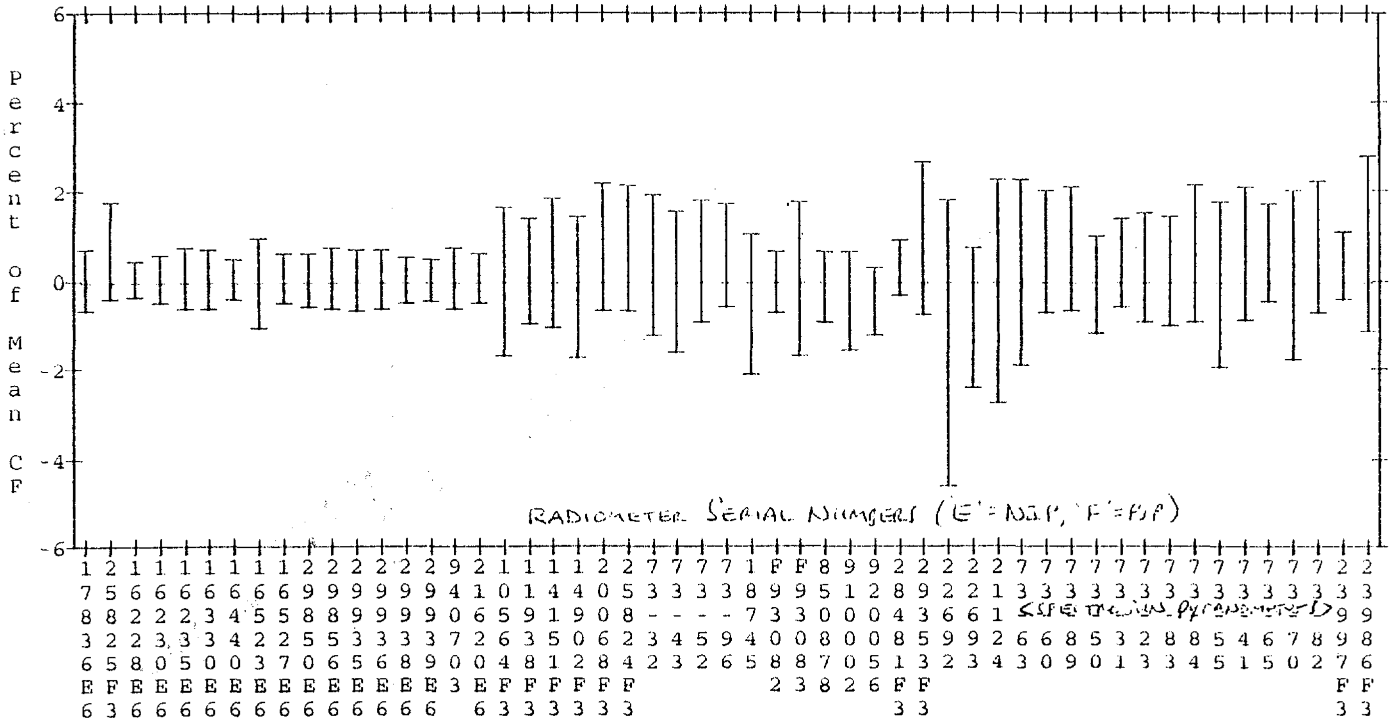


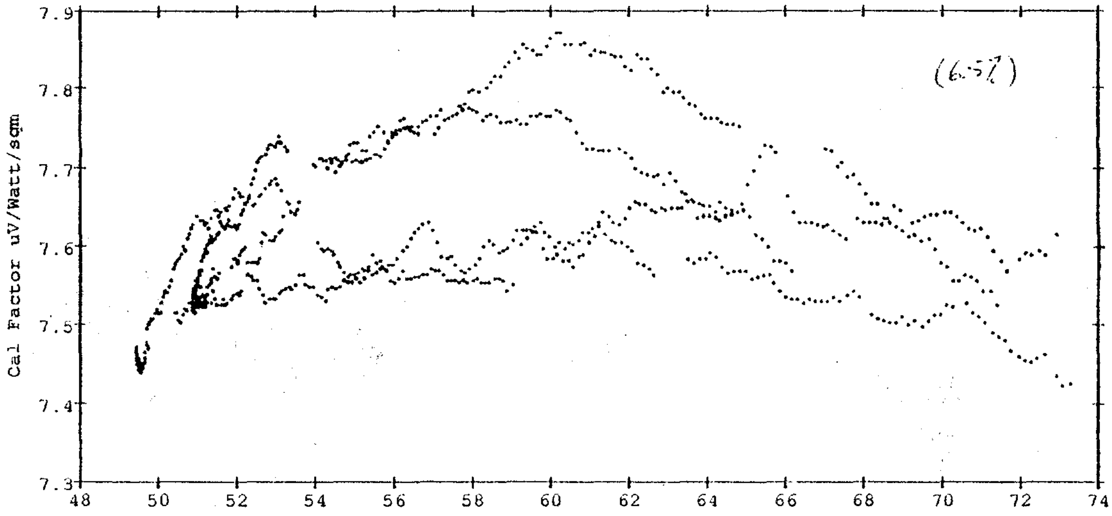
Figure 6

Reference Instruments: TMI Cavity serial # 68017, Diffuse-Eppley PSP serial # 17802F3
Calibration Dates: JUN 11 JUN 18 1995
Zenith Angle Range: 16.2 to 59.3 Degrees
Reviewed by: Kevin Eldridge

- o Error bars = RANGE of CF Results over period of calibration
- o Pyranometer Error Bars about mean of Pyranometer CF @ Z = 50 Deg.
- o Pyrheliometer Error Bars about mean of CF for ALL ZENITH Angles

Calibration Factor (Cf) for EP7724
vs Refraction Corrected Zenith Angle

Model 50 (Light Bulb)



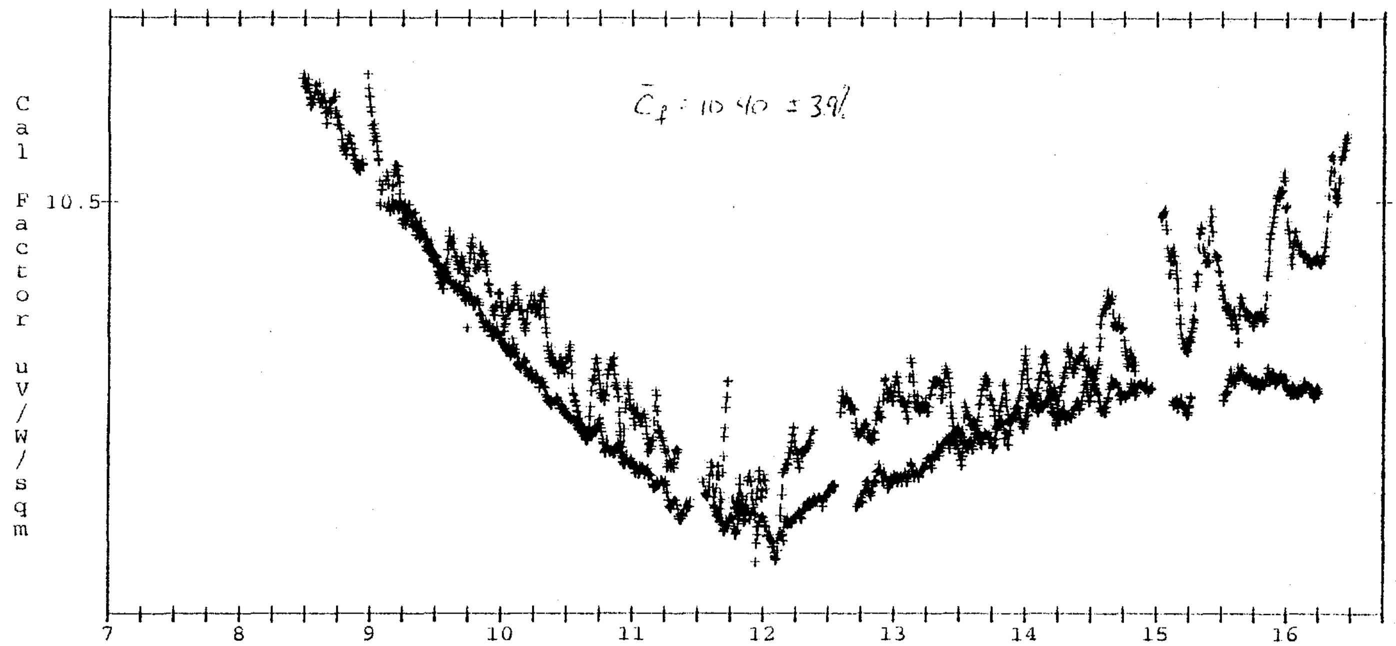
ZENITH ANGLE
[Corrected for Atmospheric Refraction AT 840 mB, 25 Deg C]

Ref. Radiometer TMI 68018 (Direct), PSP 17802F3 (Diffuse).
Dates of calibration: OCT 19 OCT 23 1989
NOTE: 49.4 <= Zen. Ang. <= 73.2 CORRECTED for ATMOSPHERIC REFRACTION for the
SERI/SRRL site @ 840 mB and 25 Deg C

Figure 34. 7

Calibration Factor (Cf) for 21124
vs TRUE Solar Time

Model (3.4%)



True Solar Time, Hours
[For NREL/SRRL, Golden, CO.]

Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

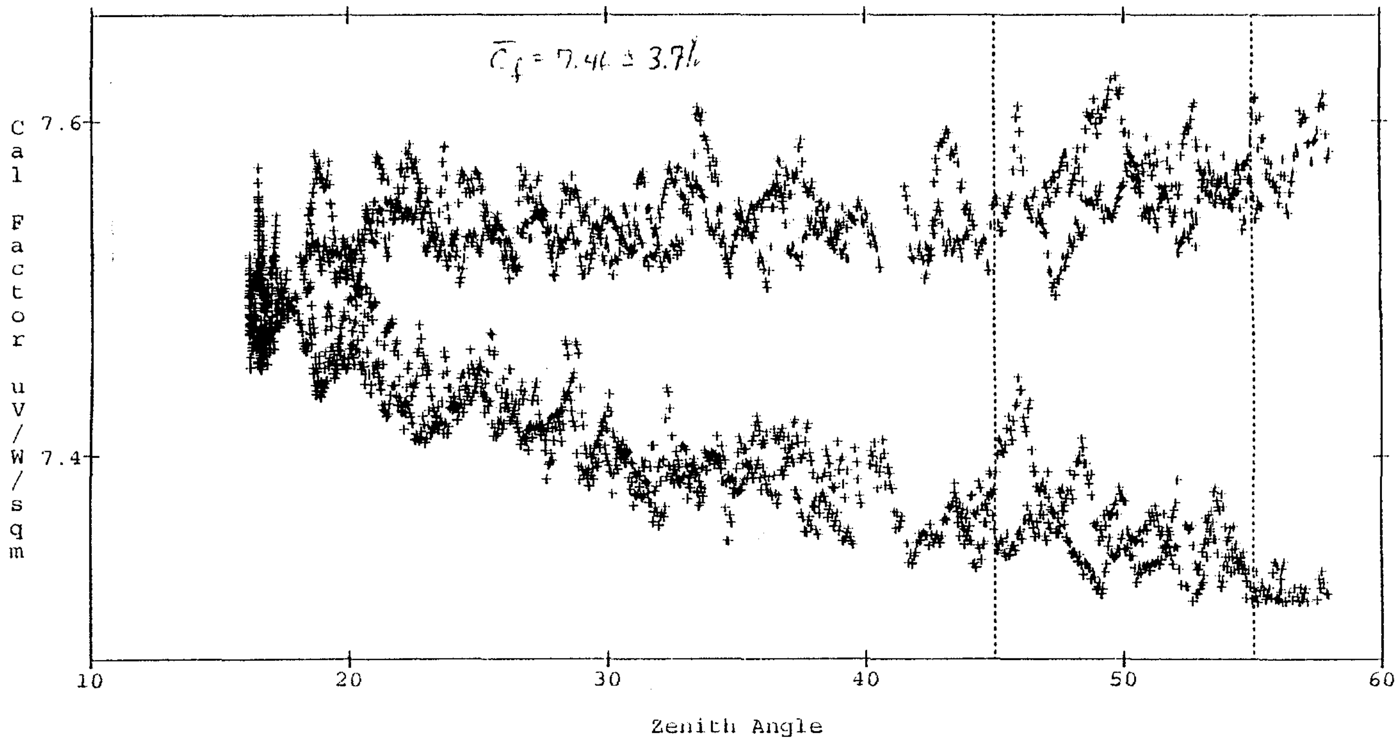
NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued
yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure 18-A

Calibration Factor (Cf) for 73-63
vs Refraction Corrected Zenith Angle

SPECTROSUN (SR-75)



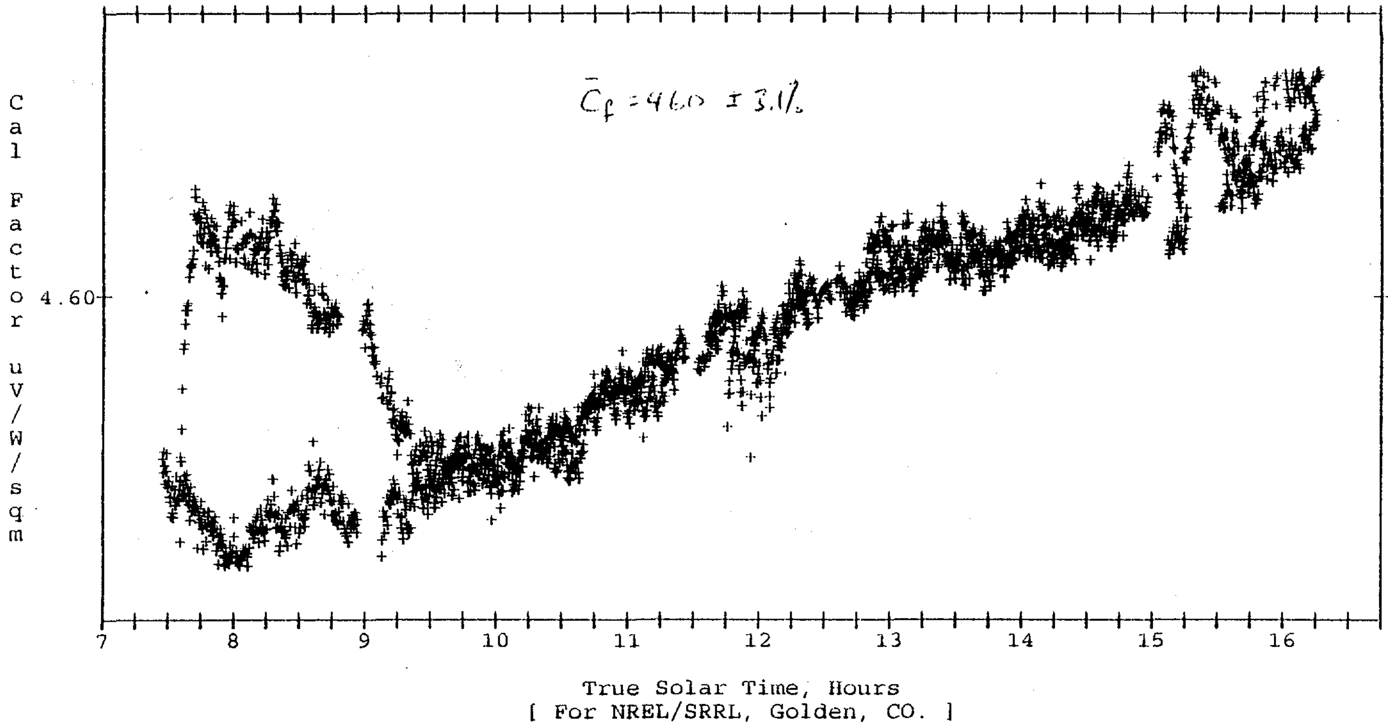
Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Dotted lines bracket calibration zenith angle Range

Figure 9

Calibration Factor (Cf) for 850878
vs TRUE Solar Time

Kipp + Zonen
(CM 11)



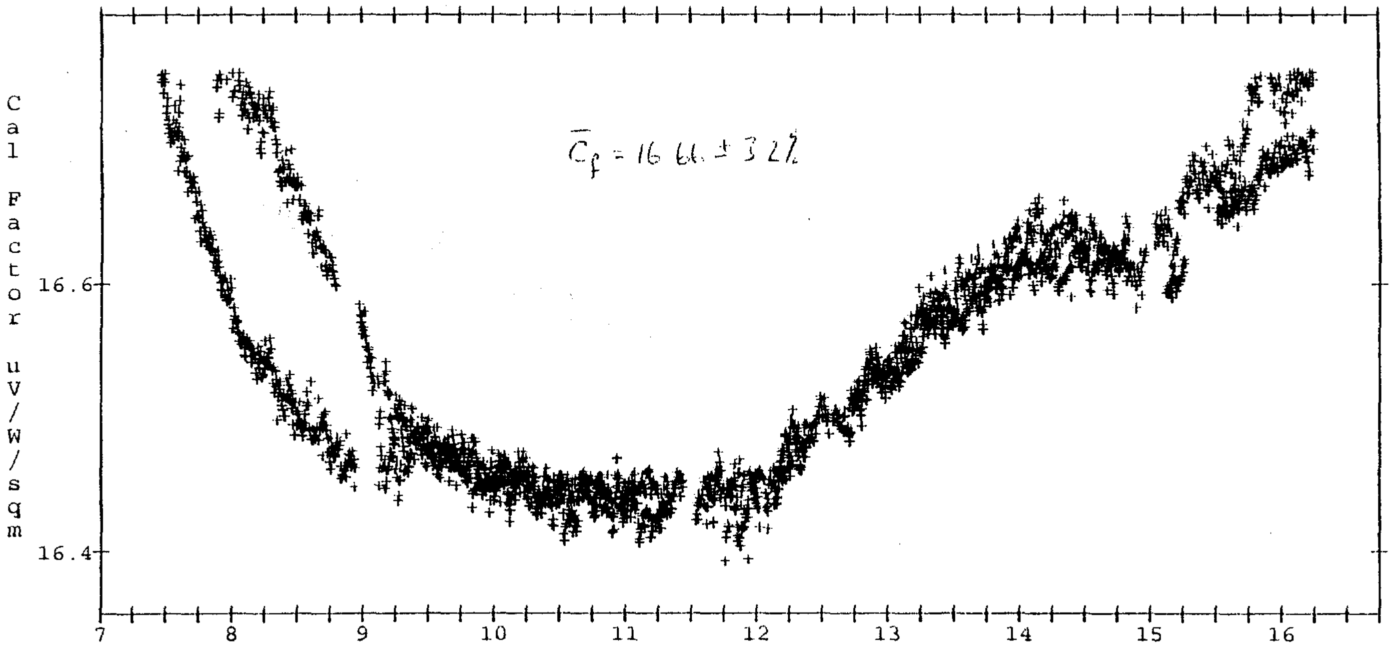
Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued
yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure 8109

Calibration Factor (Cf) for 910002 Kipp + Zonen (CM-21)
vs TRUE Solar Time



True Solar Time, Hours
[For NREL/SRRL, Golden, CO.]

Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

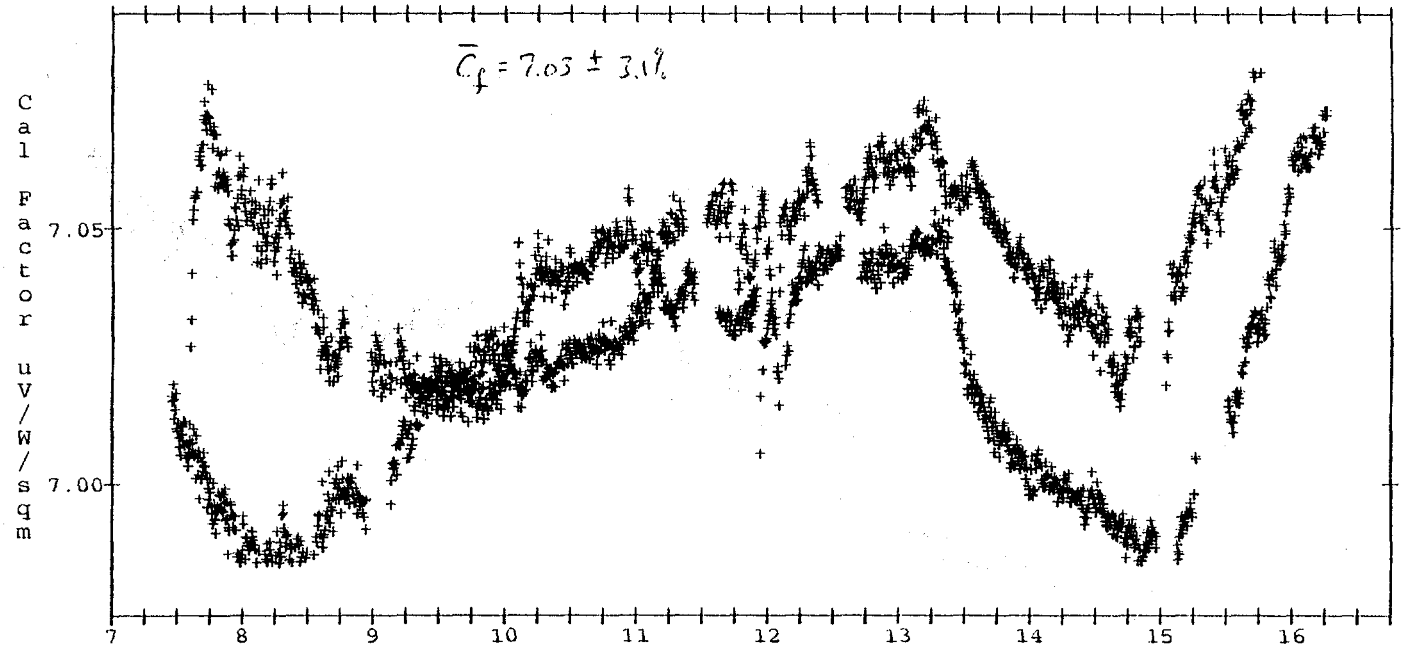
NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure ~~12-A~~ 11

Calibration Factor (Cf) for F93082
vs TRUE Solar Time

EKO



Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

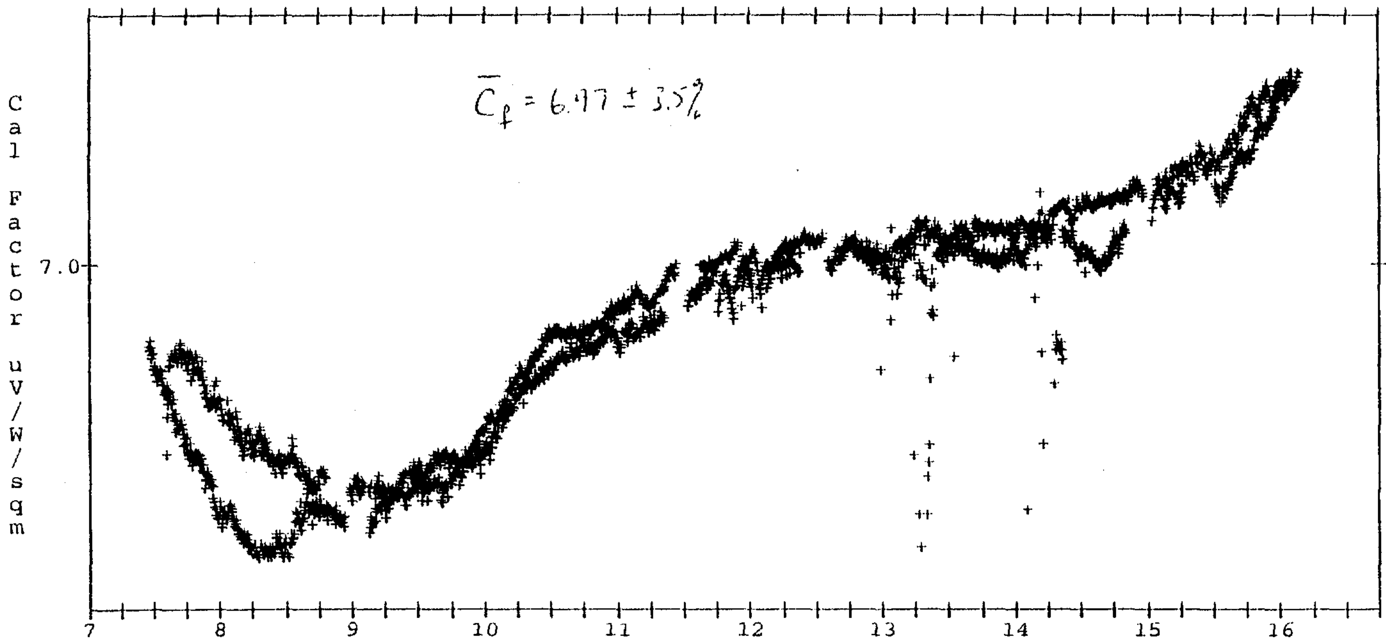
NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure 12

Calibration Factor (Cf) for F93083
vs TRUE Solar Time

EKO SCP 8??



True Solar Time, Hours
[For NREL/SRRL, Golden, CO.]

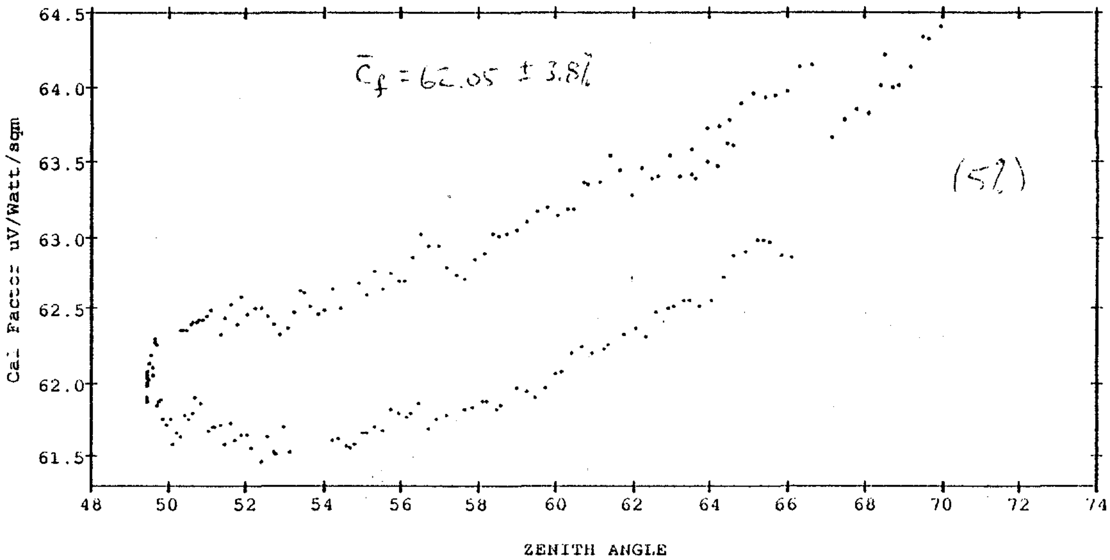
Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure ~~10-A~~ 13

Calibration Factor (Cf) for 5-153 MR5 (HOLLIS GEOSYSTEMS)
vs Refraction Corrected Zenith Angle

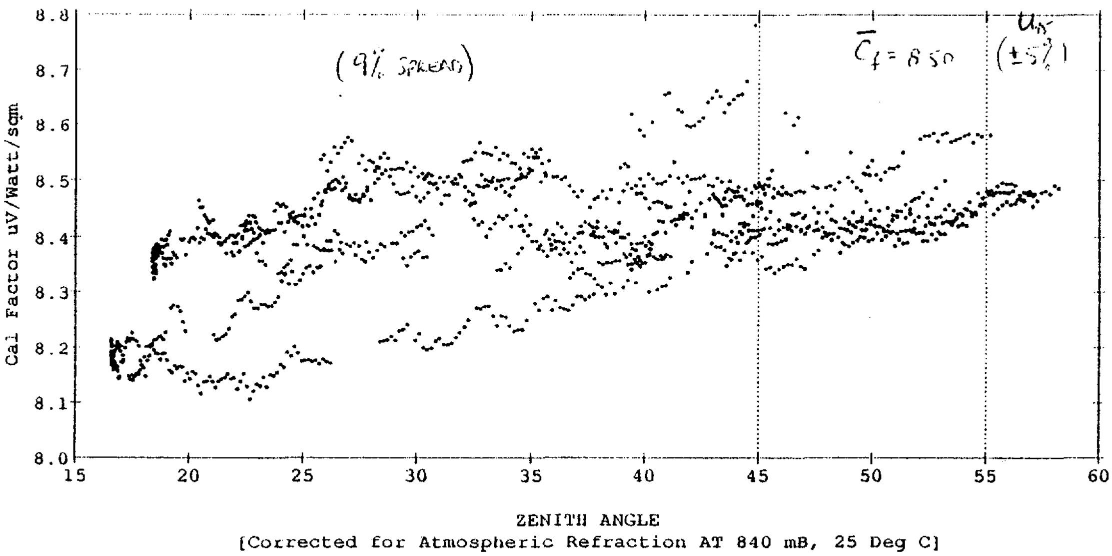


[Corrected for Atmospheric Refraction AT 840 mB, 25 Deg C]

Ref. Radiometer TMI 68018 (Direct), PSP 17802F3 (Diffuse).
Dates of calibration: OCT 19 OCT 23 1989
NOTE: 49.4 <= Zen. Ang. <= 73.2 CORRECTED for ATMOSPHERIC REFRACTION for the SERI/SRRL site @ 840 mB and 25 Deg C

Figure ~~24~~. 14

Calibration Factor (Cf) for PY1245 LI-COR
vs Refraction Corrected Zenith Angle MODEL LI-200



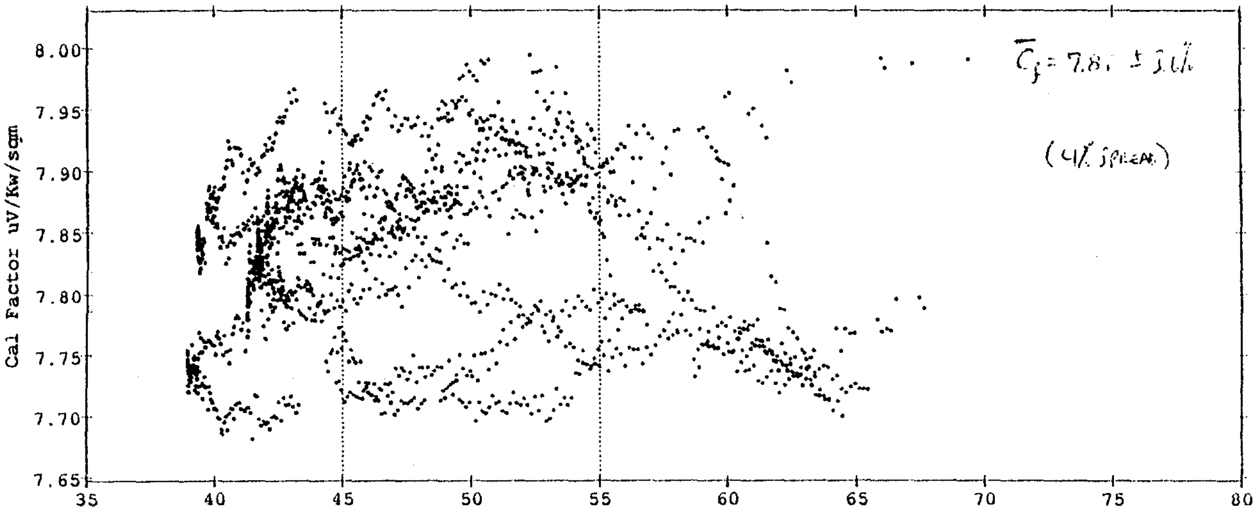
[Corrected for Atmospheric Refraction AT 840 mB, 25 Deg C]

Ref. Radiometer TMI 68017 (Direct), PSP 17802F3 (Diffuse).
Dates of calibration: JUN 28 JUL 01 JUL 09 JUL 10 JUL 15 JUL 17 1991
NOTE: 16.5 <= Zen. Ang. <= 58.2 CORRECTED for ATMOSPHERIC REFRACTION for the SERI/SRRL site @ 840 mB and 25 Deg C

Dotted lines bracket calibration zenith angle Range

Figure ~~27~~. 15

Calibration Factor (Cf) for PY2267 LI-COR MODEL LI 200
vs Refraction Corrected Zenith Angle



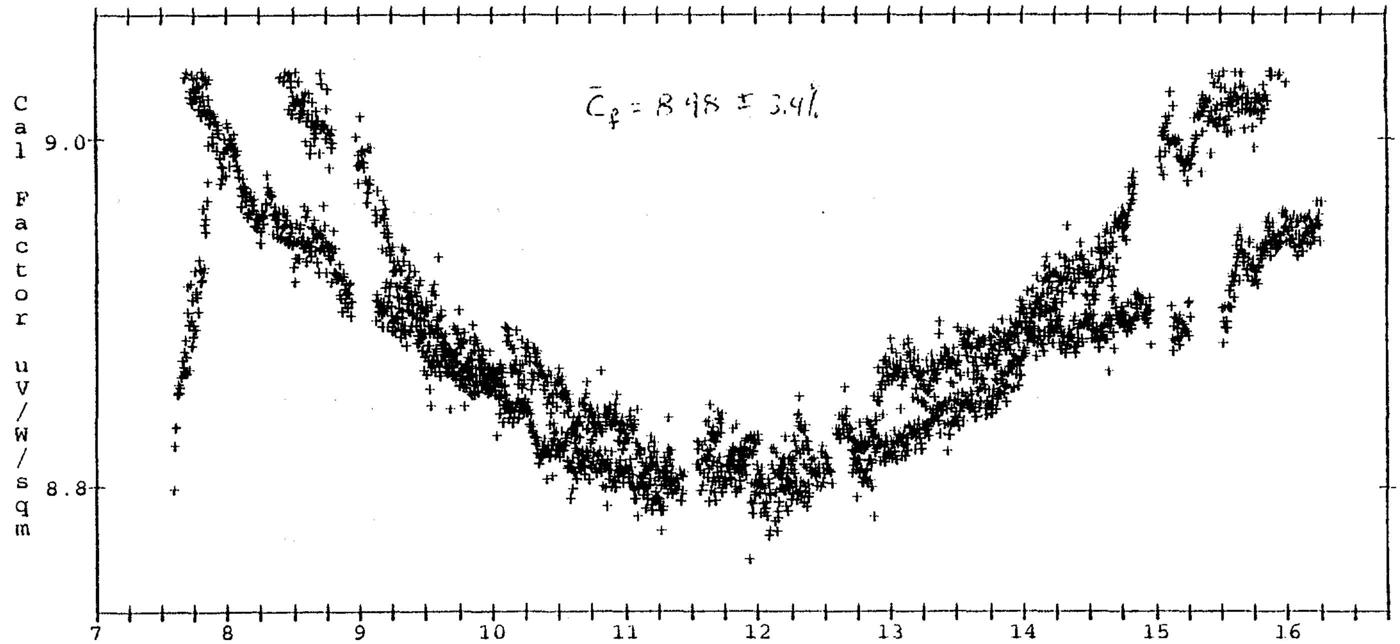
ZENITH ANGLE
[Corrected for atmospheric refraction AT 840 mB, 25 Deg C]

Ref. Radiometer TMI 68017 (Direct), WRR correction= 0.99977
Diffuse: PSP 17802F3, CF=110.6 W/sm/mV.
Dates of calibration: SEP 16 SEP 22 SEP 23 SEP 24 SEP 25 SEP 28
SEP 29 SEP 30 1992
NOTE: 38.9 <= Zen. Ang. <= 77.8 CORRECTED for ATMOSPHERIC REFRACTION for the
NREL/SRRL site @ 840 mB and 25 Deg C

Dotted lines bracket calibration zenith angle Range

Figure ~~12~~. 16

Calibration Factor (Cf) for 22693 (LT-200)
vs TRUE Solar Time



True Solar Time, Hours
[For NREL/SRRL, Golden, CO.]

