Global, direct and diffuse radiation measurements at ground by the new Environmental Station of the University of Rome Tor Vergata

A. Spena and C. Cornaro
Facoltà di Ingegneria, Dipartimento di Ingegneria dell'Impresa
University of Rome Tor Vergata
Via del Politecnico, 1 – 00133 Rome – Italy
Tel. +390672597235/7233 Fax +390672597236
e-mail: spena@uniroma2.it, cornaro@uniroma2.it

INTRODUCTION

Climate change issues as well as effective deployment of renewable energy technologies require high time and space resolution and absolute accuracy of broad band and spectral solar radiation measurements at the earth's surface. However the sparse distribution of data in space and time often leads to the use of modeled solar radiation for engineering applications. In this framework it is often desirable to deal with the separate direct and diffuse components of the solar radiation especially when errors of the order of 20% - 30% on the radiation estimation arise from using average values or when the separate components data are generated by a merely statistical approach. On the contrary, the use of the separate components requires to check the congruence of the two separate data.

Recently the observed systematic disagreement between measured and modeled solar radiation values has opened a deep debate on the effective accuracy of radiation measurements and many studies have been carried out to validate broad band solar radiation measurements. Data comparisons have been presented in the literature (Bush and Valero, 1999; Bush *et al*., 1999; Myers, 2003) together with some papers outlining the influence of a thermal offset originated by the IR radiation exchange within the instrument (pyranometer) used to measure broad band solar radiation (Bush *et al*., 2000; Haeffelin *et al*., 2001; Dutton *et al*., 2001) and of the uncertainty related to its directional response. Some authors showed that the latter can be greatly alleviated by measuring the global down-welling solar flux as the sum of the direct and diffuse components measured by two separate instruments, a pyrheliometer and a shaded pyranometer respectively (Bush and Valero, 1999).

The purpose of this paper is to illustrate the new weather and solar station mounted at the University of Rome Tor Vergata in July 2003 for renewable energy applications and to characterize their solar radiation instruments having in mind the above mentioned discussion.

THE STATION

The Environmental Station of Tor Vergata (UTVES in the following) is located on the roof top of the Engineering building of the University of Rome Tor Vergata (41,18556° latitude North, 12,6233° longitude East) and it is collecting data since July 2003. It consists of two units: a weather unit that provides temperature, pressure, wind direction and speed, rain measurements; and a solar radiation unit that can separately measure direct, diffuse, reflected and global solar radiation at ground. The latter is equipped with a Kipp&Zonen 2AP sun tracker that supports a shaded ventilated pyranometer for diffuse radiation measurements and a pyrheliometer for direct radiation measurements; global and reflected flux is measured by two unventilated pyranometers mounted on a dedicated plate. A Campbell Scientific CR10X data logger acquires radiation data every 1 minute only during diurnal period, while weather data are collected all day long and minimum, maximum and average of each variable are given on both hourly and daily basis. Fig. 1 shows a picture of the station and fig. 2 the instruments used for solar radiation measurements. Pyranometers respond to the broad band down-welling solar flux within a hemispherical field of view and the (sensing) receiving element consists of a black horizontal surface that absorbs solar radiation and converts it into heat (is heated by the incident radiation). The black surface temperature is measured by a hot junction of a thermopile and the voltage output originated by the temperature difference between the hot junction and the cold junction (pyranometer body not exposed to solar radiation) is then correlated to the radiation through the calibration curve of the instrument. Diffuse component of the solar radiation is measured by shading a pyranometer with a shadow sphere that follows the position of the sun disk in the sky, as showed in fig. 2.

Fig. 1. The Environmental Station of Tor Vergata.

