Broadband and Spectral Shortwave Calibration Results from ARESE II

J. J. Michalsky, P. W. Kiedron, and J. L. Berndt
State University of New York
Albany, New York

T. L. Stoffel, D. Myers, I. Reda, J. A. Treadwell, and A. Andreas
National Renewable Energy Laboratory
Golden, Colorado

Introduction

The second Atmospheric Radiation Measurement (ARM) Enhanced Radiation Experiment (ARESE II) was designed differently than the first. A single aircraft was used to fly near the surface (this is below cloud on cloudy days) between 100 to 400 m above ground and at the Twin Otter's altitude ceiling around 7 km; this is above cloud level except for occasional high cirrus. The aircraft flew the low altitude (albedo) runs at the beginning and/or end of the flight. Most of the flying time was spent at high altitude flying a daisy pattern centered on the Central Facility of the Southern Great Plains (SGP) Clouds and Radiation Testbed (CART). Calculated net shortwave irradiances at the altitude ceiling and at the surface were used to calculate shortwave absorption within the atmospheric layer between the surface and 7 km both with and without clouds present.

The organizers of ARESE II decided that an improvement to the first experiment would include a common calibration of instruments. This would reduce the uncertainty caused by various groups using different techniques and sources to calibrate their radiometers and spectrometers for the experiment. It was not practical to have the instruments characterized for angular and spectral response by the authors; therefore, the calibration provided was only the absolute irradiance calibration of the instruments. Spectral and angular response measurements and corrections were made by the instruments' owners.

Only shortwave radiometers and spectrometers were used on the Twin Otter aircraft that carried three types of broadband pyranometers that pointed to zenith and to nadir and three types of spectral instrumentation for measuring zenith and nadir irradiances. Before and after the flight series all broadband radiometers were brought to the Blackwell-Tonkawa airport and pointed to the zenith for measurements against a standard broadband radiometer measurement suite. The spectral instruments were calibrated in a darkroom at the Ponca City airport using National Institute of Standards and Technology (NIST) traceable standard lamps.

Instruments of the same types as those flown were stationed on the ground at the SGP CART Central Facility during the flight series. These zenith-viewing instruments were calibrated before and after the flight series as well.

The spectral instruments will be compared for response stability before and after the flight series in a future paper. Only the spectral calibration standard and protocol for calibration are described. The results discussed here will include clear- and cloudy-day broadband calibration data before, after, and during the flight series.

Spectral Calibration

Since some of the spectral instruments used for ARESE II had spectral responses between 350 and 2200 nm, we used the extended wavelength spectrometer of the National Renewable Energy Laboratory (NREL) to establish our spectral standards. NREL's Optronics OL-750 was illuminated with six ARM-owned NIST 1000W FEL standard lamps that are maintained at NREL. The average response of these six lamps serves at the ARESE II irradiance standard. We used this to calibrate four EG&G Gamma Scientific 1000W FEL lamps for field use at the Ponca City airport darkroom. At least two lamps were used to calibrate each instrument before and after the flight series. We also calibrated three LI-COR lamps for use in the LI-COR calibrator, which was used to periodically check the National Aeronautics and Space Administration (NASA) Ames Solar Spectral Flux Radiometer (SSFR) during the flight series.

Based on the ± 2% spread of the NIST lamps relative to their average and additional uncertainty when transferring the standard to the EG&G lamps and to the spectral instruments, we estimate the total uncertainty to be between 2.5% and 3%.

Standard NIST protocol of horizontal illumination at 50 cm using recommended alignment procedures allowed us to repeat the calibrations to better than 0.5%. Measured scattered radiation with the beam blocked revealed that subtraction of the scattered light was not a problem in the temporary darkroom.

Broadband Shortwave Calibration Standard

The most accurate broadband shortwave measurements are made with absolute cavity radiometers. For the ARESE II calibration we used an Eppley Model AHF cavity that had been compared with the World Radiometric Reference (Fröhlich 1978). We estimate the 95% uncertainty for direct beam measurements with this cavity under calm conditions to be ± 3 W/m^2.

There is no similar standard measurement for total horizontal irradiance. The Baseline Surface Radiation Network (BSRN) recommends that total horizontal irradiance be calculated from two measurements (McArthur 1998).

The direct normal irradiance is measured with a cavity. The direct component normal to the horizontal surface is calculated by multiplying by the cosine of the solar-zenith angle, and added to the diffuse horizontal irradiance measured with a pyranometer. Direct beam irradiance is blocked using a shading device for this latter measurement. Dutton et al. (2001) discuss the zero-offset problem with some thermopile pyranometers used for diffuse irradiance measurements and ways to correct the offset. This offset can represent 10% to 30% of the diffuse signal for clear skies. Rather than measure with one of the pyranometers with large offsets and try to correct, we opted to use the Eppley 8-48 pyranometer that has a very minor offset of about 1 W/m^2. Figure 1 contains clear-sky diffuse data on April 8, 2000.

