U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

DOE Solar Energy Technologies Program Peer Review

Solar Radiometry & Metrology

D. R. Myers, A.M. Andreas, I.M. Reda, P. Gotseff, S.M. Wilcox, T.L. Stoffel, M. Anderberg, B.A. Kay

Denver, Colorado

April 17-19, 2007

Relevance/Objective

Quality and *quantity* of solar and optical radiation a critical driver for solar energy technologies

- Centralized source for traceable optical radiometric calibrations, measurements, and measurement expertise
- Characterize and monitor NREL and PV industry Solar Simulators and light sources used for performance testing, rating and labeling PV products.
- Develop, locate, and distribute information, solar radiation resource data, and models for Solar Energy Technology Program applications, stakeholders
- Integrated into the NREL quality system and audited for ISO17025 compliance for Reference Cell and Module Calibrations for PV Industry and Measurements and Characterization Task

Summary of Activities

- **Metrology / Consensus Standards Activities:** (Reda, Andreas, Myers, Kay)
  - Optical Radiometry Reference Standards traceable to World Radiometric Reference (WRR), National Institute of Standards and Technology (NIST)
  - Participate in American Society for Testing and Materials (ASTM), International Lighting Commission (CIE)

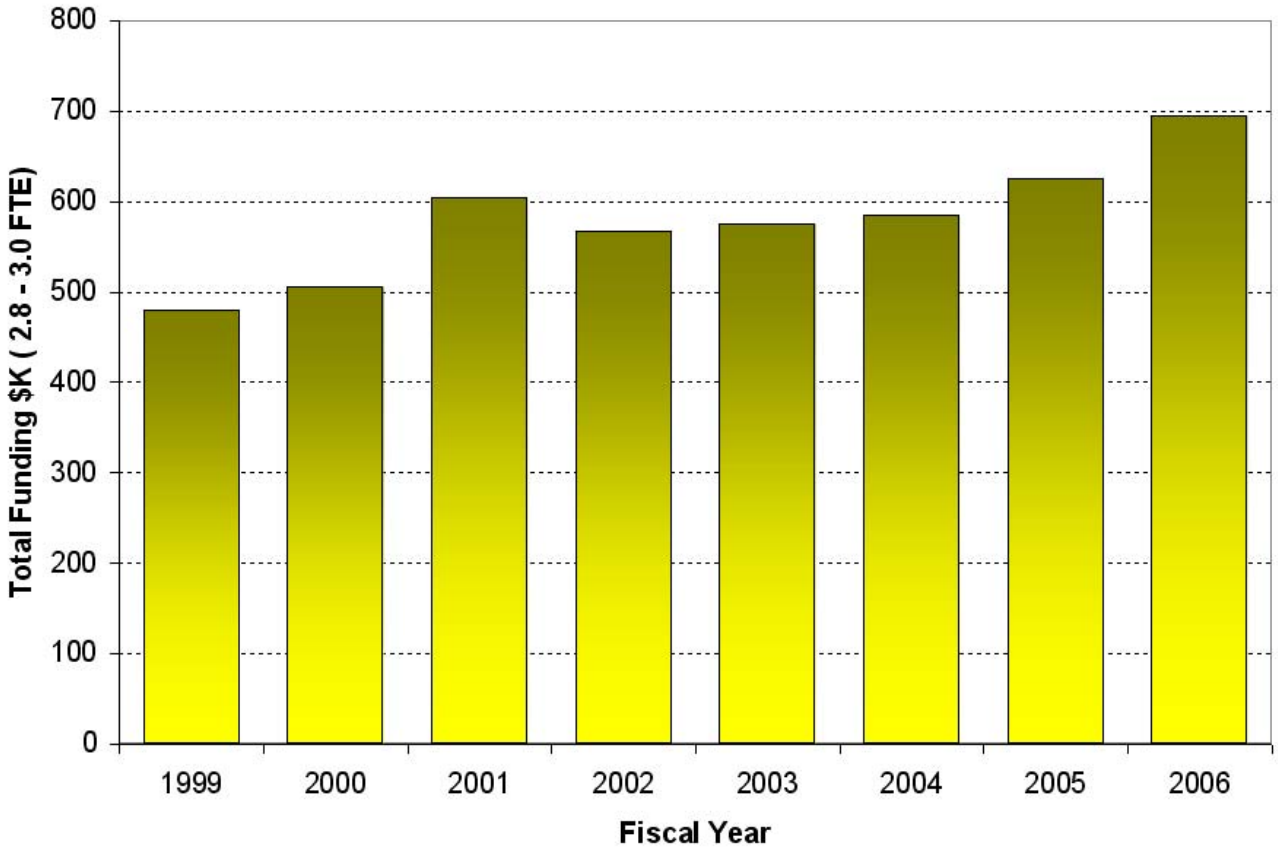
- **Calibration, Measurements, Data Analysis** (Andreas, Wilcox, Stoffel, Myers, Kay, Gotseff)
  - Broadband Outdoor Radiometer Calibrations BORCAL http://www.nrel.gov/srrl/borcal.html
    - Implement calibrations and reports in accordance with ISO 17025
    - On-line data base of radiometer calibration results/files (since 1996) http://www.nrel.gov.aim
  - Spectral Radiometer Calibrations
  - Measurement & characterization of NREL and PV Industry Solar Simulators

