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Current Issues in Terrestrial Solar Radiation Instrumentation for Energy, Climate and Space Applications

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Current Issues in Terrestrial Solar Radiation Instrumentation for Energy, Climate, and Space Applications

T.L Stoffel, I. Reda, D.R. Myers, D. Renne, S.W. Wilcox, J. Treadwell

Abstract. Reductions of uncertainty in terrestrial solar radiation measurements are needed to validate the Earth's radiation balance derived from satellite data. Characterisation of solar energy resources for renewable technologies requires greater time and spatial resolution for economical technology deployment. Solar radiation measurement research at the National Renewable Energy Laboratory addresses calibrations, operational characteristics, and corrections for terrestrial solar radiation measurements. We describe progress in measurements of broadband diffuse-sky radiation, and characterisation of field instrument thermal offsets and spectral irradiance. The need and prospects for absolute references for diffuse and longwave terrestrial solar radiation measurements are discussed. Reductions in uncertainty of broadband irradiance measurements from tens of watts per square meter to a few (one to two) watts per square meter are reported, which reduce time and labour to quantify and identify trends in artificial optical radiation sources, terrestrial solar radiation, and the Earth's radiation budget.

1. Introduction

Solar radiation is the energy source driving the Earth's weather and climate, and the source of organic and renewable energy sources that can mitigate anthropogenic greenhouse gas emissions. Technical issues relating to climate change and renewable energy options require improved accuracy of solar broadband and spectral measurements at the Earth's surface. The Intergovernmental Panel on Climate Change (IPCC)[1] and World Climate Research Program (WCRP)[2] of the World Meteorological Organisation (WMO), the U.S. Global Change Research Program (USGCRP) [3], encourage research in climate change detection. Such research is conducted by the WMO WCRP Baseline Surface Radiation Network (BSRN) [4], the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) [5] Program, and the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) [6] program. Effective deployment of renewable energy technologies such as photovoltaic and solar thermal conversion systems requires high temporal and spatial resolution and absolute accuracy.

The U.S. DOE National Renewable Energy Laboratory (NREL) has an active solar radiation measurement program with excellent capabilities, and it participates in the ARM, BSRN, and NASA/EOS satellite remote sensing validation projects. We describe technical issues and research results associated with broadband and spectral solar irradiance measurements related to these projects.

2. Broadband Shortwave Radiation

Shortwave solar radiation is defined as the spectral band from 285 nanometers (nm) to 2400 nm. Some objectives of climate change programs are to detect changes in the Earth's *radiation budget*, the difference between incoming (downwelling) and outgoing (upwelling) radiation, and changes in *radiative forcing*, the ratio of fluxes in one atmospheric state to the flux in a "clear" atmosphere. Climate modeller's clear-sky models consistently over-estimate shortwave radiation with respect to the best measurements available [7,8]. Attempts to resolve the discrepancies have led to improved knowledge of measurement-error sources.

On a horizontal surface, the total (global) radiation, I_g, is the sum of the vertical component of the direct beam, I_d, and the diffuse-sky radiation, I_s, or

$$I_g = I_d \cos(z) + I_s, \qquad (1)$$

where z is the solar zenith angle. Radiation reflected from the ground, clouds, and atmosphere, and longwave (> 3000 nm) radiation emitted by the Earth, propagate as upwelling radiation.

Pyranometers measure sky-diffuse and global shortwave radiation (180° field of view) and pyrheliometers measure the direct beam, (5° field of view). Diffuse measurements are made by shading the sensor with a disk subtending the pyrheliometer field of view. Thermopile sensing elements are protected under quartz domes or windows.

Thermopile signals are proportional to the temperature difference between the hot (absorbing) and cold thermopile junctions. Infrared (IR) exchange between domes and sensors can contribute errors to the desired measurand[9].

2.1 Radiometer Calibrations

Radiometers are calibrated with respect to the World Radiometric Reference (WRR), the mean of group of well-characterised absolute cavity pyrheliometers. Absolute cavity radiometers are calibrated using the equivalence of electrical heating and solar radiation heating of thermopiles in thermal contact with cavity receivers [10,11]. WRR is maintained to an estimated uncertainty of 0.3%, by the WMO World Radiation Center (WRC) at Davos, Switzerland. Romero et al. [12] showed equivalence between WRR and the International System of Units (SI) radiation scale realised with cyrogenic absolute cavity radiometers to better than 0.05%. The WRR is transferred to working reference absolute cavity radiometers every five years during International Pyrheliometer Comparisons (IPC) conducted at the WRC.