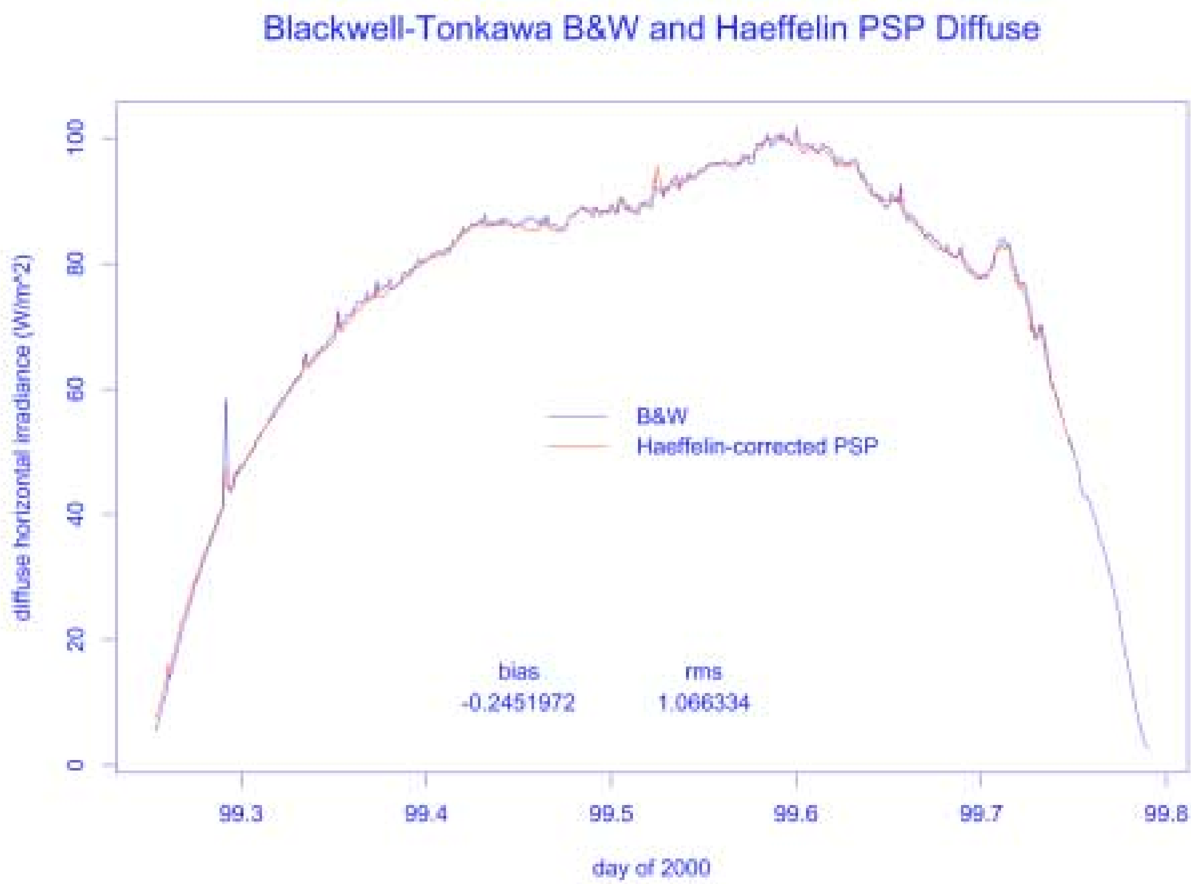


Figure 1. Clear-day diffuse horizontal irradiance measurement comparison between Eppley 8-48 (black & white) and Eppley PSP using the inner-dome/case temperature difference to correct.

The blue line represents 1-minute averaged data from the Eppley 8-48. The red line is 1-minute averaged data from an Eppley Precision Spectral Pyranometer (PSP). The PSP is one of the thermopile instruments with a significant zero offset. However, M. Haeffelin (private communication) has instrumented this PSP to measure the temperature difference between the inner dome and the case that is responsible for the offset, and he corrects for the offset with a high degree of accuracy. The bias between these measurements in Figure 1 is less than 1 W/m^2 and the root mean square (rms) difference is just over 1 W/m^2, some of which may be caused by the difference in response times of the two instruments. We estimate that diffuse measured with the 8-48 has ±5 W/m^2 uncertainty at the 95% confidence level. Our estimate of the absolute uncertainty in calculated total horizontal irradiance at the 95% confidence level when using the cavity and the Eppley 8-48 is 7 W/m^2.

At times we were unable to use cavity data because it was not operating or the wind speed exceeded 5 m/s. Wind disrupts the thermal balance of the instrument leading to unacceptable uncertainties in direct beam irradiance. For these cases, we substituted an Eppley Normal Incidence Pyrheliometer (NIP). This increases our uncertainty at the 95% confidence level to 12 W/m^2.

Broadband Shortwave Calibrations

For the calibration of all broadband pyranometers used on the aircraft and on the ground at the SGP Central Facility we compared 1-minute averages of data at the Blackwell-Tonkawa airport both before and after the flight series. Clear-sky 1-minute ratios with the sun between 45° and 55° solar-zenith angles were averaged to derive a calibration. The top of Figure 2 is a plot of the total horizontal irradiance measured by all of the flown broadband instruments and most of the surface instruments used for this experiment on a day before the flight series. The top of Figure 3 is a similar plot, but after the flight series. Our hope for these measurements is agreement within 10 W/m^2. The bottom of Figure 2 suggests that we have nearly achieved this. However, the bottom of Figure 3 indicates a serious disagreement with the standard. The data in the latter figure and a few leveling checks made following this day's measurements strongly suggest that the instruments were not level on the calibration day after the flight series.

Overcast sky measurements are not very sensitive to leveling errors and Figures 4 and 5 indicate consistent patterns before and after the flight series for the Kipp & Zonen CM-22's (operated by Sandia National Laboratories [SNL]) and Scripps Institution of Oceanography (SIO) radiometers. The Meteorological Research Institute's (MRI) Kipp & Zonen CM-21's used on the aircraft are less consistent having readings lower than the standard before the flights and higher after the flights, although the readings are most often within the uncertainty target of 10 W/m^2.

Perhaps, a better indication of just how well these instruments can perform is given in the next four figures. Figures 6 and 7 are clear-day measurements made on the ground at the SGP CART Central Facility with each group in complete control of the measurement process, i.e., each group aligned their own instruments and acquired their own data. At Blackwell-Tonkawa airport the Twin Otter-flown instruments were mounted and leveled by others, and data were acquired with a common logging device. All data have been corrected for errors including temperature and angular response. On each of these two clear days the patterns of agreement with the standard are similar for each instrument. This level of agreement, which is near or better than the 10 W/m^2 goal is a good indication of the best agreement we might expect during ARESE II. Figures 8 and 9 are cloudy days and the bottom panels of these figures show similarities to the cloudy days at Blackwell-Tonkawa airport. The Meterological Research Institute (MRI) data show the least consistent behavior on the cloudy days with several data exceeding the 10 W/m^2 level. In drawing this conclusion we have ignored the spikes in the MRI data that resulted from an unknown electromagnetic interference.

These results are summarized in Table 1. The entries are for eight days, both clear and overcast as noted in the top labels, and for days before, during, and after the flight series. Of course, there are no surface data from the Otter instruments on the flight days and the other blank entries indicate that those instruments were not available on those days. The mean value of the irradiance for whatever data were compared, as measured by the standard system, is the first entry, the rms difference is the second, and the bias with respect to the standard is the third entry in each cell. Table 1 indicates that bias and rms errors are generally within the target values of 10 W/m^2. Notable exceptions are most entries on April 8, 2000, where we have noted in discussion above that the instruments appear unleveled. On clear days, such as the 8th, the angular response error for misaligned instruments can be clearly seen. Several rms errors that exceed the targeted 10 W/m^2 uncertainty appear in the table for MRI-operated Kipp & Zonen CM-21 pyranometers. Large rms differences result in some part from large spikes caused by electromagnetic interference.