Reference Radiometer: TMI 68017, WRR correction = 1.000227
Diffuse Radiometer: Eppley PSP 17802F3, CF = 112.7 W/sm/mV.
Dates of calibration: JUN 11 JUN 18 1995

NOTE: 16.2 <= Zenith Angle <= 59.3 Corrected for NREL/SRRL site (@ 840 mB and 25 Deg. C)
Solar Time = [Standard Time] + [Longitude Correction] + [Equation of Time]

(See: American Ephemeris and Nautical Almanac, issued yearly by the U.S. Naval Observatory, Washington, D.C.)

Figure 17-A

Radiometer Measurement Uncertainty

$$U_{95} = \pm[\ Bias^2 + (2\ Sigma)^2\ ]^{1/2}$$

Estimated NREL Calibration Abilities for a "Typical" Instrument:

- **Pyrheliometer ±2.0% (B=1.6%)**

- **Pyranometer ±2.8% (B=2.1%)**

FIGURE 18

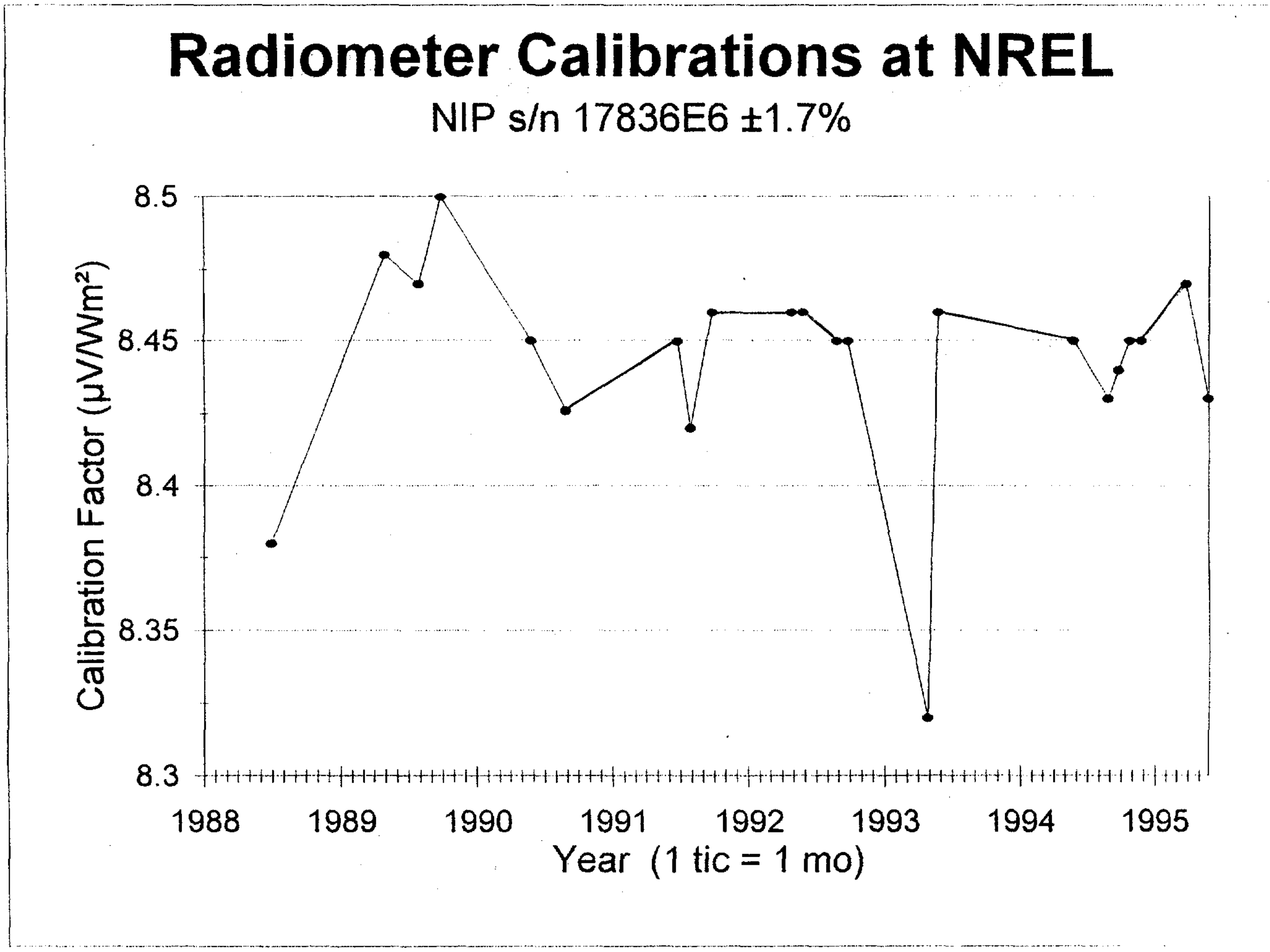


FIG. 19 CONTROL PYRHELIOMETER

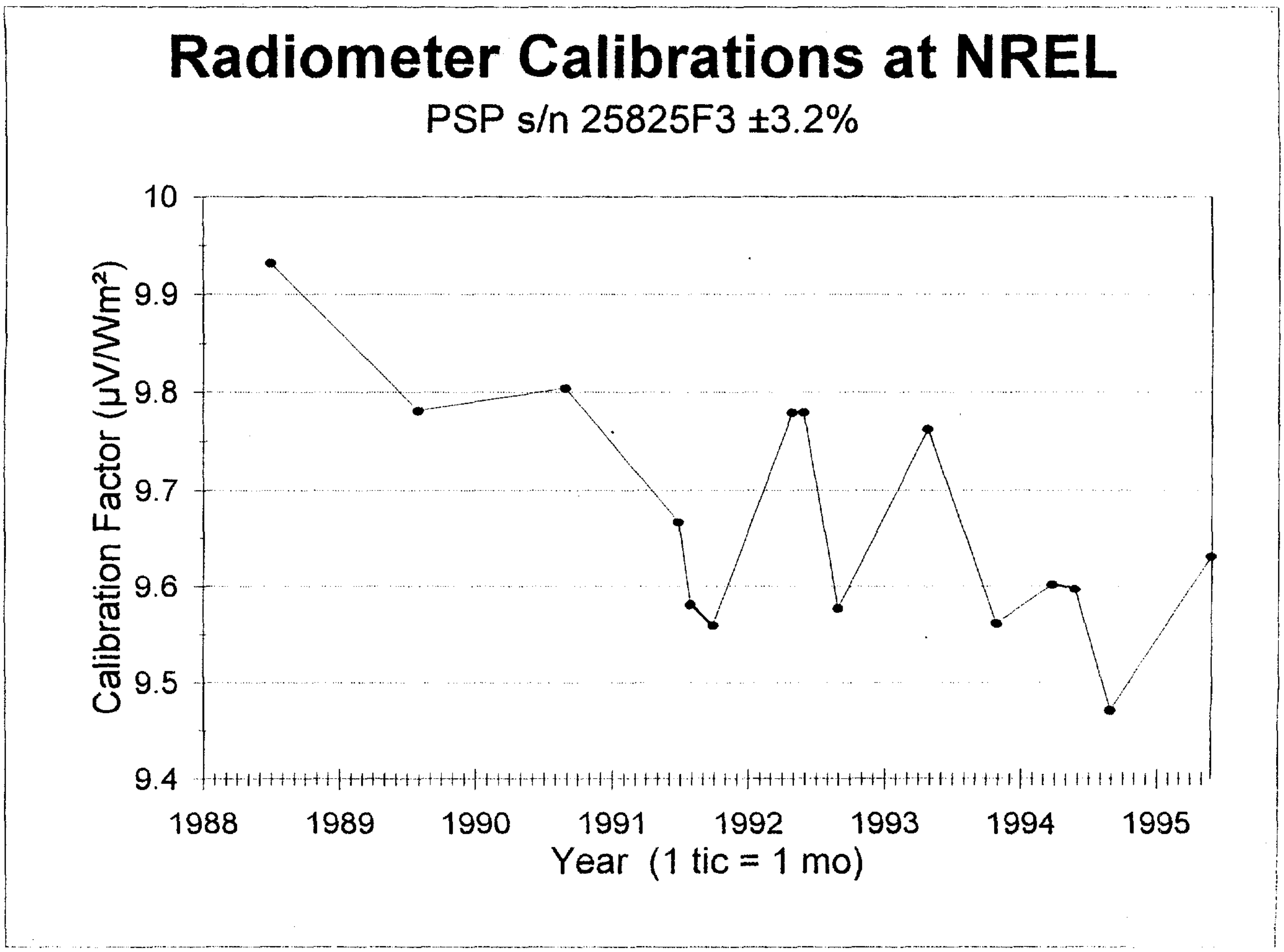


FIG. 20 CONTROL PYRANOMETER

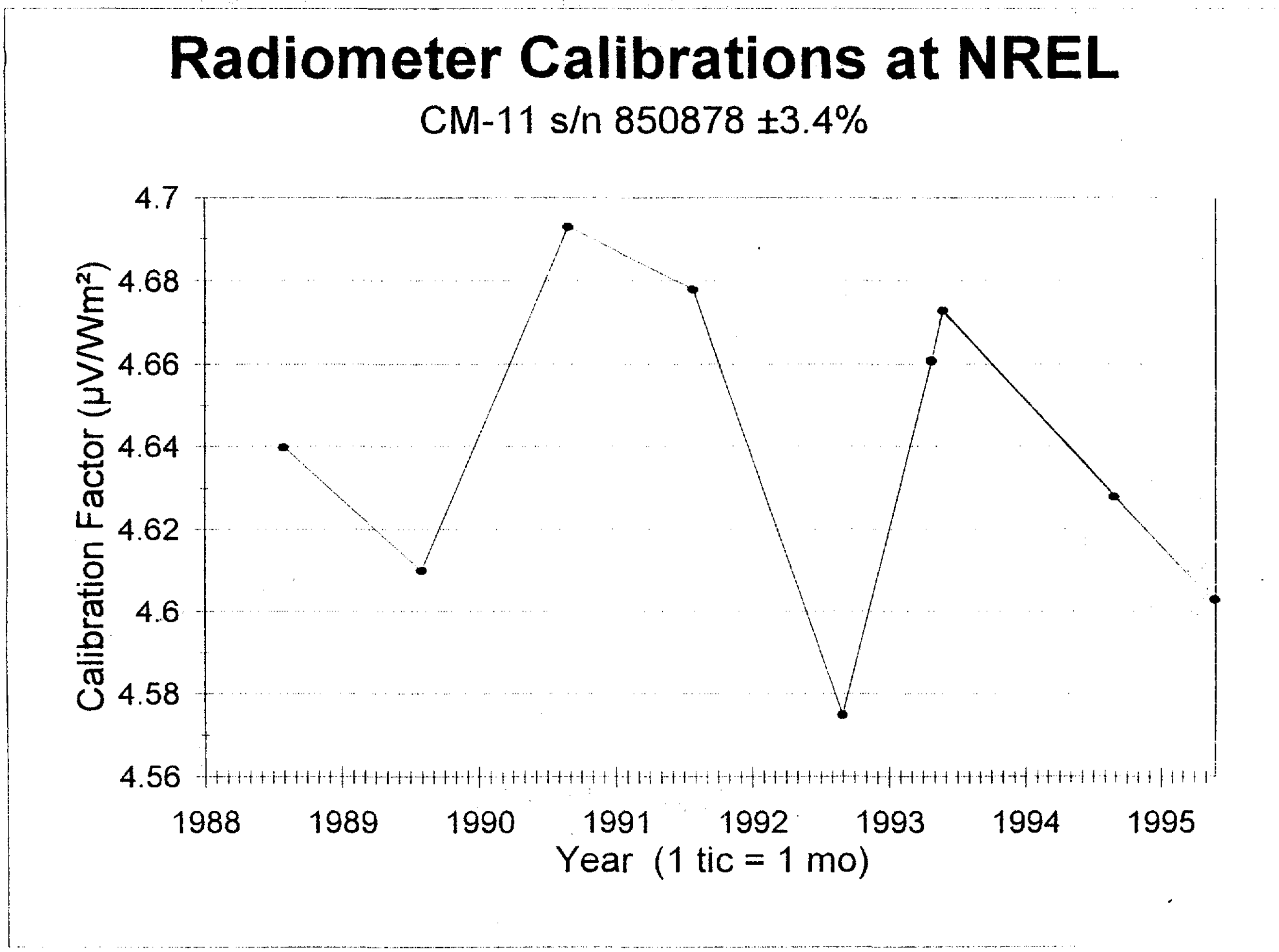


FIG. 21 Kipp + Zonen Pyranometer

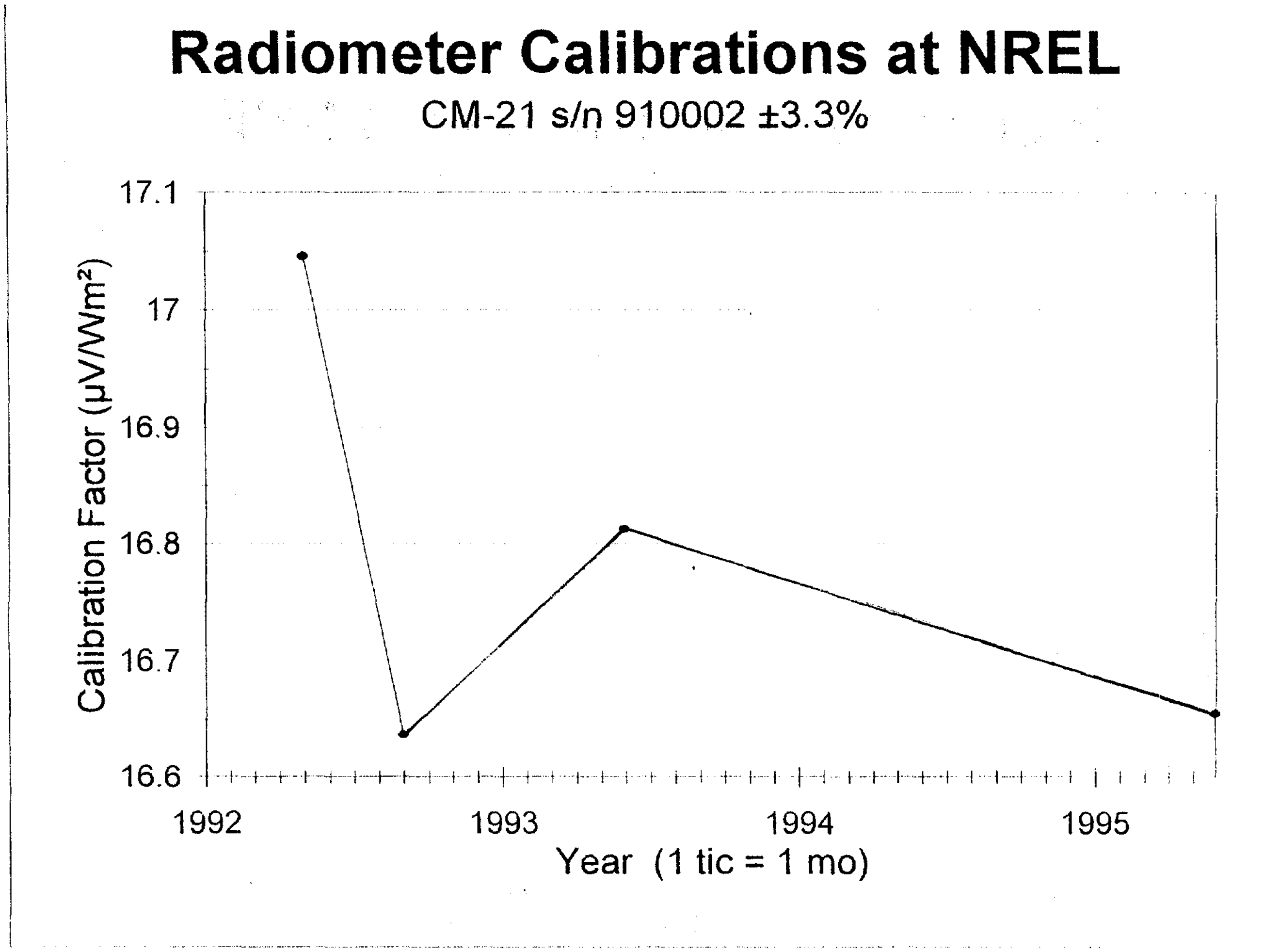


FIG. 22 Kipp + Zonen Pyranometer

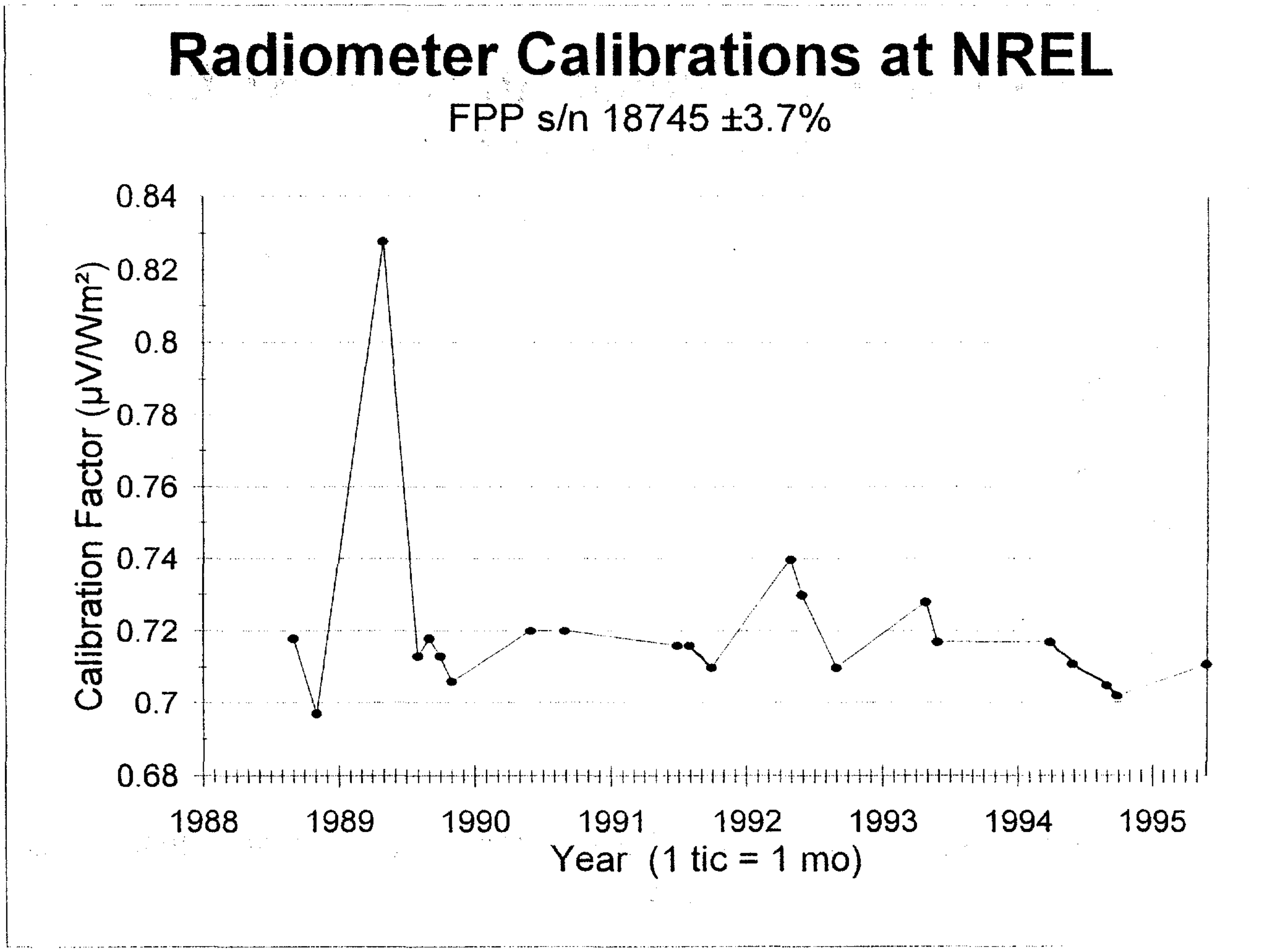


FIG. 23 EPPLEY FLAT PLATE PYRANOMETER (CONTROL)

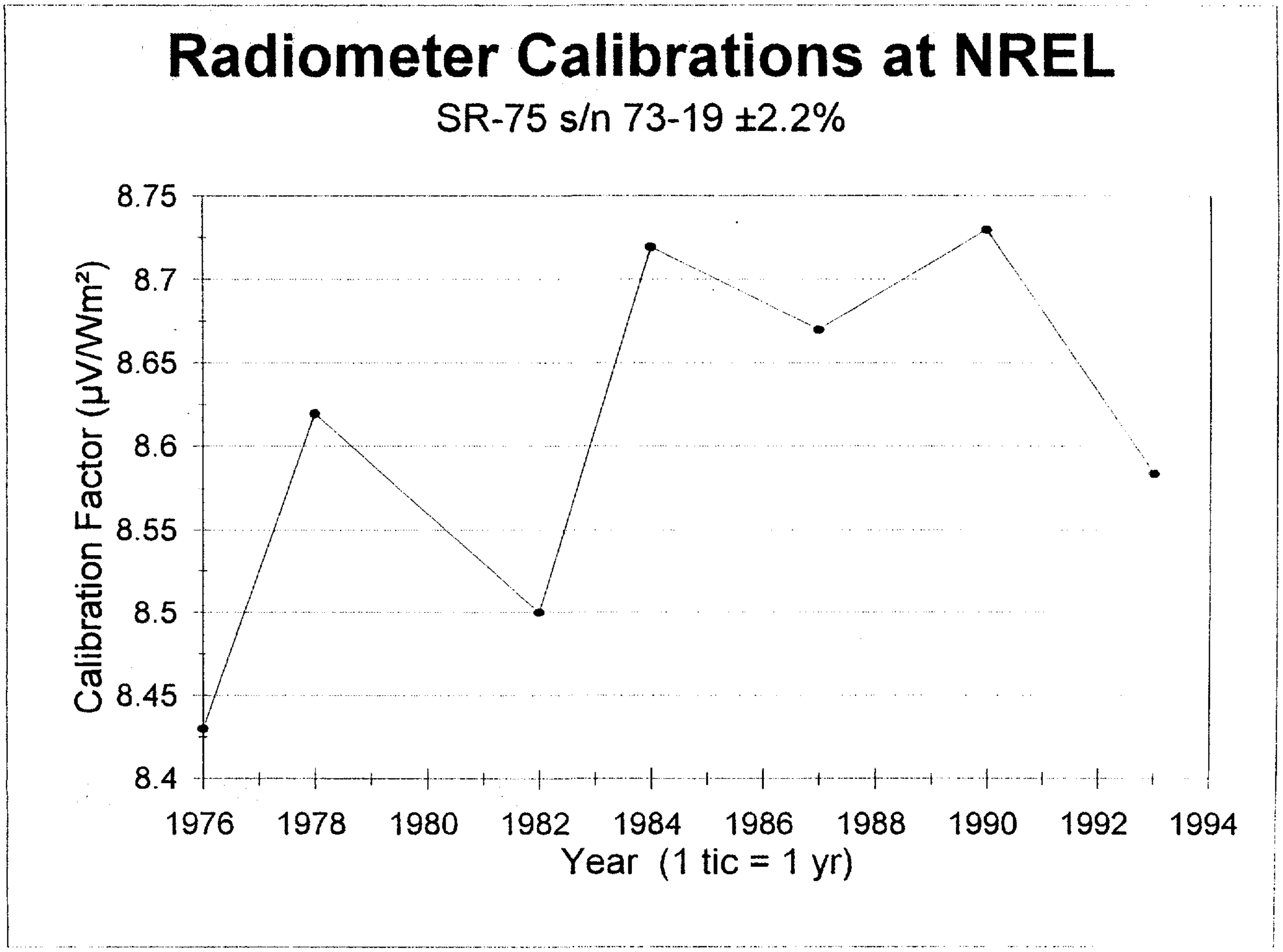


FIG. 24 SPECTROSUN PYRANOMETER

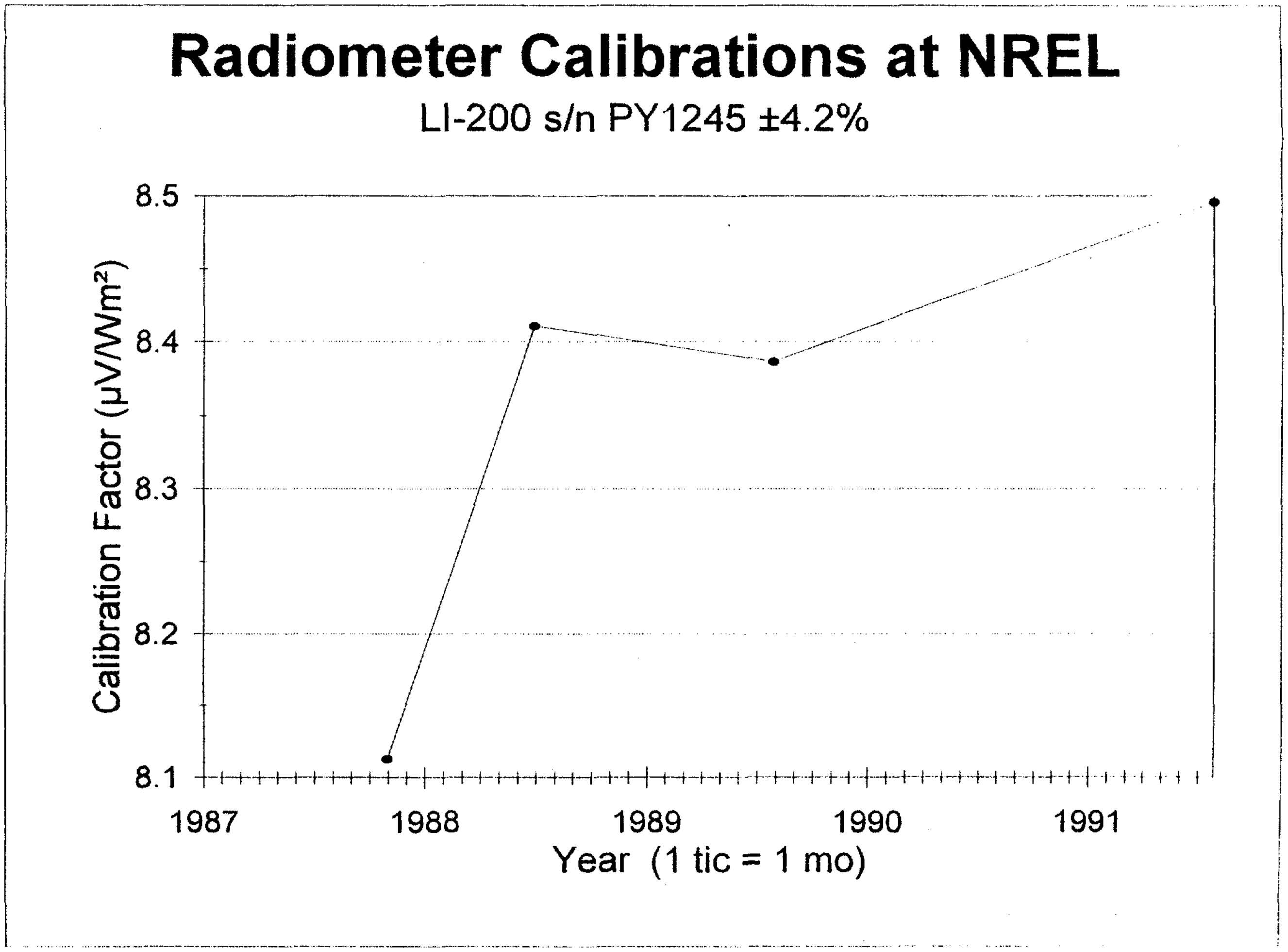


FIG. 25 LI-COR PYRANOMETER

SPECTRAL RADIOMETRIC INSTRUMENTATION AND MODELLING FOR PV APPLICATIONS

by

Theodore W. Cannon
National Renewable Energy Laboratory
Golden, Colorado 80401

ABSTRACT

This paper describes issues dealing with instrumentation and atmospheric transmission modelling for determining solar spectral irradiance for outdoor photovoltaic (PV) applications. The relevance of these determinations to PV testing and evaluation is discussed with examples.

INTRODUCTION

The direct conversion of solar energy to another form of energy (i.e. biomass, solar thermal, solar electric) is a wavelength-dependent process, i.e. the conversion efficiency is a function of wavelength. For PV devices, the conversion can be quantified as the spectral response (Amperes out/Watt in) at specific wavelengths. Fig. 1 shows the spectral response for representative samples of three PV materials: crystalline silicon (x-Si, open squares), amorphous silicon (a-Si, asterisks) and copper indium diselenide (CIS, solid squares), in relative units. Because of this spectral dependance, it is essential to know the spectral content (i.e. power per unit area per unit wavelength, typically $W/m^2/nm$) of the incident solar radiation whenever PV devices are calibrated (reference cells) or tested. Studies have been made to examine the spectral effects on PV design [1].

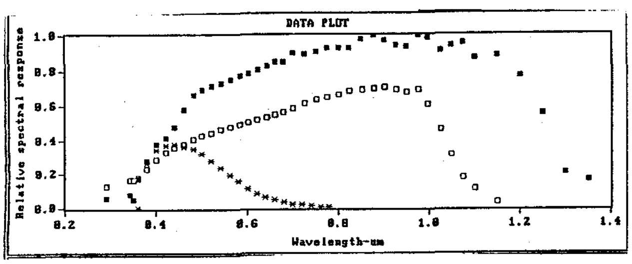


Figure 1. The relative spectral response for three representative PV materials: crystalline silicon (x-Si, hollow squares), amorphous Si (a-Si, asterisks) and copper indium diselenide (CIS, solid squares).

Spectral data, either measured concurrently with the PV measurements or modelled using concurrent atmospheric optical conditions, are used 1) to determine the appropriateness of performing PV measurements based on current spectral conditions and, if appropriate, 2) calculate spectral mismatch corrections for each PV device and 3) to compare integrated solar spectra with broadband data as a check of instrument integrity. Additionally, spectral data bases consisting of spectral measurements made at specific sites over extended periods of time [2-8] are useful for predicting long-term PV performance and evaluating and predicting degradation of PV materials.

At the National Renewable Energy laboratory (NREL), spectral measurements are made using spectroradiometers, each incorporating a precision, mechanically scanning monochromator*. To measure essentially all of the solar spectral range (about 99 percent of the energy lies between 0.3 and 3.0 um), at least two detectors are used together with two or three interchangeable gratings and five interchangeable order-sorting filters. Stepper motors for controlling grating position as well as the detector, grating and filter selections at predetermined wavelengths, are all controlled by a computer. The measurements process, including calibrations, scanning, and data processing, is a complex operation and requires considerable attention to detail.

At NREL, we have developed special software to facilitate automatic calibration, measurement and data display, storage and analysis processes. This software is proving invaluable by reducing the tedium and effort

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* Another option is to use one or more array radiometers to capture the entire spectrum instantaneously. See References [9-10] for a discussion of errors introduced by use of array radiometers.

required to make the measurements and by avoiding costly mistakes in manual entry of the spectroradiometer control parameters. An automatic logging feature provides a complete, automatic file record of all scan parameters, including (optional) user comment entry after each scan.

Because of the cost, complexity and inconvenience of making outdoor solar spectral measurements, it is expedient in some circumstances to use atmospheric transmission models to calculate the solar spectra. Models such as those described by Nann and Riordan [11] can be used to estimate solar spectra based on cloud conditions and broadband (total) radiation measurements. Sunphotometry, the measurement of direct-beam solar irradiance over narrow bandpass regions at specific wavelengths [12,13], can be used to provide input to a model. The Atmospheric Optical Calibration System (AOCS) developed at NREL by Hulstrom and Cannon [14-19] and currently in use at NREL, uses a combination of sunphotometry and broadband measurements to determine if use of a model is appropriate. It has been shown experimentally that, if atmospheric transmission and scattering conditions nearly match reference conditions, the AOCS software accurately calculates the modelled spectrum using the single-layer (SPCTRAL2) model of Bird and Riordan [30]. Additionally, spectral mismatch corrections using the method described by Osterwald [42] and Emery and Osterwald [43] are calculated using the AOCS for selected PV materials as the PV measurements are made.

It is the purpose of this paper to: make the reader aware of some of the principal problems encountered in making outdoor solar spectral measurements using a spectroradiometer, describe software developed at NREL to automatically control a spectroradiometer designed for making repetitive outdoor measurements, and to describe and show examples of calculations using a computer program developed at NREL to facilitate use of solar spectral models. The model program includes calculation of PV-device short-circuit current density Isc and mismatch factors corresponding to each calculated spectrum for selected devices with known spectral responses. Finally, a short section on quality assurance is included.