- **Baseline Solar Radiation and Meteorological Data** (Andreas, Stoffel, Gotseff)
  - 25 year record available on line http://www.nrel.gov/srrl and http://www.nrel.gov/midc

- **Broadband and Spectral Solar Radiation Data and Model Distribution Renewable Resource Data Center (Rredc) http://Rredc.nrel.gov**
  (Anderberg, Myers, Wilcox, Stoffel)
  - National Solar Radiation Data Base, Typical Meteorological Year (TMY2) Data Files
  - LBL Circumsolar Data Base Archive
  - Solar Radiation Data Manual for Flat Plate and Concentrating Collectors
  - Solar Radiation Data Manual for Buildings
  - SERI Solar Spectral Data Base, Clear Sky Broadband and Spectral Models (and documentation)
    - Bird & Hulstrom, Direct Insolation Simulation Code-DISC, SPCTRL2, SMARTS2
  - Links to NREL MAP SERVER and Solar Radiation Atlas

Budget History

Solar Radiometric Metrology FY 99- FY 06



Budget History

Project Task(s)	Total Value (FY 06)
Solar Radiometric Metrology	$173,000
Calibrations, Measurements, Data Analysis	$347,000
Model and Data Development, Identification, Distribution, and Analysis	$173,000
Grand Total FY 06 (2.9 Full Time Equivalent)	**$695,000**