Albedo Runs

To this point we have discussed ground-based comparisons only. As a check on some of the aircraft data we compared measurements on the lowest altitude legs, which are referred to here as albedo runs. Typically, these measurements were made between 100 and 400 m above the surface at the beginning and/or end of the flight. We used albedo runs from three clear days that are tabulated in Table 2. Surface measurements that were available are listed as well as zenith and nadir radiometer measurements averaged over the typical 5-minute run. The last column is the calculated surface albedo based on aircraft instruments except for the last row that contains the broadband albedo from the SGP CART Central Facility instruments. There is remarkable agreement in the highlighted last column among the SIO, SNL, MRI, and SIRS-C1 albedo measurements. Comparing surface measurements with the zenith pointing radiometers we expect the radiometers that are between 100 and 400 m above the surface to measure 5 to 15 W/m^2 more irradiance, depending on the altitude, based on clear-sky modeling. Using the State University of New York (SUNY) calibration standard for the ground-based measurement, we find that most of the time SIO, SNL, and MRI have zenith pointing irradiances that are plausible in this regard. The MRI nadir irradiances are slightly higher than the SNL or SIO irradiances suggesting that these measurements give rise to somewhat larger albedoes in the last column.

Summary

SNL, SIO, and MRI aircraft data appear acceptable based on the agreement between surface albedo measurements and albedoes calculated using the nadir and zenith radiometers. Further, compared with the calibration standard measurement at the surface and the zenith measurements during the albedo runs adjusted for the 100 to 400 m height difference we find generally all sets of data acceptable. MRI albedoes may be slightly high because of high nadir readings from that instrument.

Comparisons among instruments on the ground suggest agreement to within the target accuracy of 10 W/m^2 most of the time. The MRI instrument performance for the surface measurements was near that of the SNL and SIO instruments, but somewhat less consistent.

Finally, we suggest that differences of absorption that are smaller than about 15 W/m^2 are clearly within the uncertainty of these radiometer measurements.

Corresponding Author

J. J. Michalsky, Joseph.Michalsky@pnl.gov, (509) 375-6494

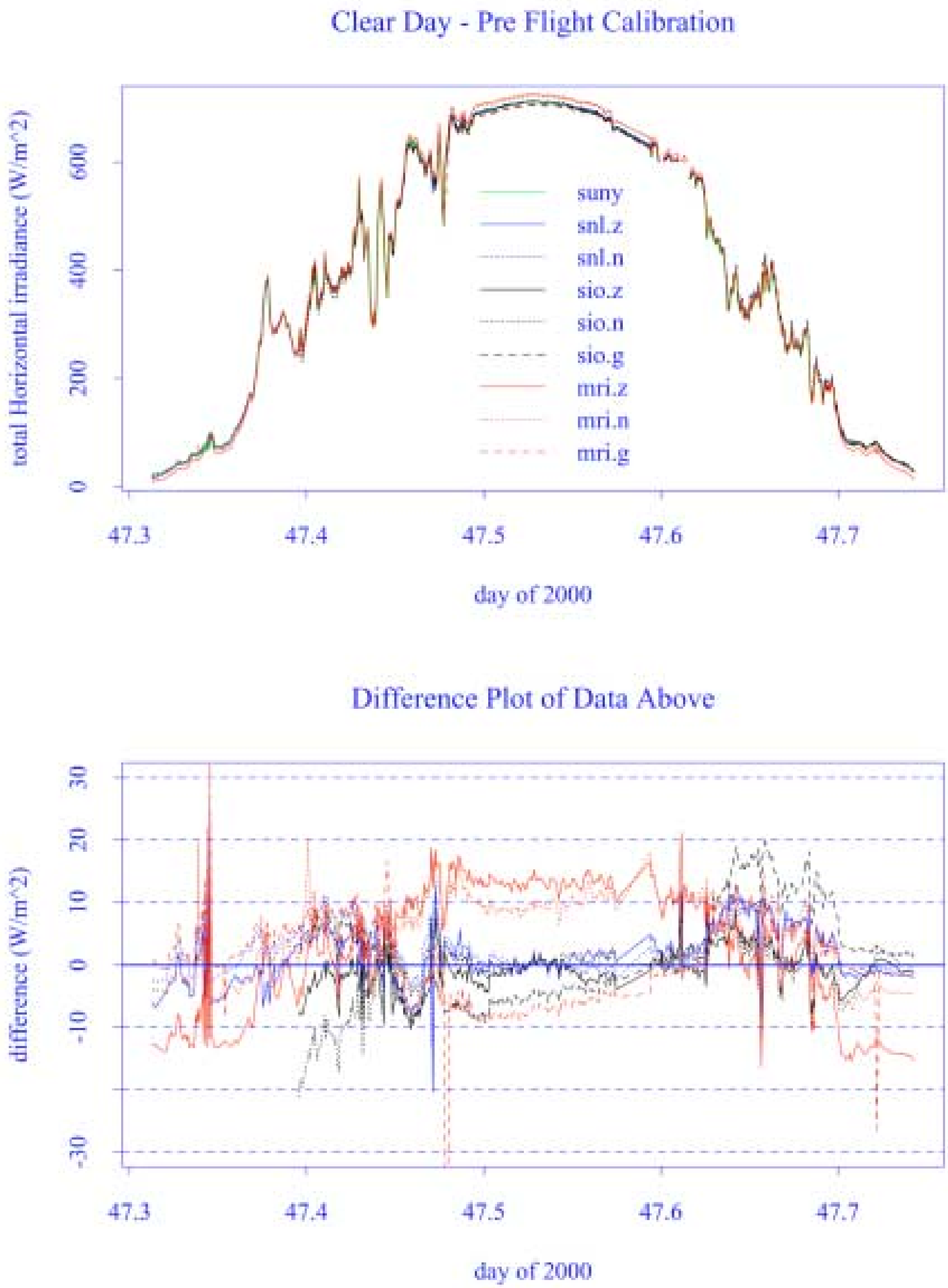


Figure 2. Clear-day, pre-flight irradiance comparison of calibrated broadband radiometers (top). Difference plot of irradiance compared with SUNY/NREL standard described in paper (bottom).