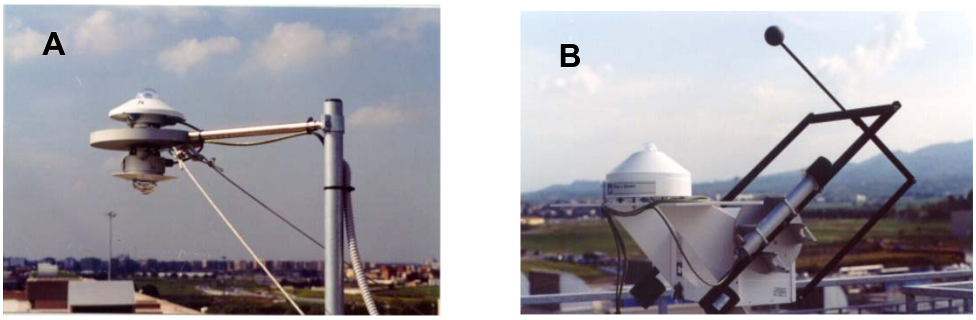

Fig. 2. Solar radiation instruments: A) albedometer; B) pyranometer for diffuse radiation measurements and pyrheliometer mounted on the 2AP suntracker.

Pyrheliometers are narrow field instruments that measure the nearly collimated radiation from the sun disk and a small part of the sky. They use the same measurement principle of pyranometers. Depending on the instrument characteristics the International Standard ISO9060 defines three different categories for pyranometers that indicate the instrument accuracy and reliability. They are in order of increasing importance: second class instruments, first class instruments and secondary standard instruments. The UTVES pyranometers are classified as “secondary standard” indicating a maximum uncertainty of 3%. The pyrheliometer is classified as “first class” introducing an accuracy ranging from 2% to 3% (Myers *et al.*, 2004).

DATA PRESENTATION

Fig. 3 shows an example of radiation data collected on a clear sky day of August 2003. The direct component, *DR*, is the projection on the perpendicular to a horizontal plane and is calculated with the following:

$$DR = DR_p \sin(\alpha) \tag{1}$$

Where DR_p is the radiation measured by the pyrheliometer and α is the elevation angle.
The diffuse radiation is measured by the shaded and ventilated pyranometer while the global radiation is measured by the unshaded pyranometer.

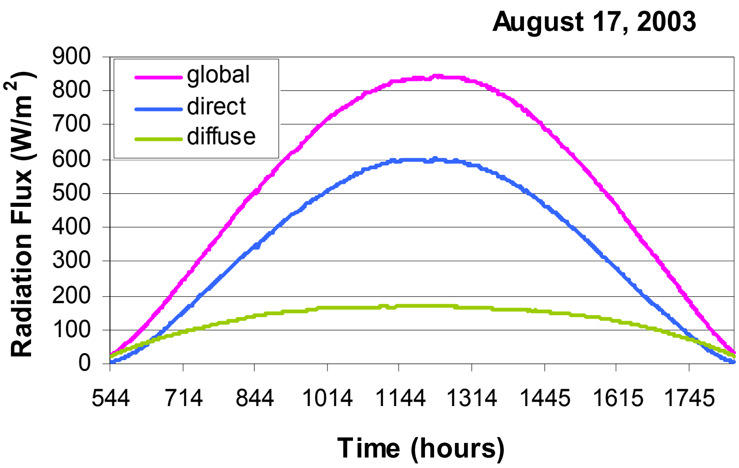

Fig.3. Example of radiation data collected on a clear sky day.

A simple test to verify the reliability and accuracy of the radiation data consists in testing the direct (*DR*) and diffuse (*SR*) radiation against the global radiation (*GR*), especially during clear sky days. The global radiation can be given by the sum of the two components as follows:

$$GR_s = DR_p \sin(\alpha) + SR \tag{2}$$

During clear sky conditions the difference between the global radiation measured by the pyranometer and the sum given by (2) should lye within the uncertainty levels given to the instruments. Using well calibrated instruments this difference should result reasonably lower than 3% - 5% or, approximately, than 20 W/m^2, whichever is less. If differences greater than those are founded further investigations are needed in order to determine the cause (McArthur, 2000).

