

**Solar Resource and Meteorological Assessment Project (SOLRMAP)**  
**Solar and Meteorological Station Options:**  
**Configurations and Specifications**

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## **Purpose**

This document provides guidance for standard measurement system configurations to produce solar resource information consistent with accuracy requirements for site-specific resource assessment and/or installed power system performance validation. The measured data will also be used for improving satellite-based modeling of solar radiation and for validation of solar resource forecasting methods. The configurations listed present a range of instrument accuracies from which to choose for the fundamental measurements as well as information necessary for data validation.

In support of the Solar Technologies Program, NREL will provide expert advice and assistance on configuring, installing and operating commercially available equipment for a solar radiation measurement station. Additionally, NREL will provide expert data analysis, including data quality assessment, archive the data and provide access to the historical and nearly real-time data via the internet through the Measurement & Instrumentation Data Center (<http://www.nrel.gov/midc>).

## **Background**

Accurate site-specific measurements of solar radiation resources are important for the design of solar energy conversion systems and for assessing installed system performance. Measuring the electrical output of a solar power plant is a fairly straightforward effort and can be accomplished with high accuracy. However, evaluating the efficiency of renewable energy conversion requires knowledge of the solar energy incoming to the plant as measured with commercially available radiometers with varying accuracies.

Estimates of historical (1991 – 2005) hourly solar irradiance from satellite-based cloud imagery and surface cloud observations have been used to produce the National Solar Radiation Database Update (NSRDB) [[http://rredc.nrel.gov/solar/old\\_data/nsrdb/1991-2005/](http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/)]. A limited amount of accurate measurements of solar irradiance were used to validate these models. Measurements from additional locations are needed to develop improved models and address research needs for developing solar radiation forecast methods.

High quality instruments are available from various manufacturers. Price estimates from three manufacturers are included here for instruments with which we have experience. *This list does not constitute an endorsement, nor does it preclude the selection and use of equipment from other manufacturers.* However, equipment not listed here may be incompatible with the NREL calibration procedures or data acquisition and distribution infrastructure. The prices listed here are approximate and based on manufacturer's price lists. Firm and final pricing is available by quote from the manufacturers.

## Equipment

Two basic instrument packages are described below for making site-specific solar resource measurements or for instrumenting a solar energy conversion power plant to support operational needs for system performance and/or solar resource forecasting. The two configurations offer a range of measurement uncertainty and maintenance requirements. Each configuration provides sub-hourly data for the direct normal irradiance (DNI), diffuse (DIFF) irradiance, and the global horizontal (GH) irradiance, as well as ambient air temperature (TEMP), wind speed (WS) and direction (WD), and relative humidity (RH). Additional instrumentation can be added as required for site-specific applications, e.g., plane-of-array (POA) irradiance, barometric pressure (BP), and/or precipitation (PRECIP). The estimates below do not include infrastructure costs, such as underlying support surfaces or structures, electrical power, telephone/internet connectivity, etc.

Both configurations require a location for the instruments that provides good daily solar access throughout the year. This should be an area with a clear horizon without any obstructions that might shade the instruments or introduce reflected solar radiation (for instance, a building roof is often a good location). But the location should also have safe and secure access, which is required for regular equipment inspections.

Equipment spares are recommended to provide replacement due to failure and/or calibration, especially for the radiometers. Please consult with the manufacturer or NREL to determine the optimum types and quantity of equipment spares.

A total sky imager can supplement the data recorded from either recommended configuration. This all-weather instrument provides sky images and cloud amounts important for interpreting the coincident solar radiation and meteorological data. (See <http://www.yesinc.com/products/cloud.html> or [http://www.nrel.gov/midc/srrl\\_bms/](http://www.nrel.gov/midc/srrl_bms/))

### Configuration 1 – Silicon Photodiode Radiometers – Lower Cost / Lower Maintenance / Higher Measurement Uncertainty Potential