INSTRUMENTATION FOR OUTDOOR SOLAR SPECTRORADIOMETRY

Hardware Issues

Making accurate solar spectral measurements using a spectroradiometer presents some very interesting and challenging problems for both the instrument manufacturer and user [44,45]. A typical instrument, such as the Optronic Laboratories* Model OL750 single-grating monochromator instrument described here, see Fig. 2, is capable of measuring very small signals over several orders of magnitude intensity with a wavelength accuracy and precision of ±0.05% and ±0.01% respectively.

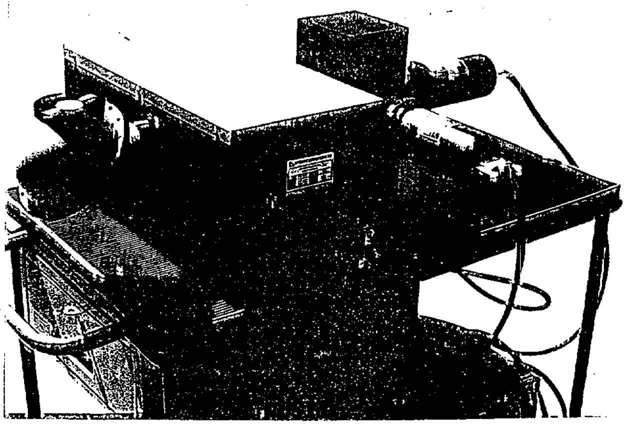

Figure 2. The Optronic Laboratories Model 750, single-monochromator spectroradiometer used to automatically acquire outdoor solar spectral data at NREL. Note the integrating sphere foreoptics, left, and computer-selectable Si and PbS detectors on the right.

Because of the rapid falloff in irradiance with decreasing wavelength in the ultraviolet (UV) region (~0.285 - 0.4 um), accurate UV measurements require a double monochromator and higher precision and accuracy than for the remainder of the spectral region [46,47].

Some outstanding hardware problems are:

- Front-end optics (foreoptics). The entrance optics for the spectroradiometer ideally provides uniform cosine response over a large range of solar azimuth

*Reference to a specific manufacturer's product does not constitute an endorsement by the Department of Energy, Midwest Research Institute or the National Renewable Energy Laboratory, but refers to products that are representative of instruments used for the purposes described in the text.

and zenith angles (e.g. ±60° from north, 18-64° respectively at 40° degrees north latitude) while providing a well-integrated beam at the entrance slit of the monochromator. Near-ideal cosine response is provided by use of an integrating sphere, see Fig. 3.

A well-placed, inclined baffle is attached to the exit side of the sphere's interior to assure full integration at most solar incidence angles. The instrument is positioned so that solar radiation hits the inside of the sphere on the side opposite the exit port and baffle for most solar positions.

The sphere must be provided with a transparent dome over the entry port (not shown) to prevent entry of contamination which rapidly degrades sphere throughput, resulting in changes in calibration. Ray trace analysis is used for anticipated solar and integrating sphere orientations to determine a design that will integrate the radiation well at all incoming angles and sphere orientations. Fig. 4 is a computer generated plot of a zenith pointing sphere for the summer and winter solstices and the equinoxes at 40° north latitude.

Figure 3. The six-inch diameter integrating sphere used on the OL750 to obtain near-ideal cosine response for outdoor solar measurements.

- Instrument temperature. Detector sensitivity and noise, electronics sensitivity and noise and mechanical changes are all influenced by temperature. The detector's temperature sensitivity is a function of wavelength and can be as high as 2%/°C at 0.11 um for a Si detector. While detectors used in the infrared (e.g. PbS, InSb, HgCdTe) are typically cooled to a preset temperature, Si detectors are often not temperature regulated. Although an instrument may be operating within the manufacturer's specified ambient temperature range, when exposed to the direct sun, the instrument's interior temperature can rise to the point where it will fail to operate. Ideally solar spectroradiometers should be operated out of doors inside of a temperature-controlled environmental housing.

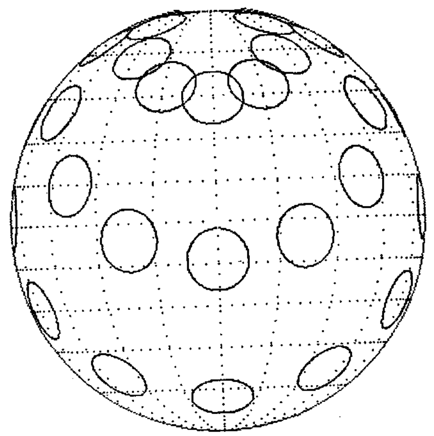

Figure 4. Elevation view of computer-generated solar spots on the north-facing interior of a zenith-pointed-port integrating sphere for the winter and summer solstices and the spring and fall equinoxes (identical paths) at the NREL site. The port diameter is 15% of the sphere diameter.

- Instrument mounting and orientation. Care needs to be taken that the monochromator is not subject to excessive mechanical bending torques that could affect the operation and/or wavelength calibration. Instruments developed for laboratory use are calibrated and used on a laboratory table, but may behave differently if mounted on a sloping surface or tracker.

Software Issues.

Because of the complexity of the spectroradiometer's measurement task, the process is controlled by a computer. The computer must synchronize the detector, filter and grating selections as the selected wavelengths are scanned. The computer program to do this is generally a proprietary one developed by the instrument manufacturer. The operator selects a file of calibration (for scanning) or standard lamp (for calibration) factors, and selects the scan type and speed, minimum, maximum and wavelength increment (or a user entered set of specific wavelengths) to scan. In a typical instrument, it requires about 20 menu selections to implement a single spectral scan and view a plot of the data on the control computer.

For routine, repetitive outdoor calibration of PV reference cells at NREL, it was necessary for NREL to develop software to automatically control the OL750 from a master computer used to orchestrate the PV data acquisition and solar radiation (broadband and spectral) measurements. On a start signal from the master computer, this software will: assign a data file name based on the year, date and time; start the OL 750 scan; on completion of the scan, download the raw data (wavelength and signal in amperes or volts) from the spectroradiometer; convert the data to spectral irradiance values; save the spectral data to the data file; upload the data file to the master computer when a request signal is sent from the master computer; display the data and automatically log all of the scan parameters to an "autolog" file. Following completion of all of these tasks, the program waits for the next start signal from the master computer and then repeats the cycle. A flow diagram for this software is shown in Fig. 5. Note that each module can be selected by software switches, so that, for example, automatic plotting or data storage can be bypassed at the user's discretion. The program reads all control parameters from a file which is easily edited to fit the specific application.

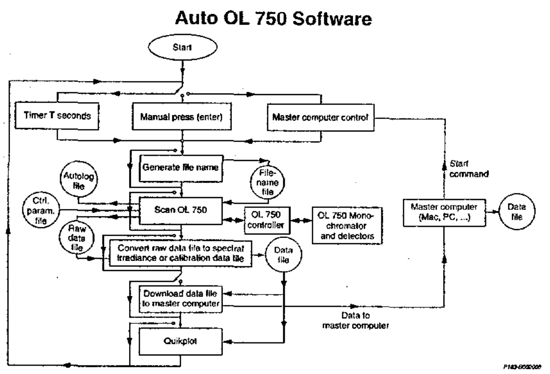

Figure 5. Flowsheet for the software used to automatically acquire and display the Model 750 spectroradiometer data. The small arrows indicate software switches used to select software components depending on the user's application. In this example the software is set up to do a data acquisition on command from the master computer.

An Application to Photovoltaics.

Fig. 6 shows spectra measured with the OL750 spectroradiometer at 09:59 and 10:17 MST day 153 under cloud-free and cloudy conditions respectively at NREL. Histograms for these data are shown in Fig. 7 (top) and the histogram ratios in Fig. 7 (bottom). Figs. 8-9 show the same plots normalized to unit total area under the spectral curves.

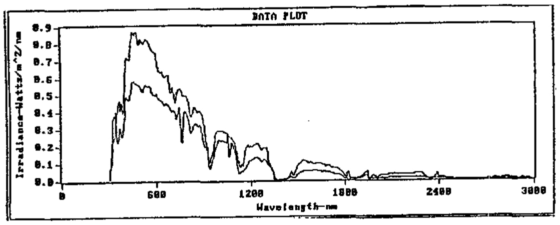

Figure 6. Measured spectra at the NREL site using the OL750 spectroradiometer for clear-sky conditions (upper curve) and cloudy-sky conditions (lower curve) at 09:59 MST and 10:17 MST respectively on 2 June 1995. Data were taken in 0.002 um increments.

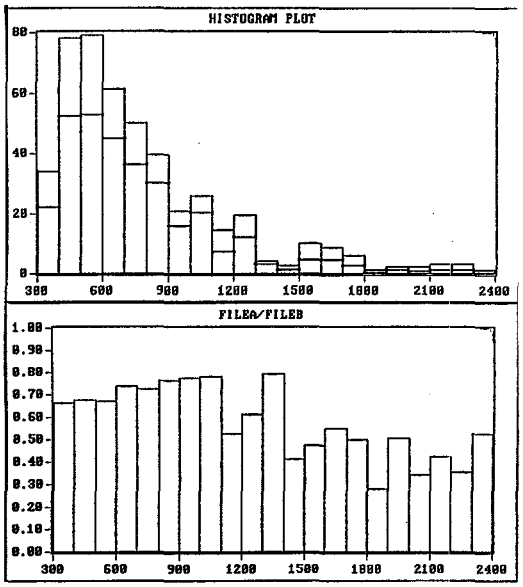

Figure 7. Histograms of the data of Fig. 6 (top), histogram ratios (bottom).

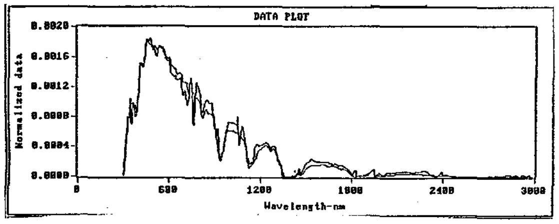

Figure 8. Data of Fig. 6 normalized to unit area under each curve.

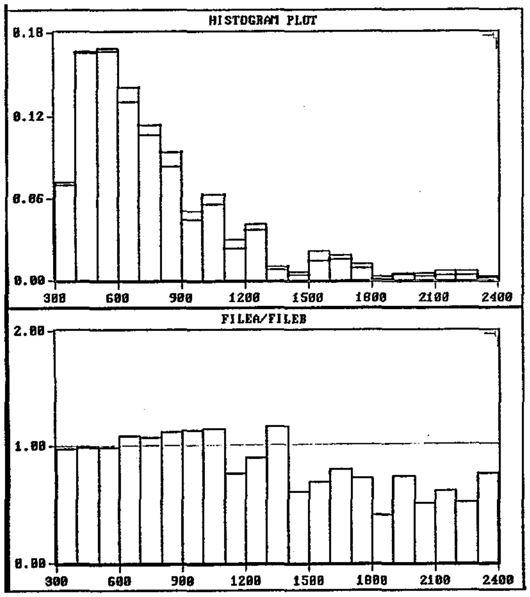

Figure 9. Histograms of the data of Fig. 8 (top), histogram ratios (cloudy over cloud-free, bottom).

Note the enhanced attenuation due to clouds for wavelengths >~1.1 um which seems to be a characteristic of many cloud conditions, based on a limited number of spectral measurements made at NREL up to this time.

Spectral mismatch values based on a x-Si reference device and ASTM E892 standard spectrum [53] are computed for the three PV materials shown in Fig. 1 with the results shown in Table I.

SOLAR SPECTRAL MODELLING

Models are useful for estimating solar spectral values when measured values are unavailable over all or part of the wavelength range of interest. When no measured input parameters are available, educated estimates of the values for a specific site and for assumed meteorological conditions can be used. In other cases, input data may be available from a sunphotometer, AOCS, or a spectroradiometer measuring part of the spectrum. Osterwald et all [21] describes a method for using a model to extend the spectrum beyond the cutoff wavelength of a Si-detector spectroradiometer.

A number of atmospheric transmission models have been developed for calculating terrestrial solar spectra [20-41]. These vary from "simple", single-layer models, to multilayer models of considerable sophistication. Models are selected based on the desired accuracy for a particular application. A single-layer transmission model (SPCTRAL2) developed at NREL by Bird and Riordan [30] based on the earlier works of Justus and Paris [33], is used for the calculations in this paper. This model modifies an extraterrestrial spectrum to generate the terrestrial spectrum based on the transmission and scattering properties of the atmosphere's aerosols, gasses, water vapor and ozone. The turbidity τ_λ at each wavelength λ is determined using the Ånstrom's turbidity formula $\tau_\lambda = \beta\lambda^{-\alpha}$ described in Iqbal [48], where the wavelength coefficient α is assumed to be 1.14 and β is calculated using the turbidity formula from the input turbidity at 0.5 um ($\tau_{.5}$).

User control and access to solar spectral models is complicated because there are so many parameters that must be selected for each run. This complexity has been simplified by the recently NREL-developed, model-driver software "Quikspec" reported here. A user-friendly, visual panel allows the user to set up the parameters needed for each model run using mouse clicks and keyboard entry. These input parameters are shown in Table II and the outputs are listed in Table III. The software is currently being used with the SPCTRAL2 simple spectral model, but can be modified to drive essentially any model. Ranges of all but the site parameters can be selected using nested control loops for automatically generating families of spectra.

Table I. Spectral Mismatch Values for Three PV Materials Calculated for Cloud-Free and Cloudy Conditions from Measured Data of Fig. 6.

Date	Time MST	Atmospheric Conditions	Material	Spectral Mismatch
2 Jun 95	09:59	Clear	x-Si	1.014
			a-Si	1.162
			CIS	1.002
2 Jun 95	10:17	Cloudy	x-Si	1.012
			a-Si	1.094
			CIS	0.989

Table II. Control Parameters for Quikspec

Site:
- time zone
- longitude
- latitude
- pressure altitude

* Receiving-surface orientation and tracking:
- non-tracking at selected aspect (east is 90°, south 180°) and tilt angles (flat is 0°, vertical 90°), including global horizontal
- single axis, zenith tracking at a selected aspect angle
- single axis, azimuth tracking at an selected tilt angle
- two-axis tracking

* Solar Geometry:
- relative airmass †, local apparent (solar) time or local standard time
- Julian day**

* Atmospheric optical properties:
- turbidity at 0.5 um
- precipitable water vapor in cm.
- ozone (in matm-cm)†
- wavelength (in um)†

Photovoltaics:
- Short-circuit current density, Isc, with optional normalization, for selected PV materials
- mismatch values for selected PV materials

Plotting:
- Normalization(none,area or peak)
- x-max, x-min, and x-divisions
- y-min, y-max, and y-divisions
- y-axis log plot or normal

*minimum, maximum and incremental values or † optional default values can be selected
**can be automatically calculated by entering the calendar date or clicking "today"

Table III. Outputs from Quikspec

Displays:

Plots up to 25 spectra of 125 data points each can be displayed simultaneously in user-selectable units of $W/m^2/nm$, $photons/m^2/nm/sec$ or $photons/m^2/ev/sec$.

Ratio of two, cursor-selected spectra over all wavelengths.

Histograms of either one or two cursor-selected spectra and, for spectral pairs, histograms of their ratios. Bin wavelength limits for the histograms are entered via files which can be edited from the interactive window.

A summary table listing the following:
Julian day (DAY)
Relative airmass (RAM)
Solar zenith angle (ZEN)
Solar azimuth angle (AZI)
Incidence angle (INC)
Turbidity at 0.5 um (TAU5 = $\tau_{.5}$)
Precipitable water vapor (PWV)
Hour angle (OMEGA)
Local apparent time (LAT)
Local standard time (LST)
Integrated irradiance over all plotted wavelengths (INT)
Receiver tilt angle (TLT)
Receiver aspect angle (ASP)
Integrated irradiance between dot-cursor pair (DOT)
Integrated irradiance between square-cursor pair (SQR)
Ratio SQU/DOT (RATIO)
Minimum and maximum wavelengths selected by the above cursor pairs (DMIN,DMAX,SMIN,SMAX)
Earth-sun radius vector (ERV)
PV normalized or unnormalized short-circuit current density Isc for selected materials
PV mismatch correction for selected material
Orientation mode (i.e. global normal/direct normal, global tilt or global horizontal) (MODE)
Component (Total, direct, diffuse, three-component, AOCS transmission vs diffuse/global ratio $(SH/GH)_{0.4-0.7\ um}$ or AOCS TAU5*RAM vs $(SH/GH)_{0.4-0.7\ um}$.

Optional output disc files:
summary tables
spectral irradiance

Application to PV performance calculations.

In addition to calculating spectral irradiance values, the software can currently generate PV Isc and mismatch factors based on spectral responsivity curves for selected materials. Some examples are shown here to illustrate the efficacy of the method. **These examples should not be used as the basis for quantitative PV evaluation or design, but are shown to illustrate the method. Radiometric data measured at the specific site should be used as inputs to the model.** These illustrations are of Isc calculations and are shown in Figs. 10-20. Figure 10 shows model calculated Isc for the x-Si device as a function of local apparent time (LAT or solar time) for the NREL site, day 152, for two-axis tracking total irradiance (open squares), two-axis tracking direct component (asterisks), fixed, south facing 37-degree tilted surface total component (solid squares), 37-degree tilted solar-azimuth tracking total component (squares with dots) and south-facing, zenith-angle tracking total component (solid squares). Isc is normalized to the output Isc under near-ASTM E892 [53] standard south-facing, 37-degree tilt conditions at the NREL test site with turbidity at 0.5 μm (τ_5) = 0.27, precipitable water vapor (PWV) = 1.42 cm, relative airmass (RAM) = 1.5 for direct-normal irradiance. The bottom plot is the ratio of the two-axis tracking, total component to the total on a south-facing, 37-degree tilted surface, total component. Conclusions about the relative merits of different tracking and non-tracking orientations from calculations based on both total irradiance and spectral content can be drawn from studies of this type.

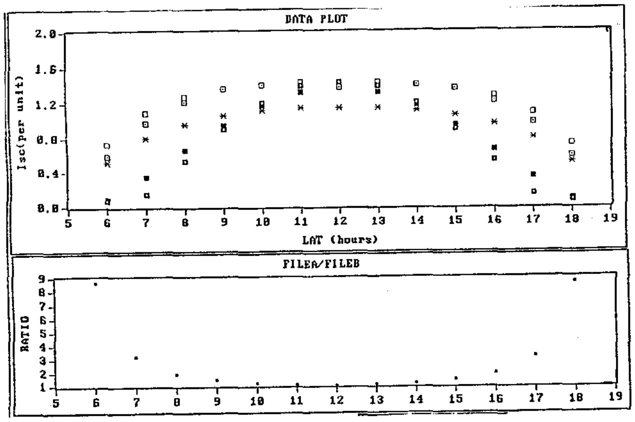

Figure 10. Isc as a function of RAM for the x-Si material using four tracking and one non-tracking mode (top, see text). The ratio of Isc for the two-axis tracking, total irradiance mode to that of 37-degree, south-facing fixed-tilt total irradiance case is shown (bottom).

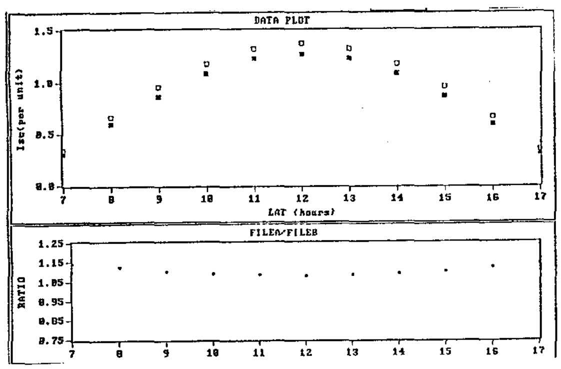

Figure 11. Comparison of Isc of x-Si as a function of LAT for a high-plains case (open squares, P.ALT = 810 mb, τ_5 = 0.10, PWV = 0.5 cm.) and a sea-level case (closed squares, P.ALT = 1013 mb, τ_5 = 0.3, PWV = 4 cm.) total irradiance at 37-degrees, south facing tilt. Isc values are plotted at the top, the ratio of Isc for the high-plains to sea level case at the bottom.

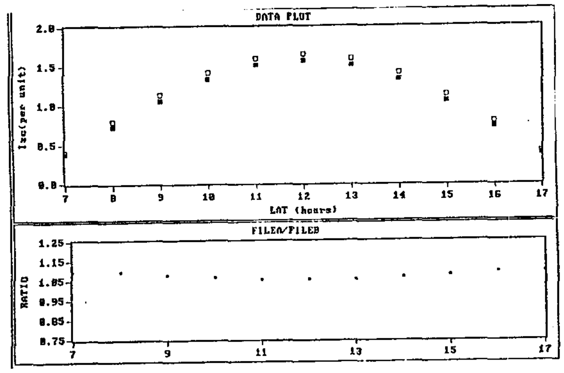

Fig. 12. Same as Fig. 11 for a-Si.

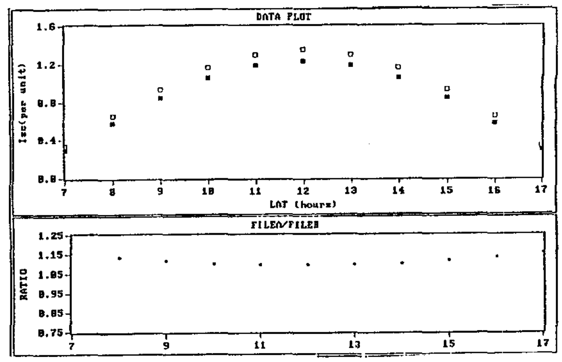

Figure 13. Same as Fig. 11 for CIS.

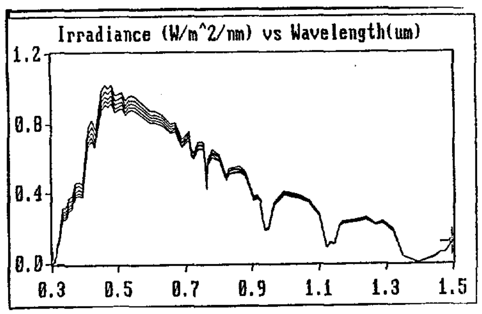

Figure 14. Modelled spectra for 0.1 <= τ_5 <= 0.5 in 0.1 increments at the NREL site, day 152, total component on a 37-degree, south-facing tilted surface, PWV = 1.42, RAM = 1.5. The total irradiance, 0.3 to 1.5 um, varies from 547 W/m^2 at τ_5 = 0.1 to 502 W/m^2 at τ_5 = 0.5.

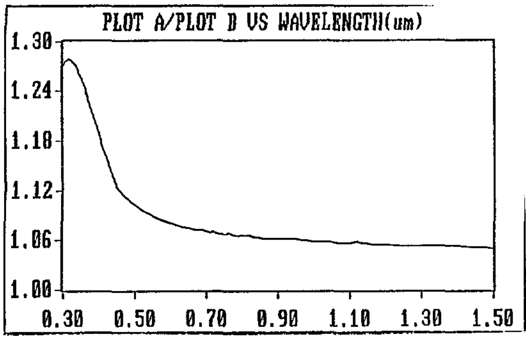

Figure 15. Ratio of $\tau_5 = 0.1$ to $\tau_5 = 0.5$ spectra from Fig. 14 illustrates the increasing absorption/scattering by the atmosphere with increasing turbidity at lower wavelengths.

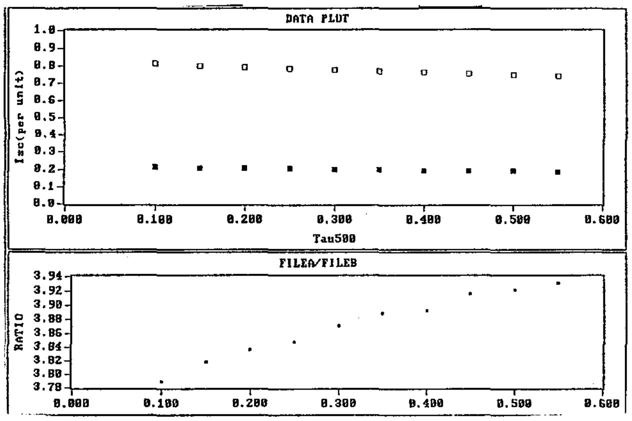

Fig. 16. Isc as a function of τ_5 (top) for x-Si (open squares) and a-Si (solid squares) for the spectral data of Fig. 14. Data for both devices are normalized to x-Si at near-ASTM reference conditions. The ratio of the two plots (bottom) shows how the Isc of the a-Si decreases more rapidly than that of the x-Si with increasing τ_5.

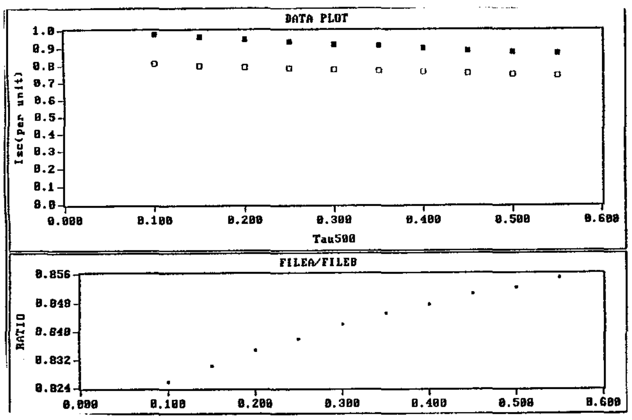

Fig. 17. Isc as a function of τ_5 (top) for x-Si (open squares) and a-Si (solid squares) for the spectral data of Fig. 14. This figure is the same as Fig. 16 except that for both devices are normalized to the Isc for the individual devices at near-ASTM reference conditions. Ratio of the two plots (bottom) shows how the Isc of the a-Si decreases more rapidly than that of the x-Si with increasing τ_5.

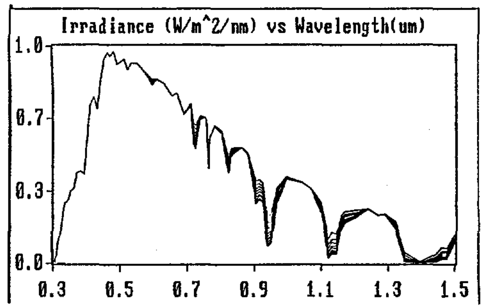

Fig. 18. Modelled spectra for 1 <= PWV <= 5 in one-unit increments at the NREL site, day 152, total component, 37-degree, south-facing tilted surface, τ_5 = 0.27, RAM = 1.5. The total irradiance, 0.3 to 1.5 um, varies from 532 W/m^2 at PWV = 1 to 501 W/m^2 at PWV = 5 cm.

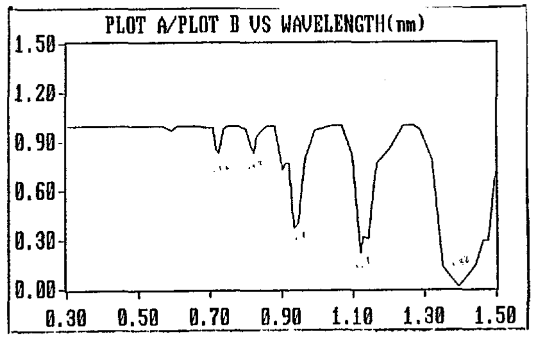

Figure 19. Ratio of PWV = 1 to PWV = 5 spectra from Fig. 18 shows the strong water-vapor absorption bands between 0.3 and 1.5 um. These bands are centered at or near 0.593, 0.7233, 0.824, 0.942, 1.12 and 1.335 um; additional bands are at or near 1.86 and 2.7 um.

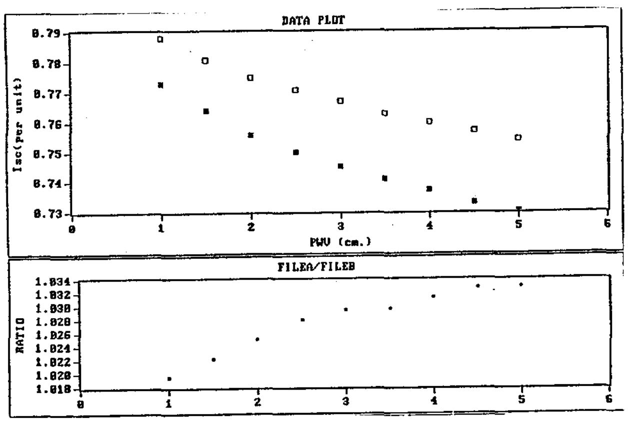

Figure 20. Isc as a function of PWV (top) for x-Si (open squares) and CIS (solid squares) for the spectral data of Fig. 19. The ratio of the two plots (bottom) shows how the Isc of the CIS decreases more rapidly than that of the x-Si with increasing PWV primarily due to CIS extended spectral response into the strong water vapor absorption bands.

Figures 11-13 show Isc values for x-SI, a-SI and CIS respectively as a function of local apparent (solar) time (LAT) at a high-plains site (NREL) with assumed pressure latitude (P.ALT) = 820 mb (about 1800 meters elevation), τ_5 = 0.10, PWV = 0.5 cm. compared with a sea-level site, Florida Solar Energy Center, Cape Canaveral, FL, P.ALT = 1013 mb , τ_5 = 0.3, PWV = 4 cm.. Differences in Isc based on total spectral irradiance differences over the 0.3 - 1.5 um wavelength range are x-Si 9.3 percent, a-Si 6.8 percent and CIS 11.1 percent; the larger differences corresponding to overlaping of more water-vapor bands.

Figs. 14-17 illustrate the effect of changing τ_5 on the x-Si and a-Si devices, while Figs. 18-20 show the effect of changing PWV on the x-Si and CIS devices. In the former case, the relative short-wavelength response of the a-Si device results in greater relative falloff in Isc with increasing τ_5 than for the x-Si device. In the changing PWV case, the CIS Isc falls off more rapidly with increasing PWV due to strong absorption by the water-vapor absorption bands at the longer wavelengths. Studies of this type should be useful for studying the relative merits of various PV materials as a result of changing atmospheric parameters.

Model studies using this technique can be used to predict the performance for any PV device of known spectral response at any location on the earth (and extraterrestrial as well) under cloud-free conditions where the aerosol turbidity at one or more wavelengths and precipitable water vapor are known or can be estimated. The model-driver software is very fast with setup, generation, plotting and saving each set of spectra; all of the above examples required less than one minute using a 486/33 PC.

QUALITY ASSURANCE

In addition to paying close attention to hardware and software details, quality measurements can only be obtained if adequate attention is paid to calibration and performance issues. Two calibrations are required for solar spectroradiometers: irradiance and wavelength. The NREL instruments are regularly calibrated to either type FEL or T-10, 1000 Watt spectral irradiance standards provided by the National Institute of Standards and Technology (NIST). Use of these lamps requires careful control of the positioning of the lamps relative to the spectroradiometer's entry port; an error of 1 mm results in an irradiance error of about 0.4 percent. Baffling may be required to reduce stray light. Accurate calibrations are best facilitated by using an alignment jig and laser to properly locate the spectroradiometer and assure beam orthagonality. A wavelength-dependent error, increasing toward the short-wavelength end of the spectrum, will result if the lamp's current is not carefully regulated. Computer-controlled, commercial current sources, such as the Optronic Laboratories Model OL 83A, are available which are designed for this specific application and provide output current accuracy of ±0.025 percent at 8.0 Amperes. Use of standard lamps, including error analysis, are discussed in a NIST publication [49].

A quality calibration laboratory will have more than one standard source- generally three are recommended. The sources can be periodically intercompared to be certain that there has not been significant deterioration of one of the lamps due to filament degradation, adjacent coil welding or other cause.

Wavelength calibrations can be facilitated by using commercially-available line sources, fluorescent light fixtures (Hg lines), atmospheric absorption lines (Fraunhofer lines) or the minima of atmospheric absorption bands.

A useful adjunct to the spectroradiometer is the check source. The Optronic Laboratories model OL754 instrument includes sources for checking both wavelength (a fluorescent tube emitting Hg spectral lines) and tungsten-halide lamp with regulated current source. The check source provides a way to quickly check the instrument's calibration in the laboratory or field. The instrument can be recalibrated if calibration is indicated by measurement using either of the check sources.

If more than one model of spectroradiometer is available, it is sometimes desirable to intercompare these instruments in order to look for discrepancies in spatial (cosine and azimuthal) response, temperature-dependent changes and other differences that could effect data quality.

Errors in azimuth response can be determined by running a scan with the spectroradiometer on a flat table and oriented at each of the four cardinal directions, then returning to the original orientation to check atmospheric stability.

Sometimes it is necessary to use more than one spectroradiometer to measure a solar spectrum. This is especially true when high accuracy is required in the UV, necessitating use of a double monochromator instrument as mentioned above. Composite spectra, using the best data from each instrument, can be generated from simultaneous measurements made by the instruments. Special software has been developed at

NREL to match spectra from two or more instruments and select the best data from overlapping regions; wavelength calibration are automatically applied to the data using atmospheric absorption lines and bands.

It is important to use a short time constant, broad band detector (e.g. a silicon detector) to monitor the total solar irradiance during each spectral scan. Variations of, say, one or two percent in total irradiance would invalidate the data as corrections cannot be made for changes in overall spectral shape which generally accompany changes in the atmospheric optical properties during the scan.

Uncertainty analysis for radiometric applications of PV, such as described by in References [50-52], is important to understanding the contribution of various calibration and measurement errors to the overall errors of the measurement process and to assigning error limits to each spectrally-corrected PV measurement.

A single solar spectrum from 0.3 to 3.0 um in 0.002 um steps will contain 1351 data points. A large amount of data can be generated over a short period with these instruments. The data handling problem is complicated by the use of different formats and units of spectral irradiance by each manufacturer. Also comparisons are made between measured and modelled sources and between measured values and standard values from NIST, each with a different data file format. NREL has now developed extensive software to facilitate these comparisons and handle the data in such a way that format and units differences are transparent to the software user. Software development tools, such as National Instruments LabView® and LabWindows® have greatly facilitated the development of visual, user-friendly software for spectroradiometric applications.

CONCLUSIONS

It should be apparent from reading this article that accurate measurement of outdoor solar spectra is a complex task requiring excellent instrumentation and attention to detail in calibration, measurement and data handling. Failure to have appropriate instrumentation or to use proper techniques can result in errors in measurement which can be costly and misleading in terms of drawing erroneous conclusions about he real-time performance and stability of PV devices.