Budget History

Cumulative Trends

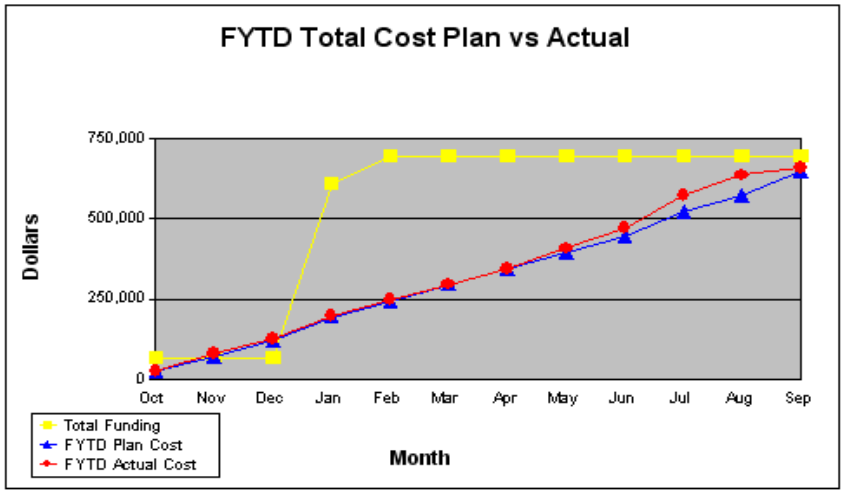
Fiscal Year 2006

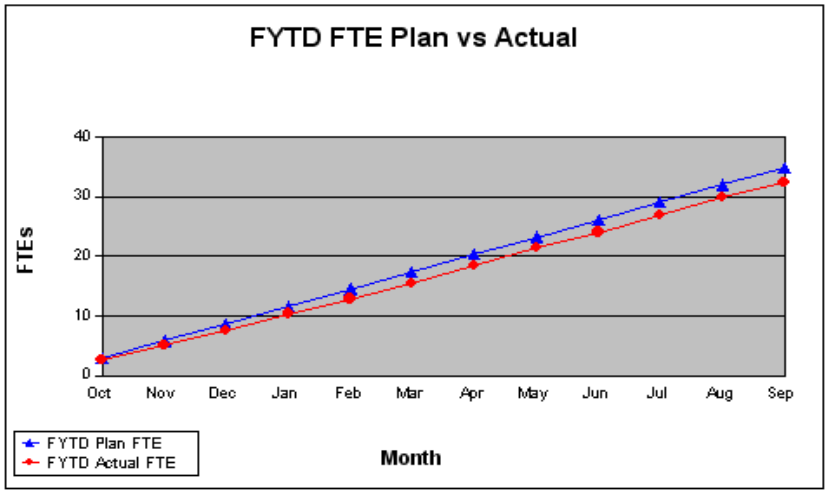
Project/Task Number: PVC6.PVC67301

Project/Task Name: SOLAR RADIOMETRY & M

Project/Task Leader: Daryl Myers

Project/Task Leader's Center Number: 5810





	Oct-05	Nov-05	Dec-05	Jan-06	Feb-06	Mar-06	Apr-06	May-06	Jun-06	Jul-06	Aug-06	Sep-06
Total Funding	68,893	68,893	68,893	610,000	695,000	695,000	695,000	695,000	695,000	695,000	695,000	695,000
FYTD Plan Cost	24,164	72,495	120,826	194,946	245,167	295,388	345,609	395,830	446,051	521,384	571,605	646,938
FYTD Actual Cost	25,845	81,932	126,401	197,346	247,644	295,960	346,309	409,540	470,042	572,969	635,727	659,068
FYTD Cost Variance	(1,681)	(9,437)	(5,575)	(2,400)	(2,477)	(572)	(700)	(13,710)	(23,991)	(51,585)	(64,122)	(12,130)
FYTD Plan FTE	2.90	5.80	8.70	11.60	14.50	17.40	20.30	23.20	26.10	29.00	31.90	34.80
FYTD Actual FTE	2.63	5.07	7.63	10.39	12.87	15.44	18.47	21.52	24.00	26.98	29.88	32.27
FYTD FTE Variance	0.27	0.73	1.07	1.21	1.63	1.96	1.83	1.68	2.10	2.02	2.02	2.53

Plan as of September 2006

Cost in whole dollars. FTE in monthly salaried FTEs. Total Funding includes Beginning GSO plus FYTD Authorized Amount.