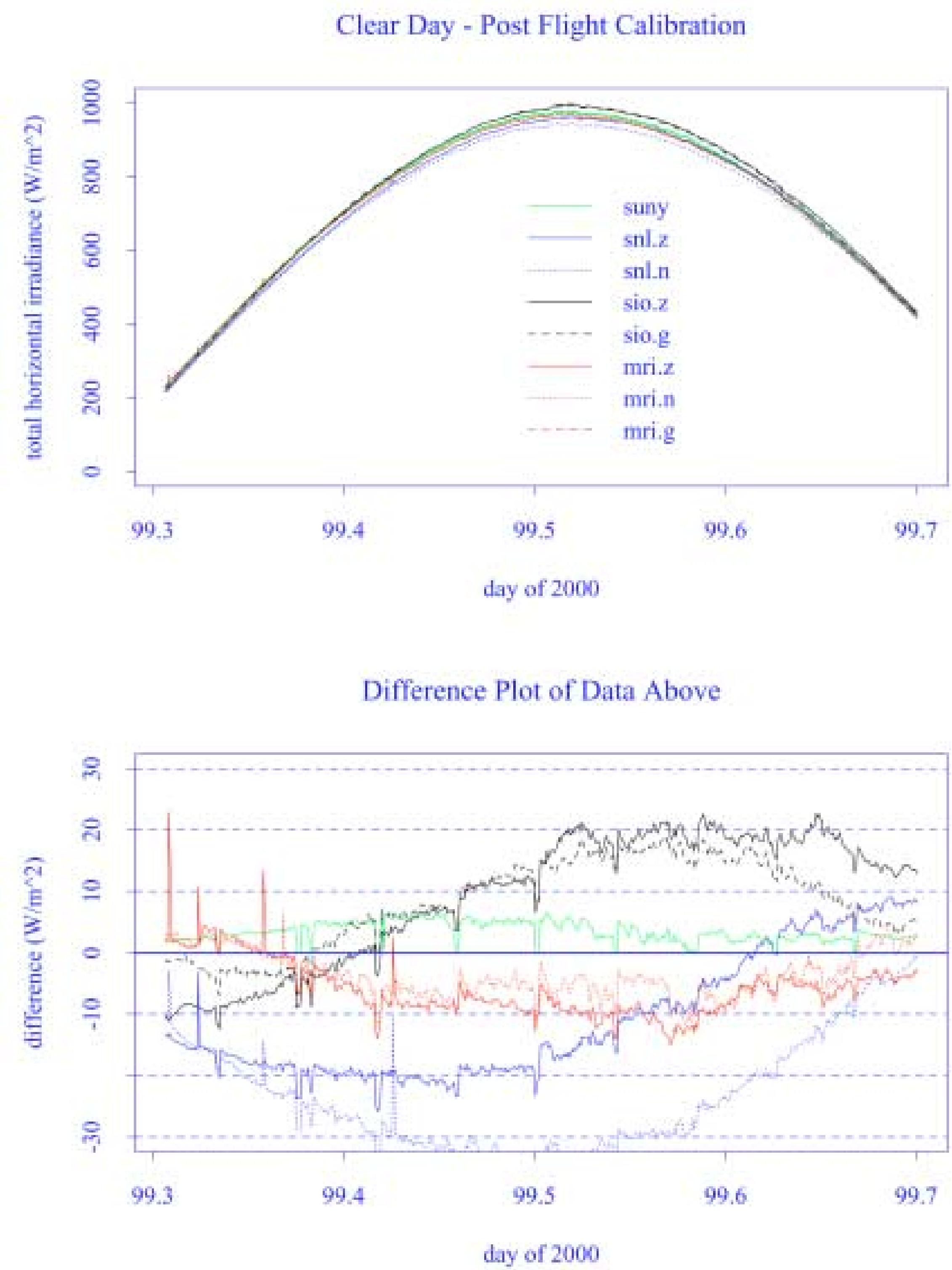


Figure 3. Clear-day, post-flight irradiance comparison of calibrated broadband radiometers (top). Difference plot of irradiance compared with SUNY/NREL standard described in paper (bottom). Large divergence probably cause by poor leveling of radiometers.

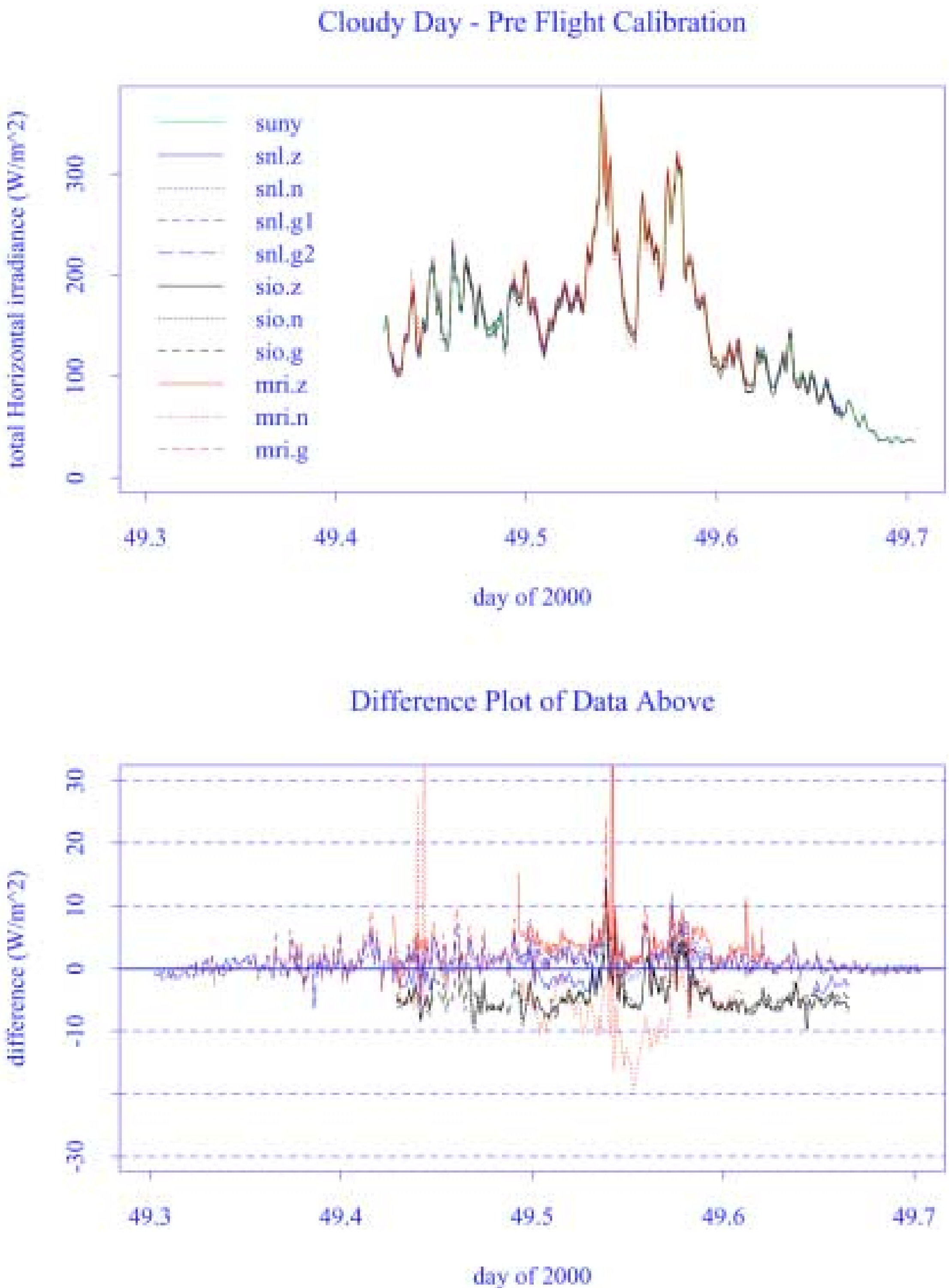


Figure 4. Cloudy-day, pre-flight irradiance comparison of calibrated broadband radiometers (top). Difference plot of irradiance compared with SUNY/NREL standard described in paper (bottom).