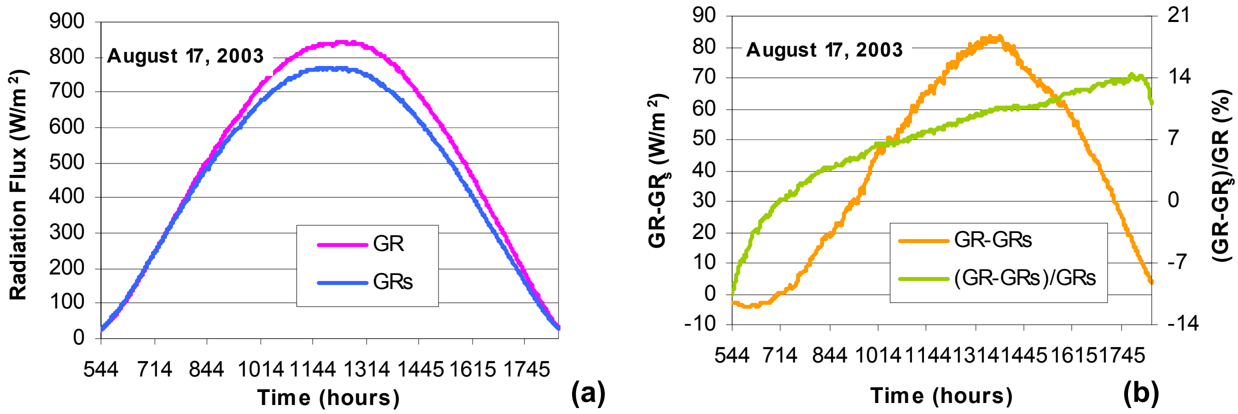

Fig. 4. a) *GR* and GR_s vs time; b) absolute and relative GR-GR_s difference versus time.

The abovementioned check has been done on the data collected during about one year of monitoring. First control has been done on some days randomly chosen for each month. Fig. 4a shows *GR* and GR_s for 17 August 2003. As it can be noted the difference between the two variables reached more than 80 W/m^2 in the central part of the day. In fig. 4b the absolute and relative differences between *GR* and GR_s are reported. A negative trend of the variables is present in the first hours of the day with a crossover around 7:00; after this point the difference increases reaching 83 W/m^2 at approximately 13:45, then it decreases again till sunset. The maximum percentage difference is reached at down and sunset and it is of the order of 15%. This trend has been observed during the year with a variation in the time (and consequently in the elevation angle) at which the crossover occurred. In Fig. 5 the elevation angle at the crossover is graphed versus the julian day of the year for July and August 2003. It can be seen that after a systematic decrease of the angle (that means that the crossover each day occurred earlier in time than the day before), at the end of August an event shifted the angle towards higher values. Various interpretations have been done to this behavior; during that days there was the first rain since almost a months or more of dry and hot days. The rain contributed to clean up the instruments and also to cool down the station; probably both factors influenced the data.

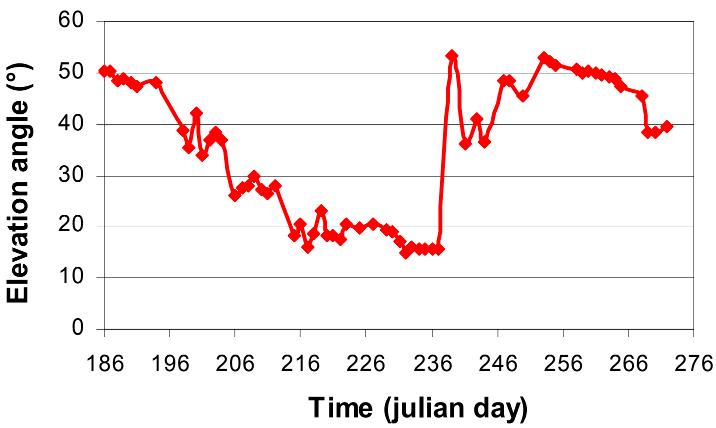

Fig. 5. Elevation angle at the crossover versus julian day.