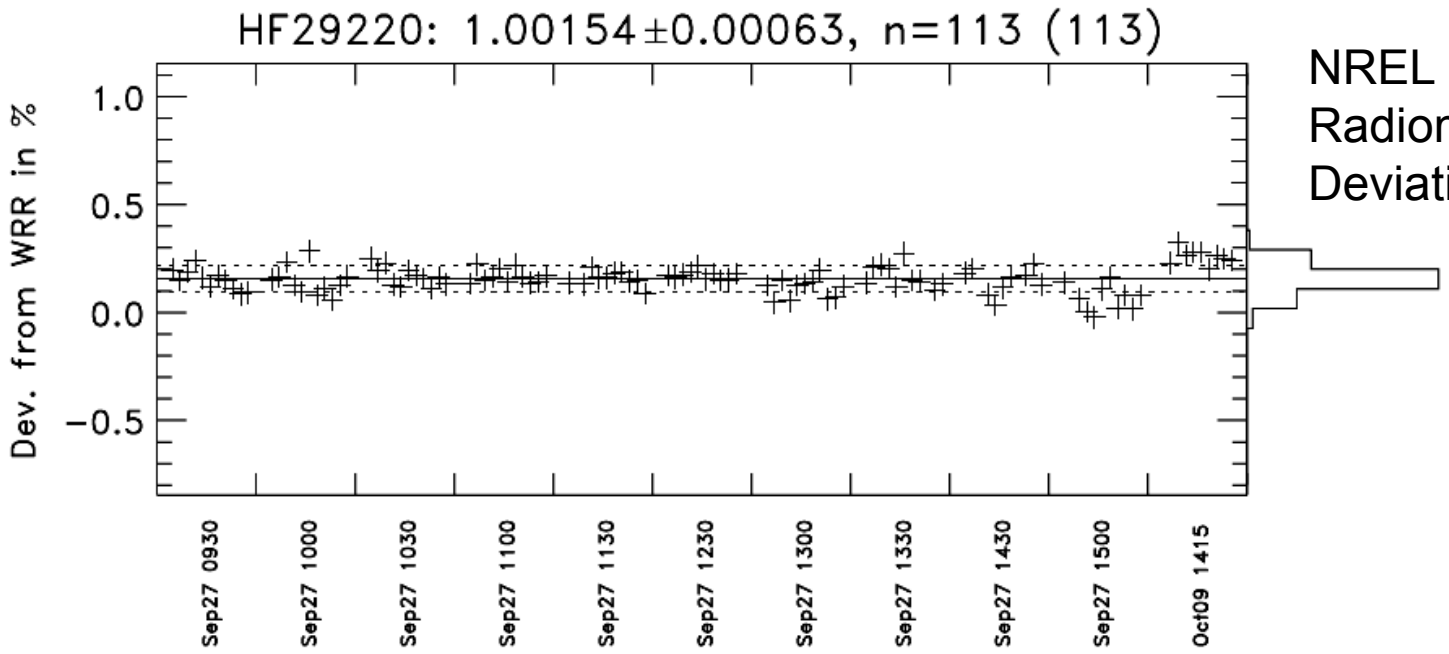
Accomplishments

- Transferred WRR to NREL Reference Cavity Radiometers Oct 2005, International Pyrheliometer Comparison X (IPC-X)
- Conducted NREL Pyrheliometer Comparison (NPC) Sep 2006, transferring WRR to 23 participating radiometers, and verifying stability of NREL WRR reference.
- Calibrated over 200 broadband solar radiometers and 10 spectroradiometer systems for research, industry, academia
- All metrology, including optical radiation, activities, passed American Association of Laboratory Accreditation (A2LA) ISO 17025 external audit with zero deficiencies (rare!)
- Twenty five characterizations of NREL and PV Industry solar simulators (flash and continuous)
- Responded to over 180 industry, academic, and research requests for technical data:
  - sources of broadband and spectral data (Local, City, State, Foreign Countries)
  - calibration and measurement methods
  - technical details of radiometers (accuracy, uncertainty, design)
  - solar radiation models

Accomplishments

- 200 GB of measured solar radiation data from MIDC downloaded by 28,000 visitors
- 580 GB solar radiation data and models from Rredc downloaded by 420,000 visitors
- Revisions to 3 ASTM Radiometer Calibration Standards Accepted by Society Ballot, July 2006.
- Developed and published Cloud Cover Modifier for Bird Clear Sky Model
- Characterized environmental influences on pyrheliometer direct beam calibration and measurement sources of error (~ 20 Watt per square meter)
- In co-operation with the World Meteorological Organization, using World Infrared Standard Group (WISG), developed NREL Infrared Reference Group (NIRG) of radiometers and calibration transfer method for infrared radiometers
  - Reducing infrared radiation measurement uncertainty from +/- 15 Watt per square meter to +/- 3 Watt per square meter.