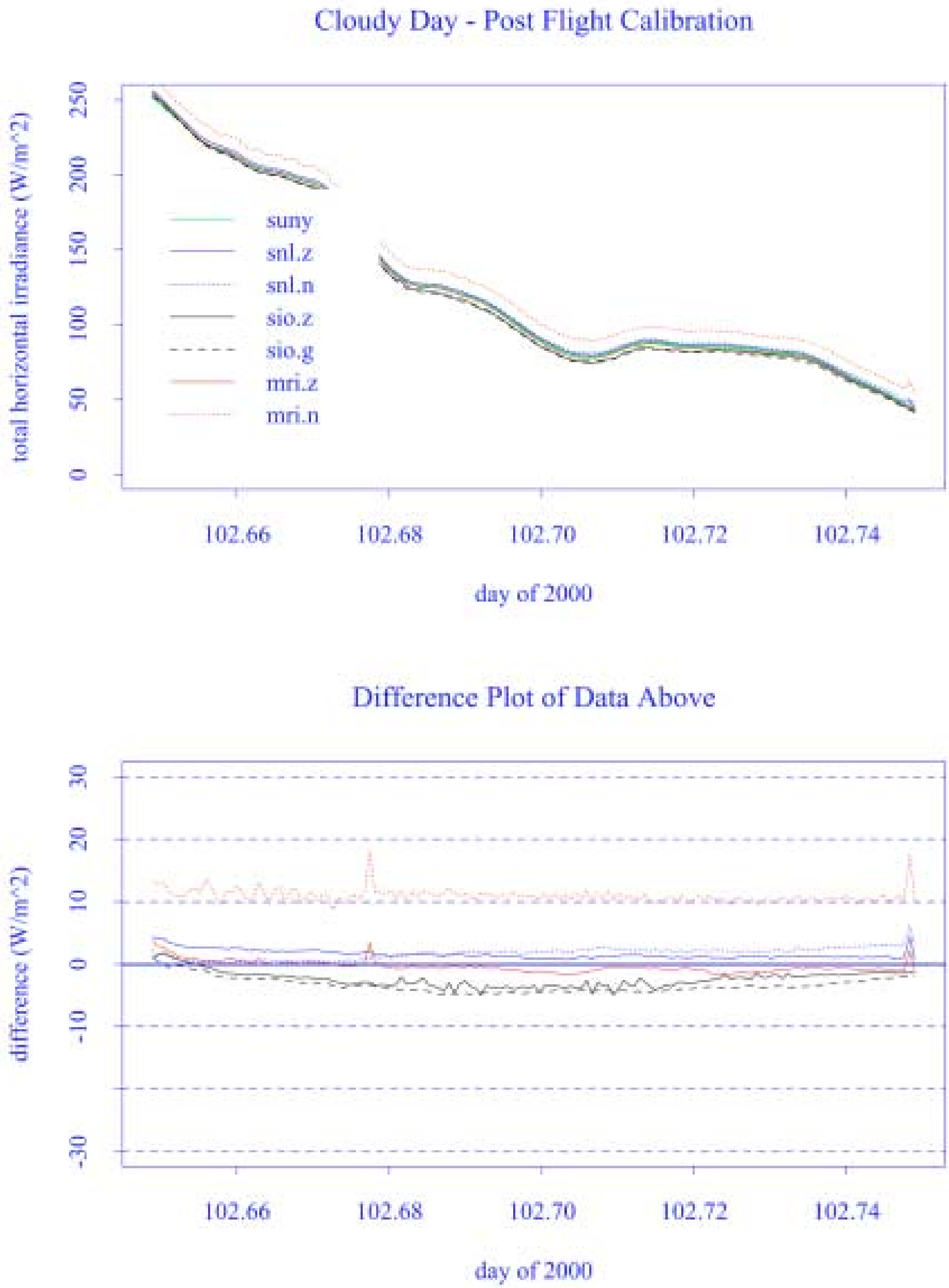


Figure 5. Cloudy-day, post-flight irradiance comparison of calibrated broadband radiometers (top). Difference plot of irradiance compared with SUNY/NREL standard described in paper (bottom).