ANALYSIS

In order to verify a possible systematic behavior starting from the randomly chosen days, all available data have been screened using a statistic approach. All data collected have been classified for each month into one of three categories using the direct radiation data as grouping factor describing the atmospheric conditions: "clear" if for all data checked the direct radiation resulted higher than 100 W/m^2, "overcast" if the direct radiation was lower than 2 W/m^2; "partly cloudy" if direct radiation resulted between 2 and 100 W/m^2. It is important to point out that the selected categories are not necessarily related to a real "clear" or "overcast" day, since the direct radiation can reach the limit values of the category only for some hours of the day owing to variable sky conditions or to particular elevation angles. Each datum, therefore, is no more related to the day in which it has been collected but only to the direct radiation conditions observed at that time. For each category a histogram of the occurrence of the absolute and relative differences between *GR* and GR_s for each month has been built. Overcast data have been binned into 0,5 W/m^2 intervals of the derived difference while clear data have been binned into 5 W/m^2 intervals of the same parameter. Fig. 6 shows the so arranged data for "clear" and "overcast " conditions. Fig. 6a and 6b show the absolute difference versus frequency for all the considered months.

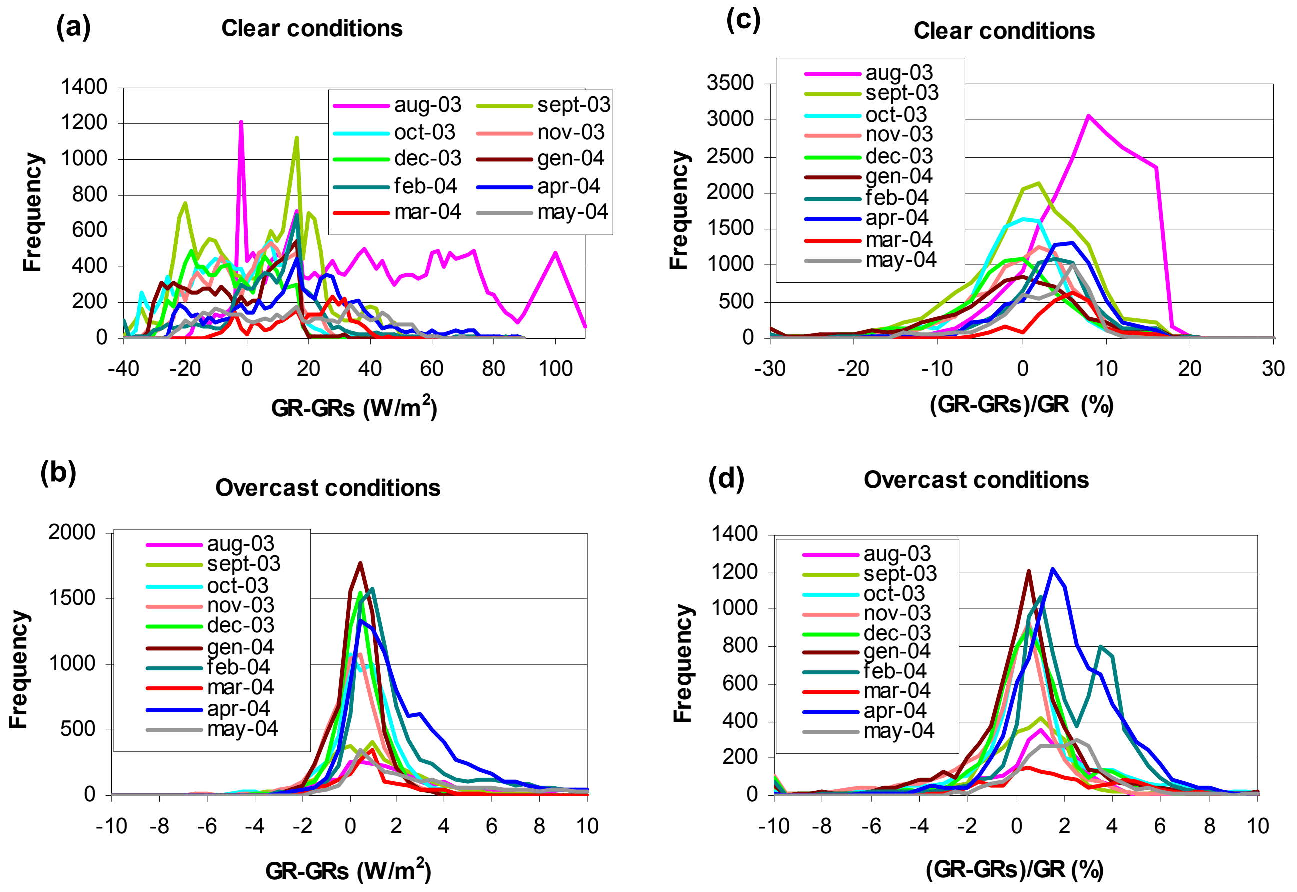

Fig. 6. a) and b) absolute GR-GR_s difference histograms for clear and overcast conditions, respectively; c) and d) relative GR-GR_s difference histograms for clear and overcast conditions, respectively.