Pyrheliometer responsivities are derived by direct comparisons with absolute cavity pyrheliometers. Pyranometer responsivities are derived using equation 1 to generate a reference global irradiance from an absolute cavity radiometer beam measurement and shaded (diffuse) pyranometer measurement. The responsivity (RS) of the diffuse-measuring pyranometer is derived in a shade-unshade calibration from

$$RS = (Vu-Vs)/[I_d*\cos(z)], \qquad (2)$$

where Vu and Vs are the unshaded and shaded voltages output from the sensor[13].

2.2 Direct-Beam Radiation

Combining the uncertainties due to the uncertainty in the WRR (0.3%), the transfer of WRR to working reference cavity radiometers (0.2%), the changing thermal environment (1.0%), and the data acquisition uncertainty (0.2%), typical uncertainty in thermopile pyrheliometers is about 2.0%, or 20 Watt/m² at 1000 W/m². The WMO BSRN network recommends an all-weather absolute cavity radiometer for measuring direct beam-radiation at BSRN stations [14].

Absolute cavity pyrheliometers operate with open apertures. To obtain the all-weather capability required, the effects of using various window materials and the impact on cavity pyrheliometer accuracy are currently under study [15].

2.3 Total Global-Horizontal Radiation

Absolute cavity pyrheliometer direct beam plus shaded pyranometer diffuse sky radiation give the most accurate value of total flux. Figure 1 shows that responsivities of pyranometers are not flat but are a function of zenith angle.

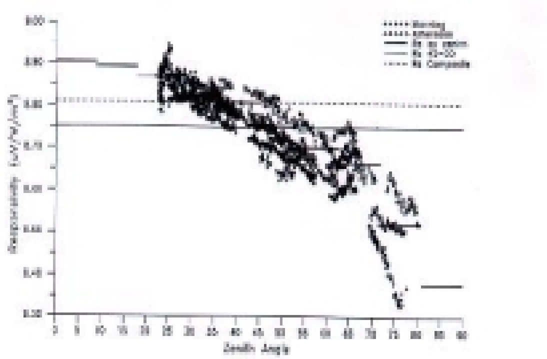

Figure 1. Cosine response of typical thermopile pyranometer.

Pyranometer data can be considerably improved using responsivities as a function of zenith angle, as shown in Figure 2.

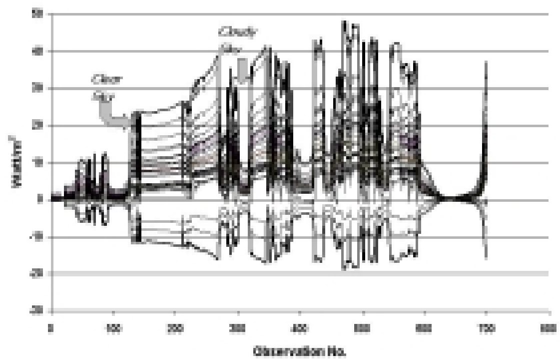

Figure 2. Difference between fluxes measured using a single versus zenith-angle-dependent responsivities for 30 thermopile radiometers.

Errors of up to 40 Watt/m² due to cosine response problems can be eliminated.

Another approach is fitting of individual cosine responses, Rs, with functions of the form:

$$Rs = \Sigma\, a_i \cos^{i} z_{i} \qquad (3)$$

for morning and afternoon zenith angles, z. Preliminary results show uncertainty reduced from ±1.8% to ±0.5% using 17 zenith angle bins (i=17) of 5° width [16].

NREL recently developed a modified shade-unshade calibration method that averages responsivity at equally spaced instrument azimuth orientations for 45° zenith angle. Uncertainty analysis for this method resulted in a factor of 3 (from ±6.4% to ±2.5%) reduction in clear-sky responsivities [13].

Zero offsets of -5 to -20 W/m² due to thermal imbalances in the instruments contribute to uncertainty in diffuse pyranometer measurements [17]. Figure 3 shows the distributions of dark (night-time) offsets for all black sensor (model PSP) in a U.S. continental climate (at NREL) and in a desert site in Saudi Arabia. The offset for a black-and-white (model 8-48) detector, insensitive to such offsets, is shown for comparison.

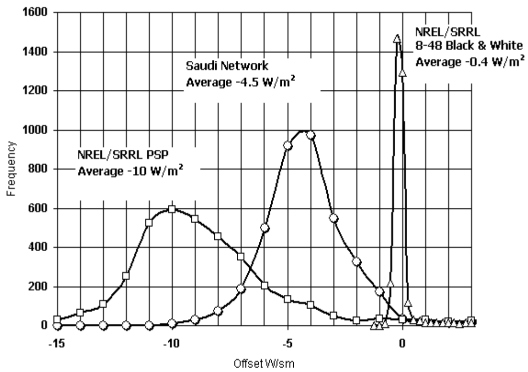

Figure 3. Distributions of dark offsets for NREL black-and-white (mean -0.4 W/m²) and all-black diffuse pyranometers (mean offset -10 W/m²), and Saudi Arabia all-black pyranometers (12-station network mean -4.5 W/m²)