Accomplishments

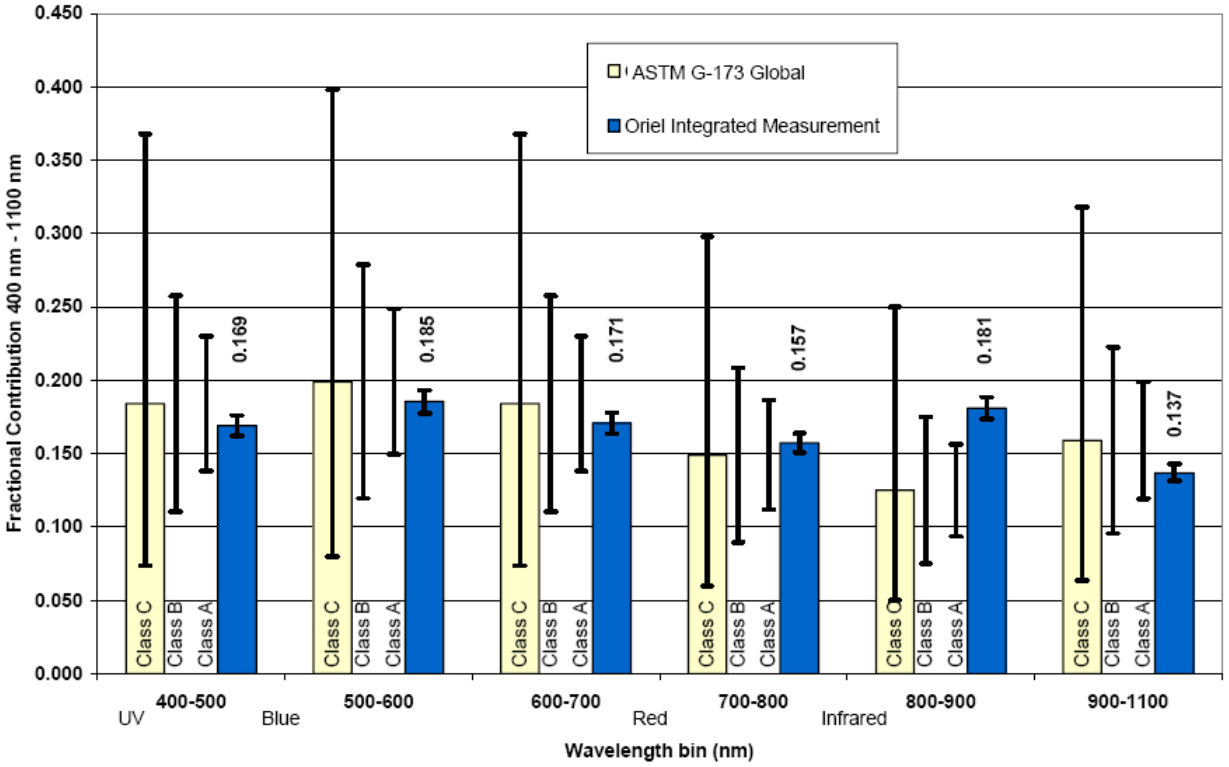


NREL Ref. Radiometer WRR Deviation

NREL Reference Cavity Radiometers

WMO/WRDC World Standard Group (WSG) Reference Cavity Radiometers

Define WRR



Sample of one of 25 solar simulator classifications referred to ASTM E927 Solar Simulator Classification Standard

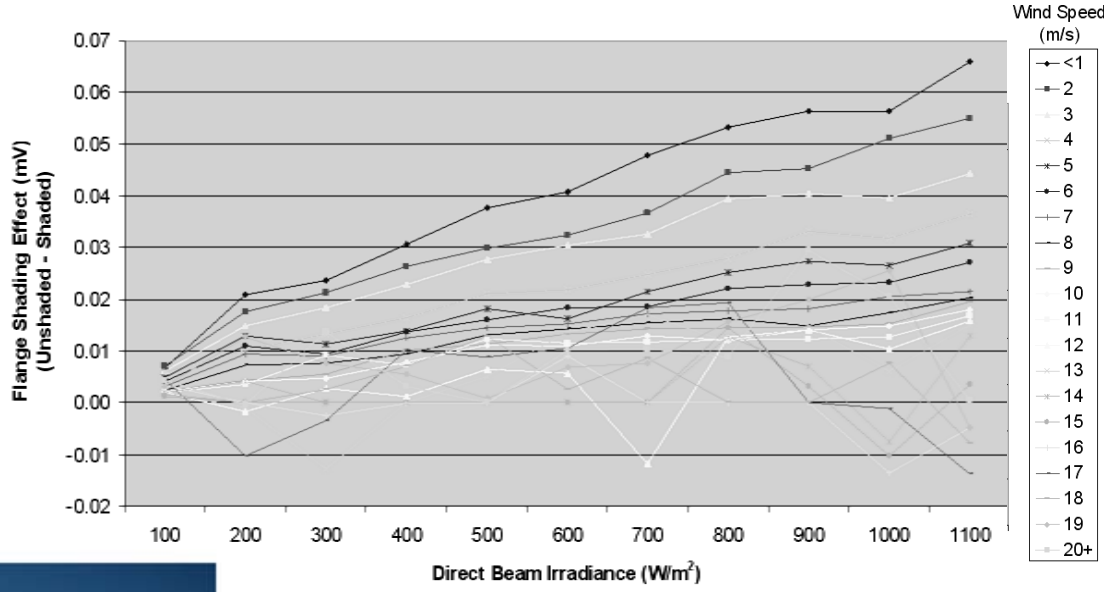
NREL designed & calibrated spectral measurement system at work in industry setting