The overcast sky shows the lower values of the difference that only for few data reaches the maximum value of 10 W/m^2. Moreover the data for each month have a tighter distribution than the clear sky conditions and it is more shifted towards positive difference (i.e. GR larger than GR_s). Positive values are more frequent during hot or mild months than to winter months for clear conditions. In particular August 2003 shows a broad distribution with high positive values of the absolute difference that reaches 110 W/m^2. Fig. 6c and 6d shows the percentage difference versus frequency for clear and overcast conditions. The percentage difference for overcast conditions is maximum 6% with most of the data in the range ±4%, while for clear conditions it reaches 15% with most of the data in the range of ±10%. August 2003, February 2004 and April 2004 show a different trend with respect to the other data but this can be attributed to poor control of the instruments in August and frequent maintenance operations in February and April.

As a result of the analysis above exposed, it can be derived that the clear conditions all showed a difference between GR and GR_s significantly larger than the overcast case average and the overcast conditions have the tightest distribution.

Further discrimination has been provided on the data for periods before and after local solar noon. Fig. 7 shows the histograms calculated for December 2003 and September 2003. The GR-GR_s difference are mostly negative before noon and mostly positive after noon. Moreover the difference is greater in magnitude (more positive) after noon in September (and in all hot months) while it is more negative in December (and in all cold months). The observed behavior confirms the presence of a crossover of the difference between the measured and derived global radiation for all data collected.

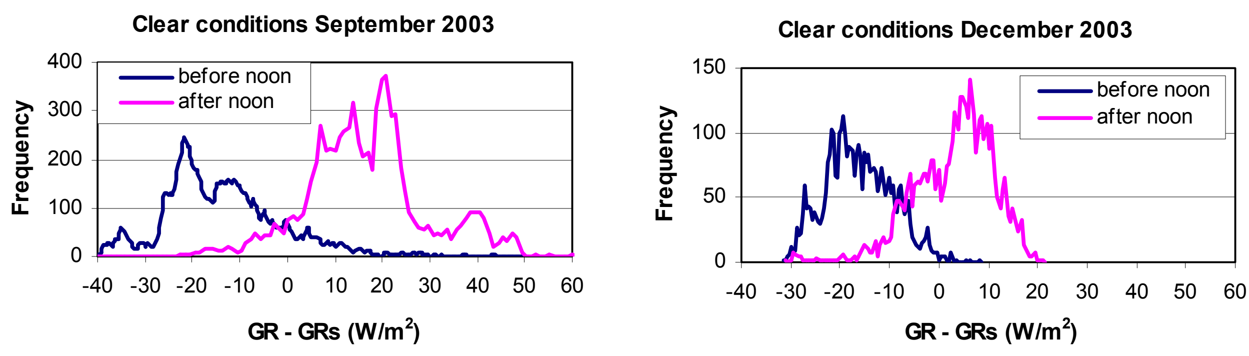

Fig. 7. Histograms for clear conditions and data discriminated in before noon and after noon.