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Radiometry for Characterizing Photovoltaic Devices in the Laboratory

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ABSTRACT

A variety of radiometric instruments are used in the laboratory to characterize the performance of photovoltaic (PV) devices. Specific applications include calibrating spectral-response measurement systems and setting the intensity of solar simulators. Radiometers can use thermal or semiconductor sensors. The most appropriate radiometer for a particular measurement depends on the goal of the measurement. It is important to understand the characteristics of the radiometer to minimize errors and uncertainty in measurement results.

SPECTRAL RESPONSE OF PV DEVICES

Spectral-response information for a PV device can help the device developer understand the physics of the device and material. This information is also necessary for accurately characterizing the performance of a device under a particular spectrum that differs from that of a laboratory solar simulator. Figure 1 shows the basic elements of a spectral-response measurement system that uses bandpass filters to produce monochromatic light.

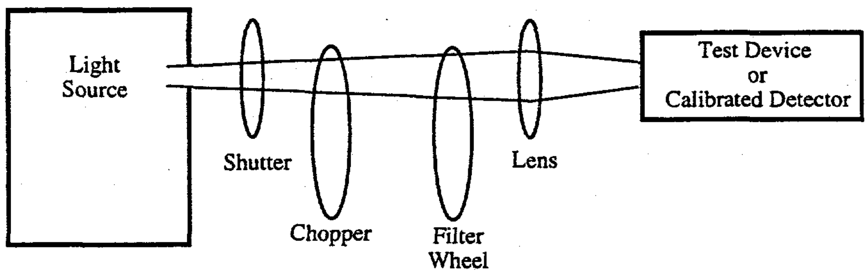

Figure 1. Basic elements of a spectral-response measurement system using bandpass filters.

Alternatively, a monochrometer can be used to select individual wavelengths of light. Figure 2 shows the essential elements of such a system.

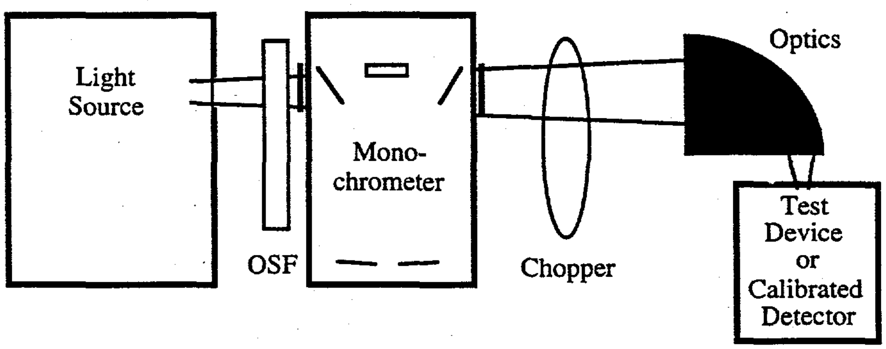

Figure 2. Basic elements of a spectral-response measurement system using a monochrometer. OSF means "Order-Sorting Filter."

The light source for either system can be a xenon arc lamp if ultraviolet (UV) response is of interest (it also enables measurement in visible [VIS] and near infrared [NIR] regions), or a tungsten lamp for investigations involving VIS and IR regions. If reflective optics are used, a monochrometer system can be used with a glow bar source to investigate device response in the IR and far-infrared spectral regions. A monochrometer-based system has the advantage of high wavelength resolution, whereas the filter-based system can provide more light intensity with simpler optics.

Calibration of either system involves measuring the radiant power of the light source at the test plane for each wavelength of interest. A thermal radiometer is well-suited to this purpose because its sensitivity does not depend (ideally) on the wavelength of light it measures. A semiconductor sensor can also be used, but only over the range to which it is sensitive.

A device's spectral response is measured by mounting the device in the test plane and measuring the amount of electrical current it generates at each wavelength of interest. Each current measurement is compared to the total irradiance information at the same wavelength to obtain the spectral response [Eq. 1]. The quantum efficiency, which is of greater interest to the researcher, is derived from the spectral response by multiplying by the photon energy [Eq. 2].

$$SR(\lambda) = \frac{I(\lambda)}{P(\lambda)} \qquad \text{Eq. 1}$$

$$QE(\lambda) = \frac{I(\lambda)}{P(\lambda)} \cdot \frac{hc}{\lambda} \quad , \qquad \text{Eq. 2}$$

where $SR(\lambda)$ is spectral response, $I(\lambda)$ is current, $P(\lambda)$ is power, $QE(\lambda)$ is quantum efficiency, h is Planck's constant, c is the speed of light, and λ is wavelength.

Calibration can also be achieved by diverting a (known) portion of the monochromatic light beam to a calibrated detector during the measurement. This method removes measurement uncertainty due to changes in light intensity between or during calibration and measurement.

RADIOMETRY WITH SOLAR SIMULATORS

Radiometry is necessary for measuring of PV device performance under a particular spectrum using a solar simulator. Figure 3 shows a reference spectrum under which most PV devices' performance is evaluated, the spectral irradiance of a projector lamp (with dichroic reflector) that could be used as a solar simulator, and the spectral response of a gallium-arsenide (GaAs) PV device.

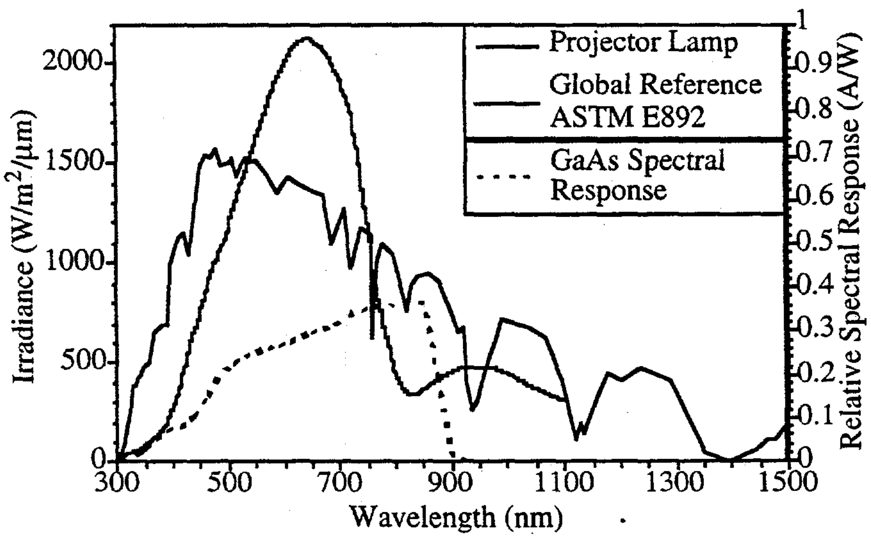

Figure 3. Global reference spectrum [1], projector lamp spectral irradiance, and GaAs PV spectral response

In Figure 3, the projector lamp irradiance is scaled so that the PV device will produce the same photocurrent under its illumination as it would if illuminated by the reference spectrum. The lamp's irradiance must exceed the reference irradiance between 540 and 750 nm to compensate for the spectral regions where it is weaker. This balance must only be obtained in the spectral region in which the PV device responds, and it is weighted by the magnitude of the spectral response at each wavelength.

If this PV device is a reference cell [2], it can be used as a radiometer to set the intensity of the solar simulator to measure the performance of another device. Procedurally, one scales the intensity of the solar simulator by setting the reference cell in its test plane and adjusting the intensity of the beam so that the reference cell generates its calibrated current for the spectrum of interest.

Figure 4 is identical to Figure 3, except that it includes the spectral responsivity of a silicon (Si) PV cell that one might want to measure.

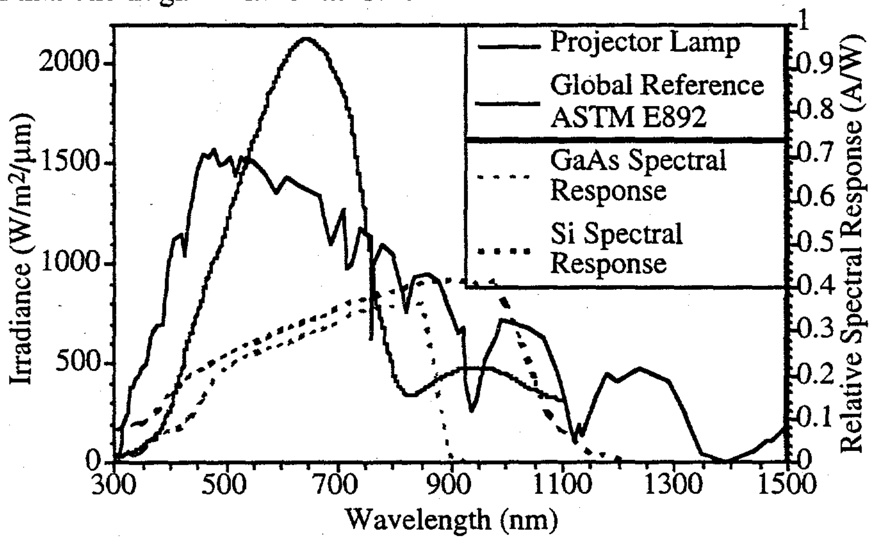

Figure 4. Global reference spectrum, ELH lamp spectrum, GaAs PV spectral responsivity, and Si PV spectral responsivity

If the projector lamp intensity chosen as described above is used to measure the performance of the Si solar cell, the data will include an error of almost 10%. This is because in the region in which the GaAs cell responds but the Si cell does not (900-1100 nm), there is a substantial difference in the two spectral irradiances. The projector lamp produces much less light than the reference spectrum in this region. Therefore, the Si cell will produce less current under the simulator than it would under the reference spectrum.

This is called the "spectral mismatch error." It can be reduced by setting the simulator intensity with a reference device whose spectral responsivity more closely resembles that of the device to be evaluated, or by using a solar simulator with a spectral irradiance that resembles the reference spectrum for which the device is being characterized.

Figure 5 shows the similarity of the X25 solar simulator and the Global Reference Spectrum.

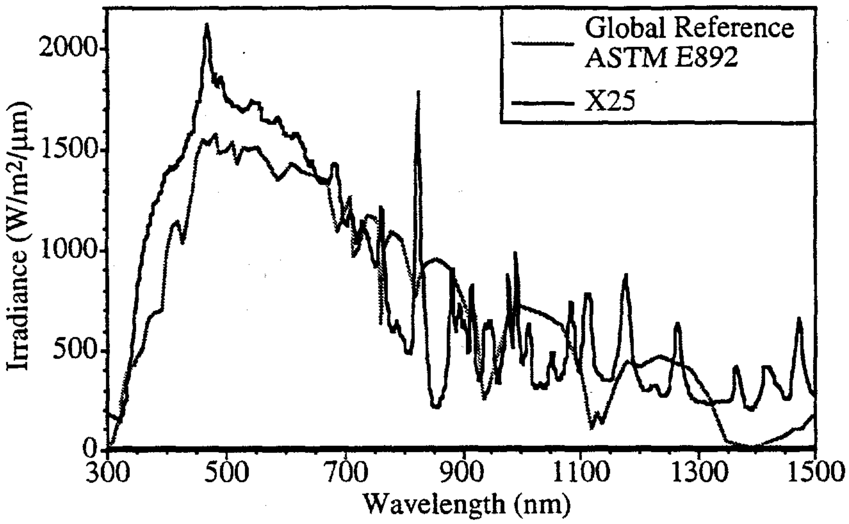

Figure 5. Spectral Irradiance of NREL's Spectrolab X25 solar simulator compared with the global reference spectrum.

Equation 3 quantifies the spectral mismatch error.

$$M = \frac{\int_{\lambda_1}^{\lambda_2} E_s(\lambda) \cdot S_t(\lambda) d\lambda}{\int_{\lambda_3}^{\lambda_4} E_s(\lambda) \cdot S_r(\lambda) d\lambda} \bullet \frac{\int_{\lambda_3}^{\lambda_4} E_{ref}(\lambda) \cdot S_r(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{ref}(\lambda) \cdot S_t(\lambda) d\lambda}, \qquad \text{Eq. 3}$$

where $E_s(\lambda)$ is the spectrum of the test source (e.g., solar simulator), $E_{ref}(\lambda)$ is the reference spectrum, $S_t(\lambda)$ is the spectral responsivity of the test device, and $S_r(\lambda)$ is the spectral responsivity of the reference device. λ is the wavelength, and λ_1 - λ_4 are chosen to include the entire range of spectral responsivity.

This equation is valid for any spectral irradiance and any combination of test and reference cell, including thermal sensors. Because they appear in both the numerator and denominator, the scaling of the integrand factors is irrelevant. The integration limits need only include the spectral region in which the reference and test device respond because elsewhere the integrand is zero. When using photovoltaic reference and test devices, this means that the spectral irradiance need not be known outside this region.

M, the "spectral mismatch correction factor," is commonly used while setting solar simulator intensities for PV device measurements. Instead of setting the simulator so that the reference cell generates its calibrated current, one sets it for the calibrated current divided by M. If M is small, it can be applied after the measurement by correcting each current measurement.

Table 1 shows five spectral mismatch correction factors recently used to set NREL's X25 Solar Simulator (xenon arc lamp source) to measure PV devices under the Global Reference Spectrum.

Table 1. Examples of spectral correction factors recently used to set NREL's X25 Solar Simulator. KG5 is an infrared-blocking filter used as a window over the Mono-Si cell.

Reference Device Material	Test Device Material	Spectral Correction Factor, M
Mono-Si	Mono-Si	0.972
Mono-Si	Mono-Si	1.003
Mono-Si	Cu(In,Ga)Se2	0.999
GaAs	CdTe	1.049
KG5/Mono-Si	GaInP	1.023

Note that simply choosing a reference cell made from the same material as the device to be tested does not guarantee a small spectral mismatch error. Also, a small spectral mismatch error can exist for reference and test devices made from different materials with similar spectral response. This is very important because stable reference cells are needed to measure materials that have unstable performance or exhibit measurement transients.

Although NREL and other laboratories often compute and apply the spectral correction factor when evaluating PV device performance, some groups do not. Those evaluating solar cells for space applications generally devote more effort to reducing the spectral mismatch error than computing it. They often require that reference cells be made of the same material and with the same process as the devices being measured. Whenever possible, they measure cells on high-altitude aircraft or balloons to obtain source spectra that very closely resemble those found in outer space. In a production environment where the test-cell material and process are static, one can use a calibrated cell from the production line as a reference and ignore the spectral mismatch factor. In this situation, the spectral mismatch factor, if applied at all, would be applied only while calibrating the reference cell.

OTHER USES OF RADIOMETRY IN A PV MEASUREMENTS LAB

Radiometry is useful in monitoring measurement systems for faults and correcting certain error sources involved in PV measurements. First, consider the consequences of a small leak in an interference filter used in a filter-based spectral-response system (see Figure 6).

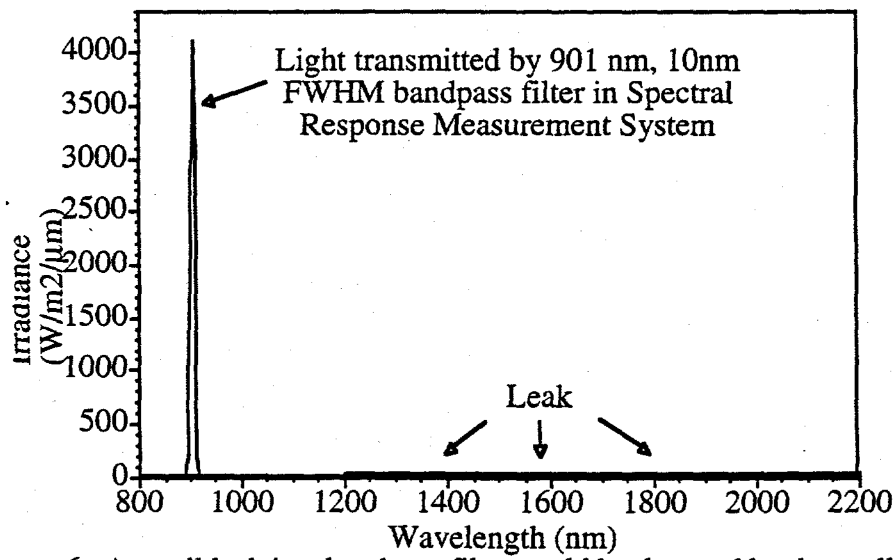

Figure 6. A small leak in a bandpass filter could be detected by thermally based calibration equipment but not by a device being tested. FWHM means Full Width Half Maximum.

In this illustration, a leak of 0.1% of maximum transmission over a broad spectral range would contribute an additional 10% to the energy detected by a themal detector used to calibrate the system. Because most PV cells are not sensitive to this range, this leak would reduce the spectral response measurement by 10%. A spectroradiometer with good dynamic range can detect some light leaks in the system and can check wavelength calibration as well. A spectrophotometer can detect smaller but still important filter leaks.

Variation in a solar simulator's intensity between measurement and calibration, and during both, can generate small errors in device current. To correct for these variations, one can use another solar cell as a radiometer to monitor these fluctuations. Figure 7 shows the calibration path of such a radiometer.

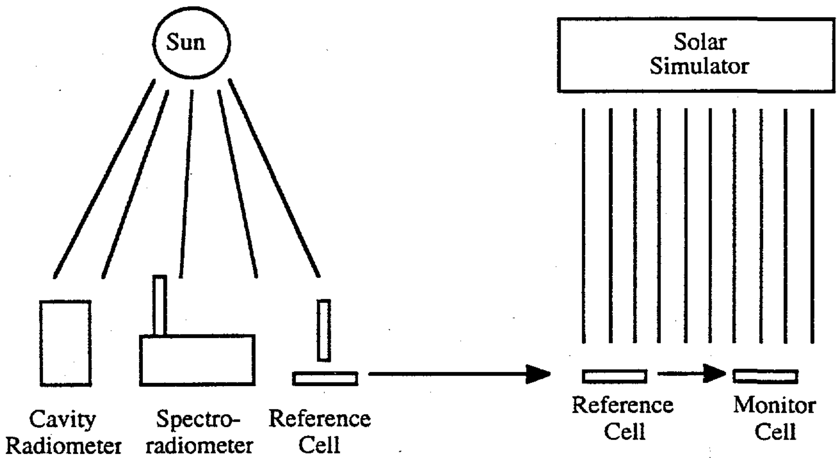

Figure 7. Equipment arrangement and calibration path of a reference cell and monitor cell.

The additional radiometer is called a "monitor cell." It works best if its spectral response resembles that of the device being measured, although if it isn't, the error caused may be negligible. Its response-time characteristics, if long, should resemble those of the device being calibrated. The response times of the monitor and test cells are unimportant if both are much shorter than the measurement period.

The test cell's voltage and current are measured simultaneously with the monitor cell's current. Small excursions in intensity cause nearly linear, proportional changes in current and negligible changes in voltage. At NREL, the measurement software corrects the test cell's current according to the difference between the monitor cell's current and its calibration, as long as these excursions are smaller than 2%.

Figure 5 shows the spectral content of NREL's X25 solar simulator, information that is required to assess and correct for the spectral mismatch. This information is collected using spectroradiometers. Because different spectroradiometers have different features and capabilities, we use various spectroradiometers to assess our source's spectrum. We have found that due to changes in xenon arc lamps over time, we periodically have to remeasure bulb spectra to maintain the accuracy of the spectral corrections we apply.

Radiometry is also used when measuring solar cells and modules in natural sunlight. Thermal and photovoltaic radiometers can measure total irradiance, and spectroradiometers can measure spectral irradiance. One can either report the device performance along with these data as prevailing conditions, or translate the performance to conditions that include a reference spectrum and irradiance.

SUMMARY

For performance measurements of PV devices, radiometry is used to calibrate spectral-response measurement systems, set solar simulator intensity, and seek and characterize faults in measurement systems. The differences in the principles on which different radiometers operate are important for PV measurements because of inherent differences in response times and spectral responsivity. It is important to select the appropriate radiometer for each application.

Partly due to the diversity and accuracy of radiometry technology, NREL's PV Device Performance and Characterization Laboratory claims to predict the performance of most solar cells with a U95 uncertainty of 2%.

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FOR FURTHER READING

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Solar simulators vs outdoor module performance in the Negev Desert

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INTRODUCTION

The power output of photovoltaic cells depends on the intensity of the incoming light, its spectral content and the cell temperature. In order to be able to predict the performance of a pv system, therefore, it is of paramount importance to be able to quantify cell performance in a reproducible manner. The standard laboratory technique for this purpose is to employ a solar simulator and a calibrated reference cell. Such a setup enables module performance to be assessed under constant, standard, illumination and temperature conditions. However, this technique has three inherent weaknesses.

First, it is difficult to synthesize a light spectrum, from electric lamps, that closely approximates that of natural sunshine. On the one hand the interference filters needed to remove unwanted peaks, particularly in the near IR, tend to be expensive and not very stable with time. Furthermore, the relatively high electric power densities needed to produce a uniform luminous intensity of 1000 Wm^{-2} over the entire area of a test module do not help to promote filter stability.

Secondly, in addition to filter instability, the lamps themselves undergo ageing. This has led to the development of so-called "flash" test techniques in which a minimum of the lamp's total serviceable life time is required for each test. But flash tests can introduce spectral variations as the lamp warms up and further uncertainties about the degree to which steady state conditions may or may not exist in the module while its I-V curve is being measured.

Lastly, although calibrated reference cells may be constructed for testing modules employing crystalline or polycrystalline silicon cells, there are materials (such as amorphous silicon) for which a stable reference cell can not be fabricated. The obvious solution, of employing a black-body pyranometer as reference standard, is not feasible for flash tests owing to the finite time (typically several seconds) such a pyranometer takes to reach steady state itself.

The present work will discuss the degree to which the natural sun conditions - at our desert test laboratory - can be employed as a reliable and reproducible standard for testing a wide variety of module types. After presenting evidence that acceptably small experimental errors may be achieved with such tests we shall compare manufacturer's module specifications, as derived from simulators in several countries, with the results of our outdoor tests.

ACHIEVING NATURAL STC TEST CONDITIONS

Standard Test Conditions (STC) are specified as being 1000 W m^{-2} insolation of spectral type AM1.5 (defined by convention) and 25° C cell temperature.

(a) Insolation conditions

In order to measure I-V curves in our outdoor test laboratory the test module is placed on a stand that enables it to be orientated at normal incidence to the incoming solar beam direction.

Measurements are made at and around solar noon on cloudless days. **Fig.1** displays the measured global insolation on a sun-tracking plane on a typical clear day at Sede Boqer (June 26, 1993). The insolation was measured with a thermopile pyranometer that is periodically compared, using the normal incidence method [**1**], with a secondary standard the calibration of which was established at the World Meteorological Organization in Davos, Switzerland. We prefer the use of this kind of radiation sensor to a calibrated reference cell because, on the one hand, its spectral sensitivity is relatively neutral, i.e. it does not favor any particular kind of module. Secondly, the available solar resource at any given site is usually measured with this kind of instrument. Hence the module efficiency as determined with a thermopile pyranometer provides a better estimate of how much available solar energy may be converted to electricity than does an efficiency figure that was derived from a reference cell.

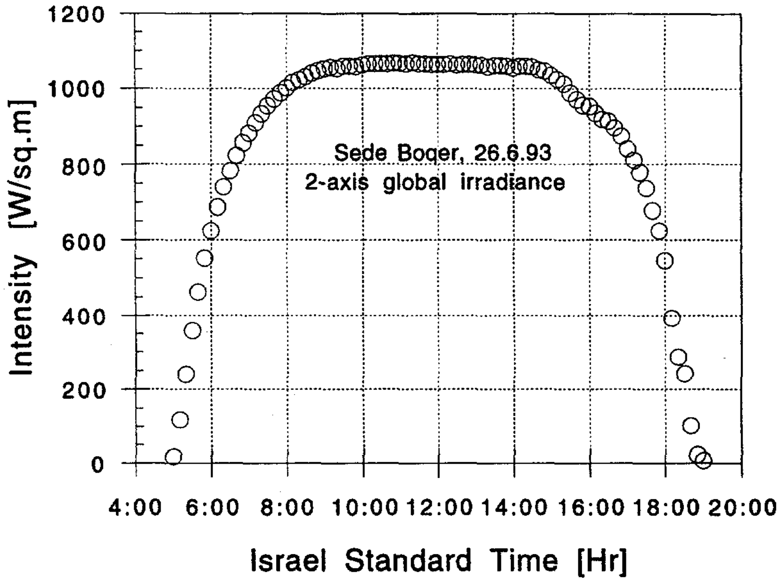

Figure 1: Global irradiance measured on a sun-tracking plane at Sede Boqer, June 26, 1993

From **Fig.1** one sees that, in spite of some slight cloudiness in the late afternoon on this particular day, the irradiance remained constant to a few parts per mille for more than two hours around solar noon. On clear days there is, accordingly, ample time to measure many I-V curves without fear that the irradiance will change either during a measurement (which lasts for several seconds) or from one measurement to the next (which may be separated by several minutes). Indeed, in summer, conditions are often sufficiently stable to enable sequences of measurements to be continued from one day to the next if, for example, many modules are to be compared [**2**].

(b) Spectral conditions

At Sede Boqer (Latitude = 30.8° N) the noon-time sun has a zenith angle Θ_z that varies from about 8° in summer to about 54° in winter. These figures correspond to the angular conditions (i.e. arcsec Θ_z) of AM1.01 to AM 1.70, respectively. We have measured the spectral content of the natural global irradiance incident on the plane of a test module set at normal incidence to the solar beam direction. Such measurements are performed with a Li-Cor spectroradiometer on days when modules are tested, i.e. on cloudless days. **Fig.2** shows a typical scan (small crosses) taken at 2 pm on March 6, 1995. At this time of day, on this date, the solar zenith angle corresponds to AM 1.5 at the latitude of our laboratory. The scanning interval of the spectroradiometer was set at 1 nm intervals in wavelength over the range 300-1100 nm. Also shown in **Fig.2** are the IEC standard intensities (circles) for AM 1.5 over this range of wavelengths **[3]**.

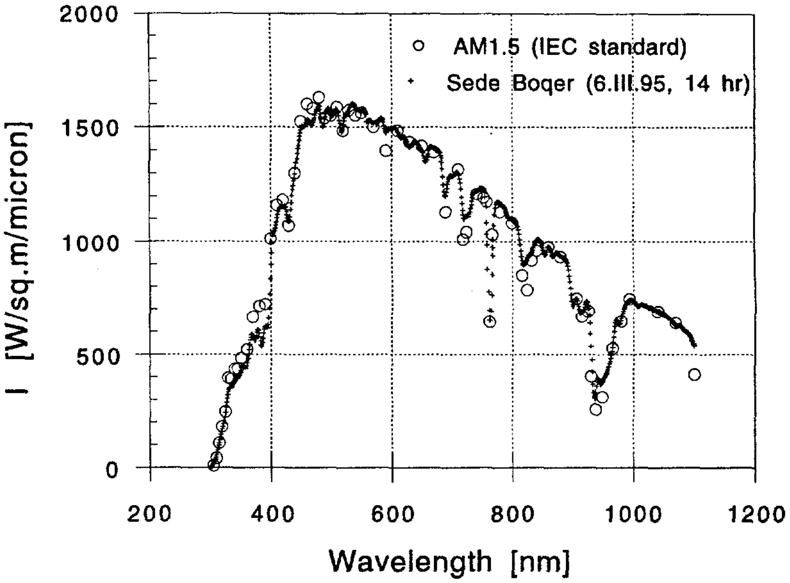

Figure 2: Natural solar spectrum measured at Sede Boqer at 2 pm, March 6, 1995 (crosses). IEC standard AM1.5 values (circles) [3] are superimposed.

Particularly striking in **Fig.2** is the fact that no re-scaling has been performed: At the time of day when the solar zenith angle corresponded to AM1.5 the measured intensity at most wavelengths was found to be extremely close to the corresponding international standard intensities. This is especially noticeable at the various peaks and troughs in the figure. If we exclude the 300-400 nm UV region, for which this instrument has poor accuracy, and assess the remaining 50 IEC points of reference our measured spectrum exhibits a mean bias error of only 3%, the two worst points being 12% low (at 757.5 nm - interpolated from measurements at 757 and 758 nm) and 32% high (at 930 nm). Since, moreover, both of these points lie on narrow, rapidly changing, parts of the spectrum (respectively, O_2 and H_2O absorption bands) their significance is not high.

Similar scans have been performed at other times of the year and at various times on either side of AM 1.5 angular conditions, in order to determine the extent to which the spectrum of **Fig.2** remains stable. At other times of day it is necessary to rescale the intensity and perform integrals over various wavelength intervals. A full discussion of these studies will be presented elsewhere but for our present purposes it suffices to state that on clear days at all months of the year the noontime natural insolation at Sede Boqer is far closer to the IEC AM1.5 spectrum than any solar simulator we know about.

Some indirect evidence for this fact may be seen by measuring I_{sc} for a reference module, at noon time, on clear days at various times of the year. This parameter is relatively insensitive to temperature uncertainties (discussed below). Therefore, provided we normalize the measurements to 1000 W m^{-2}, any variations in measured I_{sc} must be due to spectral effects. **Fig.3** shows twelve such measurements of I_{sc} that were made during 1994. One sees that, except for a single measurement that was about 2% above average, spectral variations are typically at the 1% level throughout the entire year provided measurements are performed on clear days.

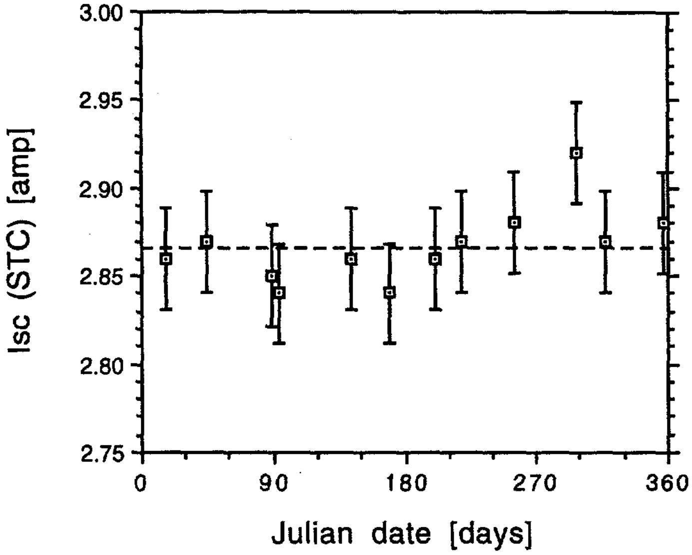

Figure 3: I_{sc} measurements, normalized to 1000 Wm^{-2}, performed on a reference module at Sede Boqer on 12 clear days throughout the year 1994. Error bars shown are a nominal 1%

(c) Temperature conditions

Our standard method for assessing cell temperature while an I-V curve measurement is in progress is to follow the output of a thermocouple taped to the rear side of the module. This offers the advantage of representing the actual in-use temperature of the module but suffers from the disadvantage that momentary fluctuations in wind speed may change the temperature by typically ± 2° C during an experimental run lasting several minutes. For more accurate out-

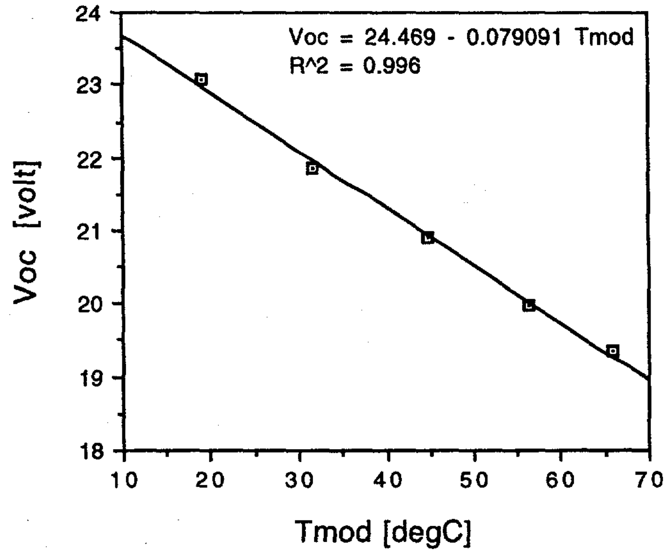

Figure 4: Typical V_{oc} vs T_{mod} curve obtained outdoors with insulated module backing

door work, specifically when measuring temperature coefficients of the various cell parameters, we insulate the rear side of the module with polystyrene sheeting in order to minimize the effect of wind. This results in the module operating at somewhat higher temperatures than would normally be the case at any given insolation level but it does result in curves that are very smooth as a function of temperature. **Fig.4** shows an example of a typical temperature coefficient curve obtained in this manner. The module under test had first been cooled in an air-conditioned room, carried outdoors with insulated panels front and back, placed in the test stand and then exposed to solar radiation. Its I-V curve and temperature were subsequently measured every few minutes - quite frequently at the beginning, as the module temperature rose rapidly, but less frequently as the module temperature neared its steady state.

STC conditions may either be read directly from curves such as **Fig.4** or the fitted slopes can be used for making adjustments to measurements obtained in the field.

PUTTING IT ALL TOGETHER

One of our experimental projects (which studies module performance degradation) involves modules being periodically tested on one clear day each month. These modules include a reference sample that is kept indoors except when tests are performed. Its parameters are therefore expected to be stable compared to those of modules that are in use under conditions of constant exposure. **Fig.5** shows the measured values of P_{max}, reduced to STC, for the reference module at various times of the year. It is important to note that the measurements in **Fig.5** are for an uninsulated module and, accordingly, subject to a temperature uncertainty of about ± 2° C, as stated above. This temperature uncertainty translates into an approximately 2% uncertainty in the measured peak power of the module under test.

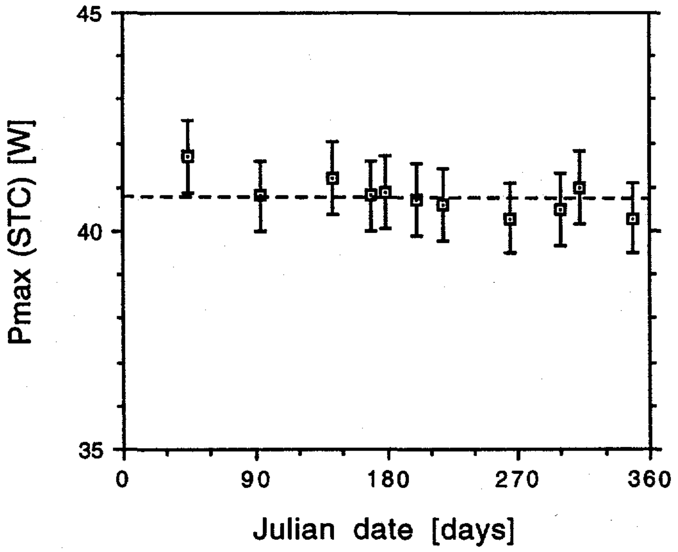

Figure 5: STC-adjusted results of P_{max} measurements on an uninsulated module on clear days at Sede Boqer during 1993-1994. Error bars shown are a nominal 2%.