Correction algorithms based on the observed correlation of night-time offsets, O, with net longwave IR radiation (downwelling less upwelling) and estimates of sky and radiometer temperatures based on Stefan-Boltzmann (σT^4) estimates [18] such as:

$$O=a+bW_{net}+cW_{inc}+d(T_{sky}-T_{amb})+eT_{amb} \quad (4)$$

where W_{net} is net IR, W_{inc} is downwelling IR, T_{sky} is $(W_{inc}/\sigma)^{1/4}$, and T_{amb} is ambient temperature in Kelvin. Figure 4 shows reductions in zero offset errors in diffuse data from -20 W/m² to -2 W/m² at NREL

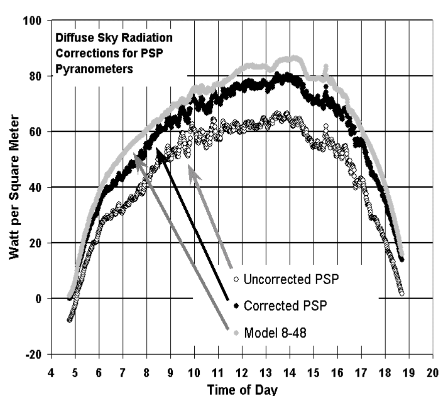

Figure 4. Zero offset corrections reduced from 20 W/m² to less than 2 W/m² for model PSP diffuse.

3. Longwave Radiation

Longwave upwelling and downwelling radiation is measured with pyrgeometers using a thermopile detector under silicon domes with interference filters to block the shortwave. IR exchange between the silicon dome, instrument body, and sensors are accounted for by monitoring temperatures of each with thermistors. The measurement equation becomes:

$$IR = K_o + K_1V+K_2\sigma T_c^4-K_3(T_d^4-T_c^4) \quad (5)$$

where the K's are calibration constants,V is the sensor millivolt signal, T_c and T_d are case and dome temperatures, and σ is the Stefan-Boltzmann constant.

Calibrations are generally performed by acquiring V at several temperatures. Two standard deviation uncertainty in the K's are on the order of 1%, resulting in ±3% accuracy. Outdoor comparison of pyrgeometers show ±6% differences between pairs of units. Blackbody calibrated units will be compared outdoor with a scanning absolute IR radiometer developed by the WRC to evaluate ways of reducing uncertainty in longwave measurements[19].

4. Spectral Irradiance Measurements

Determining where in the shortwave spectral models the overestimation of shortwave radiation may occur requires the best spectral measurements possible. Responsivities of ground-based spectrometers are determined with respect to standard spectral irradiance sources. Recent work by Kiedron et al. [20] and at NREL indicate that bias errors of up to ±2% can occur, based on intercomparisons of lamps from national standardising laboratories and third-party suppliers of spectral irradiance standards.

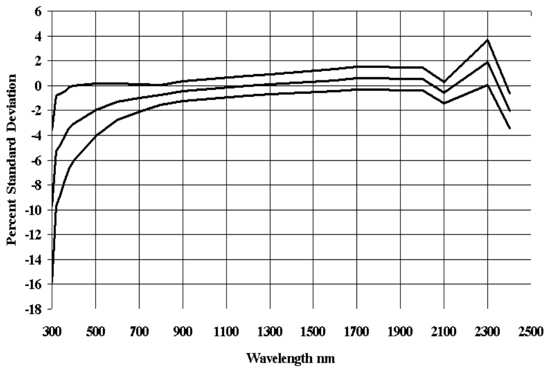

Figure 5. Envelope (mean ± 2 standard deviations) of spectral deviations between measured and reported spectral irradiance between six National Institute of Standards and Technology Spectral Irradiance Standard lamps at NREL.

Better alignment techniques and lower uncertainty in standard lamps are required to reduce uncertainty sources of this nature.

5. Conclusion

Accurate measurements of terrestrial solar radiation can enhance the deployment of solar energy conversion systems, confirm or deny long term climate change, and validate remote sensing estimates of solar energy flux and the Earth's radiation budget. Non-lambertian radiometer responses, zero offsets, and lack of high accuracy references for diffuse-sky and longwave radiometer calibrations contribute to discrepancies up to 40 W/m² between model and measured shortwave radiation. Characterisation of these effects identifies and removes errors on the order of magnitude of the discrepancies observed. Both longwave and diffuse-sky measurement accuracy could be increased if high accuracy references for these components could be developed. Improved spectral calibration standards and techniques are needed to reduce uncertainties in discrepancies between spectral models and measurements important for deriving greenhouse gas and aerosol radiative forcing related to detecting climate change.

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