DISCUSSION

From the obtained results it can be deduced that a systematic difference exists between the global radiation measured by one instrument only and the one derived by the sum of measurements of a pyrheliometer and a shaded pyranometer. This difference is larger under clear conditions and it is mostly negative before local noon and mostly positive after noon. Moreover the positive difference is greater in magnitude for the major part of the year, especially during hot weather periods. Overcast conditions show the smallest difference between the two parameters with a tighter distribution and mostly positive values.

In order to correct this systematic difference a check on all instrument has been performed through the year. Since the major problems arose during clear conditions a first check on the pyrheliometer alignment has been done monitoring systematically the instrument by visual inspection. In fact a slight misalignment has been observed during the day, having a sinusoidal trend that recalled the observed trend for the difference between *GR* and GR_s. However this was not the only factor that affected the measurements: the misalignment could explain the difference trend but not its negative value (i.e. $GR_s > GR$) observed before local noon. Considering the recent developments on measurement uncertainty on pyranometers related to the presence of thermal offsets (Bush *et al.*, 2000) the attention has been focused on the different environment of the two pyranometers used for diffuse and global radiation measurement.

The transfer of infrared between the different components of the instruments (i.e. the dome and the black detector) affects the performance of pyranometers by generating an internal infrared signal that is superimposed to the output signal. This spurious signal is originated by the temperature difference between the dome and the detector. Thermal offset can be quantified using the pyranometer at night. In this conditions the signal should be zero. Negative radiation values are measured due to radiation heat transfer with the sky that is cooler than the instrument (Bush *et al.*, 2000; Haeffelin *et al.,* 2001; Dutton *et al.*, 2001). In this way the temperature of the dome is lower than the one of the detector and an outward heat flux is originated by this temperature difference. This thermal offset is present also during the day and is superimposed to the solar radiation input. Moreover thermal offset vary with environmental conditions such as temperature, wind speed, cloud cover, magnitude of the radiation measured. It has also been demonstrated that this parameter is influenced by the shading device used for the pyranometer that measures the diffuse radiation, and by the ventilation system (Bush *et al.*, 2000).

At the UTVES, the pyranometer used for diffuse radiation is both shaded and ventilated, while the one used for the global radiation is not. Therefore they exhibit a different thermal offset and their behavior during the day vary with the thermal conditions of the instruments. In particular, ventilation contributes to uniform the temperature of the pyranometer, while the shading cools down more effectively the outer dome, increasing the negative offset. These two different mechanism act differently during the day and with varying sky conditions. For example, in overcast conditions the sky is warmer than in clear conditions and it can increase the temperature dome: in this way for an unventilated pyranometer dome temperature is higher than detector temperature and the thermal offset is reduced. On the contrary, the pyranometer for the diffuse radiation, being ventilated, has a cooler dome than the pyranometer for the global radiation: this could explain why *GR* is larger than GR_s for almost all data.

For clear conditions the dome temperature is always lower than the detector temperature and the pyranometer for the diffuse radiation has a more negative offset due to the shading sphere, however the ventilation contributes to reduce this offset. The observed crossover of the difference between the two global radiations could be explained by the progressive heating of the domes during the day that is different for the ventilated and the unventilated instruments producing the crossover effect.