Accomplishments

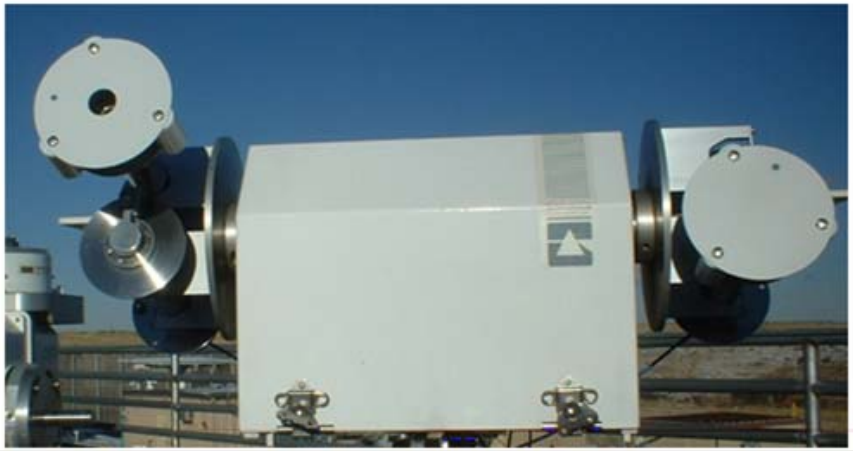
Experimental Correlations

DNI error signals with wind speed and irradiance (0.1 mV ~ 20 Wm^{-2})

Based on year of NREL/SRRL test data



Direct Normal Irradiance Instrumentation characterization experiment



Accomplishments

Revisions to 3 ASTM Radiometer Calibration Standards Accepted by Society Ballot, July 2006.

4	.09	REVISION OF E0816-95(2002) TEST METHOD FOR Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers WK6253 REVISE AS INDICATED(SEE VOLUME 14.04) (CONCURRENT WITH .0900) TECHNICAL CONTACT: DARYL R MYERS DARYL_MYERS@NREL.GOV (303) 384-6768	○ Affirmative ○ Affirm with comment ○ Negative ○ Abstain ○ Abstain with commen Deselect
5	.09	REVISION OF E0824-94(2002) TEST METHOD FOR Transfer of Calibration From Reference to Field Radiometers WK6252 REVISE AS INDICATED(SEE VOLUME 14.04) (CONCURRENT WITH .0900) TECHNICAL CONTACT: DARYL R MYERS DARYL_MYERS@NREL.GOV (303) 384-6768	○ Affirmative ○ Affirm with comment ○ Negative ○ Abstain ○ Abstain with commen Deselect
6	.09	REVISION OF G0167-00 TEST METHOD FOR Calibration of a Pyranometer Using a Pyrheliometer WK6249 REVISE AS INDICATED(SEE VOLUME 14.04) (CONCURRENT WITH .0900) TECHNICAL CONTACT: DARYL R MYERS DARYL_MYERS@NREL.GOV (303) 384-6768	○ Affirmative ○ Affirm with comment ○ Negative ○ Abstain ○ Abstain with commen Deselect

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Designation: E 816 – 05

Standard Test Method for
Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers[1]

Designation: G 167 – 05

Standard Test Method for
Calibration of a Pyranometer Using a Pyrheliometer[1]

INTRODUCTION

Designation: E 824 – 05

Standard Test Method for
Transfer of Calibration From Reference to Field Radiometers[1]

INTRODUCTION

Accurate and precise measurements of total solar and solar ultraviolet irradiance are required in: *(1)* the determination of the energy incident on surfaces and specimens during exposure outdoors to various climatic factors that characterize a test site, *(2)* the determination of solar irradiance and radiant exposure to ascertain the energy available to solar collection devices such as flat-plate collectors, and *(3)* the assessment of the irradiance and radiant exposure in various wavelength bands for meteorological, climatic and earth energy-budget purposes. The solar components of principal interest include total solar radiant exposure (all wavelengths) and various ultraviolet components of natural sunlight that may be of interest, including both total and narrow-band ultraviolet radiant exposure.