This lower-cost option provides solar measurements adequate for many applications and also requires a lesser amount of maintenance. The Rotating Shadowband Radiometer (RSR) system design is based on the fast response (10  $\mu$ sec) of the silicon photodiode detector used in the pyranometer. The RSR



system includes a data logger that provides additional input channels for optional sensors. The base configuration includes measurements for temperature, humidity, wind speed, and wind direction. The communications interface is a telephone modem (optional internet connectivity is highly desirable to allow for more frequent data access and display). This system is self-powered via photovoltaic panels and is desirable for use in areas without reliable grid electrical power. Instrumentation, measurement parameters, equipment purchase price, installation labor, and estimated measurement uncertainties for Configuration 1 are summarized in Table 1. Typical RSR installations are shown in Figure 1.

Figure 1. RSR installations at NREL (Left) and at Pueblo, Colorado (Right).

**Table 1. Equipment Configuration 1 – Lower Cost / Lower Maintenance / Higher Measurement Uncertainty Potential**

	Instrument	Data Parameter(s)	Purchase Price	Installation (Person-Hrs)	Data Uncertainty*	
					Bias (mean deviation)	Random (std deviation)
Baseline Configuration	Rotating Shadowband Radiometer System (Irradiance, Inc Model RSR2)	Measured GH and DIFF irradiances. Computed DNI. Includes secondary sensor, CR800 data logger with air temperature and gill shield.	\$9,100	4	-3.5 to -7.5% DNI +1.0 to -1.2% GH +3.0 to -0.2% DIF	16 to 19%† 4 to 6% 5 to 6%
	Mounting Method	• Simple pipe for flat surface (e.g. concrete pile)	\$95	4	N/A	N/A
		• Ballast plate for flat surface (e.g., roof)	\$185			
		• Tripod for ground mounting (e.g., desert floor)	\$575			
	Choose Power Supply (as needed)	10-watt module, charge controller and battery for high insolation (>3 kWh/m <sup>2</sup> day average during minimum month)	\$500	N/A	N/A	N/A
		20-watt module, charge controller and battery (>2 kWh/m <sup>2</sup> /day minimum)	\$700			
	Temperature and Relative Humidity	Campbell CS 215	\$535	1	±0.2° temp ±2% RH	Not evaluated
	Barometric Pressure	CS106	\$885	1	±1 mbar	Not evaluated
Wind	03001-L RM Young WS/WD set with supporting 10 ft mast	\$1050	2	±5° WD ±1.5% WS	Not evaluated	
Communications	Telephone wired modem	\$550	N/A	N/A	N/A	
Optional Upgrades	Licor LI-200 pyranometer (optional)	POA for fixed tilt collector	\$270	2	+2.8 to -2.0%	3 to 8%
	Texas Electronics Tipping Bucket (Campbell p/n TE525-20)	PRECIP	\$615	3	± 0.01"	Not evaluated
	Communications Upgrades	Ethernet (hard wired)	\$640	N/A	N/A	N/A
		Ethernet (cellular gprs/edge)	\$1125			
Data logger upgrade to Campbell CR-1000	Required for meteorological instruments and optional solar instruments	\$700	N/A	N/A	N/A	
<b>Total</b>	Minimal configuration	\$12,620	12			
	With all options	\$15,555	17			

\* Estimated measurement uncertainty for sub-hourly data intervals over a wide range of zenith angles, based on annual instrument calibrations traceable to national and international measurement standards and other NREL evaluations. Assumes proper equipment installation and regular maintenance at two to three times per week. Radiometer uncertainty ranges account for spectral irradiance variations due to changes in atmospheric conditions. Uncertainties for daily, monthly, or annual means may be less. Radiometer uncertainties do not include data logging uncertainties.

† High random error may be exaggerated due to slower response of reference thermopile instruments (10 µsec vs. 1 sec)

## Configuration 2 – Thermopile Radiometers – Higher Cost / Higher Maintenance / Lower Measurement Uncertainty Potential

This option, while of greater cost for both equipment acquisition and on-going maintenance, provides the lowest uncertainty measurements of global, direct beam, and diffuse solar irradiance. This configuration is recommended for operators requiring the best possible solar resource measurements for assessing power plant performance.