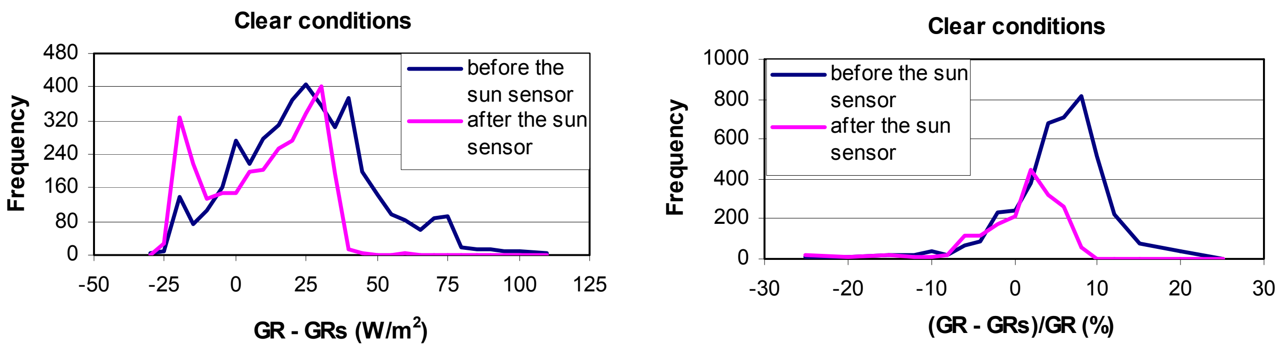

Fig. 8. Histograms of data collected for clear conditions before and after the sun sensor installation.

IMPROVEMENTS AND FIRST CONCLUSIONS

Based on the above considerations, some actions have then been done in order to improve the measurements accuracy. First of all, a sun sensor has been installed on the sun tracker in order to correct the misalignment of the pyrheliometer. This sensor is pointed to the sun disk and correct the tracker position when the sun is out of target. The sun sensor has been installed in mid April 2004. Fig. 8 shows the histogram of the clear data before and after this action. It can be noted that

the instrument insertion has reduced the difference parameter adopted, especially for the positive values indicating that part of the systematic error was due to misalignment.
As far as the other sources of error are concerned, another ventilation unit has been installed but unfortunately it could not yet been fully tested at the time the present issue has been released. However, the magnitude of this error is expected to be lower than the pyrheliometer misalignment value. A further campaign of measurements is presently in course, and first results are encouraging.

REFERENCES

Bush, B.C., Pope, S.K., Bucholtz, A., Valero, F.P.J. and Strawa, A. (1999). Surface radiation measurements during the ARESE campaign. *J. Quant. Spectrosc. Radiat. Transfer,* 61(2), 237-247.

Bush, B.C. and Valero, F.P.J. (1999). Comparisons of ARESE clear sky surface radiation measurements. *J. Quant. Spectrosc. Radiat. Transfer,* 61(2), 249-264.

Bush, B.C., Valero, F.P.J., Simpson, A.S. and Bignone, L. (2000). Characterization of thermal effects in pyranometers: a data correction algorithm for improved measurement of surface insolation. *J. of Atmospheric and Oceanic Technology,* 17, 165-175.

Dutton, E.G., Michalsky, J.J., Stoffel, T., Forgan, B.W., Hickey, J., Nelson, D.W., Alberta, T.L. and Reda, I. (2001). Measurement of broadband diffuse solar irradiance using current commercial instrumentation with a correction for thermal offset errors. *J. of Atmospheric and Oceanic Technology,* 18, 297-314

Haeffelin, M., Kato, S., Smith, A.M., Rutlrdge, C.K., Charlock, T.P. and Mahan R.J. (2001). Determination of the thermal offset of the Eppley precision spectral pyranometer. *Applied Optics,* 40(4), 472-484.

International Standard ISO9060 (1990). Solar Energy – Specification and classification of instruments for measuring hemispherical solar and direct solar radiation.

McArthur, L.J.B. (2000). Baseline Surface Radiation Network (BSRN) operations manual. World Climate Research Programme, WMO/TD-No. 879.

Myers, D.R., Reda, I.M., Wilcox, S.M. and Stoffel, T.L. (2004). Uncertainty analysis for broadband solar radiometric instrumentation calibrations and measurements: an update. Preprint NREL/CP-560-36201, to be presented at the World Renewable Energy Congress VIII, Denver, Colorado, August 28 – September 3, 2004.