From **Fig.5** it is evident that, in our outdoor tests at Sede Boqer, module efficiency can be determined to an accuracy of approximately ± 2% at any time of the year provided measurements are made in the noontime period on clear days. It is interesting to observe that this is approximately the degree of accuracy with which solar insolation can be measured using a well-maintained pyranometer.

MANUFACTURER'S SIMULATOR TESTS

At the present time we have a solar simulator under construction at Sede Boqer. In principle we could present data of module I-V curves obtained using this instrument and compare the results with parallel outdoor measurements. However, in the light of all that has been said above, such a comparison, useful as it would doubtless be to us, would provide no more useful information than how good our simulator is. Of greater interest is the question of how good the simulators of the various module manufacturers are. To this end, we present in **Table 1** a list of STC P_{max} values provided by several manufacturers for specific modules we have purchased. Also shown are the corresponding parameters obtained from our outdoor measurements. In order to prevent embarrassment the various modules are identified by their country of origin only.

Module	P_{max}(Simulator) [W]	P_{max}(Outdoors) [W]	Difference [%]
Germany 1	53.7	46.6	- 13
Japan 1	68.5	62.8	- 8
Japan 2	80.2	78.6	- 2
Russia 1	54.2	44.3	- 18
Spain 1	52.6	48.8	- 7
USA 1	47.2	43.4	- 8

Table 1: Comparison of various manufacturer's STC peak power simulator ratings, for specific modules, compared to outdoor measurements at Sede Boqer.

From **Table 1** it is apparent that only one of the simulator measurements is in reasonable agreement with the outdoor tests. The others are widely divergent.

SUMMARY AND CONCLUSIONS

(1) Noontime outdoor lighting conditions on clear days at Sede Boqer closely correspond to the IEC definition [3] of the AM1.5 solar spectrum at all times of the year.

(2) At such times, climatic conditions are sufficiently stable to enable the determination of P_{max} to a precision of $\pm$ 2%. This is comparable to the accuracy of a well-maintained pyranometer.

(3) A sample of I-V curves provided by module manufacturers from various parts of the world all over-rated the peak power. In some cases the over-rating was in the 10% - 20% range.

(4) At the present state of the art, the sun itself appears to be the most accurate solar simulator.

ACKNOWLEDGMENTS

This work was funded by the Israel Ministry of Energy and Infrastructure. The author is indebted to Mr. David Berman for performing the outdoor module tests, and to various colleagues in the photovoltaics industry (whose need for anonymity is here respected) for kindly providing the simulator data quoted in **Table 1**.

REFERENCES

[1] D. Faiman, D. Feuermann and A. Zemel, *Accurate field calibration of pyranometers*, Solar Energy **49** (1992) 489.
[2] D. Berman, S. Biryukov and D. Faiman, *EVA laminate browning after 5 years in a grid-connected, mirror-assisted, photovoltaic system in the Negev desert: effect on module efficiency*, Solar Energy Materials and Solar Cells (in press).
[3] International Standard CEI/IEC 904-3, *Photovoltaic devices, Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data* (1989).

An Evaluation of Regional Differences in Module Performance for Various PV Technologies using the National Solar Radiation Data Base

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National Renewable Energy Laboratory
Golden, CO USA

Photovoltaic Radiometric Measurements Workshop
July 1995

NREL Photovoltaics Program

PV MODULE & SYSTEM PERFORMANCE and ENGINEERING PROJECT

Team/Task:

PV Module Exploratory/Qualification Testing and Test Method Development

Acknowledgements

- R. DeBlasio, L. Mrig, R. Hulstrom
- S. Rummel, Y. Caiyem, L. Ottoson
- D. Myers, T. Cannon, D. Trudell
- C. Osterwald, K. Emery, B. Kroposki

Photovoltaics:

Areas of Research, Development & Deployment

- Resources
- Materials
- Cells
- ***Modules***
- Systems
- Markets

Photovoltaic Modules: DOE Goals

Achieve:
- High Efficiency
- Low Cost (i.e., economically-competitive)
- Environmentally-friendly
- **Long-term Performance: i.e., Reliability and Durability**
- **Safety**

NREL PV Module Reliability Testing

Goals:
- Improve module long-term performance: reliability, durability and stability
- Predict module service lifetime

Strategy:
- Perform tests; develop test procedures
- Validate ASTM & IEEE test methods
- Correlate indoor & outdoor test results
- Identify module failure mechanisms
- Help find solutions to reliability problems

Indoor PV Module Reliability Testing

- Qualification Testing
- Photostability Studies
- Accelerated Weathering

Outdoor PV Module Reliability Testing

- Natural, Real-time Exposure

PV Module Performance Characterization

PV Module Reliability Tests

- **Electrical**: Dry & Wet Hi-pot; Wet Megger, Ground Continuity, Bypass-Diode, Hot-Spot
- **Environmental**: Thermal and Humidity-Freeze Cycling, Damp Heat, Outdoor Exposure
- **Optical**: Light-Soaking, UV/Thermal
- **Mechanical**: Dynamic and Static Loading, Hail Impact, Surface-Cut Susceptibility, Twist

MQT Program: Test Plan & Status

- 13 PV manufacturers, ~ 9 modules each: commercial products, R&D prototypes
- Entire IEEE (Proposed) Module Qualification Test (MQT) Sequence being run

Manufacturer (Batch)	*Model*	*Structure/Composition*
APS (#1)	EN-25	a-Si
Solarex (#1)	SA-5	a-Si
UPG (#1)	PowerGlass	a-Si *and* a-Si/a-Si
USSC (#1)	UPM-880	a-Si/a-Si
ECD (#2)	1' x 4'	a-Si/a-Si/a-Si:Ge
Siemens Solar (#1)	Black Frame	CIS ($CuInSe_2$)
Golden Photon (#2)	2' x 2'	CdTe
Solar Cells, Inc. (#2)	2' x 5'	CdTe
Siemens Solar (#1)	M55 & PC-4JF	mono x-Si
Solarex (#1)	MSX-60	multi x-Si
Texas Instruments (#1)		Spheral Silicon
AstroPower (#2)		Silicon-Film
ASE (Mobil Solar) (#2)		Ribbon Silicon

PV Module

Performance

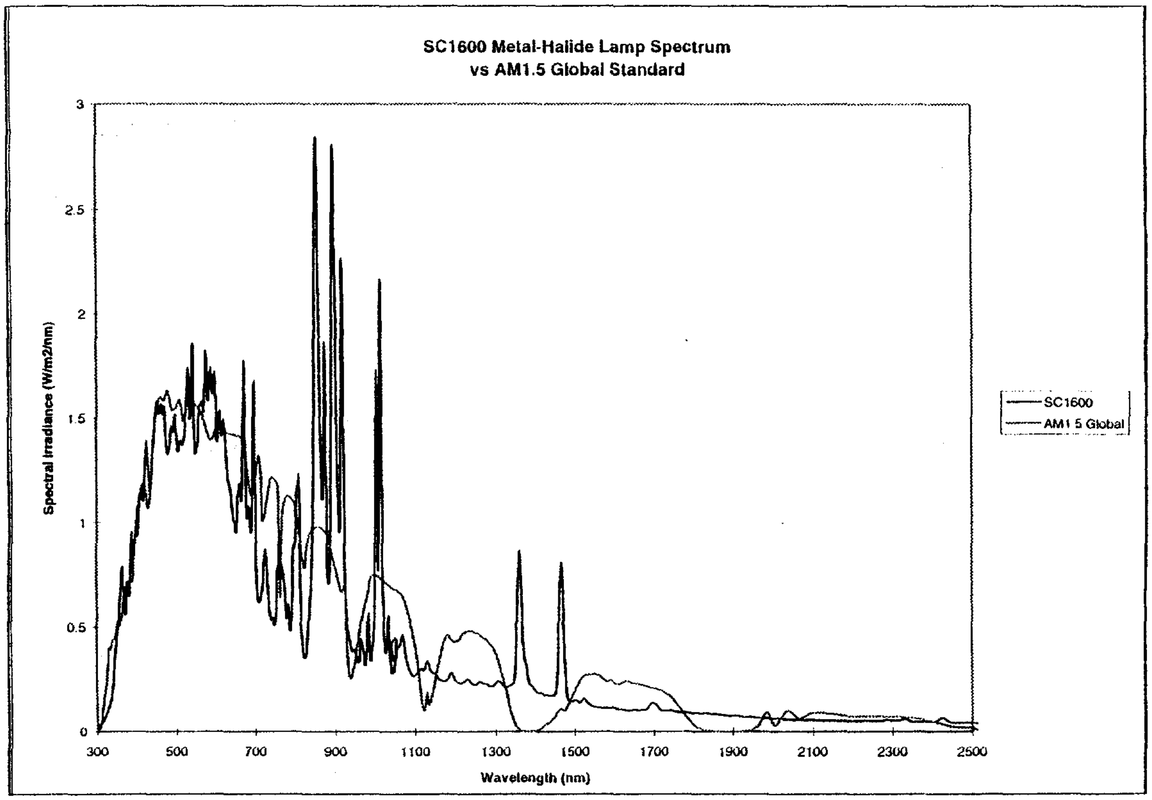
Characterization

- **I-V Measurements vs Irradiance & Temperature**

- **Computer Modeling of Regional Differences in PV Module Performance**

I-V Measurements

- **5 Module Technologies**
  (a-Si/a-Si, a-Si/a-Si/a-Si:Ge, CIS, mono & multi x-Si)
- **Environmental Chamber w/ Metal Halide Lamps**
  (Atlas SolarClimatic 1600)
- **6 Irradiances**
  (200, 400, 600, 800, 1000, 1100 W/m^2)
- **6 Temperatures**
  (0, 15, 25, 40, 60, 80 °C)



- **Measured 180 I-V Curves**
  (5 Modules x 6 Irradiances x 6 Temperatures)

- Generated an **Irradiance vs Temperature matrix** for the I-V parameters (I_{sc}, V_{oc}, FF, P_{max}, Eff.) for each module

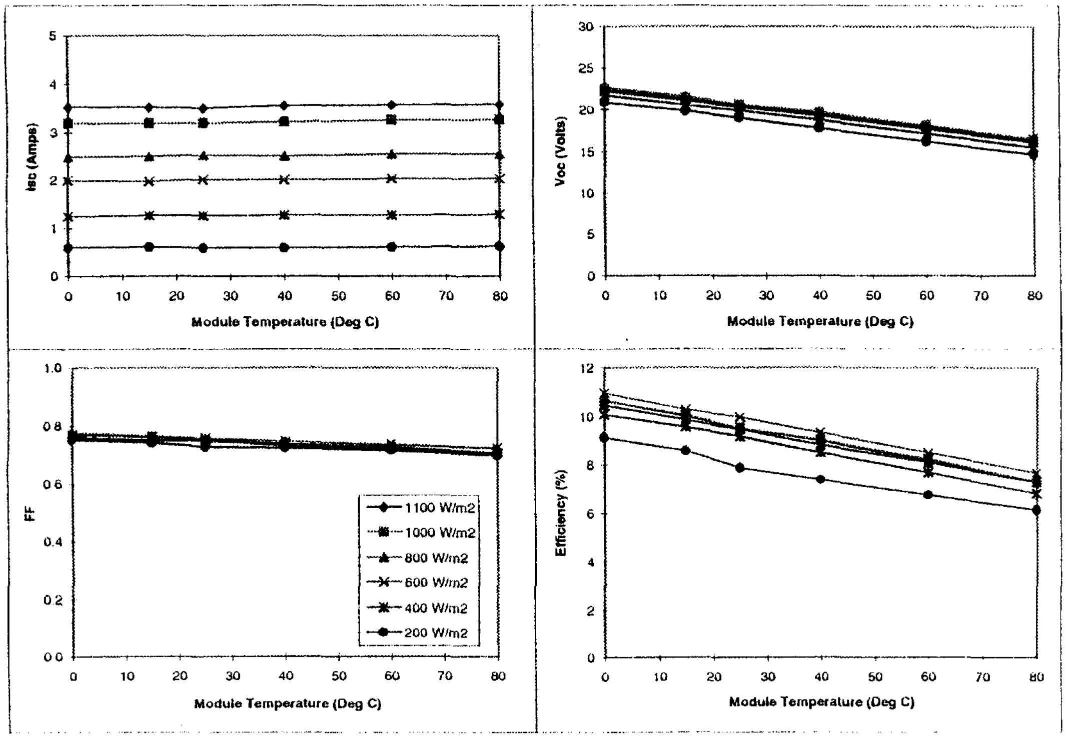


Figure 2. Multi x-Si PV module: I-V parameters vs irradiance and temperature.

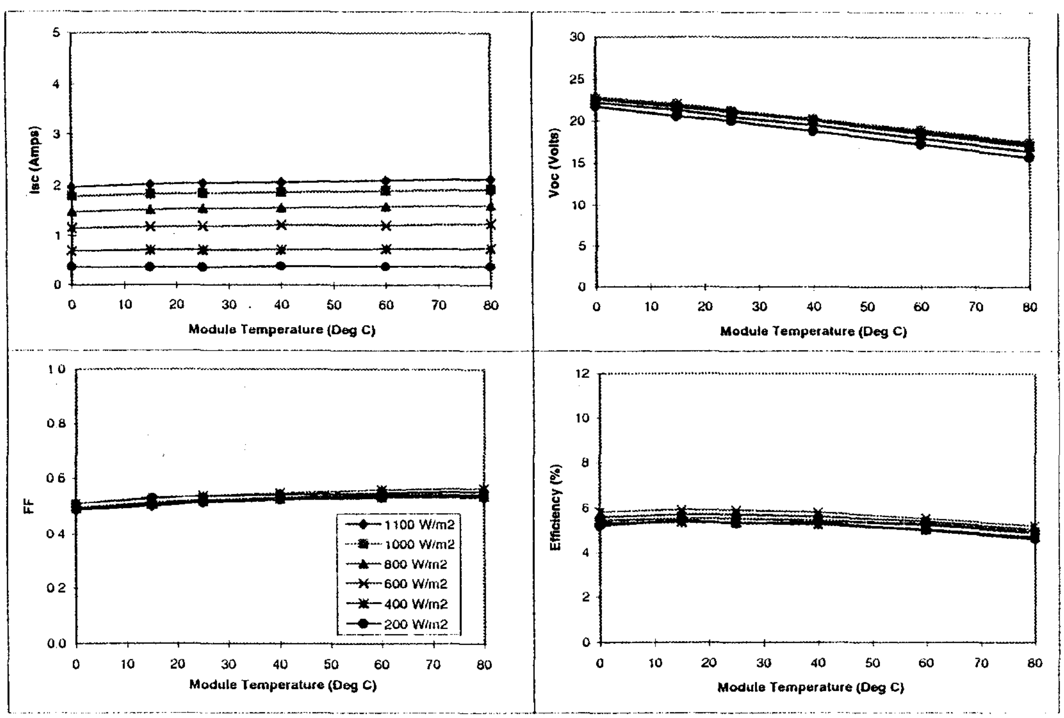


Figure 3. a-Si dual-junction PV module: I-V parameters vs irradiance and temperature.

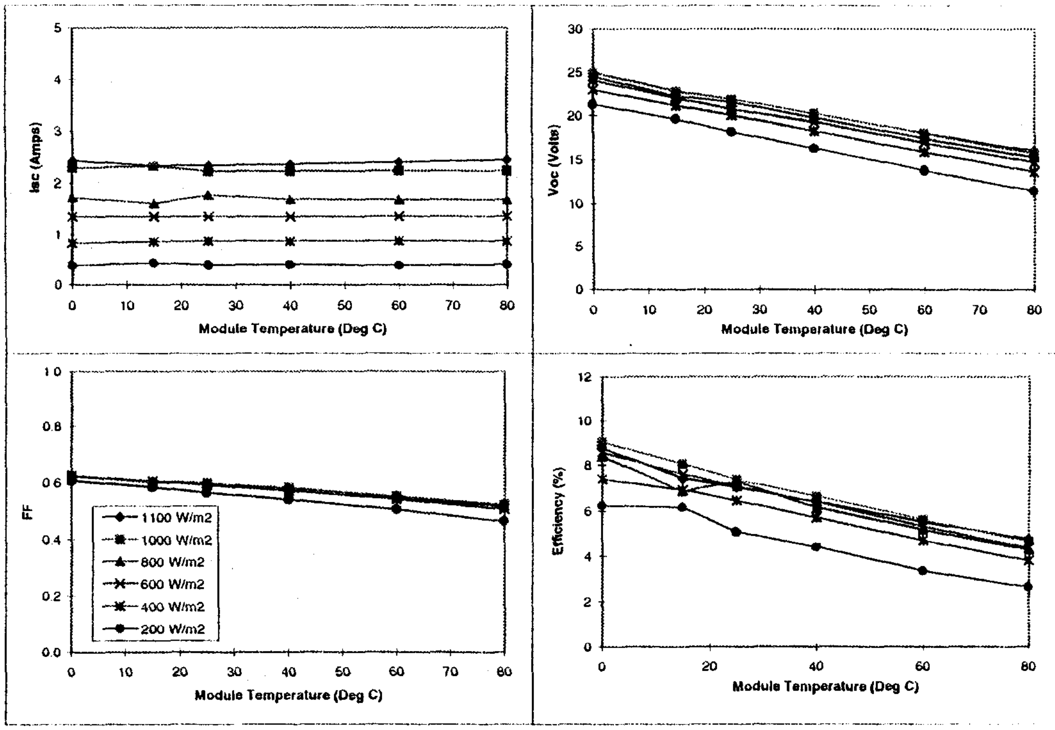


Figure 4. $CuInSe_2$ (CIS) PV module: I-V parameters vs irradiance and temperature.

Meteorological (Weather) Data

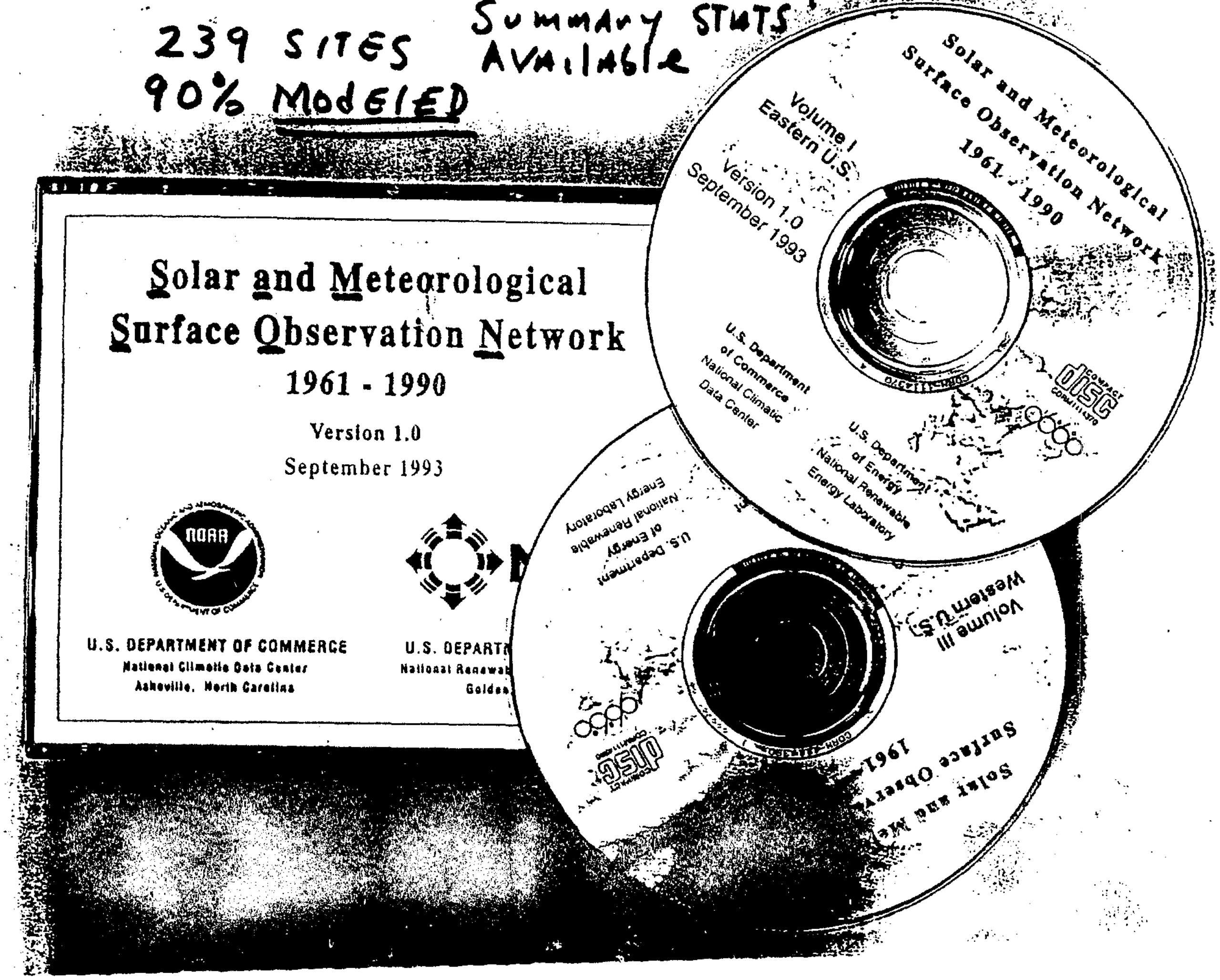
- **National Solar Radiation Data Base** weather data
  => SAMSON (<u>S</u>olar <u>A</u>nd <u>M</u>eteorological <u>S</u>urface <u>O</u>bservation <u>N</u>etwork)

- **Chose 8 Sites** (with a variety of climates)
  (Boston, Boulder, Detroit, Miami, Phoenix, San Francisco, Seattle, St. Louis)

- **Chose 5 Years**
  (1961, 1968, 1975, 1982, 1990)

ANNUAL + 30 YR SUMMARY STATS AVAILABLE

239 SITES
90% MODELED



SAMSON DATA ELEMENTS

Header Elements (For First Record of File)

WBAN Number	City	State	Time Zone	Latitude	Longitude	Elevation
23050	ALBUQUERQUE	NM	-7	N35 03	W106 37	1619

Year	Month	Day	Hour	Extraterrestrial Horizontal Radiation	Extraterrestrial Direct Normal Radiation	Global Horizontal Radiation	Source and Uncertainty Flags	Direct Normal Radiation	Source and Uncertainty Flags	Diffuse Horizontal Radiation	Source and Uncertainty Flags	Total Sky Cover	Opaque Sky Cover	Dry Bulb Temperature	Dew Point Temperature	Relative Humidity	Atmospheric Pressure	Wind Direction	Wind Speed	Visibility	Ceiling Height	Present Weather	Precipitable Water	Broadband Aerosol Optical Depth	Snow Depth	Days Since Last Snowfall
61	1	1	1	0	0	0	?0	0	?0	0	?0	0	0	-5.0	-7.8	81	835	110	1.5	96.6	77777	0999999999	4	0.010	0	18
61	1	1	2	0	0	0	?0	0	?0	0	?0	0	0	-3.9	-7.8	75	836	0	0.0	96.6	77777	0999999999	4	0.010	0	18
61	1	1	3	0	0	0	?0	0	?0	0	?0	0	0	-4.4	-7.2	81	836	110	1.5	96.6	77777	0999999999	4	0.010	0	18
61	1	1	4	0	0	0	?0	0	?0	0	?0	0	0	-5.0	-7.8	81	836	110	2.1	96.6	77777	0999999999	4	0.010	0	18
61	1	1	5	0	0	0	?0	0	?0	0	?0	0	0	-5.0	-7.2	85	835	140	1.0	96.6	77777	0999999999	4	0.010	0	18
61	1	1	6	0	0	0	?0	0	?0	0	?0	0	0	-5.6	-7.2	88	835	140	1.0	96.6	77777	0999999999	4	0.010	0	18
61	1	1	7	0	0	0	?0	0	?0	0	?0	0	0	-5.6	-8.3	81	836	0	1.5	96.6	77777	0999999999	4	0.010	0	18
61	1	1	8	93	967	46	C4	375	E4	10	E5	0	0	-6.1	-8.3	84	836	50	1.0	96.6	77777	0999999999	3	0.010	0	18
61	1	1	9	297	1415	184	C4	838	E4	21	E5	0	0	-2.2	-5.6	78	837	70	1.0	96.6	77777	0999999999	3	0.010	0	18
61	1	1	10	501	1415	364	C4	965	E4	31	E5	0	0	0.6	-5.0	67	838	0	1.0	96.6	77777	0999999999	3	0.010	0	18
61	1	1	11	650	1415	504	C4	1020	E4	39	E5	0	0	2.8	-6.1	52	838	320	5.7	96.6	77777	0999999999	3	0.010	0	18
61	1	1	12	732	1415	585	C4	1042	E4	43	E5	0	0	4.4	-8.9	38	837	320	7.2	96.6	77777	0999999999	3	0.010	0	18
61	1	1	13	744	1415	603	C4	1045	E4	44	E5	0	0	5.0	-13.3	25	837	340	8.2	96.6	77777	0999999999	3	0.010	0	18
61	1	1	14	683	1415	549	C4	1029	E4	41	E5	0	0	5.6	-13.9	23	837	340	5.2	96.6	77777	0999999999	3	0.010	0	18
61	1	1	15	554	1415	428	C4	998	E4	34	E5	0	0	5.6	-16.1	19	839	340	8.8	96.6	77777	0999999999	2	0.010	0	18
61	1	1	16	366	1415	252	C4	902	E4	25	E5	0	0	4.4	-16.7	20	839	340	7.2	96.6	77777	0999999999	2	0.010	0	18
61	1	1	17	133	1415	67	C4	636	E4	13	E5	0	0	2.8	-18.9	19	839	340	5.7	96.6	77777	0999999999	2	0.010	0	18
61	1	1	18	11	0	0	?0	0	?0	0	?0	0	0	0.6	-18.9	22	840	340	5.2	96.6	77777	0999999999	2	0.010	0	18
61	1	1	19	0	0	0	?0	0	?0	0	?0	0	0	-0.6	-18.3	25	840	0	5.2	96.6	77777	0999999999	2	0.010	0	18
61	1	1	20	0	0	0	?0	0	?0	0	?0	0	0	-2.2	-17.2	31	841	0	2.6	96.6	77777	0999999999	2	0.010	0	18
61	1	1	21	0	0	0	?0	0	?0	0	?0	1	0	-2.2	-15.0	37	841	0	5.2	96.6	77777	0999999999	2	0.010	0	18
61	1	1	22	0	0	0	?0	0	?0	0	?0	3	1	-5.0	-15.0	46	842	110	1.5	96.6	77777	0999999999	2	0.010	0	18
61	1	1	23	0	0	0	?0	0	?0	0	?0	4	2	-4.4	-14.4	46	842	0	0.0	96.6	77777	0999999999	3	0.010	0	18
61	1	1	24	0	0	0	?0	0	?0	0	?0	4	2	-6.1	-15.0	50	842	0	0.0	96.6	77777	0999999999	3	0.010	0	18

Data Elements (For All Except the First Record of File)

M18 G0623202

33

Figure 3-1. Data for Albuquerque, New Mexico, in the NSRDB synoptic format

SAMSON "EXTRACT"

- **Obtained (24 hrs x 365 days) data points:**
  - Direct Normal Irradiance
  - Global Horizontal Irradiance
  - Diffuse Horizontal Irradiance
  - Ambient Temperature
  - Wind Speed

- **Total Irradiance** and **Temperature** only are considered; no **spectral irradiance** corrections are made

- Used Perez [1] model to obtain **Global Plane-of-Array (POA) Irradiance**

  => PV Module at Fixed, Latitude Tilt

[1] Perez, R. et. al., "Modeling Daylight Availability and Irradiance Components from Direct and Global Irradiance", *Solar Energy*, 44(5), 1990, pp. 271-289.

PEREZ DIFFUSE RADIATION MODEL

Parameters required:

Global Horizontal, Direct Normal (Beam), Diffuse Horizontal, Solar Zenith Angle, Surface's Slope, Ground Albedo, Solar Incidence Angle on Surface

D_{perez} = Tilted Diffuse + Reflected Irradiance

Global POA = [Direct Normal * Cos(Z)] + D_{perez}

- Used "thermal-balance" model [2] to obtain **Module Temperature** from ambient temperature and wind speed

  => Temperature model has limitations

[2] Emery, K. and Anderson, J., private communication.

AMBIENT-TO-MODULE TEMPERATURE CONVERSION ALGORITHM

Parameters required:

Ambient Temperature, Wind Speed, Global POA Irradiance, PV Efficiency

Etot = Global POA irradiance converted to Watts / ft^2

WSmph = Wind Speed converted to mph

$$\Delta T(°F) = \frac{(0.3413 * Etot) * (1 - EFFpv)}{[1 + (0.4 * Sqrt(WSmph))]}$$

$$Tair(°F) = ((9 / 5) * AmbTemp(°C)) + 32$$

$$ModTemp(°F) = \Delta T(°F) + Tair(°F)$$

$$ModTemp(°C) = (ModTemp(°F) - 32) * (5 / 9)$$

Regional Differences in PV Module Performance: RESULTS

- Converted the NSRDB (SAMSON) Data to Global Irradiance and module Temperature (GIT) Data

- Interpolated our Pmax (vs Irrad., Temp.) data to obtain the module's Pmax for each hour (throughout the year) given the irradiance and temperature for that site and time (from the NSRDB weather data)

- Performed these calculations for all 5 PV module technologies, for the 8 sites, and each of the 5 years

- Obtained:

    - ♦ % Occurrence of Pmax < STC Value
    - ♦ Total Annual Energy Production / Module
    - ♦ Annual Efficiency Range
    - ♦ Total Annual Energy / Pmax @ STC

Radiometric Networks and Data Bases for PV Design and Performance Evaluation

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National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

ABSTRACT

Access to reliable sources of solar radiation data is an important aspect of photovoltaic (PV) system design and performance evaluation. The purpose of this paper is to provide an overview of non-commercial sources of solar radiation data and related meteorological information available nationally and internationally to the PV system designer. Important technical aspects of the available resource data are reviewed to prepare the designer for applying the information to a PV system. A summary of measurement types, associated instrumentation, and sources of measured data are presented.

1. INTRODUCTION

The needs for international solar radiation information have increased with the growing interest in the use of renewable energy resources for world energy production and related concerns of global climate change. Funded by the United States Department of Energy, the Resource Assessment Program (RAP) at the National Renewable Energy Laboratory (NREL) has developed a database of national and international renewable resource information in support of these needs. The purpose of this paper is to provide an overview of sources for solar radiation data and related meteorological information used to estimate the amount of solar radiation reaching the earth's surface.

2. BACKGROUND

Proper engineering design and economic evaluation of a PV system depends on the availability of accurate and representative climate information. The availability of accurate, long-term measurements of solar radiation on a global scale is greatly limited in comparison to other surface meteorological data. Historical solar radiation data and related meteorological parameters include observations of:

- bright sunshine duration (typically expressed as a percentage of available daylight hours) measured with a sunshine recorder;
- total hemispherical solar irradiance (termed global horizontal irradiance) measured with a pyranometer;
- direct beam solar irradiance (termed direct normal irradiance) measured with a pyrheliometer mounted in a sun-following tracker;
- diffuse sky solar irradiance measured with a pyranometer shaded from the direct rays of the sun;
- spectral solar irradiance distributions such as ultraviolet, visible, photosynthetically active radiation, and infrared regions measured with instruments similar to those listed above for broadband irradiance components, but equipped with filters or other means of partitioning the irradiance reaching a detector;
- cloud amounts and type (total and opaque clouds according to layer or height above the ground) as recorded by a trained observer.

At present, cloud observations and sunshine duration data are the most prevalent surface-based information available nationally and internationally. Modeling techniques for estimating solar irradiance values from the available meteorological observations continue to be developed (Maxwell, 1994a, 1994b, 1994c; Randall and Bird, 1989). Cloud observations are generally available for hourly intervals. Sunshine data are usually summarized on daily intervals. Time scales for solar radiation data can range from less than hourly to monthly and annual mean daily irradiation totals. Estimates of the uncertainty of these modeled data range from ±10% for monthly mean daily total global irradiance to greater than ±100% for estimates of monthly mean daily total direct normal irradiance (Randall and Bird, 1989).

Satellite remote sensing techniques for estimating solar irradiance at the earth's surface are also under development. Observations from a satellite offer the unique ability to improve the spatial density of solar radiation resource estimates (Czeplak, et al., 1991; Gautier, et al., 1980; WMO, 1981). Research and development activities continue within a number of federal programs to improve modeling techniques using ground-base measurements of solar irradiance.

Users of solar radiation data should understand the source of the information. Were the data measured or modeled? If measured, what instrument was used? How and when was it calibrated? How was it maintained and how were the measurements recorded? If modeled, what physical property was measured (cloud amount, bright sunshine duration, or other?) and which model was used to estimate the solar radiation? In either case, the user should understand the data quality assessment method(s) used to archive the data. Quality assessment of such data and determining proper uncertainty limits are important aspects of successfully applying the information. Marion, et al. (1992) provides a guide to the issues associated with using solar radiation data.

3. INFORMATION SOURCES

The following material is not intended to be a comprehensive inventory of solar radiation information on a global scale. Listed here are those *non-commercial* sources currently in or to be included in the Renewable Resource Data Center (RReDC) at NREL.

3.1 Principal Organizations

There are at least four organizations with meteorological data responsibilities on a global scale. The World Meteorological Organization (WMO) is an agency of the United Nations created, in part, to facilitate international cooperation for making meteorological observations (WMO, 1980). The WMO established the World Radiation Data Center (WRDC) in St. Petersburg, Russia. The International Council of Scientific Unions (ICSU) was established in 1931 as a nongovernmental body to promote international science and its application (CDIAC, 1993). World Data Centers (WDCs) operate under the auspices of the ICSU providing international exchange of data in many earth sciences, including global climate (ICSU, 1993). In the United States, there are also two organizations with missions involving international meteorological data. The United States Air Force operates the Environmental Technical Applications Center (ETAC) providing world wide weather data collection and processing capabilities for the Department of Defense (Squires, 1994). The United States Department of Commerce provides funding for the National Climatic Data Center (NCDC) through the National Oceanic and Atmospheric Administration (NOAA). As its name implies, the NCDC is a source of climate data with surface meteorological data for over 15,000 worldwide stations (Plantico, 1994).