While a specific application may not require all three of the recommended solar components, one critical advantage of this option is the ability to maintain much tighter controls on data quality assessment through redundant measurements. That is, data quality tests include checks of internal consistency based upon:

$$GH = DNI * \cos(Z) + DIFF$$

where,  $Z$  = solar zenith angle for the time of measurement.

Thus, removing one or more of the solar components that do not directly support a particular application will result in a much higher post-measurement uncertainty.

This system requires reliable electrical power or an adequate uninterruptible power supply such that electricity can be maintained without interruption for many weeks. A stand-alone PV system rated for at least 600 Watts with battery storage has been used successfully for this purpose. A site specific analysis should be done if PV power is required.

Maintenance for this option is more critical than Configuration 1. Daily instrument cleaning and tracker alignment checks are necessary to maintain the lower measurement uncertainty potential for this option. Routine preventative maintenance can be accomplished in about 15 minutes per visit. Corrective maintenance (e.g., solar tracker failure) can require several hours. Without a commitment to this ongoing maintenance schedule, much of the advantage afforded by higher instrumentation cost will be lost. Instrumentation, measurement parameters, equipment purchase price, installation labor, and estimated measurement uncertainties for Configuration 2 are summarized in Table 2. The system installation used for the DOE Atmospheric Radiation Measurement Program is shown in Figure 2 (see also <http://www.arm.gov/about>).

### **Maintenance**

Proper operations and maintenance of the measurement system is critical for the production of accurate solar resource data.

Measuring solar radiation requires clean optics to prevent attenuation of the solar signal that reaches the instrument sensor and accurate solar tracking for proper alignment of instruments with the solar disk. Site operators will be responsible for maintaining the instrumentation as required by the application.

Studies have shown that the instrumentation in Configuration 1 is less prone to soiling from environmental conditions than that specified in Configuration 2 (see <http://www.nrel.gov/docs/fy99osti/25374.pdf>, section 8.3). The recommended interval for cleaning instruments in Configuration 1 is two to three times a week, depending on weather conditions, whereas *daily maintenance* is required for Configuration 2 to fully exploit the reduced uncertainty of the instruments. NREL has developed real-time data quality control test methods that can be used to alert

the station operator of suspected equipment problems. On-site maintenance needs for either configuration are summarized in Table 3. A permanent record of maintenance activities is a critical tool for evaluating the quality of the measured data (see <http://www.nrel.gov/midc/apps/maint.pl?BMS>).

### Data processing/analysis

NREL may provide expert analysis and quality checks for all data. Data may be acquired in near-real time (depending on internet connectivity at the station location) and analyzed for quality. NREL may provide easy internet access to sanctioned data sets in a standard format. Data may appear on an NREL web site, similar to this (data from the Nevada Power Clark Station): <http://www.nrel.gov/midc/npcs/>

Special access limitations can be provided for proprietary data sets. To help maintain the greatest potential for the site operator's investment, NREL may also fund data analysis, distribution costs and provide expertise as required to understand and interpret the data.



Figure 2. Unshaded pyranometer (Left) for GH measurement, shaded pyranometer and pyrgeometer (on solar tracker horizontal platform) for DIFF and downwelling longwave (infrared – for atmospheric science study), and pyrhelioscope (on side of solar tracker) for DNI measurements at the DOE/ARM Southern Great Plains station near Lamont, Oklahoma.