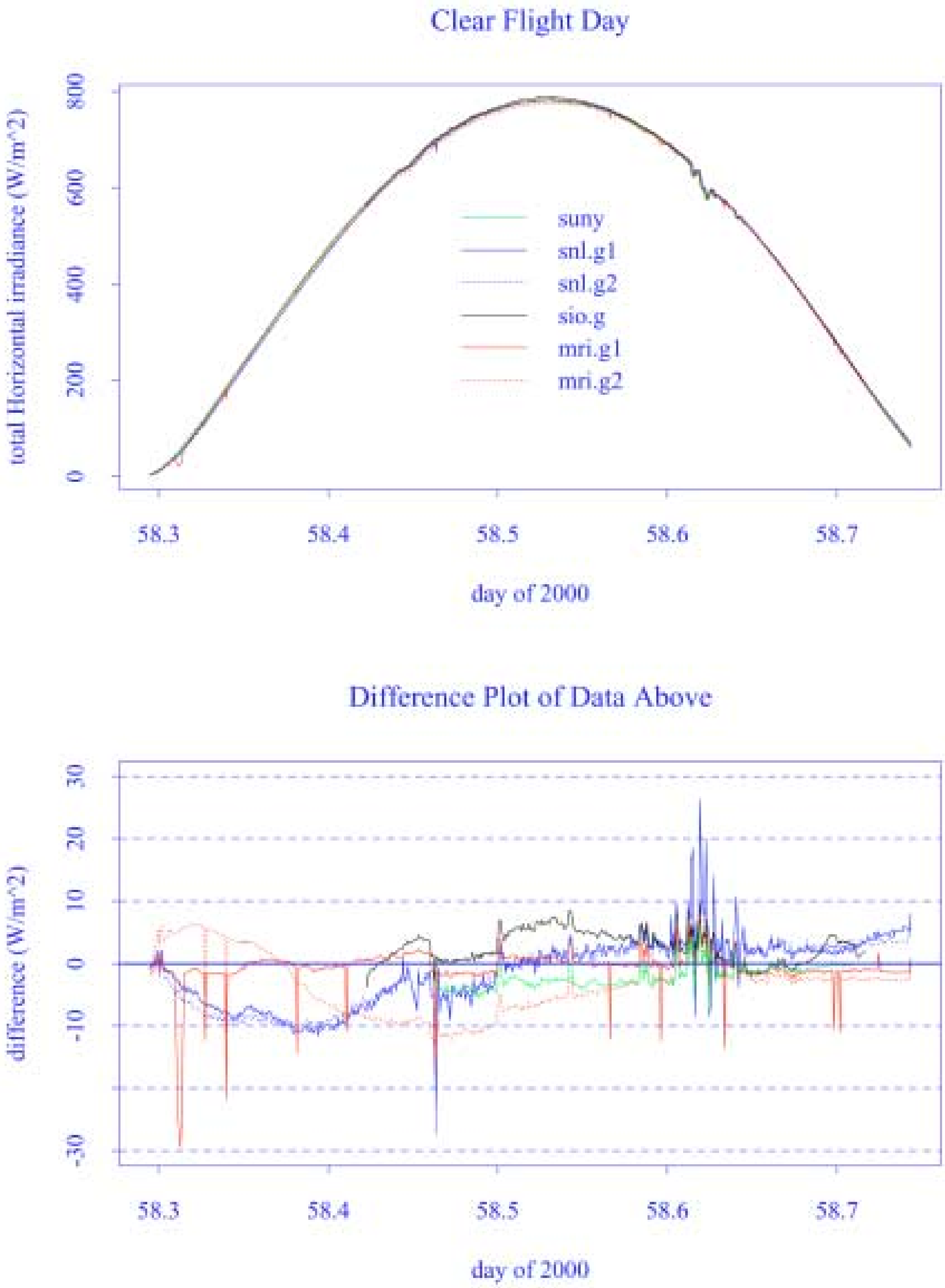


Figure 6. Clear-day irradiance comparison of ground-based broadband radiometers at the SGP CART site.

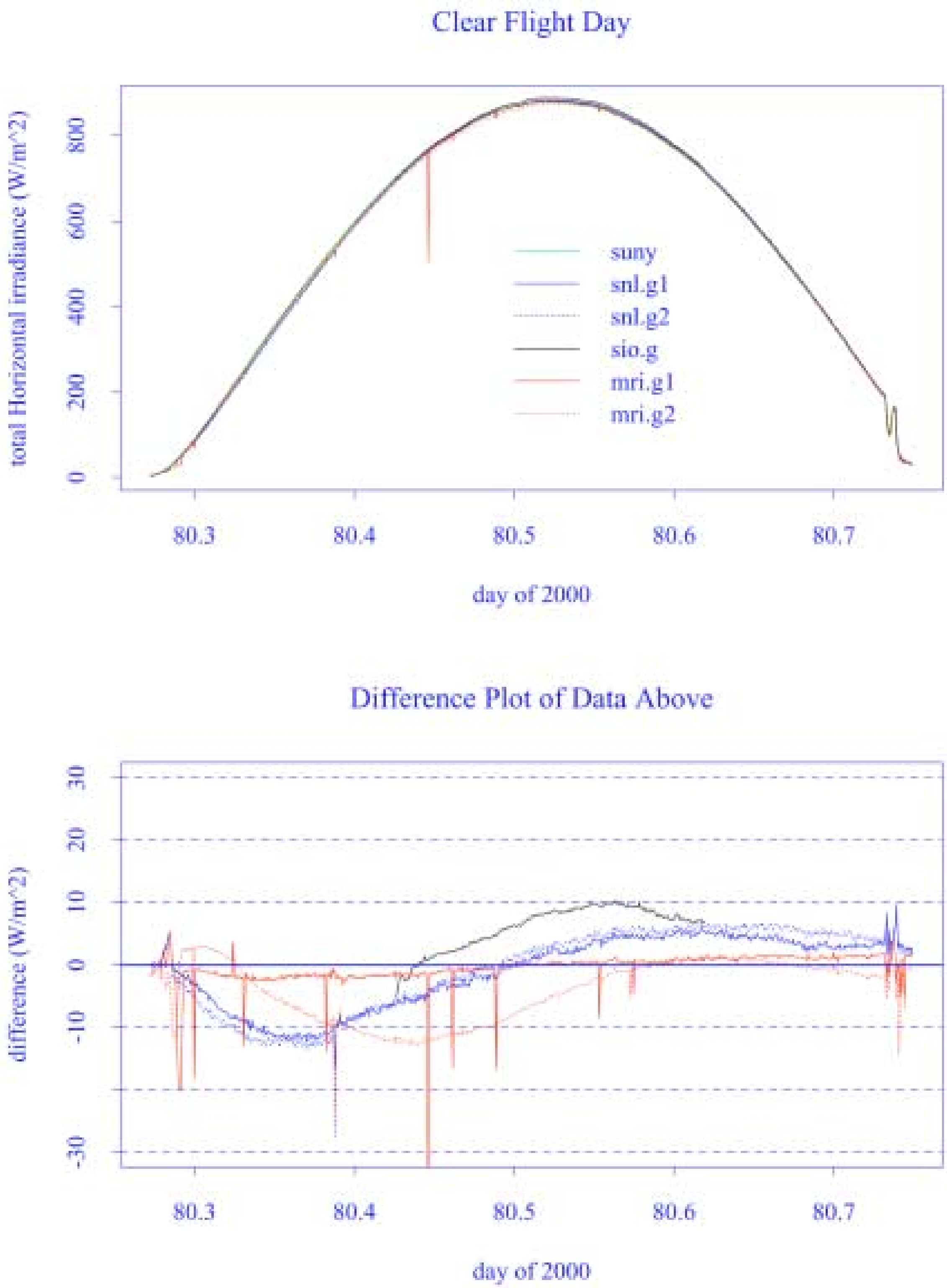


Figure 7. Same as Figure 6 but for a different day.