3.2 National Information at NREL

The Renewable Resource Data Center (RReDC) is an Internet-accessible information source for solar radiation resources provided by the National Renewable Energy Laboratory (NREL). The RReDC provides data and information relevant to the design and performance evaluation of PV systems. The address is http://rredc.nrel.gov.

3.2.1 National Solar Radiation Data Base Products

The Daily Statistics Files (DSFs) for each of the 239 cities in the *National Solar Radiation Data Base (NSRDB)* are available from the RReDC. Hourly data from 1961 through 1990 were used to generate the statistical summary information which includes maximum, minimum, standard deviation, and other useful summary information for PV design.

The new *Typical Meteorological Year Version 2 (TMY2)* data set is also available on the RReDC. A composite of typical meteorological months, the TMY2 provides hourly NSRDB data for each of the 239 locations representative of average weather conditions. Not intended for designing PV systems because the data are not representative of extreme conditions, the TMY2 can provide performance comparisons between systems and different locations.

The complete text and data summaries from NREL's *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors* is also available from the RReDC. Here, monthly summary statistics of solar radiation available to a variety of collector types and surface meteorological conditions are available for the 239 NSRDB locations. The uncertainty estimates for each data element are also provided to guide the designer.

The complete NSRDB with 30 years of hourly data for 239 cities is available on CD-ROM (set of 3 for all U.S.) from the National Climatic Data Center as the *Solar and Meteorological Surface Observing Network (SAMSON).*

3.2.2 NOAA 1977-1980

The National Oceanic and Atmospheric Administration (NOAA) operated a 39-station network of solar measurement stations from 1977 through 1985. Hourly data from the *SOLRAD* network are available for the period 1977 through 1980. These data represent the most complete national measurement effort in the history of the U.S. and provides the most comprehensive data set with measured direct normal solar radiation. A network map is available on the RReDC for determining the station locations during this period.

3.2.3 WEST Associates

Measured global and direct normal solar irradiance at 15-minute intervals is available from the *Western Energy Supply &Transmission (WEST) Associates* data set. A consortium of electric utilities, the WEST Associates network of 52 stations provides data for the period 1976 through 1980 for the southwestern U.S. Data from this network-period were used to develop and test modelling techniques used in the production of the NSRDB.

3.2.4 SEMRTS

The DOE *Solar Energy and Meteorological Research Training Sites (SEMRTS)* project resulted in a 1-minute set of measured solar radiation and other surface meteorological data elements from 5 universities. Probably the best high-resolution data sets available to date, the SEMRTS data period of record is generally 1980 to 1981. Data are available from Fairbanks, Alaska; Atlanta, Georgia; Albany, New York, San Antonio, Texas; and Davis, California.

3.2.5 HBCU

Five-minute averages of 10-second samples of measured global, diffuse, and direct normal solar radiation are available from the 6-station *Historically Black Colleges & Universities (HBCU) Solar Measurement Network.* Fully operational in December 1985, the HBCU network continues to provide high quality solar radiation measurements as part of the DOE/NREL Resource Assessment Program. The HBCU participants are:

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

3.2.6 SRRL

The *Solar Radiation Research Laboratory (SRRL)* was begun at NREL in 1979 for the purposes of measuring solar radiation and other surface meteorological elements to build a resource climatology, to provide outdoor calibrations of pyranometers and pyrheliometers, and to support the outdoor measurement needs of the renewable technologies. Located on South Table Mountain (elevation 1829 m or 6,000 ft), the SRRL provides an unobstructed horizon for solar measurements. The *Baseline Measurement System (BMS)* consists of the following measured data elements:

- Global Horizontal Irradiance (0.3 µm to 3.0 µm)
- Global Horizontal Irradiance (0.8 µm to 3.0 µm)
- Diffuse Horizontal Irradiance (0.3 µm to 3.0 µm)
- Direct Normal Irradiance (0.3 µm to 3.0 µm)
- Direct Normal Irradiance (0.8 µm to 3.0 µm)
- Direct Normal Total Ultraviolet Irradiance (0.295 µm to 0.385 µm)
- Direct Normal Irradiance (500 nm photometer)
- Global Irradiance on South-facing, 40° Tilted Surface (0.3 µm to 3.0 µm)
- Global Normal Irradiance (Pyranometer on 2-Axis Solar Tracker)
- Global Irradiance on 1-Axis Tracker (North-south axis of rotation)
- Total Ultraviolet Irradiance on Horizontal Surface (0.295 µm to 0.385 µm)
- Wind Speed at 10 m AGL
- Wind Direction at 10 m AGL
- Dry Bulb Temperature at 2 m AGL
- Relative Humidity at 3 m AGL
- Barometric Pressure at 2 m AGL.

Quality-assessed hourly data from the BMS (1981-1991) are available on diskette (Marion, 1993). Internet access to the historical and current 5-minute BMS data is planned for completion in 1996.

3.2.7 Spectral

A collection of spectral irradiance measurements (2 nm resolution from 0.3 μm to 1.1 μm) are available from three locations:

- San Ramon, California (PG&E)
- Golden, Colorado (SERI)
- Cape Canaveral, Florida (FSEC).

More than 3000 measured solar spectra are cataloged from measurements taken from 1986 through 1988. Coincident broadband irradiance measurements and all-sky photographs are also part of this archive.

3.2.8 Circumsolar

As part of the DOE Energy Resource Assessment Program, the Lawrence Berkeley Laboratory developed an instrument to measure the amount of forward scattering around the solar disc as a function of atmospheric conditions. A collection of 10-minute observations from the following locations during the period 1976 - 1980 are available:

- Boardman, Oregon
- Colstrip, Montana
- Argonne, Illinois
- Atlanta, Georgia
- Edwards AFB, California
- China Lake, California
- Barstow, California
- Albuquerque, New Mexico (2 locations)
- Fort Hood, Texas (2 locations).

This 200 megabyte data base contains detailed intensity profiles of the solar and circumsolar region (out to 3° from the sun's center), the total and spectrally divided direct normal radiation, and the total hemispherical solar radiation (global) in the horizontal plane and the plane facing the sun. Measurements were made by four automatic scanning circumsolar telescopes that operated about 16 hours a day. The number of data sets per station ranges from 616 to 38,405. These data would be of interest to designers of concentrating PV collectors.

3.3 International Solar Radiation Information Sources

The following sources provide solar radiation information on a global or continental scale and have been identified during our development of the International Renewable Resource Database (IRRD) at NREL. They are listed alphabetically and include contact information. The IRRD also contains summary statistics, radiation atlases, and technical papers relating to solar radiation resources for 31 countries. Many of these country-specific items were found by on-line bibliographic searches of the scientific literature listed in Table 1.

3.3.1 ASHRAE

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) publishes the *Handbook of Fundamentals* which they update periodically. Chapter 24, "Weather Data," contains tabulated seasonal temperature and prevailing wind information for 856 locations in the United States and Canada and 227 international cities. Chapter 27, "Fenestration", contains tabular estimates of the direct normal solar radiation for monthly solar hour intervals according to site latitude (applicable to any location). Contact the author for more information about these data or about Technical Committee 4.2 Weather Information.

3.3.2 Baseline Solar Radiation Network

In 1990, the World Meteorological Organization (WMO) and International Council of Scientific Unions (ICSU) Joint Scientific Committee (JCS) for the World Climate Research Program (WCRP) began planning a world-wide network to continuously measure radiative fluxes at the earth's surface (WMO, 1991). The Baseline Solar Radiation Network (BSRN) began data collection by January 1992. Measurements of solar radiation and atmospheric properties from 27 stations will be available from this global network. A detailed data transmittal format has been established for the BSRN (WMO, 1993). Data are archived at the World Radiation Monitoring Center (WRMC). The WRMC is run by the Division of Climate Sciences, Department of Geography, ETH Zurich, Winterhurerstrasse 190, CH 8057, Zurich, Switzerland.

3.3.3 Carbon Dioxide Information Analysis Center

The Carbon Dioxide Information Analysis Center (CDIAC) acquires, quality-assures, and distributes to the scientific community numeric data packages (NDPs) and computer model packages (CMPs) dealing with topics related to global climate change (Boden et al., 1993). Numeric data are available in the printed NDPs and CMPs, in CD-ROM format, and from an anonymous file transfer protocol directory on Internet. CDIAC is funded by the U.S. Department of Energy to support its Global Change Research Program. All CDIAC information products are available at no cost. Presently, 42 NDPs and 2 CMPs are available.

The following NDPs offer opportunities for solar radiation resource assessment:

- NDP-012 (1985) *Climatic Data for Northern Hemisphere Land Areas: 1851-1980*
- NDP-016 (1985) *Climatic Data for Selected U.S. and Canadian Stations 1941-1980*
- NDP-021/R1 (1991) *Historical Sunshine and Cloud Data in the United States*
- NDP-026 (1988) *Climatological Data for Clouds over the Globe from Surface Observations*
- NDP-040 (1993) *Daily Temperature and Precipitation Data for 223 USSR Stations*
- NDP-041 (1992) *The Global Historical Climatological Network: Long-Term Monthly Temperature, Precipitation, Sea Level Pressure, and Stations Pressure Data*

Table 1. On-line Databases

Database Name	Agency	Phone
Energy Science & Technology (EST)	U.S. Department of Energy Office of Scientific and Technical Information (OSTI) P.O. Box 62 Oak Ridge, TN 37831	(615)576-1189
Meteorological and Geoastrophysical Abstracts (MGA)	American Meteorological Society (AMS) 45 Beacon St. Boston, MA 02108	(617)227-2425
COMPENDEX*PLUS™	Engineering Information, Inc. (Ei) Castle Point on the Hudson Hoboken, NJ 10017	(201)216-8500
PASCAL	France Institut de l'Information Scientifique et Technique (INIST) 2, allee du Parc de Brabois F-54514 Vandoeuvre-les-Nancy Cedex France	83504600
INSPEC	Institution of Electrical Engineers (EE) Michael Faraday House Six Hills Way Stevenage, Herts SG1 2AY England	0438 742857
NTIS Bibliographic Data Base	U.S. National Technical Information Service (NTIS) 5285 Port Royal Rd. Springfield, VA 22161	(703)487-4929
Aerospace Database	American Institute of Aeronautics and Astronautics (AIAA) Technical Information Division 555 W. 57th St., Suite 1200 New York, NY 10019	(212)247-6500
SPIN (Searchable Physics Information Notices)	American Institute of Physics (AIP) 500 Sunnyside Blvd. Woodbury, NY 11797	(516)576-2262
GEOBASE	Elsevier/Geo Abstracts Regency House 34 Duke St. Norwich NR3 3AP England	0603 626327
Geological Reference File (GeoRef)	American Geological Institute (AGI) GeoRef Information System 4220 King St. Alexandria, VA 22302-1507	(703)379-2480 (800)336-4764

The Center also recently announced the availability of data for up to 205 observing stations in China (DOE, 1993).

Contact: Carbon Dioxide Information Analysis Center, MS-6335, Building 1000, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6335. Tom Boden, CDIAC, (615) 574-0390.

3.3.4 CIBSE Guide

The Chartered Institution of Building Services Engineers (CIBSE) first published an engineering manual for the United Kingdom in 1940. Now in its fifth edition, the *CIBSE Guide* provides building design data (wet- and dry-bulb temperature, precipitation, and sunshine duration) for 350 world locations. The design temperature data were taken from the ASHRAE *Handbook of Fundamentals* (ASHRAE, 1977). Tabular solar radiation data for Kew, SE England, from 1959 through 1968, are presented by month in ten equal bands (statistical bins). Generalized solar radiation data estimates are presented in terms of solar elevation and azimuth angles and also according to station latitude. The *Guide* also provides a thorough review of the solar radiation estimation methods used to make the generalized tables of direct normal, diffuse, and global irradiance on horizontal and vertical surfaces with various azimuthal orientations. Design data are also presented in map form for the UK. The concept of typical meteorological year information is described in the section on *Example Weather Year.*

Contact the Chartered Institution of Building Services Engineers, Delta House, 222 Balham High Road, London SW12 9BS.

3.3.5 Commission of the European Communities

The Commission of the European Communities has published two references with solar radiation information.

The *European Solar Radiation Atlas* is a two volume publication of monthly and annual availability of solar radiation for western Europe and parts of the Middle East (CEC, 1984a; CEC, 1984b). The maps and tabular summaries were made from sunshine duration and global solar irradiation observations at 340 meteorological stations in Europe and the Middle East over a ten year period. Volume 1 provides spatial distributions of the global horizontal solar irradiation and selected statistics such as energy above given thresholds and frequency distributions. Volume 2 provides estimates of the irradiation available on south-facing inclined surfaces and statistical summaries.

The *Climatic Data Handbook for Europe* provides climatic data for the design of solar energy systems (Bourges, 1993). Monthly mean daily total and daily peak solar radiation data are provided in tabular form for 37 European cities. Estimates include the global irradiation on collectors with range of azimuth and tilt angles. The handbook also summarizes heating and cooling degree-day data for 186 cities using base temperatures of 14°, 16°, 18°, and 20° C.

Contact Verlag TÜV Rheinland GmbH and SIC, Brussels for *European Solar Radiation Atlas* and Center d'Energétique, Ecole des Mines de Paris, 60, Bd Saint-Michel, 75272 PARIS CEDEX 06, France or Energy Research Group, School of Architecture, University College Dublin, Richview, Clonskeagh, DUBLIN 14, Ireland regarding the availability of the computer programs and data described in the *Climate Data Handbook for Europe.*

3.3.6 Global Atmospheric Watch

In 1989, the WMO integrated the background air pollution monitoring (BAPMON) stations, in operation since the mid-1960's, with the Global Ozone Observing System (GO_3OS), started in 1957, to form the Global Atmospheric Watch System (GAW) (WMO, 1992). Solar radiation measurements are presently being incorporated at six sites in this developing global network (China, Indonesia, Nepal, United States, and 2 stations in South America). Data from GAW is forwarded to the World Radiation Monitoring Center (WRMC).

Contact the WRMC at the Division of Climate Sciences, Department of Geography, ETH Zurich, Winterhurerstrasse 190, 8057 Zurich, Switzerland.

3.3.7 Global Energy Balance Archive

As part of the WMO's World Climate Program-Water, the Geographisches Institut, Eidgenössische Technische Hochschule (ETH) in Zurich, Switzerland has developed the Global Energy Balance Archive (GEBA). Solar radiation data, typically the mean daily global horizontal radiation, from about 200 stations have been processed into GEBA (Ohmura, 1989).

Contact the WRMC at the Division of Climate Sciences, Department of Geography, ETH Zurich, Winterhurerstrasse 190, 8057 Zurich, Switzerland.

3.3.8 Sandia National Laboratories (SNL)

The Photovoltaic Design Assistance Center at SNL has prepared a design manual for photovoltaic (PV) solar electric conversion systems (SNL, 1988). The manual provides world maps depicting monthly mean daily total global irradiation based on the work published by the University of Wisconsin (Löf, et al., 1966)

Contact Peggy Valencia, Media Specialist, Sandia National Laboratories, Division 6218, Albuquerque, New Mexico 87185, (505)844-3698.

3.3.9 University of Massachusetts Lowell

In 1991, the University of Lowell Photovoltaic Program assembled the *International Solar Irradiation Database, Version 1.0* for personal computers (IBM- and Apple-compatible). With funding from the U.S. Department of Energy, the database was produced using data from many sources. Monthly mean daily total global irradiation data are available for 110 countries. The period of record varies with country and station. The unbiased standard deviation of the data is also presented for the monthly and annual means. Limited data quality assurance tests were applied to the database entries. The source contacts or references are included on the single diskette containing the database.

Contact Dr. Bill Berg, Photovoltaic Program Coordinator, University of Massachusetts Lowell, 1 University Avenue, Lowell, MA 01854, (508)934-3376.

3.3.10 University of Wisconsin

The College of Engineering published *World Distribution of Solar Radiation* (Löf, et al., 1966) which contains monthly mean daily total global irradiation data for over 900 cities around the world. The information is presented in tabular and map forms. Much of the solar radiation information is based on bright sunshine duration measurement records rather than pyranometer measurements.

Although somewhat dated, this report offers good spatial representation of solar radiation for the world.

Contact the University of Wisconsin, College of Engineering, Wendt Library, 250 North Randall, Madison, WI 53706, (608) 263-1586.

3.3.11 World Meteorological Organization (WMO)

The WMO published a report with large-format world maps showing isopleths of the percent possible mean daily total global horizontal irradiation base on model estimates from about 18 months of satellite observations (WMO, 1981). The report provides a summary of the modeling technique including the use of ground-truth measurements.

Contact the American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693, (617)227-2425.

3.3.12 World Radiation Data Center

More than 20 years ago, the WMO established the World Radiation Data Center (WRDC) in what is now St. Petersburg, Russia. The mission of the WRDC continues to include the compilation of solar radiation measurements taken around the world by contributing countries. These data are primarily recordings of bright sunshine duration or daily integrated values of global solar radiation. The WRDC periodically publishes tabular summaries of these data from as many as 470 locations world wide in their *Solar Radiation and Radiation Balance Data, The World Network* (WRDC, 1992). The IRRD has copies of this periodical dating from March 1979.

Contact the National Climatic Data Center, Research Customer Service Group, Federal Building, Asheville, NC 28801-2733, telephone (704) 271-4800, FAX (704) 271-4876, Internet orders@ncdc.noaa.gov.

3.4 Meteorological Data Sources

Certain meteorological elements can be used as input to atmospheric radiation models to estimate the solar radiation resources (Randall and Bird, 1989; Iqbal, 1983; Dahlgren, 1984). Observations of total and opaque cloud amounts, bright sunshine duration, atmospheric water vapor content at the surface or an atmospheric profile, barometric pressure, aerosols, or turbidity can generally be used in estimating solar radiation resources. These model estimates can be used to:

- estimate solar radiation resources in the absence of radiometer measurements
- improve the spatial resolution of available solar radiation data sets by using nearby meteorological observing stations,
- provide climatological estimates of solar radiation by using historical meteorological observations.

3.4.1 National Climatic Data Center

NCDC is the office for the World Data Center-A for Meteorology and exchanges foreign data with the other World Data Centers in Japan, China and the CIS. NCDC also works with international institutions such as the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) to develop standards for exchanging data and making data more accessible (Plantico and Lott, 1994). In 1990 the NCDC, the U.S. Air Force's Environmental Technical Applications Center Operating Location A (USAFETAC/OL-A), and the U.S. Navy's Fleet

Numerical Meteorology and Oceanography Detachment was established as the Federal Climate Complex (FCC). As a result of these associations, the NCDC has access to many sources of international meteorological observations and has products in the form of summary reports and digitized data sets.

The following products are useful for international solar radiation resource assessment.

- *Monthly Climatic Data for the World (MCDW)* - Publication with monthly mean values of surface and/or upper air measurements from over 3000 stations worldwide.
- *Comprehensive Aerological Reference Data Set (CARDS)* - Digital data set of monthly averages for about 7000 worldwide stations.
- *Summary of Day (TD3210)* - Digital data set with sunshine duration as one element for National Weather Service (U.S.) and Department of Defense (foreign) sites.
- *USAFETAC.OL-A Real Time Nephanalysis (RTNEPH)* - Digital data set of global gridded cloud analysis with a 25 nautical mile spatial resolution.
- *Air Weather Service's (AWS) DATSAV2 Surface (TD9950)* - Digital data set of hourly synoptic observations available from the Global Telecommunication System (GTS) and other sources.
- *International Station Meteorological Climate Summary (ISMCS)* - Version 3.0 of this read-only, compact disk (CD-ROM) product contains detailed climatological summaries for more than 2000 locations.
- *Global Daily Data* - A CD-ROM with summary data for about 10,000 stations.
- *Global Upper Air Climatic Atlas (GUACA)* - A two-volume CD-ROM set with monthly upper air statistics for 15 vertical levels in a 2.5 x 2.5 degree grid for the Northern and Southern Hemispheres.

Contact the NCDC Climate Services Branch, Federal Building, Asheville, NC 28801-2733, attention: Bill Skinner, telephone (704) 271-4800, FAX (704) 271-4876, Internet orders@ncdc.noaa.gov.

3.4.2 United States Air Force Environmental Tactical Applications Center (USAFETAC)

Hourly and three-hourly meteorological observations from around the world are available from the WMO's Global Telecommunications System (GTS). In the United States, these observations are collected and decoded at the Air Force Global Weather Central where they are used for forecasting purposes. The data are then sent to USAFETAC Operating Location A, collocated with the NCDC in Asheville, North Carolina, where they are further decoded, reviewed for quality, and archived in DATSAV2 format (Squires, 1994).

The DATSAV2 archive format includes meteorological observations suitable for use as input data to existing solar radiation estimating techniques (see section 2). Meteorological data from surface observations at about 20,000 stations, with nearly 10,000 of these currently active, are available from the NCDC as a digital data set TD9950. The data are collected from the GTS and the Automated Weather Network (Plantico and Lott, 1994).

Contact the NCDC Climate Services Branch, Federal Building, Asheville, NC 28801-2733, attention: Bill Skinner, telephone (704) 271-4800, FAX (704) 271-4876, Internet orders@ncdc.noaa.gov.

4.0 CONCLUSIONS

There are a variety of sources for national and international solar radiation data available to the PV designer. The DOE/NREL Renewable Resource Data Center (RReDC) provides Internet access to the principal body of information (reports, data files, maps, tutorials, etc.) for the United States. Sources of international resource information were identified with the help of on-line bibliographic searches, exchanges with colleagues from foreign countries, and direct requests by us to solar radiation monitoring network operators for available radiation measurement data and analyses. Twelve sources of international solar radiation and related meteorological data were described briefly.

Historically, solar radiation measurements have been limited in scope and generally not part of routine meteorological monitoring. This is because solar radiation measurements are not used for meteorological forecasts or aviation-related applications. Therefore, much of the available solar radiation data have been derived from model estimates based on typical synoptic observations of cloud amount, relative humidity, horizontal visibility, or sunshine recorders.

The recent interest in global climate change and the use of solar radiation as an energy source have increased the number of solar radiation monitoring networks under development and in operation around the world. Hopefully, this interest will provide the much needed stability for long-term data collection, resulting in an accurate climatological database of measured solar radiation resources.

Quality assessment of solar radiation data and determining proper measurement or model uncertainty limits are important aspects of successfully applying the information.

The World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) are two international organizations sponsoring the collection, quality assessment, archival, and dissemination of solar radiation data. The National Climatic Data Center (NCDC) and the Carbon Dioxide Information Analysis Center (CDIAC) are two sources of world climate data, including solar radiation, in the United States.

ASHRAE Technical Committee 4.2 Weather Information is working to incorporate more international data into design data sets and climatological summaries. The DOE/NREL Resource Assessment Program is similarly working to include more foreign sources of solar radiation data in the RReDC. The reader is encouraged to forward information concerning sources of national and international solar radiation measurements to the author.

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6.0 ACKNOWLEDGEMENTS

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RADIOMETRIC MODELS AND GENERATION OF THE U.S. NATIONAL SOLAR RADIATION DATA BASE

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Introduction

More than 90% of the solar radiation data in the National Solar Radiation Data Base(NSRDB Vol. 1 1992) were either derived using a METeorological/STATistical (METSTAT) model or were modified using a procedure that involved METSTAT. The impact of modeling on the NSRDB is not unique. All of the data in the SOLar radiation and METeorological (SOLMET) data base and the Typical Meteorological Year (TMY) data sets derived from it were affected in one way or another by modeling (SOLMET Vol. 2 1979).

This paper describes several types of solar radiation models and the models used in producing both the SOLMET and NSRDB data bases. The results of evaluations of METSTAT provide insight into the overall quality of the NSRDB. Differences between the SOLMET and NSRDB data bases are then examined with respect to the different models used in their development. This provides the reader with information regarding the effect of modeling on these data bases and their relative strengths and weaknesses.

The paper concludes with a brief description of current research at the National Renewable Energy Laboratory (NREL) involving the use of a simplified version of METSTAT to estimate monthly mean daily-total solar radiation for every point on a uniform grid covering the United States, Mexico, and the Caribbean.

General Description of the NSRDB

The National Solar Radiation Data Base (NSRDB) consists of 30 years (1961-1990) of hourly values of 5 solar radiation elements and 15 meteorological elements for 239 stations in the United States and its territories. All National Weather Service (NWS) stations that had continuously collected the meteorological data needed for estimating solar radiation from 1961-1990 were included in the data base. Figure 1 is a map of the United States showing the location of the 239 stations. The Primary stations are those locations for which at least one year of measured solar radiation data were available. The solar radiation data for the Secondary stations were modeled using the model described in this paper.

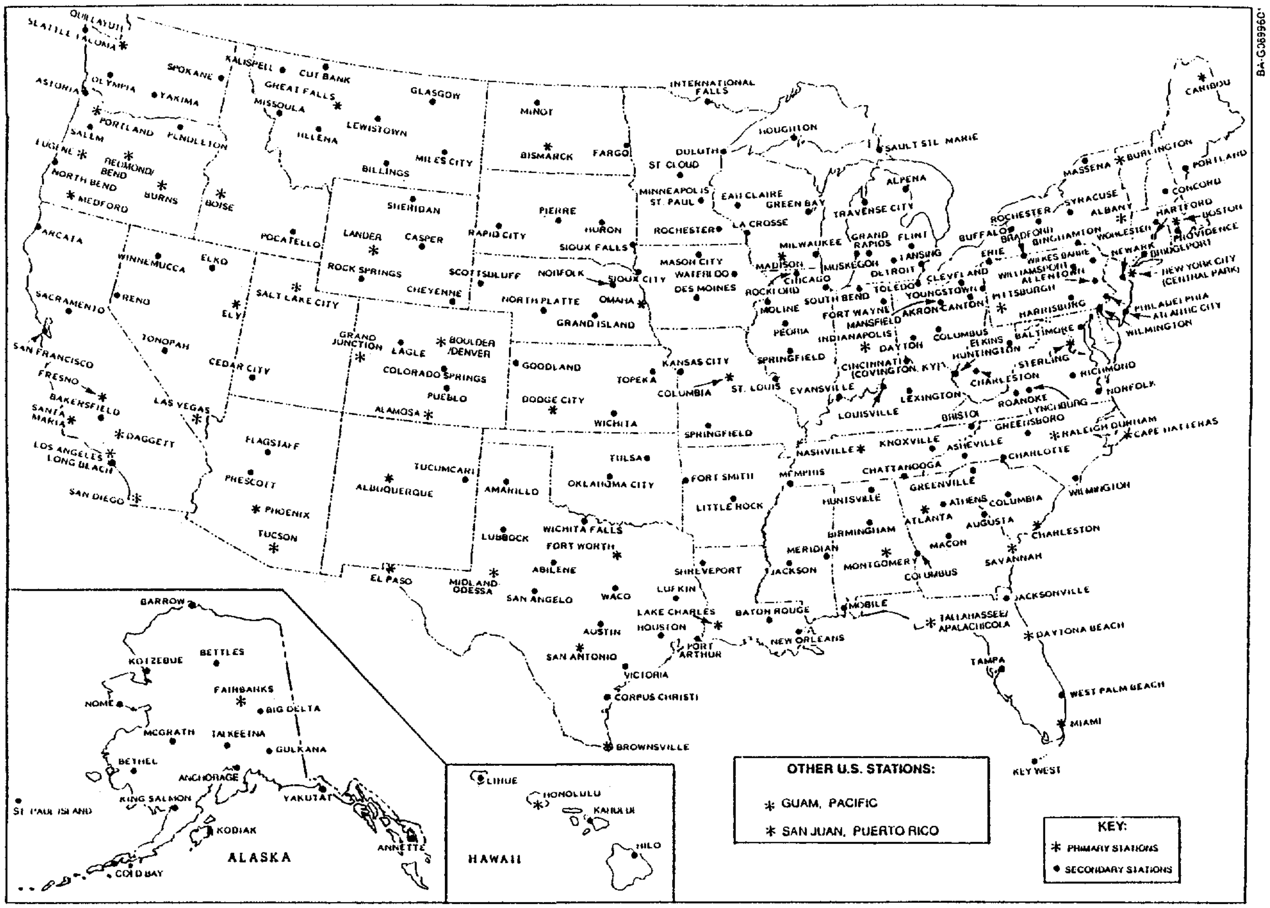

Fig. 1. Map showing the location of all the Primary and Secondary Stations in the NSRDB

The solar radiation elements in the NSRDB include:

Global horizontal radiation in $Watts/m^2$
Direct normal radiation in $Watts/m^2$
Diffuse horizontal radiation in $Watts/m^2$
Extraterrestial radiation (ETR) in $Watts/m^2$
Direct normal ETR in $Watts/m^2$

The meteorological elements in the NSRDB include:

Total sky cover in tenths
Opaque sky cover in tenths
Dry-bulb temperature in °C
Dew-point temperature in °C
Relative humidity in percent
Atmospheric pressure in millibars
Wind direction in degrees
Wind speed in m/s
Horizontal visibility in kilometers
Ceiling height in meters
Present weather
Total precipitable water vapor in mm
Aerosol optical depth (broadband - solar spectrum)
Snow depth in cm
Days since last snowfall

The NSRDB data are available in two formats, TD-3282 and synoptic. The TD-3282 format is similar to the TD-3280 format used by the National Climatic Data Center (NCDC) to archive meteorological data. This format uses daily interleaving of elements and facilitates ordering data for individual elements. The TD-3282 format is available only on magnetic tape or floppy disks.

The synoptic format presents all of the 20 elements in each record for each hour. This is likely the format with which most users are familiar. Figure 2 shows data for Albuquerque, NM in the synoptic format. The entire NSRDB data base is available from the NCDC on three CD-ROM disks at a very modest cost.

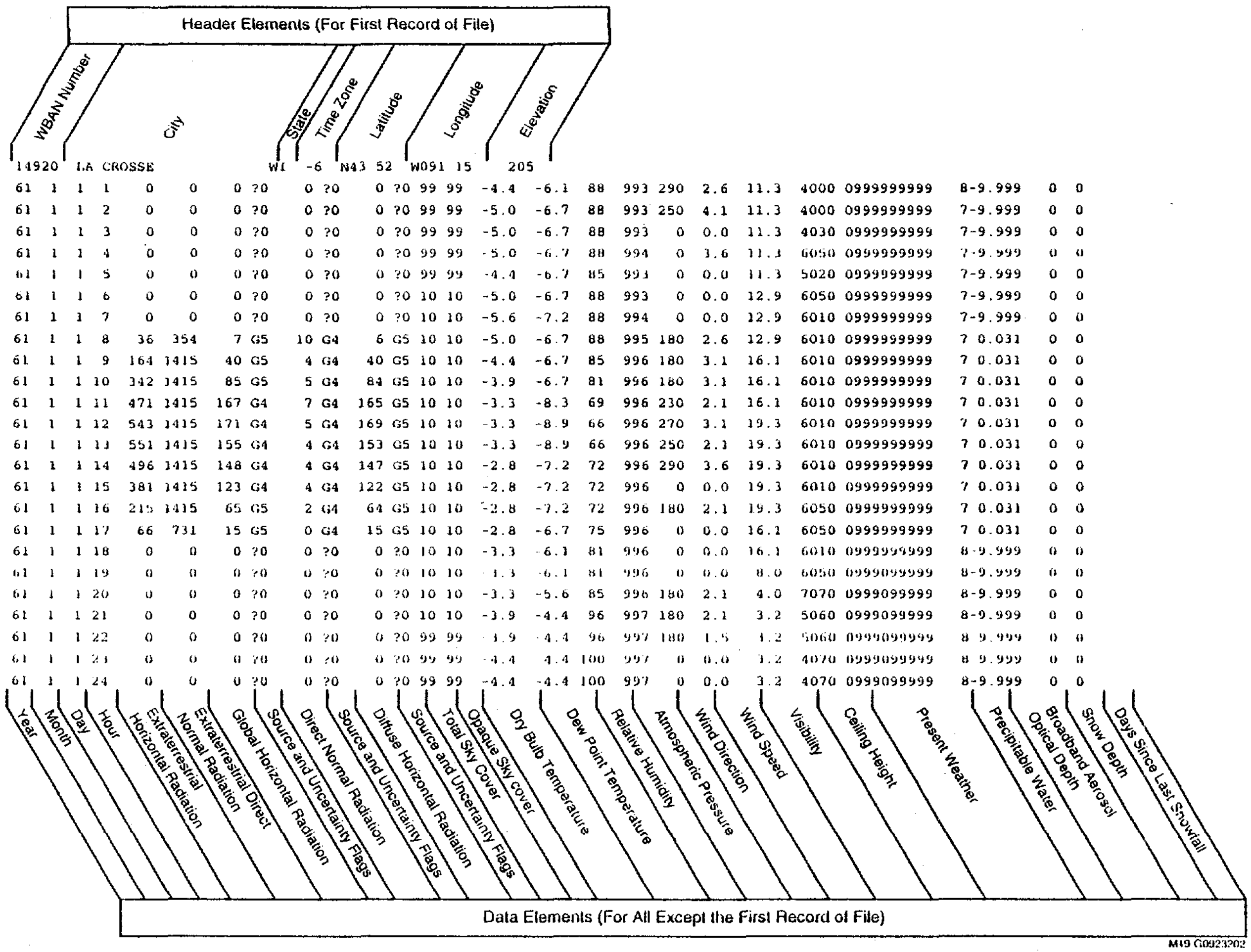

Fig. 2. Data for Albuquerque, NM in the NSRDB synoptic format

As shown on Figure 2, the synoptic format contains source and uncertainty flags for the three surface solar radiation elements. These flags give the user the option of selecting data on the basis of source and/or uncertainty.

In addition to the hourly values, statistical summaries have been prepared for the entire period of record for all stations. Statistics have been computed for each station-year-month and for each station-year. In addition, monthly and annual statistics have been computed for the 30 years from 1961 through 1990. The following statistics are available for each of the time periods indicated:

Hourly Statistics

- Mean and standard deviation hourly radiation in Wh/m^2 for global, direct, and diffuse

- In addition to the above statistics, the hourly data have been placed in 24 50-Wh/m^2 bins from 0 to 1,200 Wh/m^2. The mean number of hourly values falling into each bin is recorded. This statistic can be used to plot histograms and/or determine cumulative frequency distributions.