**Table 2. Equipment Configuration 2 – Higher Cost / Higher Maintenance / Lower Measurement Uncertainty Potential**

	Instrument	Data Parameter(s) / comments	Purchase Price	Installation (Person-Hrs)	Data Uncertainty*	
					Bias (mean deviation)	Random (std deviation)
<b>Baseline Configuration</b>	<b>Pyrheliometer</b>					
	Eppley Model NIP	DNI	\$2,350 <sup>1</sup>	2	+0.46 to -0.53%	0.4 to 0.6%
	Kipp & Zonen Model CH1		\$3,500 <sup>2</sup>		+0.23 to +0.1%	0.4 to 0.5%
	<b>Ventilated Pyranometer</b>					
	Eppley Model PSP w/VEN ventilator	GH	\$3,200 <sup>1</sup>	6	+1.6 to -11.3%	2 to 8%
	Kipp & Zonen Model CM22 w/CV-2 Ventilator and CVP-2 Power supply		\$9,016 <sup>2</sup>		+0.6 to +0.4%	2 to 3%
	<b>Ventilated Pyranometer</b>					
	Eppley Model 8-48 w/VEN ventilator	DIFF	\$2,475 <sup>1</sup>	6	±5% of reading or 10 W/m <sup>2</sup>	±3W/m <sup>2</sup>
	Kipp & Zonen Model CM22 w/CV-2 ventilator and CVP-2 Power supply		\$9,016 <sup>2</sup>		±2% of reading or 5 W/m <sup>2</sup> +	±3W/m <sup>2</sup>
	<b>Automatic Solar Tracker</b>					
Eppley SMT-3	(Radiometers and ventilators installed on solar tracker. Includes tripod or mount†, shade mechanism, and other accessories.)	\$18,975 <sup>1†</sup>	4	<0.1° (1/50 5°FOV)	±0.02° (1/250 5°FOV)	
Kipp & Zonen Model 2AP-GD		\$29,350 <sup>2</sup>		<0.05° (1/100 5°FOV)	±0.01° (1/500 5°FOV)	
<b>Meteorological Tower</b>						
Campbell Scientific	(Tripod 10 ft tower supports data logger and meteorological instruments:		4	N/A	N/A	
CM10 10 ft steel tripod tower		\$450				
ENC12/14 Enclosure for logger		\$205				

	<b>Meteorological Instruments</b> Vaisala HMP-50C Temp & RH	Co-located meteorological measurements of air temperature, relative humidity, wind speed, and wind direction	\$400	2	N/A	N/A
	Campbel 41003-5 Radiation Shield		\$120			
	03001-L RM Young WS/WD set		\$650			
	<b>Data Logger</b> Campbell Scientific, Inc. Model CR1000	Programmable control and data acquisition system. Includes extended temperature range and 4MB memory	\$1,640	6	(OFFSET) 22 $\mu$ V ( $\sim$ 2-3 Wm <sup>-2</sup> at 7 $\mu$ V/W)	4.2 $\mu$ V ( $\sim$ 0.5 Wm <sup>-2</sup> at 7 $\mu$ V/W)
<b>Telephone Modem</b> Campbell Scientific, Inc. Model COMM220	(Access data logger recordings by land line)	\$400	2	N/A	N/A	
<b>Miscellaneous</b>	Cabling, connectors, conduit, hardware, etc.	\$400	3	N/A	N/A	
<b>Optional Upgrades</b>	<b>Network Link Interface</b> Campbell Scientific, Inc. Model NL100	(Access data logger recordings by internet connection to NREL/MIDC)	\$500	2	N/A	N/A
	<b>Ventilated Pyranometer</b> Eppley Model PSP w/VEN ventilator	POA for tracking flat plate collector	\$3,200 <sup>1</sup>	2	$\pm$ 1.6% ‡	2 to 3%
	Kipp & Zonen Model CM22 w/CV-2 Ventilator and CVP-2 Power supply		\$9,016 <sup>2</sup>			
	<b>Ventilated Pyranometer</b> Eppley Model PSP w/VEN ventilator	POA for fixed tilt collector	\$3,200 <sup>1</sup>	2	+1.6 to -11.3%	2 to 8%
	Kipp & Zonen Model CM22 w/CV-2 Ventilator and CVP-2 Power supply		\$9,016 <sup>2</sup>			
<b>Barometer</b> Vaisala CS106	BP	\$590	1	$\pm$ 1 mbar	Not evaluated	
<b>Total</b>	<b>Base system</b>		\$31,265 <sup>1</sup> \$55,147 <sup>2</sup>	45	N/A	
	<b>With all options</b>		\$38,355 <sup>1</sup> \$73,869 <sup>2</sup>	52		

<sup>1</sup> Eppley Configuration

<sup>2</sup> Kipp & Zonen Configuration

† SmartTracker estimate includes \$800 allowance for tripod or mounting fixture, not supplied by Eppley

\* Estimated measurement uncertainty for *sub-hourly data intervals* over a wide range of zenith angles based on annual instrument calibrations traceable to national and international measurement standards and other NREL evaluations.