This test method for transferring calibration from reference to field instruments is only applicable to pyranometers and radiometers whose field angles closely approach 180° ... instruments which therefore may be said to measure hemispherical radiation, or all radiation incident on a flat surface. Hemispherical radiation includes both the direct and sky (diffuse) geometrical components of sunlight, while global solar irradiance refers only to hemispherical irradiance on a horizontal surface such that the field of view includes all of the hemispherical sky dome.

For the purposes of this test method, the terms pyranometer and radiometer are used interchangeably.

1. Scope

1.1 The method described in this standard applies to the transfer of calibration from reference to field radiometers to be used for measuring and monitoring outdoor radiant exposure levels. This standard has been harmonized with ISO 9847.

1.2 This test method is applicable to field radiometers regardless of the radiation receptor employed, but is limited to radiometers having approximately 180° (2π Steradian), field angles.

1.3 The calibration covered by this test method employs the use of natural sunshine as the source.

1.4 Calibrations of field radiometers may be performed at tilt as well as horizontal (at 0° from the horizontal to the earth). The essential requirement is that the reference radiometer shall have been calibrated at essentially the same tilt from horizontal as the tilt employed in the transfer of calibration.

1.5 The primary reference instrument shall not be used as a field instrument and its exposure to sunlight shall be limited to calibration or intercomparisons.

Note 1—At a laboratory where calibrations are performed regularly it is advisable to maintain a group of two or three reference radiometers that are included in every calibration. These serve as controls to detect any instability or irregularity in the standard reference instrument.

1.6 Reference standard instruments shall be stored in a manner as to not degrade their calibration.

1.7 The method of calibration specified for total solar pyranometers shall be traceable to the World Radiometric Reference (WRR) through the calibration methods of the reference standard instruments (Test Methods G 167 and E 816), and the method of calibration specified for narrow- and broad-band ultraviolet radiometers shall be traceable to the National Institute of Standards and Technology (NIST), or other internationally recognized national standards laboratories (Test Method G 138).

Major Events/Milestones

Solar Radiometry & Metrology Milestones:	Why?	Status:
Transfer World Radiometric Reference to NREL Reference Absolute Cavity Radiometers through results if IPC-X. 5/31/06	Establish and verify traceable reference for accurate, scientifically valid radiometric measurements Meet national and international criteria for high quality radiometric measurements	Results in WMO document IOM Report #91, WMO/TD No. 1320 PMOD/WRC internal Report, Davos, May 2006. I. Reda one of three Invited Experts to review IPC -X analysis and results at meeting at World Radiation Center, Davos Switzerland, Feb 6-10 2006.
Revise and submit ASTM pyrheliometer and pyranometer calibration standard documents for final ASTM Ballot approval. 7/31/06	Provide industry with state-of-the art (recently improved) knowledge on solar radiometric measurement techniques and expected uncertainties (accuracies) for outdoor performance	Three ASTM solar radiometer calibration standards balloted and approved with no negative comments, July 2006
Publish journal article on environmental influences on solar radiometer calibration errors. Report. 9/30/06	Metrology (calibration) data analysis identified source of systematic error in all direct beam resource/performance data.	**"Environmental Thermal Effects on the Eppley Normal Incidence Pyrheliometer"** to NREL publication process and to journal Solar Energy for formal external peer review process. Sep 28 2006.

Future Directions

- Further improve calibration and reduce uncertainty to improve quality of solar radiometric measurement data
- Update spectral calibration methods and reduce spectral calibration uncertainty with stable, high optical power, super-continuum “white light laser” source and detector based spectral scale
- Maintain support to Rredc; update models and data sources, continue to respond to technical requests as resources permit
- Utilize unique measurement and data acquisition capability of MIDC to conduct research on improved radiometer calibration and measurement instrumentation and characterization

- Summary
  - Task supports solar program with quality solar and optical radiation calibrations, measurements, and highly sought data.
  - Task responds to industry and research requests with high quality Information; feedback very positive!
  - Increasing strain on budget and personnel with increasing number of requests, need for improved measurements.