Daily Statistics

- Mean and standard deviation daily-total radiation at the earth's surface in Wh/m^2 for global, direct, and diffuse elements

- Mean global horizontal and direct normal daily-total ETR in Wh/m^2

- Mean total and opaque sky cover

- Mean total precipitable water vapor in centimeters

- Mean broadband aerosol optical depth

- Maximum daily temperature in °C

- Minimum daily temperature in °C

- Mean daily temperature in °C

- Mean daily temperature during daylight hours in °C

- Mean relative humidity in percent

- Heating and cooling degree days

- Mean wind speed

Quality Statistics

- Percentage of the hourly values of global, direct, and diffuse radiation to which each source and uncertainty flag has been assigned

Persistence Statistics

- Number of sequential days for which the daily-total radiation (global, direct, and diffuse) exceeded specified thresholds from 0 to 10,000 Wh/m^2

- Number of sequential days for which the daily-total radiation (global, direct, and diffuse) was less than specified thresholds from 0 to 10,000 Wh/m^2

All of these statistical products can be obtained on floppy disks from NCDC or NREL. More detailed information on the NSRDB and the products produced from it are available in the NSRDB User's Manual (NSRDB Vol. 1 1992).

Solar Radiation Models

The assessment of solar radiation resources will always require the use of models because solar radiation is a viable energy resource, for certain applications, at virtually any location on the surface of the earth. The blanket coverage that this requires cannot be provided by actual measurements of solar radiation. There will always be a shortage of solar radiation measurements which means that some form of model will be required. This is clear from the fact that more than 90% of the solar radiation data in the NSRDB was model generated.

There are many ways of categorizing models, but the one most useful for our application identifies four types: physical, parametric, simple regression, and conversion. Physical models employ wavelength dependent algorithms that simulate the actual physical interactions (quantum, Rayleigh, Mie, and optical) between solar radiation and the molecules and particles in the atmosphere. The spectral transmittances calculated by these models are integrated across the solar spectrum to obtain the broadband transmittance for each atmospheric constituent. Typically, the input data for models of this type are based on standard atmospheres such as the U.S. Standard (USS) described by Iqbal (1983). These standard atmospheres include information on the types and size distributions of aerosols. Although interesting for theoretical studies and for providing a plane of reference for other models, physical models are of little value for estimating solar radiation resources because information on the atmospheric constituents are never known in the detail required for such models.

The algorithms for parametric models use readily available or derivable meteorological parameters such as total cloud cover, precipitable water vapor, aerosol optical depth, and ozone. The algorithms do not simulate the actual molecular or particulate interactions, but they do calculate broadband solar transmittances for each of the meteorological input parameters as well as Rayleigh and uniformly mixed gas transmittances. The algorithms are capable of accurately representing the effects of the input parameters on the solar radiation observed at the Earth's surface and should not show undue seasonal or geographic biases.

Simple regression models are usually used when the input variables required for parametric models are not available or there is not enough information to develop a parametric model. We will define simple regression models as those that calculate solar radiation values directly. In other words, they do not calculate transmittances for each of the atmospheric constituents. Rather, the algorithms calculate global, direct, or diffuse radiation directly from the input parameters.

Because the algorithms usually use a limited number of input parameters and do not represent physical processes, the regression coefficients are usually applicable for only a limited set of conditions. For example, the simple regression models employed to estimate solar radiation for the SOLMET data base (SOLMET Vol. 2 1979) used third-order polynomials in zenith angle and opaque cloud cover to estimate global horizontal radiation. Separate coefficients were developed for each of the 26 locations for which measured data were available and the equations were applied only within areas judged to have similar climatic conditions. As a result, the differences between the SOLMET and NSRDB data bases are directly related to the 26 regions within which the SOLMET regression models were applied (Maxwell, Marion, and Myers 1995).

Conversion models are used to estimate missing solar radiation elements from elements for which measured data are available. For example, the ADIPA (Randall and Whitson 1977) and DISC (Maxwell 1987) models estimate direct normal radiation from global horizontal radiation and the Hay (1979) and Perez (Perez et al. 1983) models estimate radiation on tilted surfaces from global, direct, and diffuse radiation. Conversion models are often of the regression type, hence, their effectiveness may be limited to specific regions or conditions.

The SOLMET Models

Simple regression models developed for each of the 26 SOLMET stations were used to estimate global horizontal data for the SOLMET data base and conversion models developed by the Aerospace Corporation (Randall and Whitson 1977) were used to estimate direct normal values from global horizontal values.

Third-order polynomials were used to estimate global horizontal radiation for clear skies (SRCS) as a function of zenith angle (ZA),

$$SRCS = a_o + a_1 \cos ZA + a_2 \cos^2 ZA + a_3 \cos^3 ZA \qquad (1)$$

Synthetically calibrated clear sky data were used to derive coefficients (a_o, a_1, a_2, a_3) for each of the 26 SOLMET stations. Different coefficients were derived for morning (AM) and afternoon (PM) conditions and different values for ao were derived for each month.

The clear sky estimates of solar radiation were then modified according to actual sky conditions, indicated by cloud cover, sunshine, and rain data. The modifing algorithms incorporated a third order polynomial for opaque cloud cover and linear terms for sunshine and rain. When both opaque cloud cover and sunshine data were available, the algorithm took on the form,

$$MOD = b_0 + b_1 SS + b_2 OPQ + b_3 OPQ^2 + b_4 OPQ^3 + b_5 RN \qquad (2)$$

where SS is that portion of the hour during which the sun shown brightly,
OPQ is opaque cloud cover in tenths, and
RN is 1 if precipitation is present and 0 otherwise.

These algorithms were used to estimate global horizontal radiation, at the station for which they were developed, for those hours when measured data were missing. They were also used to estimate all of the global data for stations for which no solar radiation measurements had been made (called ERSATZ (synthetic) stations). With the exception of the station in Central Park, New York City, each SOLMET station functioned as a control station for a group of ERSATZ stations that were deemed to have a similar climate. Central Park was considered to be unlike any other station.

At the time the SOLMET data base was developed there were good models for estimating direct normal radiation under clear skies, using meteorological parameters. However, there were no proven algorithms applicable to cloudy conditions and there were insufficient direct normal data to develop an algorithm. Therefore, Randall and his associates, Whitson and Biddle, developed algorithms for estimating direct normal radiation using global horizontal radiation as the only independent variable (Randall and Whitson 1977; and Randall and Biddle 1981). They used a few years of direct normal data from Albuquerque, NM; Fort Hood, TX; Livermore, CA; Maynard, MA; and Raleigh, NC to develop the ADIPA and ETMY models.

The ADIPA model was used to estimate period-of-record direct normal data for the 26 SOLMET control stations. ADIPA used ogives (look-up tables of empirical distributions) to simulate the distribution of the direct normal values. The ETMY model estimated direct normal data for a Typical Meteorological Year (TMY) for the 222 ERSATZ stations. ETMY did not use ogives to distribute the direct normal values.

METSTAT

METSTAT is a parametric model developed to support the production of the National Solar Radiation Data Base (NSRDB Vol. 1 1992 and NSRDB Vol. 2 1995). Our objective was to develop a computer model capable of accurately simulating monthly and annual solar radiation data sets. This objective does not require the accurate estimation of individual hourly values. In fact, under partly cloudy skies, it is impossible to accurately estimate individual hourly values, because the position of the clouds is not known. Under these conditions, the measured hourly values will fluctuate greatly during the day, as the position of the clouds change with respect to the sun.

Model Description

METSTAT is a computer model that can be used to calculate hourly values of solar radiation at any location on the earth's surface, for which the required meteorological input variables are available. The block diagram of the model shown in Fig. 3 identifies the input variables. The deterministic algorithms have been designed to meet the objective of creating data sets with accurate monthly and annual means. The statistical algorithms randomly vary the input parameters such that monthly data sets exhibit representative statistical characteristics.

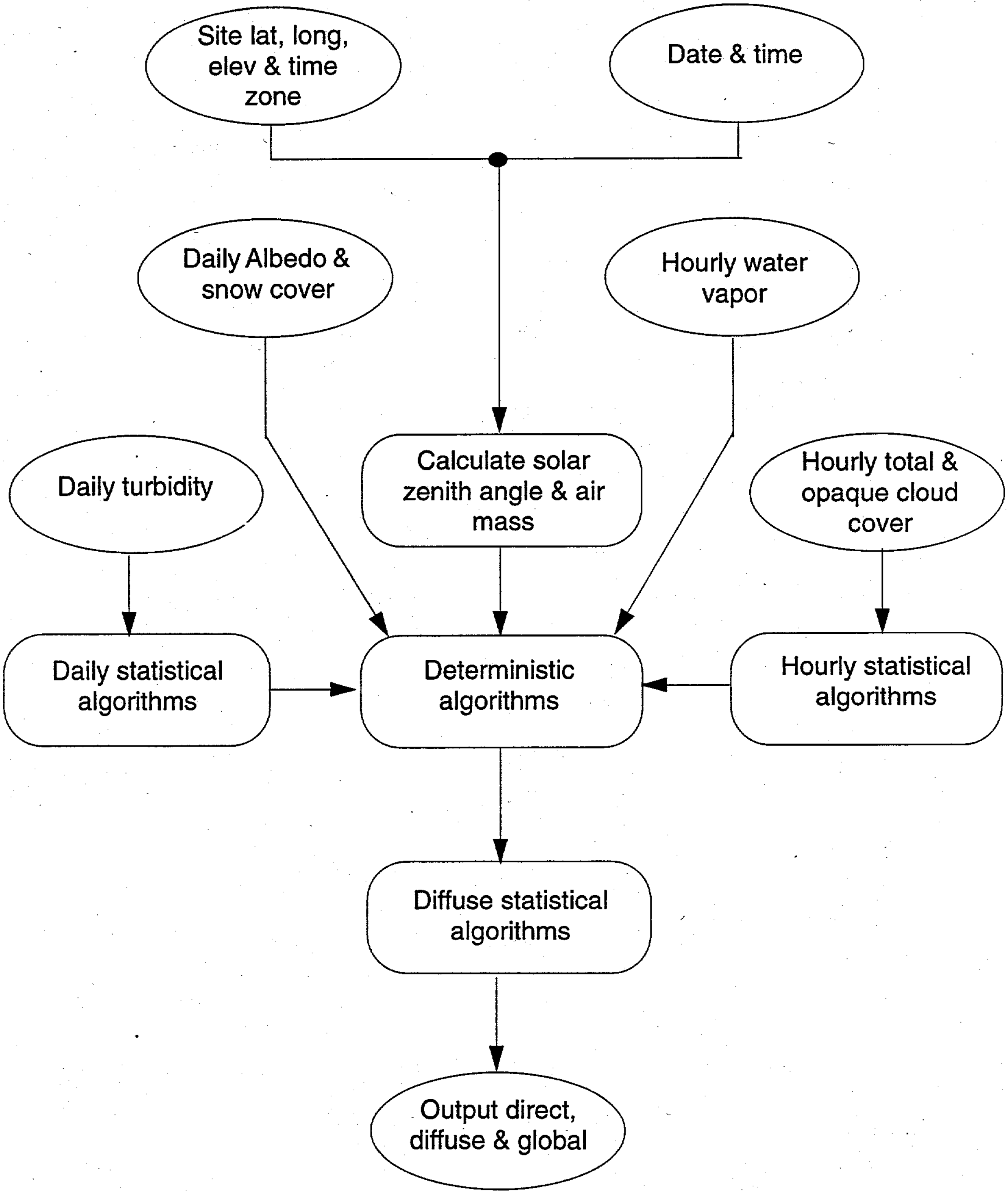

Fig. 3. Block diagram of the meteorological-statistical (METSTAT) model developed for estimating solar radiation from meteorological parameters.

The user can operate the model with or without enabling the statistical algorithms. With the statistical algorithms turned off, the model calculates identical solar radiation values each time the input variables and the solar geometry variables are repeated. This mode of operation yields the best estimates of hourly, daily-total, mean monthly, and mean annual solar radiation.

When METSTAT's statistical algorithms are activated, some of them simulate the effects of cloud movement with respect to the position of the sun. This does not simulate the actual position of the clouds, it only simulates the hour-to-hour variation in solar radiation that results from cloud movement. Other statistical algorithms simulate the effects of random variations of aerosol optical depth.

METSTAT is too complex to allow a detailed description of every algorithm, including look-up tables, in the space allowed for these workshop proceedings, therefore, this paper will only list the algorithms used with a brief explanation. Anyone interested in getting the model or more information about it should contact the author.

Consistent with our description of parametric models, the deterministic algorithms calculate broadband (solar spectrum) transmittances for each of the meteorological input parameters. A special effort was made to create a model free of seasonal or regional bias. This was accomplished by developing algorithms using subsets of measured data compiled from all 12 months and from 29 stations across the U.S.

Standard algorithms found in the literature are used to calculate the solar position and the relative length of the path (air mass) traversed through the atmosphere by the solar beam. The solar zenith angle and the relative optical air mass are computed using the most recent equation from Kasten and Young (1989). The solar constant used by METSTAT is 1367 W/m^2.

Statistical Algorithms

The statistical algorithms randomly vary the aerosol optical depth and opaque cloud cover inputs to the deterministic algorithms. This is accomplished by using a random number generator and cumulative frequency distributions that simulate natural processes in the atmosphere. A log normal distribution was used to simulate the daily variation of aerosol optical depths, in keeping with the work of Valko (1980) and our own analyses. Empirical distributions were derived to represent the hour-to-hour variation of effective cloud cover, resulting from the changing position of the clouds.

A statistical algorithm to vary precipitable water vapor was not needed because hourly values of water vapor were available. Translucent cloud cover was not varied statistically because its effect was small compared to opaque cloud cover and there was inadequate data to derive reliable distributions.

Clear Sky Algorithms

METSTAT's clear sky algorithms were borrowed from the Bird Clear Sky model (Bird and Hulstrom 1981) and are listed below. Those marked with an asterisk (*) were modified.

Direct Normal Transmittance (beam radiation from the solar disk)

- T_R - Transmittance of Rayleigh scattering
- T_O - Transmittance of ozone absorption
- T_{UM} - Transmittance of uniformly mixed gas absorption (CO_2 & O_2)
- T_W - Transmittance of water vapor absorption*
- T_A - Transmittance of aerosol scattering & absorption*

Diffuse Horizontal Transmittance (diffuse radiation from the sky)

- K_{SR} - Normalized diffuse radiation from Rayleigh scattering*
- K_{SA} - Normalized diffuse radiation from aerosol scattering*

Normalization refers to the division of surface values by extraterrestrial (outside the atmosphere) values.

Cloudy Sky Algorithms

The cloud cover algorithms use total and opaque cloud cover amounts rather than amounts by cloud type and layer. This simplified the development of a statistical algorithm to account for random changes in cloud positions. The cloudy sky algorithms use opaque cloud cover and translucent cloud cover, which is calculated by subtracting opaque cloud cover from total cloud cover.

Direct Normal Transmittance (beam radiation from the solar disk)

- T_{OPQ} - Transmittance of opaque clouds
- T_{TRN} - Transmittance of translucent clouds

Diffuse Horizontal Transmittance (diffuse radiation from the sky)

- K_{SOPQ} - Normalized diffuse radiation from opaque clouds
- K_{STRN} - Normalized diffuse radiation from translucent clouds

Normalization refers to the division of surface values by extraterrestrial (outside the atmosphere) values.

Special Algorithms

The special algorithms account for multiple scattering of radiation between the surface and the atmosphere (especially clouds) and reduction of radiation during precipitation (rain) events.

- K_{SRFL} - Normalized diffuse radiation resulting from multiple scattering

- PSW - Precipitation switch {1.0 (off) or 0.6 (on, during rain events)}

There are many factors that affect multiple scattering, including the surface albedo, the atmospheric albedo, and the initial irradiance reaching the surface. The surface albedo of natural surfaces can range from near zero for clean water to greater than 0.8 for freshly fallen snow. Similar ranges of atmospheric albedo exist.

Calculating Radiation Values

The final steps in the calculation of solar radiation include the combination of direct normal transmittances and normalized diffuse radiation values to form normalized direct normal (Kn) and diffuse horizontal (Kd) radiation:

$$Kn\ \ T_R\, T_O\, T_{UM}\, T_W\, T_A\, T_{OPQ}\, T_{TRN} \qquad (3)$$

$$Kd = \{[f(AM) * (K_{SR} + K_{SA})] + K_{SOPQ} + K_{STRN} + K_{SRFL}\} * PSW \qquad (4)$$

The normalized direct normal and diffuse horizontal radiation values are then combined to obtain normalized global horizontal radiation (Kt), which is often referred to as a cloudiness or clearness index:

$$Kt = Kn + Kd \qquad (5)$$

Finally, radiation in Wh/m^2 is obtained by multiplying the normalized values by the appropriate extraterrestrial terms:

$$Global = Kt * ETR \qquad (6)$$

$$Direct = Kn * ETRN \qquad (7)$$

$$Diffuse = Kd * ETR \qquad (8)$$

Where ETRN is extraterrestrial radiation on a surface normal to a vector from the sun and ETR is extraterrestrial radiation on a horizontal surface (relative to the surface of the earth).

METSTAT Performance

The differences between measured and modeled hourly values of solar radiation data collected between 1977 and 1990 were studied for the 30 stations with the largest collection of good quality data. Mean monthly differences were calculated for each of the three solar radiation elements for each station. Figure 4 shows the distributions of the station-month differences given in percent of the mean monthly hourly radiation. Each bin is 5% wide, centered on the value given on the horizontal axis. These results suggest that the direct normal differences are largely related to measurement errors, which most frequently are the result of failures to track the sun. If all measurements represented the true values, the positive skew of the direct normal and diffuse horizontal differences would be reflected in the global horizontal differences. Although there is a slight skew to the global differences, they certainly do not represent the sum of the direct and diffuse differences. The diffuse differences are as likely to be the result of modeling errors as measurement errors.

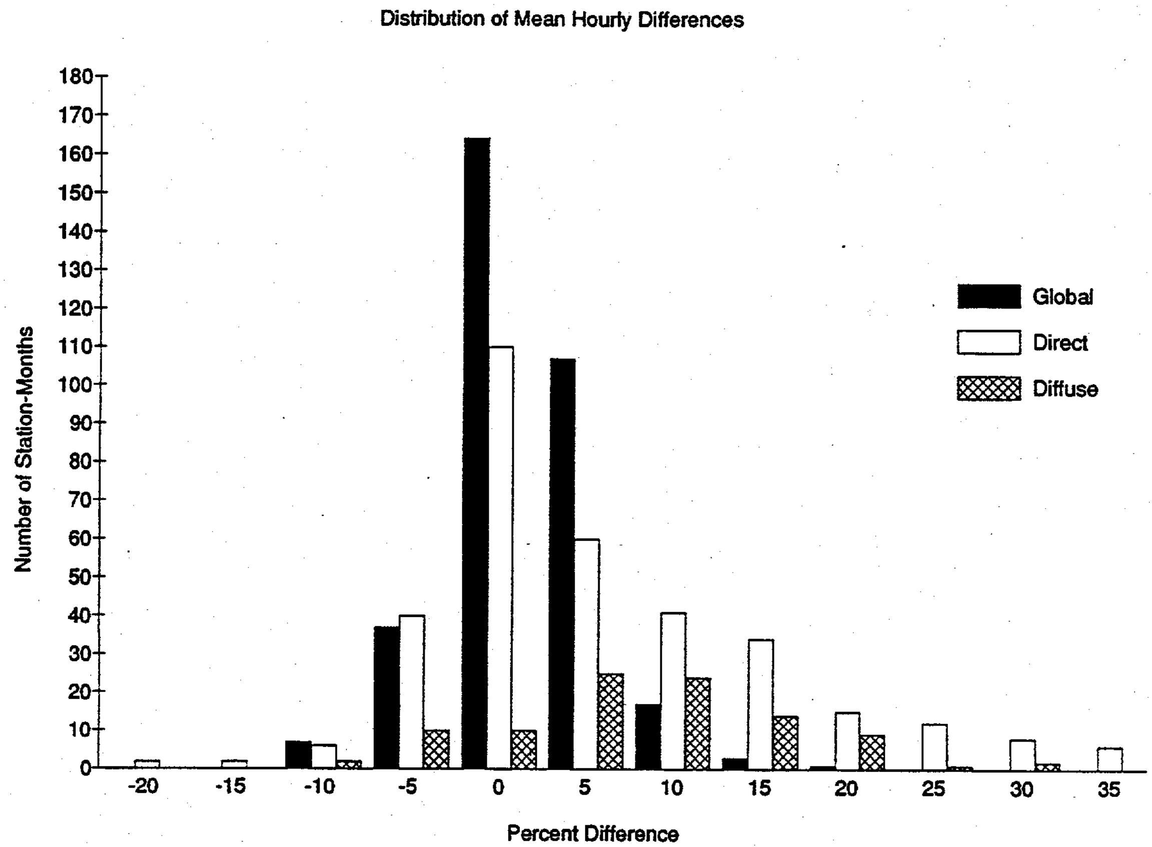

Fig. 4. The distribution of percent differences between measured and modeled mean monthly hourly solar radiation values [((modeled - measured)/measured) * 100] for data collected from 1977 to 1990 at 30 U.S. stations

Figures 5 and 6 show scatter plots of measured vs. modeled hourly global horizontal data for Daggett, CA and Eugene, OR. The data from these stations were not used in the development of the METSTAT algorithms. Only data from one representative year, for the months of January, April, July, and October, were plotted, such that the location of individual hourly values could be seen. The grouping of the data around the diagonal at all intensities indicates a lack of seasonal or diurnal bias. It should also be noted that Daggett is situated in a southwest desert with an annual average cloud cover of 3.2 tenths whereas Eugene is situated in a northwest coastal agricultural/ forestry region with an annual average cloud cover of 6.9 tenths. The good results for these and other stations suggests that METSTAT is free of climate or geographical biases.

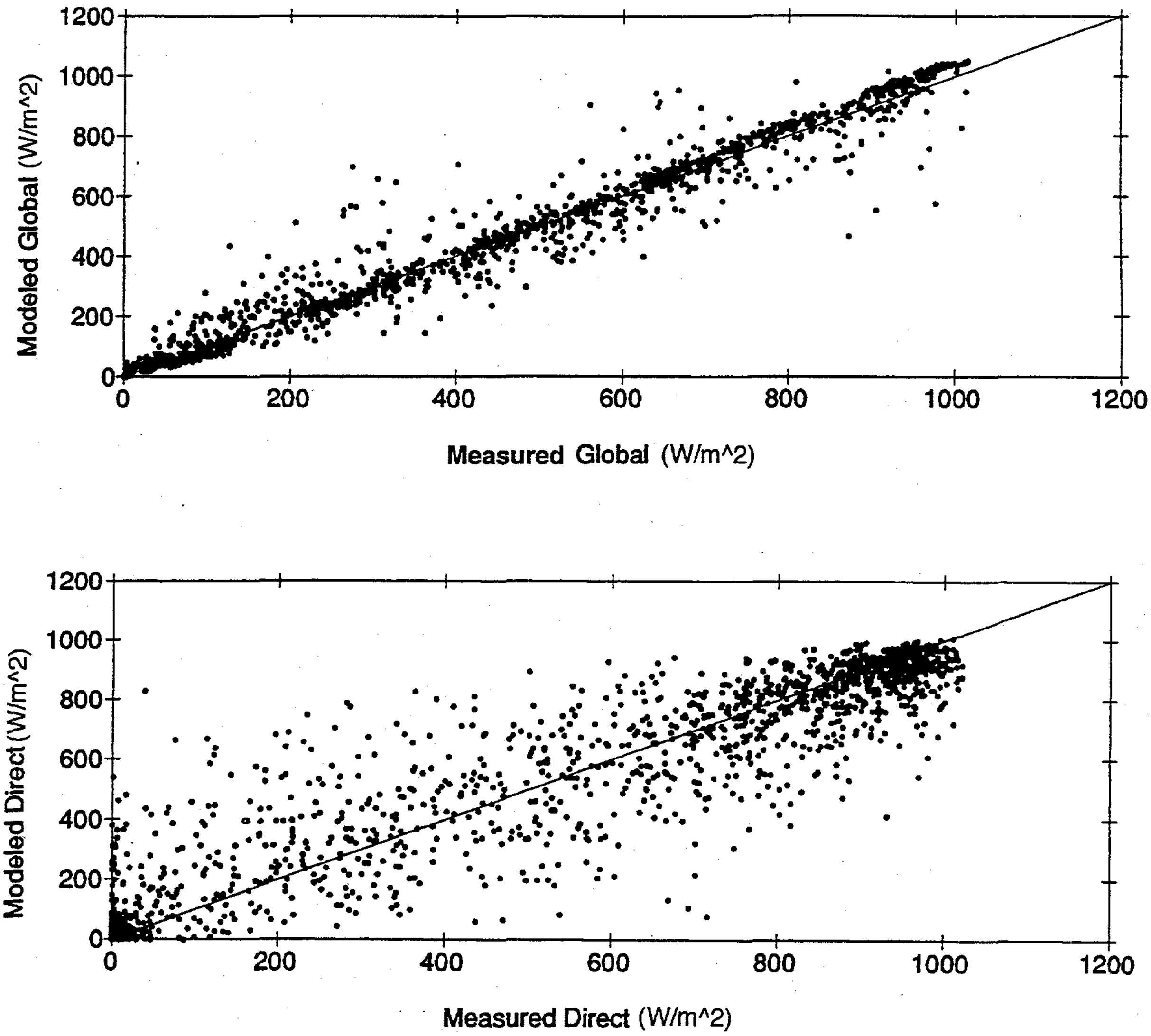

Fig. 5. Scatter plots of measured vs. modeled global horizontal and direct normal solar radiation data for Daggett, CA. Data from this station were not used in the development of METSTAT.

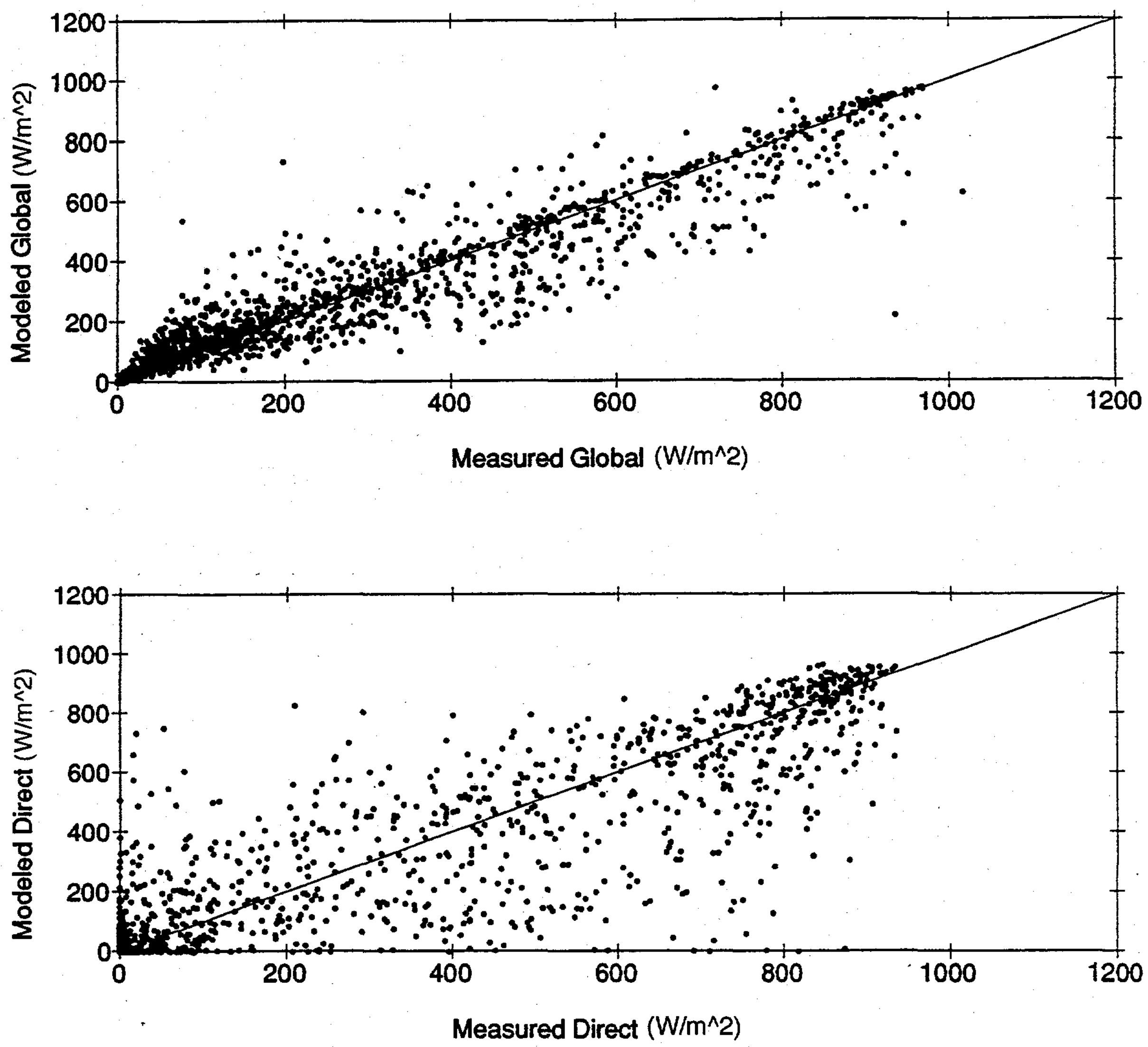

Fig. 6. **Scatter plots of measured vs. modeled global horizontal and direct normal solar radiation data for Eugene, OR. Data from this station was not used in the development of METSTAT**

NSRDB and SOLMET Comparisons

Long term (20 to 30 year) monthly and annual mean daily total solar radiation (kWh/m^2/day) as derived from the SOLMET and NSRDB data bases were compared. It was noted that the differences between the two data bases appeared to be grouped, with the groups being related to the SOLMET control stations. In other words, all of the stations for which solar radiation data had been calculated with regression equations from the same SOLMET station were seen to exhibit similar differences. This is illustrated in Figure 7 for differences in annual average daily total direct normal radiation.

The *between groups* standard deviation (standard deviation of the group differences) is 8.56% whereas the average *within groups* standard deviation is 3.78%. Furthermore, the maximum positive and negative differences span a range of 36.3%, greater than four times the between groups standard deviation and almost ten times the average within groups standard deviation. All of which strongly supports the hypothesis that the SOLMET/METSTAT differences are related to the SOLMET control station data and the regression models derived therefrom.

Current Data Grid Task

The NSRDB data base and products derived therefrom provide valuable information on solar radiation resources in the United States. The distance between stations, however, limits its usefulness for locating the best sites for large solar systems such as power plants and for extimating the performance of solar systems at locations some distance from the stations included in the NSRDB. For these reasons, NREL initiated a data grid task in 1995 that will provide estimates of monthly mean daily-total solar radiation (direct, diffuse, and global) for all cells in a 40-km (approximate) grid covering all of the United States, Mexico, the Caribbean, and the lower part of Canada (as far north as 52° N latitude). In the future, this work will be expanded to provide other information for each cell such as interannual variability, typical diurnal variations, and persistence information. It will also be expanded to other parts of the world.

The model to be used in estimating monthly mean values is a simplified version of METSTAT. The input data for the model will be monthly average values of the following variables:

- total cloud cover
- precipitable water vapor
- snow depth
- opaque cloud cover
- atmospheric pressure
- ozone
- aerosol optical depth
- surface albedo

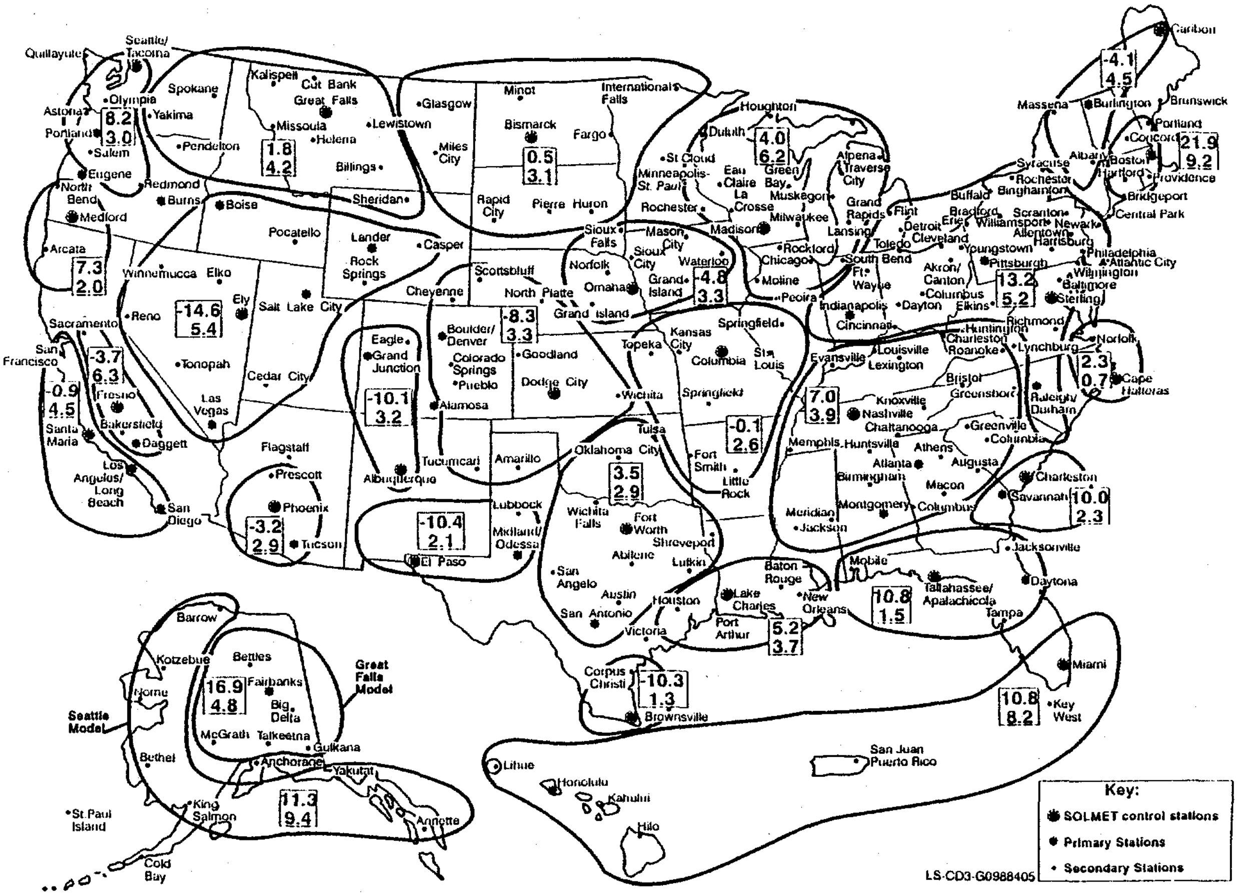

Fig. 7. Map of NSRDB stations, indicating station types, groups of stations related to SOLMET control stations, and a box with each group indicating mean (upper number) and standard deviation (lower number) percent differences (NSRDB minus SOLMET) of long-term mean annual daily-total direct normal solar radiation.