Assumes proper equipment installation and regular daily maintenance. Uncertainties for daily, monthly, or annual means may be less. Radiometer uncertainties do not include data logging uncertainties.

‡ Uncertainties for tracking plane of array radiometers assume a limited range of solar incident angles

**Table 3. Maintenance Items**

<b>Item</b>	<b>Comments</b>	<b>Approximate Time*</b>
Cleaning and inspection	Radiometer optics require cleaning using distilled water and a clean, lint-free cloth. Minimal training and expertise are necessary, but a commitment to quality and thoroughness is required.	5-10 minutes
Tracker alignment check	<u>Configuration 1:</u> Confirm shading band rotation is occurring on time (2/minute). <u>Configuration 2:</u> The tracker is software controlled and does not require regular maintenance. Proper operation can be quickly ascertained visually through the use of the built-in alignment target.	2 minutes
On-site troubleshooting	Assistance may be required for on-site troubleshooting by NREL for identified equipment problems as they occur. This may involve an instrument swap for difficult failures.	Highly variable – average of 1-2 hours per month.
Annual calibration swaps	Remove/replace radiometers during recalibration at NREL.	Four hours per year
Weather Observation	During maintenance, the operator can record cloud amount and other weather conditions relevant to interpreting the measured data.	5 minutes

\* Time estimates exclude travel to/from the equipment location.

### **Data Uses**

Developers can use the data for site resource analysis and to support site evaluations in conjunction with other large-scale solar resource databases. Plant operators can use the data sets for analysis of plant operations and conversion efficiencies. NREL will use the data for on-going research, including refinement of the long term solar resource and its variability at the site, advancing model development for direct normal irradiance using satellite imagery, and for validating solar resource forecasting methods currently under development.

### **Educational Cooperatives**

Where feasible and compliant with the needs or restrictions of power plant operators, NREL will encourage collaboration with nearby education institutions to involve students in measurement station operations. Students could be engaged to perform station maintenance (visiting the site to clean instruments and check operations in lieu of plant personnel) and to use the data for collaborative research involving the power plant operator and NREL.



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## Radiometer Manufacturers & Distributors

### **Analytical Spectral Devices, Inc.**

5335 Sterling Drive, Suite A  
Boulder, CO 80301

Telephone: (303) 444-6522

Telefax: (303) 444-6852

<http://www.asdi.com>

***Spectral Irradiance Measurements***

### **Brusag**

Chapfwiessenstrasse 14

CH-8712 Stäfa

Switzerland

Telephone: +41 1 926 74 74

Telefax: +41 1 926 73 34

***Automatic Solar Trackers***

### **Campbell Scientific, Inc.**

815 West 1800 North

Logan, Utah USA 84321-1784

Telephone: 435.753.2342 (Info)

Telephone: 435.750.9681 (Orders)

Telefax: 435.750.9540

Email: [info@campbellsci.com](mailto:info@campbellsci.com)

<http://www.campbellsci.com>

***Data Logger Systems & Weather Stations***

### **Casella London Limited**

Regent House

Britannia Walk

London N1 7ND

Telephone: 01-253-8581

Telex: 26 16 41

***Radiometers***

### **Davis Instruments, Corp.**

3465 Diablo Ave.

Hayward, CA 94545, USA

Telephone: (510) 732 9229

Telefax: (510) 670 0589

<http://www.davisnet.com>

***Weather Stations***

### **DAYSTAR**

3250 Majestic Ridge

Las Cruces, NM 88011

Telephone: (505) 522-4943

<http://www.raydec.com/daystar>

***Radiometers***

### **Delta-T Devices Ltd**

130 Low Road, Burwell

Cambridge, CB25 0EJ

UK

***Radiometers, Weather Stations and Data Loggers***

U.S. Distributor:

Gary L. Woods, Sales Manager

[garywoods@dynamax.com](mailto:garywoods@dynamax.com)

[www.dynamax.com](http://www.dynamax.com)

800-896-7108 - Toll Free

281-564-5100

281-564-5200 - Fax

### **EKO 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

<http://www.eko.co.jp/eko/english/03/a.html>

***Radiometers, Trackers, Data Loggers***

U.S. Distributor:

SC-International, Inc.

346 W. Pine Valley Drive

Phoenix, AZ 85023

Telephone: (602) 993-7877

Telefax: (602) 789-6616

### **The Eppley Laboratory, Inc.**

12 Sheffield Avenue

Newport, RI 02840

Telephone: (401) 847-1020

Telefax: (401) 847-1031

<http://www.eppleylab.com/>

***Radiometers, Trackers, Data Loggers***

(Continues)

**Hukseflux Thermal Sensors B.V.**

Elektronicaweg 25  
2628 XG Delft  
The Netherlands  
Telephone: +31-15-2142669  
Fax: +31-152574949

**Radiometers****Hukseflux U.S. Sales Representative**

Robert Dolce  
HuksefluxUSA  
P.O. Box 850  
Manorville, NY 11949  
631-251-6963  
E-mail: rdolce@HuksefluxUSA.com

**Irradiance. Inc.**

41 Laurel Drive  
Lincoln, MA 01773 USA  
Phone/Fax (781) 259-1134  
<http://www.irradiance.com/rsr.html>

**Rotating Shadowband Radiometer (RSR)****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

<http://www.kippzonen.com>

**Radiometers, Trackers, Data Loggers****US Sales Representative for K&Z:**

Joan Flamino  
Kipp & Zonen  
125 Wilbur Place  
Bohemia, NY 11716  
(631)589-2065 ext 25  
(631)589-2068 fax

**LI-COR, Inc.**

4421 Superior Street  
Lincoln, NE 68504  
Telephone: (402) 467-3576  
(800) 447-3576  
Telefax: (402) 467-2819  
<http://licor.com/>

**Radiometers, Data Loggers, Weather Stations****Matrix, Inc.**

537 S. 31st St.  
Mesa, AZ 85204  
Telephone: (480) 832-1380

**Radiometers****Medtherm Corporation**

P.O. Box 412  
Huntsville, AL 35804  
Telephone: (256) 837-2000  
Telefax: (256) 837-2001  
<http://www.medtherm.com>

**Cavity Radiometers****Middleton Solar**

factory 20, 155 Hyde Street  
Yarraville, Victoria 3013 Australia  
+61-3-9396 1890  
+61-3-9689 2384 (Fax)

**Radiometers****Ocean Optics, Inc.**

830 Douglas Ave.  
Dunedin, FL 34698 USA  
Telephone: 727.733.2447  
Telefax 727.733.3962  
<http://www.oceanoptics.com>

**Spectroradiometers****European Sales Office:**

Geograaf 24  
6921 EW DUIVEN  
The Netherlands  
+31 (0) 26 319 0500  
Fax +31 (0) 26 319 05 05

**PH. Schenk GmbH & Co KG**

Jedleseer Strasse 59  
A-1210 Wien, Austria  
Telephone: (+43/1) 271 51 31-0  
Telefax: (+43/1) 271 12 28 12  
E-Mail: office@schenk.co.at  
<http://www.schenk.co.at/schenk>

**Radiometers****Solar Light Company**

721 Oak Lane  
Philadelphia, PA 19126-3342  
Telephone: (215) 927-4206  
<http://www.solar.com/>

**Radiometers****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  
<http://www.yesinc.com/>

**Radiometers, Data Systems, Sky Imagers**