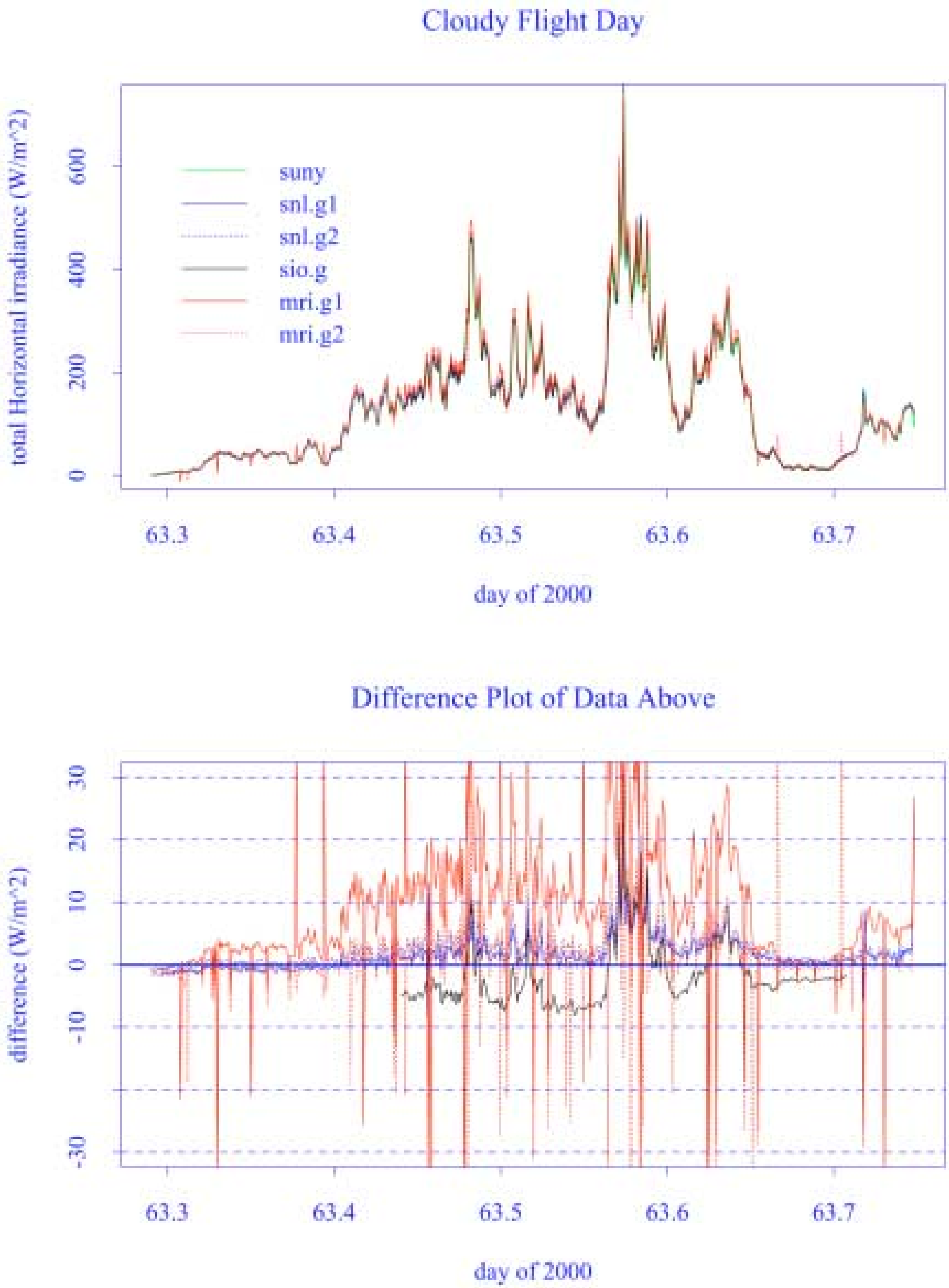
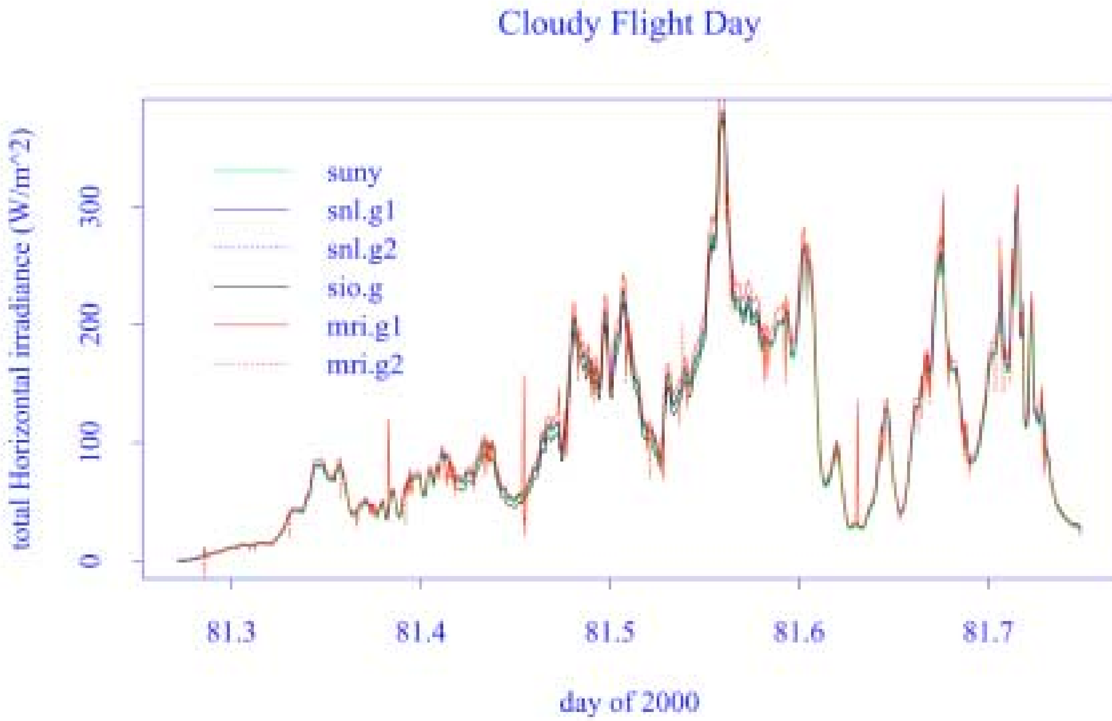


Figure 8. Cloudy-day irradiance comparison of ground-based broadband radiometers at the SGP CART site.