The cloud cover data are available on a 40-km grid from the Real-Time Nephanalysis (RTNEPH) data base produced by the U.S. Air Force and distributed by the National Climatic Data Center. Precipitable water vapor can be calculated from radiosonde and surface temperature (dry bulb and wet bulb) and pressure data. Atmospheric pressure can be derived from digitized elevation data, surface albedo and ozone are available from satellite data, and snow depth data are available from the Air Force on the same 40-km grid used for the RTNEPH data base. Obtaining aerosol optical depth data presents a major problem. These data are generally not available. However, they can be derived from direct normal solar radiation data and rough estimates can be made from visibility data.

At this time, we are not ready to publish any maps or to distribute data for any region. However, by January 1996 we should have products ready for distribution.

Summary

Models have played a dominant role in developing both the SOLMET and NSRDB data bases. The parametric METSTAT model used in the production of the NSRDB represents a significant improvement over the simple regression models used in the production of the SOLMET data base. Comparisons of METSTAT with measured data and comparisons of SOLMET and NSRDB monthly and annual means show that the improvements in modeling methods have resulted in improvements in the assessment of solar radiation resources in the United States. In the near future, modeling methods will be available to produce a high-resolution grid of solar radiation data for any location in the world.

Acknowledgements

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NEW TYPICAL METEOROLOGICAL YEARS AND SOLAR RADIATION DATA MANUAL

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ABSTRACT

A new solar radiation data manual [1] and new typical meteorological years (TMYs) [2] were developed by the National Renewable Energy Laboratory (NREL) Analytic Studies Division under the Solar Radiation Resource Assessment Project. These tasks were funded and monitored by the Photovoltaics Branch of the Department of Energy Office of Energy Efficiency and Renewable Energy. The new manual and the new TMYs were derived from the 1961–1990 National Solar Radiation Data Base (NSRDB). The new manual is entitled *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* It provides designers and engineers of solar-energy-related systems with average monthly and yearly solar radiation values for various types of collectors for 239 stations in the United States and its territories. The new TMY data sets are referred to as TMY2s. This distinguishes them from earlier TMY data sets derived from the 1952–1975 SOLMET/ERSATZ data base. This paper describes the new data manual and the new TMY2s.

1. INTRODUCTION

The new data manual and the TMY2s are based on the National Solar Radiation Data Base (NSRDB) Version 1.1, which NREL completed in March 1994. The original version of the NSRDB, Version 1.0, was completed in August 1992. Version 1.1 corrects two types of minor errors that affected about 10% of the stations [3]. The NSRDB contains hourly values of measured and modeled solar radiation and meteorological data for 239 stations for the 30-year period 1961–1990. A description of the NSRDB and its production is presented in the user's manual [4].

The NSRDB has two types of stations: primary and secondary. Primary stations, of which there are 56, measured solar radiation for a part of the 30-year period (from 1 to 27 years). The remaining 183 stations, designated secondary stations, made no solar radiation measurements and have modeled solar radiation data that are derived from meteorological data such as cloud cover. Both primary and secondary stations are at or near National Weather Service stations that collected meteorological data for the period 1961–1990. The NSRDB succeeds the older 1952–1975 SOLMET/ERSATZ data base.

A comparison [5] of the NSRDB with the SOLMET/ERSATZ data base provided the incentive for developing new solar radiation resource products, such as the data manual and the TMY2s. On an annual basis, 40% of the NSRDB and SOLMET/ERSATZ stations disagree for global horizontal radiation by more than 5%, with some stations disagreeing up to 18%. For direct beam radiation, 60% of the NSRDB and SOLMET/ERSATZ stations disagree by more than 5%, with some stations disagreeing up to 33%. Disagreement between the two data bases is even greater when compared monthly. Most of the disagreement is attributed to differences in the instruments, calibration procedures, and models.

2. SOLAR RADIATION DATA MANUAL

To determine the specific information to include in the manual, we solicited suggestions and recommendations from more than 70 designers, installers, manufacturers, consultants, university and national laboratory researchers, utility engineers, meteorologists, and state energy office staff.

2.1 Content

For each station, a data page describes its location, presents average solar radiation values for flat-plate and concentrating collectors, and gives average climatic conditions. Except for mean atmospheric pressure, given in millibars, Standard International units are used. To convert to other units, a table of conversion factors is included.

Station Description—At the top of each data page, the station is described by:

- City and state in which the station is located
- Station Weather Bureau Army Navy (WBAN) number
- Latitude (degrees; north)
- Longitude (degrees; east or west)
- Elevation of station (meters)
- Mean atmospheric pressure (millibars)
- Type of station (primary or secondary).

Flat-Plate and Concentrating Collectors—For the period 1961-1990, tables of solar radiation data for flat-plate and concentrating collectors include:

- Monthly and yearly averages of solar radiation ($kWh/m^2/day$)
- Minimum and maximum monthly and yearly averages of solar radiation ($kWh/m^2/day$)
- Uncertainty of solar radiation data (± %).

Minimum and maximum monthly and yearly averages are included to show the variability of a station's solar resource. The uncertainty of the data is presented in the table headings. The uncertainties were determined using the uncertainty method of Abernethy and Ringhiser [6]. The manual includes data for various flat-plate and concentrating collectors that include:

- Flat-plate collectors facing south at fixed tilt. Data are presented for five tilt angles from the horizontal: 0°, latitude minus 15°, latitude, latitude plus 15°, and 90°.
- One-axis tracking flat-plate collectors with axis oriented north-south. Data are presented for four axis tilt angles from the horizontal: 0°, latitude minus 15°, latitude, and latitude plus 15°. These trackers pivot on their single axis to track the sun, facing east in the morning and west in the afternoon.
- Two-axis tracking flat-plate collectors. Tracking the sun in both azimuth and elevation, these collectors keep the sun's rays normal to the collector surface.
- Concentrating collectors. Direct beam solar radiation data are presented for four concentrators: one-axis tracking parabolic troughs with a horizontal east-west axis, one-axis tracking parabolic troughs with a horizontal north-south axis, one-axis concentrators with the axis oriented north-south and tilted from the horizontal at an angle equal to the latitude, and two-axis tracking concentrator systems.

Solar Radiation Graph—A graph at the top of each data page shows the variability and distribution of monthly and yearly solar radiation for a flat-plate collector facing south with a tilt equal to the station's latitude. The data points in the graph represent individual months and years. The graph shows how the minimum and maximum values compare with the 1961–1990 average. It also shows the distribution of data points with respect to the average, minimum, and maximum.

Climatic Conditions—A table shows average climatic conditions by listing monthly and yearly values for the following parameters:

- Average temperature (°C)
- Average daily minimum temperature (°C)
- Average daily maximum temperature (°C)
- Record minimum temperature (°C)
- Record maximum temperature (°C)
- Average heating degree days, base 18.3°C
- Average cooling degree days, base 18.3°C
- Average relative humidity (%)
- Average wind speed (m/s).

2.2 Methodology

The solar radiation values presented in the manual were modeled using hourly values of diffuse horizontal and direct beam radiation from the NSRDB for the period 1961-1990. The solar radiation received by a flat-plate collector (I_c) is a combination of direct beam radiation (I_b), diffuse (sky) radiation (I_d), and radiation reflected from the surface in front of the collector (I_r),

$$I_c = I_b \cos\theta + I_d + I_r ,$$

where θ is the incident angle of the sun's rays to the collector. Algorithms [7] were used to compute the incident angles for the various collectors. For tracking collectors, these algorithms were also used to compute collector tilt angles from the horizontal. Direct beam solar radiation hourly values from the NSRDB were used to determine the direct beam contribution ($I_b \cos\theta$) for each hour.

The diffuse (sky) radiation received by the collector was calculated by an anisotropic diffuse radiation model. The Perez model [8] determined the diffuse (sky) radiation for the collector using hourly values (from the NSRDB) of diffuse horizontal and direct beam solar radiation. Other inputs to the model included the sun's incident angle to the collector, the collector tilt angle from horizontal, and the sun's zenith angle. The Perez model is an improved and refined version of the original model recommended by the International Energy Agency [9] for calculating diffuse radiation for tilted surfaces.

The ground-reflected radiation received by a collector is a function of the global horizontal radiation (I_h), the tilt of the collector from the horizontal (β), and the surface reflectivity or albedo (ρ).

$$I_r = 0.5\rho\, I_h\, (1 - \cos \beta) .$$

Surface albedo was adjusted depending on the presence of snow cover, as indicated by the snow depth data in the NSRDB. If there was snow on the ground, the surface albedo was set to 0.6 (albedo for snow ranges from about 0.35 for old snow to 0.95 for dry new snow). If there was no snow, the surface albedo was set to 0.2, corresponding to that for green vegetation and some soil types.

The concentrating collectors portrayed in the manual have small fields-of-view and do not receive diffuse radiation or ground-reflected radiation. Solar radiation received by the concentrating collectors simplifies to:

$$I_c = I_b \cos\theta .$$

For each station location, collector type, and collector orientation, hourly values of solar radiation received by the collectors were calculated. Monthly and yearly averages were then determined for the period 1961-1990.

The climatic data presented in the manual were derived primarily from climatic data sets provided by the National Climatic Data Center (NCDC), Asheville, North Carolina. These data sets included the data tape "1961-1990 Monthly Station Normals All Elements" and the data diskette "Comparative Climatic Data Tables-1991." Where needed, data from the NSRDB supplemented the NCDC data.

3. TYPICAL METEOROLOGICAL YEARS

TMYs are serially complete data sets of hourly values of solar radiation and meteorological elements for a 1-year period that are used for computer simulations of solar energy conversion systems and buildings. The TMYs provide standards for hourly data for solar radiation and other meteorological elements that permit performance comparisons of different system types and configurations for a site. TMYs are not necessarily good indicators of conditions over the next year, the next 5 years, or even the next 10 years. Rather, they represent conditions judged to be typical over a long period, such as the 30 years contained in the NSRDB.

Previous TMYs were created from the 1952-1975 SOLMET/ERSATZ data using methods developed by Sandia [10]. Studies [11, 12, 13] have shown that these methods give reasonable results, and Sandia's method has also been adopted by others [13] for developing TMYs outside the U.S. Sandia's method, with a few minor changes in the weighting criteria, was used to develop the new TMY2s from the NSRDB.

The Sandia method was modified to better optimize the weighting of the indices, to provide preferential selection for months with measured solar radiation data, and to account for missing data.

3.1 Sandia Method

The Sandia method is an empirical approach that selects individual months from different years of the period of record. For example, in the case of the NSRDB, all 30 Januarys are examined and the one judged most typical is included in the TMY. The other months are treated in a like manner, then the 12 selected typical months are concatenated to form a complete year. Because adjacent months in the TMY may be selected from different years, discontinuities at the month interfaces are smoothed for 6 hours on each side.

The Sandia method selects a typical month based on nine daily indices that consist of the maximum, minimum, and mean dry bulb and dew point temperatures, the maximum and mean wind velocity, and the total global horizontal solar radiation. Final selection of a month includes consideration of the monthly mean and median and the persistence of weather patterns. The process is a series of steps.

Step 1—For each month of the calendar year, 5 candidate months with cumulative distribution functions (CDFs) for the daily indices closest to the long-term (30 years for the NSRDB) CDFs are selected. The CDF gives the proportion of values that are less than or equal to a specified value of an index. Candidate monthly CDFs are compared to the long-term CDFs by using Finkelstein-Schafer (FS) statistics [14] for each index.

$$FS = (1/n) \sum_{i=1}^{n} \delta_i$$

where

δ_i = absolute difference between the long- term CDF and the candidate month CDF at x_i

n = number of daily readings in a month

Because some indices are judged more important than others, a weighted sum of the FS statistics is used to select the five candidate months that have the lowest weighted sums.

$$WS = \sum w_i FS_i$$

where

w_i = weighting for index

FS_i = FS statistic for index

Step 2—The 5 candidate months are ranked with respect to closeness of the month to the long-term mean and median.

Step 3—The persistence of mean dry bulb temperature and daily global horizontal radiation are evaluated by determining the frequency and run length above and below fixed long-term percentiles. For mean daily dry bulb temperature, the frequency and run length above the 67th percentile (consecutive warm days) and below the 33rd percentile (consecutive cool days) were determined. For global horizontal radiation, the frequency and run length below the 33rd percentile (consecutive low radiation days) were determined.

The persistence data are used to select the month to be used in the TMY from the 5 candidate months. The highest ranked candidate month from Step 2 that meets the persistence criteria is used in the TMY. The persistence criteria exclude the month with the longest run, the month with the most runs, and the month with zero runs.

Step 4—The 12 selected months are concatenated to make a complete year, and discontinuities at the month interfaces are smoothed for 6 hours each side using curve-fitting techniques.

3.2 Weighting and Index Modifications

The weighting for each index plays a role in selecting the typical months. Ideally, one would select a month that had FS statistics that were better than all the other months for each index. In practice, this is unlikely because the months might be typical with respect to some indices, but not others. By weighting the FS statistics, the relative importance and sensitivity of the indices may be taken into account. The Sandia weighting values and those for the TMY2s are compared in Table 1.

TABLE 1. WEIGHTINGS FOR FS STATISTICS

Index	Sandia Method	TMY2 Method
Max Dry Bulb Temp	1/24	1/20
Min Dry Bulb Temp	1/24	1/20
Mean Dry Bulb Temp	2/24	2/20
Max Dew Point Temp	1/24	1/20
Min Dew Point Temp	1/24	1/20
Mean Dew Point Temp	2/24	2/20
Max Wind Velocity	2/24	1/20
Mean Wind Velocity	2/24	1/20
Global Radiation	12/24	5/20
Direct Radiation	Not Used	5/20

For the TMY2s, an index for direct normal radiation was added. This improves the comparison between annual direct normal radiation for the TMY2s and the 30-year annual average by about a factor of 2 (based on 20 geographically diverse NSRDB stations). When only global horizontal radiation is used for the solar index, the TMY annual direct radiation values for the 20 stations were within 4% (95% confidence level) of the 30-year annual average. Using both global horizontal and direct radiation indices reduced the differences to 2%, with no adverse effect on global horizontal radiation comparisons.

Weightings for dry bulb and dew point temperature were changed slightly to give more emphasis to dry bulb and dew point temperatures and less to wind velocity, which is less important for solar energy conversion systems and buildings. Neither TMY weighting is appropriate for wind energy conversion systems.

The relative weights between solar and the other elements were not particularly sensitive. As an indicator, annual heating and cooling degree days (base 18.3°C) were compared for the TMY2s and the 30-year period for the 20 stations. With the selected solar weighting of 50% (global and direct), annual heating degree days for the TMY2s were within 5% (95% confidence level) of the 30-year annual average. As an extreme, reducing the solar weighting to zero only reduced the differences to within 2.5%. Differences between the TMY2 annual averages and the 30-year averages for cooling degree days were within 9%, for both 0% and 50% solar weightings.

3.3 El Chichon Years

The volcanic eruption of El Chichon in Mexico in March 1982 spewed large amounts of aerosols into the stratosphere. The aerosols spread northward and circulated around the earth. This noticeably decreased the amount of solar radiation reaching the United States from May 1982 to December 1984, when the effects diminished. Consequently, these months were not used in any of the TMY2 procedures because they were considered not typical.

3.4 Leap Years

TMY2 files do not include data for February 29. Consequently, leap year Februarys did not use data for February 29 to determine their candidate month CDFs. However, to maximize the use of available data, data for February 29 were included for determining the long-term CDFs.

3.5 Preference for Months with Measured Solar Data

For a station, the NSRDB may contain measured and modeled solar radiation data. Because of additional uncertainties associated with modeled data, preferences in the selection of candidate months were given to months that contained either measured global horizontal or direct normal solar radiation data. This was accomplished between Steps 2 and 3 by switching the ranking of the first- and second-ranked candidate months if the second-ranked month contained measured solar radiation data, but the first-ranked month did not.

3.6 Month Interface Smoothing

Curve-fitting techniques were used to remove discontinuities created by concatenating months from different years to form the TMY2s. These techniques were applied for 6 hours each side of the month interfaces for dry bulb temperature, dew point temperature, wind speed, wind direction, atmospheric pressure, and precipitable water. Relative humidities for 6 hours each side of the month interfaces were calculated using psychometric relationships [15] and the curve-fitted values of dry bulb temperature and dew point temperature.

3.7 Allowance for Missing Data

The NSRDB is serially complete for all solar radiation elements, but meteorological data are missing for some stations and months. Consequently, procedures were adopted to account for missing meteorological data. From these procedures, two classes of TMY2 stations evolved: Class A and Class B.

Class A stations are those with the most complete 30-year meteorological data records and at least 15 candidate months remaining after any months with data missing for more than 2 consecutive hours were eliminated. The 15 candidate month minimum permitted 90% of the stations to be completed without extensive data filling and to be designated Class A stations. For the TMY2s, 15 candidate months yielded typical months that were within the range of differences established by 25 or more candidate months when comparing monthly values of direct normal for TMY2 months with monthly averages of direct normal for the 1961-1990 period. This relationship was also true for global horizontal radiation, and heating and cooling degree days [2].

Class B stations had more missing data than Class A stations, and the data were filled for the index elements used to select the TMY2s. Other elements in Class B TMY2s were not necessarily filled and may be missing. Table 2 shows elements that may have missing data values in TMY2 files for Class A and Class B stations. A complete description of the treatment and filling of missing data is given in the TMY2s user's manual [2].

3.8 Data Elements and Format

Table 2 shows the data elements contained in the TMY2 data files. They are the same as for the 30-year NSRDB, except that illuminance and luminance elements were added to support building energy analysis. They were calculated using luminous efficacy models developed by Perez [8]. Table 2 also includes information by element and station classification to alert the user to the possibility of missing data.

The elements horizontal visibility, ceiling height, and present weather may be missing for up to 2 consecutive hours for Class A stations and for up to 47 hours for Class B stations. No data are missing for more than 48 hours, except for snow depth and days since last snowfall for Colorado Springs, Colorado.

For each station, a TMY2 file contains 1 year of hourly solar radiation, illuminance, and meteorological data. The files consist of data for the typical calendar months during 1961–1990, which are concatenated to form the typical meteorological year for each station.

File naming convention uses the WBAN identification number as the file prefix with the characters TM2 as the file extension. For example, 13876.TM2 is the TMY2 file name for Birmingham, Alabama. Each TMY2 file is 1.26 MB and contains computer-readable ASCII characters.

The first record of each file is the file header that describes the station. The file header contains the WBAN number, city, state, time zone, latitude, longitude, and elevation. Following the file header, 8760 hourly data records provide

TABLE 2. TMY2 DATA ELEMENTS

Element	Data Completeness	
	Class A	Class B
Extraterrestrial Horizontal Radiation	1	1
Extraterrestrial Direct Norm. Radiation	1	1
Global Horizontal Radiation	1	1
Direct Normal Radiation	1	1
Diffuse Horizontal Radiation	1	1
Global Horizontal Illuminance	1	1
Direct Normal Illuminance	1	1
Diffuse Horizontal Illuminance	1	1
Zenith Luminance	1	1
Total Sky Cover	1	1
Opaque Sky Cover	1	1
Dry Bulb Temperature	1	1
Dew Point Temperature	1	1
Relative Humidity	1	1
Atmospheric Pressure	1	1
Wind Direction	1	1
Wind Speed	1	1
Horizontal Visibility	2	2, 3, 4
Ceiling Height	2	2, 3, 4
Present Weather	2	2, 3, 4
Precipitable Water	1	1
Broadband Aerosol Optical Depth	1	1
Snow Depth	1	5
Days Since Last Snowfall	1	5

Notes
1. Serially complete, no missing data
2. Data may be present only every third hour
3. Nighttime data may be missing
4. Data may be missing for up to 47 hours
5. Serially complete, except for Colorado Springs, CO

1 year of solar radiation, illuminance, and meteorological data, along with their source and uncertainty flags that indicate whether the data value was measured, modeled, or missing, and to provide an estimate of the data value's uncertainty.

Each hourly record begins with the time given in local standard time (previous TMYs based on SOLMET/ ERSATZ data are in solar time). For the data records, the user's manual [2] provides field positions, element definitions, and sample FORTRAN and C read formats.

Users should be aware that the TMY2 data file format differs from that for the NSRDB and the original TMY data files. TMY and TMY2 data sets cannot be used interchangeably because of differences in time (solar versus local), formats, elements, and units. Unless they are revised, programs designed for TMY data will not work with TMY2 data.

4. TMY2 COMPARISONS WITH LONG-TERM DATA SETS

The TMY2 data were compared with 30-year data sets to show differences between TMY2 data and long-term data for the same stations. Comparisons were made on a monthly and annual basis for global horizontal, direct normal, and south-facing latitude tilt radiation; and for heating and cooling degree days. These comparisons give general insight into how well, with respect to long-term conditions, the TMY2s portray the solar resource and the dry bulb temperature environment for simulations of solar energy conversion systems and building systems. On an annual basis, the TMY2s compare closely to the 30-year data sets. The monthly comparisons are less favorable.

4.1 Solar Radiation Comparisons

Monthly and annual solar radiation for the TMY2 data sets were compared with previously determined [1] monthly and annual averages for the 1961–1990 NSRDB, from which the TMY2 data sets were derived. These comparisons were made for global horizontal, direct normal, and a fixed surface facing south with a tilt angle from horizontal equal to the station's latitude.

Agreement between TMY2s and the respective 30-year average is better on an annual basis than a monthly basis. This is a consequence of canceling of some of the monthly differences when the monthly values are summed for the annual value. Table 3 provides 95% confidence intervals, determined as twice the standard deviation of the differences between TMY2 and NSRDB values, for TMY2 monthly and annual solar radiation. The confidence intervals are given in units of kWh/m^2/day. Differences between TMY2 and NSRDB 30-year values should be within the confidence interval 95% of the time.

TABLE 3. 95% CONFIDENCE INTERVALS FOR MONTHLY AND ANNUAL SOLAR RADIATION

Element	Confidence Interval (±kWh/m^2/day)	
	Monthly	Annual
Global Horizontal	0.20	0.06
Direct Normal	0.50	0.16
Latitude Tilt	0.29	0.09

4.2 Heating and Cooling Degree Day Comparisons

Degree days are the difference between the average temperature for the day and a base temperature. If the average for the day (calculated by averaging the maximum and minimum temperature for the day) is less than the base value, the difference is designated as heating degree days. If the average for the day is greater than the base value, the difference is designated as cooling degree days.

Monthly and annual heating and cooling degree days (base 18.3°C) calculated from the TMY2 data sets were compared with those for the same stations from the National Climatic Data Center's (NCDC's) data tape, "1961–1990 Monthly Station Normals All Elements." This data tape includes temperature and degree day normals for about 4775 stations in the United States and its territories. The normals are averages computed by NCDC for the period 1961–1990.

Table 4 provides 95% confidence intervals, determined as twice the standard deviation of the differences between TMY2 and NCDC values, for TMY2 monthly and annual heating and cooling degree days. The confidence intervals are given in units of degree days. Differences between TMY2 and NCDC 30-year values should be within the confidence interval 95% of the time. Although the annual confidence interval in degree days is larger than the monthly confidence interval, if expressed as a percentage it would be less because the annual degree days are the sum of the monthly degree days.

TABLE 4. 95% CONFIDENCE INTERVALS FOR MONTHLY AND ANNUAL DEGREE DAYS

Parameter	Confidence Interval (±degree days, base 18.3°C)	
	Monthly	Annual
Heating Degree Days	45.6	182
Cooling Degree Days	28.2	98

5. SUMMARY

NREL used the recently completed NSRDB to develop two new resource assessment products: a solar radiation data manual and a new set of TMYs.

The *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors* provides designers and engineers with tabular solar radiation data for common flat-plate and concentrating collectors. The manual was completed in the spring of 1994.

New TMY data sets, referred to as TMY2s, were completed in the summer of 1995. These data sets are based on more recent and accurate data and are recommended for use in place of earlier TMY data sets derived from the 1952–1975 SOLMET/ERSATZ data base.

The solar radiation data manual and the TMY2 user's manual may be obtained from NREL's Document Distribution Service at (303) 275-4363.

The TMY2 data sets may be obtained from NREL's internet-accessible Renewable Resource Data Center (RReDC) [16]. The Universal Resource Locator (URL) address of the RReDC is "http://rredc.nrel.gov." Users should have World Wide Web (WWW) browsing software, such as Mosaic or Netscape, to access the RReDC. Plans are also under way to make the TMY2 data sets available on a CD-ROM.

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Summary of Discussion of Issues and Needs

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INTRODUCTION

All participants in the Photovoltaic Radiometric Measurements Workshop were invited to critique the status reports presented by each of the speakers in turn, as well as contribute to the discussion of needs and issues at the conclusion of each day of the program. An examination of the program shows that the workshop topics evolved from the broad perspective of radiometric standards, traceability and calibration issues to radiometric engineering (instrumentation, measurements), to resource data availability, applications, and modelling. The workshop chairman divided the discussion topics into two main areas related to the perceived radiometry related needs of the photovoltaic (PV) community: **(1) Radiometry for PV Engineering Applications** and **(2) PV Solar Radiometric Resource Data.**

This paper presents a summary of approximately 4 hours of discussions that arose under each of these areas, more or less in the order in which they were brought up during the program, reflecting the topics covered by the speakers. The paper does not reflect formal minutes of the discussion, but topics and issues that were discussed, and the author's interpretation of the remarks from notes made during the discussions. While priorities were not discussed *per se*, the conclusion section will summarize those issues identified as most useful to the PV community as a whole, and how they will be addressed in NREL PV Radiometric Measurements and Evaluation team planning as a cross-cutting support unit of the much larger PV Module and Systems Performance and Engineering Project. Some brief comments will be made on those issues more appropriately addressed by our NREL colleagues in the Solar Radiation Resource Assessment Program (SRRAP) and their products.

Finally, we wish to thank again all of the speakers and participants for stimulating and earnest discussions, both formally and informally, which contributed to the success, and the value of this record of the workshop.

RADIOMETRY FOR PV ENGINEERING APPLICATIONS

The majority of the workshop discussions were devoted to this area, and particularly to radiometric calibration, characterization, measurement techniques. The issues discussed included:

- *Traceability* to the World Radiometric Reference Working Standard Group of absolute cavity radiometers for broadband solar radiometric standards, and National Institute of Standards and Technology reference standards of spectral irradiance is critical to maintaining high standards of radiometric measurements.

- *Radiometric measurement guides for the PV community* are needed which are easily understood and widely disseminated to document broadband and spectral calibration, characterization, and measurement techniques developed over the past ten years that adequately address many instrumentation issues.

- *Specific, well defined goals for PV radiometric measurements* must be described and documented to define PV radiometric measurements needed; e.g. whether with respect to a standard spectrum (say, for translation to Standard Reporting Conditions), which requires spectral information; or prevailing conditions (say, for energy rating or performance considerations) which depend on broadband radiometric data.

- *Documented uncertainty analysis* must accompany broadband and spectral radiometric data to justify and/or limit the interpretation of PV calibration or PV performance data.

- *Periodic calibration checks and Statistical Process Control* need to be incorporated into radiometric measurements to meet quality assurance needs, and the requirements already set forth in accreditation standards, including interlaboratory collaborations.

- *Accreditation of PV testing, rating, and performance laboratories* will require addressing the points above to meet national and international accreditation and certification standards.

- *Current Broadband radiometric accuracy of ±3.0%* (with well documented uncertainty) may be satisfactory for long term (more than 5 year) monitoring, but is inadequate for efficient, accurate study of 1% per year degradation in PV performance measurements or reference devices.

- *Increased participation in radiometric standards development* is needed to better disseminate procedures, methods, and techniques developed specifically for PV calibration and performance testing, and support national (ASTM, IEEE) and international (ANSI, ISO) consensus standards with U.S. interests and technical knowledge in mind,

- *Solar radiometric instrumentation* has improved over the past 10 years, but at the price of increased cost. Therefore, instrumentation characterization (second bullet above) is very important (but is itself a very labor intensive, and costly endeavor). Better, but less expensive instrumentation is still a need.

- *Indoor vs outdoor PV performance correlations* are relatively poor, though within quoted uncertainties of ±5%; study of the relationship between diffuse (sky) radiation contributions versus simulator collimated radiation distributions may resolve some of the discrepancies.

- *PV module and system ratings* are still needed representing the kiloWatthours produced as a function of kiloWatthours available for conversion, and will rely on radiometric measurements (for test and characterization) and resource data (for energy/performance rating).

- *PV system and radiometric data correlations* should be studied for quality assurance of both system performance instrumentation and radiometric instrumentation, on a near real time (hourly or daily) time scale, in a complimentary manner.

- *Accelerated weathering* and correlations with realistic exposure conditions require better measurements and understanding of enhanced, artificial radiation sources (Ultraviolet, Infrared, etc.) as well as the real radiometric and meteorological environment of various climates.

The above issues represent areas which the PV Module and System Performance and Engineering Project is addressing in general, and where progress is being made, within the resources of the project. It was recognized by workshop participants that the project, and the Solar Radiometric Measurements and Evaluation Team in particular, are at the forefront of radiometric engineering measurements an analysis; *the overriding need is for better communication by the team of the existing NREL radiometric methods, procedures, practices, and expertise to the PV community as a whole.* In addition, the current level of radiometric accuracy, attention to detail, and knowledge must be maintained, if not improved, to continue to meet the radiometric measurement requirements for adequate calibrations and measurements for PV performance testing and reference cell calibrations.

PV SOLAR RADIOMETRIC RESOURCE DATA

In addition to the engineering test and measurements and standards issues addressed above, issues concerning the collection, availability, accuracy, modeling, and applications of solar radiation resource assessment data were discussed. These issues are more suitably addressed by the NREL/DOE Solar Radiation Resource Assessment Program (SRRAP), but are reported here for completeness. The issues raised included:

- *Blanket coverage, including international coverage* for resource assessment data is always needed. There is hardly ever measured (or measured meteorological data for modelling purposes) for a specific site of interest.

- *Application guides* for correct use and interpretation of resource assessment data such as measured, statistically summarized, or "typical" data are needed; including:

- *Encourage use of a single data base* for default values or comparison purposes by industry as a whole. This would eliminate confusing comparison results based on different data bases such as 1952-1970 SOLMET/ERSATZ based TMY versus 1961-1990 National Solar Radiation Data Base related TMY2.

- *Interpolation and extrapolation* techniques for are needed, even for dense, gridded data sets, to obtain the 'blanket coverage' mentioned above.

- *Availability of data*, whether via hardcopy publications, magnetic media, or electronic transfer (Internet or e-mail) needs to be more effectively communicated.

- *Radiometric models and conversion algorithms* must be made available, validated and continually improved, and if possible made simpler to use, with less sophisticated input data requirements, as it is clear that, as one participant stated, "there will never be enough measured data".

As with the comments concerning the PV Module and System Performance and Engineering Project, it is clear from the presentations and the program of the workshop that many of these issues are currently being addressed by the SRRAP; and it is a question of improving awareness of these activities and distribution of information within the PV community.

CONCLUSION

The PV engineering issues raised above have been continually addressed to some extent by the NREL PV Module and System Performance and Engineering Project, the Solar Radiometric Measurements and Evaluation team, and the former PV Solar Radiation Research task. Therefore the workshop participants recognize that a significant body of state-of-the-art knowledge about PV related spectral and broadband solar radiometric instrumentation, calibrations, measurement procedures and techniques is resident in the current project. The most important immediate objective is to communicate this knowledge, and its import, to the PV community at large.

Accepting this challenge, the Radiometric Measurements and Evaluation team has identified three immediate goals as near term objectives:

(1) **Disseminate NREL PV Radiometric expertise** by producing documentation such as a technical manual, guide, technical report and/or journal article describing NREL PV Module and System Performance and Engineering Project "best practice" for radiometric instrumentation, methods, and practices.

(2) **Maintain radiometric calibration traceability** to the World Radiometric Reference (WRR) by regular intercomparison of the two (2) PV absolute cavity radiometers with the NREL reference absolute cavity radiometers, especially those participating in the upcoming 8th International Pyrheliometric Comparisons to be conducted in Davos, Switzerland in October 1995. Continue liason and traceability to the National Institute of Standards and Technology Radiometric Physics Division for spectral radiometric calibrations, and improving radiometry for PV applications in general.

and

(3) **Increase participation in consensus standard development and validation** by actively participating in consensus standards organizations, such as the American Society of Testing and Materials (ASTM), Institute of Electrical and Electronic Engineers (IEEE), and the Council for Optical Radiation Measurements (CORM), to aid in development and validation of radiometric standards related to PV performance and evaluation applications.

These goals will be in addition to the on-going radiometric instrumentation and analysis support provided on a daily basis to the PV Module and System Performance and Engineering Project and interactions with the PV industry.

Finally, the team will continue to maintain a close collegial relationship with the Solar Radiation Resource Assessment Program, keeping up-to-date on measured and modeled radiometric products, models, and data, as well as proper application and interpretation of PV performance modelling and analysis based on those products. Hopefully, the team can provide engineering perspective on PV performance, calibrations, and evaluation as useful input to the SRRAP for the development of appropriate, useful products.

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13. ABSTRACT *(Maximum 200 words)*

This reports documents presentations and discussions held at the PV Radiometrics Workshop, conducted July 24-25, 1995, in Vail, Colorado. The workshop provided a forum for technical presentation and discussion of the state-of-the-art and immediate and long-term needs for solar and optical radiometric measurements and data as applied to improving photovoltaic engineering, testing, performance evaluation, and performance prediction. Twenty-six attendees from industry, utilities, national laboratories, and universities provided expertise and insight during discussions of current and future radiometric needs and issues regarding photovoltaic applications.

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