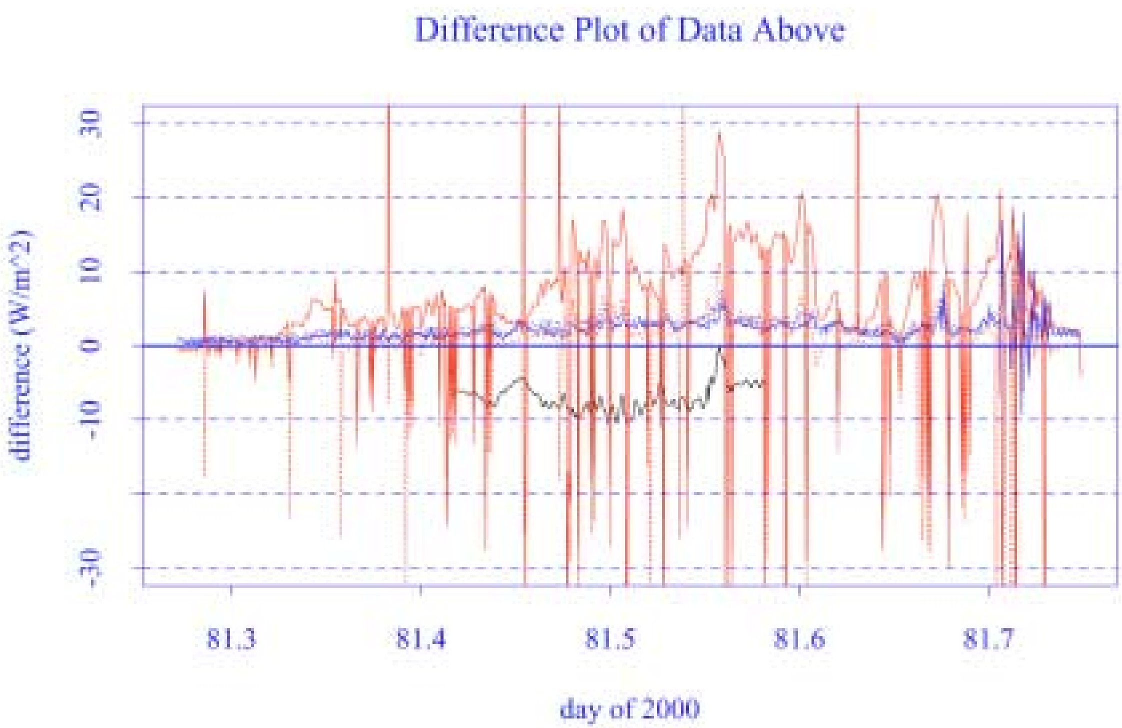


Figure 9. Same as Figure 8 but for a different day.

Table 1. Mean irradiance plus root mean square difference and bias between SUNY/NREL standard and ARESE II instruments for selected days of ARESE II.

Date	Feb 16 clr/pc W/m^2	Feb 18 over W/m^2	Feb 27 clr W/m^2	Mar 3 over W/m^2	Mar 20 clr W/m^2	21 Mar over W/m^2	Apr 8 clr W/m^2	Apr 11 over W/m^2
MRI-G	mean = 397 rms = ±6.9 bias = +0.5	126 ±2.9 +1.3	490 490 ±3.2 ±5.7 -0.7 –3.3	132 132 ±14.7 ±9.5 +8.5 +0.1	556 556 ±10.1 ±11.9 -0.9 –4.4	107 107 ±12.8 ±9.2 +5.5 –1.0		
MRI-O	397 397 ±10.4 ±7.9 +2.3 +4.9	182 187 ±7.1 ±10.0 +4.2 –5.5					739 739 ±7.5 ±5.3 -6.0 -3.8	123 123 ±1.0±11.1 -0.4 +11.0
SIO-G	457 ±7.7 +2.2	164 ±4.7 -4.1	619 ±3.7 +2.6	181 ±5.4 -1.7	822 ±7.0 +6.0	146 ±7.2 -7.0	739 ±10.8 +8.2	123 ±3.6 -3.4
SIO-O	457 457 ±3.3 ±4.9 -1.0 -1.0	163 163 ±5.3 ±5.3 -4.4 -4.3					739 ±14.0 +9.2	123 ±2.7 -2.4
SNL-G		127 127 ±1.8 ±2.4 +0.7 +1.5	490 490 ±5.6 ±5.7 -1.3 –1.5	133 133 ±3.3 ±4.2 +1.6 +2.7	557 557 ±5.7 ±6.6 -1.0 –0.6	107 107 ±2.6 ±3.1 +2.0 +2.6		
SNL-O	397 397 ±4.6 ±4.7 +1.3 +2.5	146 181 ±2.3 ±5.6 -1.8 +2.9					739 ±14.9 ±25.2 -11 -23.5	123 123 ±1.7 ±2.0 +1.6 +1.7

Table 2. Comparison of surface measurements and aircraft measurements on clear flight days for the low-altitude, albedo runs.

February 27, 2000				
535 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	597 W/m^2	W/m^2	W/m^2	
SIO	597	594	117	0.20
SNL	592	-	-	-
MRI	598	586	147	0.25
SIRS-C1	-	-	-	0.21
487 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	753 W/m^2	W/m^2	W/m^2	
SIO	756	756	144	0.19
SNL	755	763	148	0.19
MRI	752	763	162	0.21
SIRS-C1	-	-	-	0.20
March 20, 2000				
435 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	760 W/m^2	W/m^2	W/m^2	
SIO	761	750	142	0.19
SNL	756	769	140	0.18
MRI	748	757	158	0.21
SIRS-C1	-	-	-	0.19
April 5, 2000				
639 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	940 W/m^2	W/m^2	W/m^2	
SIO	948	946	150	0.16
SNL	-	965	170	0.18
MRI	-	929	174	0.19
SIRS-C1	-	-	-	0.17
688 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	946 W/m^2	W/m^2	W/m^2	
SIO	953	960	155	0.16
SNL	-	962	167	0.18
MRI	-	955	176	0.18
SIRS-C1	-	-	-	0.17
576 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	948 W/m^2	W/m^2	W/m^2	
SIO	956	955	158	0.17
SNL	-	964	170	0.18
MRI	-	960	182	0.19
SIRS-C1	-	-	-	0.17

Table 2. (contd)

659 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	949 W/m^2	W/m^2	W/m^2	
SIO	958	959	161	0.17
SNL	-	965	172	0.18
MRI	-	958	183	0.19
SIRS-C1	-	-	-	0.17
554 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	949 W/m^2	W/m^2	W/m^2	
SIO	958	955	159	0.17
SNL	-	966	171	0.18
MRI	-	966	183	0.19
SIRS-C1	-	-	-	0.17
593 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	947 W/m^2	W/m^2	W/m^2	
SIO	956	957	160	.17
SNL	-	965	172	0.18
MRI	-	957	184	0.19
SIRS-C1	-	-	-	0.18
653 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	945 W/m^2	W/m^2	W/m^2	
SIO	954	952	162	0.17
SNL	-	959	173	0.18
MRI	-	956	185	0.19
SIRS-C1	-	-	-	0.18
594 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	940 W/m^2	W/m^2	W/m^2	
SIO	951	945	159	0.17
SNL	-	958	172	0.18
MRI	-	961	183	0.19
SIRS-C1	-	-	-	0.18
591 m	**Surface**	**Zenith**	**Nadir**	**Albedo**
SUNY	934 W/m^2	W/m^2	W/m^2	
SIO	943	944	157	0.17
SNL	-	948	171	0.18
MRI	-	940	182	0.19
SIRS-C1	-	-	-	0.18

References

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

Fröhlich, C., 1978: WMO Final Report, 490, 108-112.

McArthur, L.J.B., 1998: Baseline Surface Radiation Network (BSRN) operations manual. WMO/TD-No. 879, World Climate Research Program, p. 69.