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IEA Comparisons of Global Solar Radiation Reference Radiometers

BYGGFORSKNINGSRÅDET
The Swedish Council for Building Research

INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

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SOLAR HEATING AND COOLING PROGRAMME

International Energy Agency

The International Energy Agency, headquartered in Paris, was formed in November 1974 as an autonomous body within the framework of the Organization for Economic Cooperation and Development to establish cooperation in the area of energy policy. Twenty-one countries are presently members, with the Commission of the European Communities participating under a special arrangement.

Collaboration in the research, development and demonstration of new energy technologies to help reduce dependence on oil and to increase long-term energy security has been an important part of the Agency's programme. The IEA R&D activities are headed by the Committee on Research and Development (CRD) which is supported by a small Secretariat staff. In addition, four Working Parties (in Conservation, Fossil Fuels, Renewable Energy and Fusion) are charged with monitoring the various collaborative energy Agreements, identifying new areas for cooperation and advising the CRD on policy matters.

Solar Heating and Cooling Programme

On of the first collaborative R&D agreements was the IEA Solar Heating and Cooling Programme which was initiated in 1977 to conduct joint projects in active and passive solar technologies, primarily for building applications. The twenty members of the Programme are:

Australia	France	Spain
Austria	Germany	Sweden
Belgium	Italy	Switzerland
Canada	Japan	Turkey
Denmark	The Netherlands	United Kingdom
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A total of nineteen projects or "Tasks" have been undertaken since the beginning of the Programme. The overall programme is managed by an Executive Committee composed of one representative from each of the member countries, while the leadership and management of the individual Tasks is the responsibility of Operating Agents. These Tasks and their respective Operating Agents are:

*Task 1:	Investigation of the Performance of Solar Heating and Cooling Systems - Denmark
*Task 2:	Coordination of Research and Development on Solar Heating and Cooling - Japan
*Task 3:	Performance Testing of Solar Collectors - United Kingdom
*Task 4:	Development of an Insolation Handbook and Instrument Package - United States
*Task 5:	Use of Existing Meteorological Information for Solar Energy Application - Sweden
*Task 6:	Solar Heating, Cooling, and Hot Water Systems Using Evacuated Collectors - United States
*Task 7:	Central Solar Heating Plants with Seasonal Storage - Sweden
*Task 8:	Passive and Hybrid Solar Low Energy Buildings - United States
*Task 9:	Solar Radiation and Pyranometry Studies - Germany
*Task 10:	Material Research and Testing - Japan
*Task 11:	Passive and Hybrid Solar Commercial Buildings - Switzerland
Task 12:	Building Energy Analysis and Design Tools for Solar Applications - United States
Task 13:	Advanced Solar Low Energy Buildings - Norway
Task 14:	Advanced Active Solar Systems - Canada
Task 16:	Photovoltaics in Buildings - Germany
Task 17:	Measuring and Modelling Spectral Radiation - Germany
Task 18:	Advanced Glazing Materials - United Kingdom
Task 19:	Solar Air Heating - Switzerland (in planning stage)
Task 20:	Solar Retrofit Systems for Buildings - Sweden (in planning stage)

*Completed Task

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Abstract

In solar energy research the ability to accurately measure the incoming solar irradiance level is important. One percent (1σ) uncertainty is often required, for example for solar collector testing. Within Task 9F of the International Energy Agency (IEA) Solar Heating and Cooling Program (SHCP), mobile reference instruments were developed in order to be able to accurately perform measurements of global solar irradiance at specific collector testing sites. Three instruments were developed, one each in Canada, Germany and Sweden. A combination of an absolute pyrheliometer and a pyranometer shaded by a sun tracking disk was used. A comparison of the three reference instruments was performed in Norrköping during August 1990. The intention was to verify the 1 % uncertainty and also to assess the state of the art. The result of this comparison was to some extent disappointing, with slightly more than 1 % disagreement between the instruments. Therefore the comparison was repeated in Care, Toronto during July 1991. From the experience of the two comparisons, it can be concluded that global irradiance can be measured with less than 1 % uncertainty during clear days.

Key words: Solar, irradiance, global, pyranometer, pyrheliometer, IEA, measurement, uncertainty

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Preface

This report is the result of collaboration within Task 9 of the IEA Solar Heating and Cooling Program. The first phase ran from October 1982 until June 1987 and covered the following subtasks (lead countries in parentheses):

- Subtask A: Small-Scale Time and Space Variability of Solar Radiation (Switzerland)
- Subtask B: Validation of Solar Irradiance Simulation Models (Denmark)
- Subtask C: Pyranometry (Canada)

The second phase of the Task ran from July 1987 until June 1991 and included:

- Subtask D: Techniques for Supplementing Network Data for Solar Energy Applications (Switzerland)
- Subtask E: Representative Design Years for Solar Energy Applications (Denmark)
- Subtask F: Irradiance Measurements for Solar Collector Testing (Canada)

The intercomparisons of reference radiometers for measuring global solar irradiance, which are the subject of this report, were performed within Subtask F with the following participants:

AES	Atmospheric Environment Service, 4905 Duffering Street, Downsview, Ontario M3H 5T4, Canada (D. Wardle, B. McArthur)
MOH, DWD	Deutscher Wetterdienst, Meteorologisches Observatorium Hamburg, Frahmredder 95, D-22393 Hamburg, Germany (K. Dehne)
SMHI	Swedish Meteorological and Hydrological Institute, S-60176 Norrköping, Sweden (L. Dahlgren)
SP	Swedish National Testing and Research Institute, S-50115 Borås, Sweden (L. Liedquist)

1 Background

In solar collector testing, one of the most fundamental parameters is measurement of the solar irradiance falling on the collector. The uncertainty in this measurement will directly influence the uncertainty of the performance test of the collector or the collector system. Usually, a set of pyranometers is used to measure the irradiance. One pyranometer is positioned horizontally for measurement of global irradiance. A second one, also horizontal, measures the diffuse component of the irradiance, and a third pyranometer is positioned in parallel with the collector to measure the hemispherical irradiance which also includes the reflected radiation from the surface in front of the pyranometer and the collector. For large systems, more pyranometers are necessary in order to take into account local variations in the reflectance of the ground.

Solar engineers require a measurement uncertainty of less than 1 % of the hemispherical irradiance at a 68 % (1σ) confidence level. This is in general very difficult to achieve with available pyranometers , even at a calibration institute, because of their weather dependency (temperature, direction of irradiance, etc.). There are also practical problems, such as alignment of the pyranometer with the collector surface, finding a point of measurement for the pyranometer that is representative for the collector irradiance. The access to a local reference standard pyranometer of high quality is needed for calibration of the pyranometers used, but the calibration process itself contributes to the total uncertainty.

It was therefore decided within Task 9, subtask F, to study the state-of-the-art of the measurement of global solar irradiance. Three reference instruments, global radiation reference radiometers (GRRR), were built and intercompared twice (at SMHI, Norrköping, Sweden in August 1990 and at AES in Care outside Toronto, Canada in July 1991) [1]. The best available instruments were used, i.e. absolute pyrheliometers for measurements of the direct irradiance and pyranometers with good cosine response for measurements of the diffuse part of the global irradiance. These GRRRs were developed by Atmospheric Environment Service (AES), Canada, Deutscher Wetterdienst (DWD), Germany and the Swedish National Testing and Research Institute (SP). Intercomparison was also made with a system consisting of an Eppley NIP pyrheliometer and a shaded pyranometer owned by the Swedish Meteorological and Hydrological Institute (SMHI).

The first intercomparison (Norrköping 1990) showed differences on the order of 1-2 %, mainly as a result of rather unstable weather conditions. Consequently, the fluctuations in the result were higher than expected. Therefore, the subtask F group decided to repeat the intercomparison and AES offered to host it in Toronto in 1991.

Another reason for developing GRRRs, which are compact and transportable units, was to make it easier to set up such a reference instrument at the collector test facility for calibration of the pyranometers in situ. On exceptionally clear days it is quite possible to expect the uncertainty of the global irradiance measured by the GRRR to be as low as 0.5 %. But during semi-clear days with rapidly changing direct irradiance, the uncertainty could easily increase to several percents.

2 Measurement uncertainty

Only three cases ware taken into consideration: 1) Shaded horizontal pyranometer for measurement of diffuse irradiance, 2) the GRRR, i.e. measurement of global irradiance using a combination of a shaded pyranometer and a pyrheliometer, and 3) measurement of global irradiance with a conventional unshaded horizontal pyranometer. As all the GRRRs use Kipp&Zonen CM11 pyranometers, only this type is studied here. But as there is always a certain variability of characteristics among different individual instruments, the values in the error budgets below should only be considered as examples.

2.1 Diffuse irradiance measurement using a shaded pyranometer

A reference pyranometer for diffuse irradiance must have good cosine response for angles of incidence up to a least 80°. The cosine error, which generally increases with the angle, should be less than about 2 % at 80°, or alternatively a directionality error of about max. 4 Wm^{-2} for 1000 Wm^{-2} normal incident irradiance in the range 0° - 80°. The latter error is defined as the difference between the measured 1000 Wm^{-2} beam irradiance projected on the pyranometer and the true irradiance for the given projection angle.

No basic reference instrument for diffuse irradiance is available on the market. A regular pyranometer equipped with a shading disk is normally preferred for this purpose and the pyranometer is calibrated against a pyrheliometer, using the alternating shading technique. Usually, the pyranometer is mounted horizontally during that process. If the pyranometer output voltage is V_n when unshaded and V_o when shaded, and the irradiance measured by the pyrheliometer is E_p, then the responsivity r of the pyranometer is calculated as

$$r = \frac{V_n - V_o}{E_p \cos\theta} \qquad (1)$$

where θ is the angle of incidence of the direct irradiance. This responsivity is then assumed to be true for the shaded pyranometer measuring the diffuse component. It is essential that the solid angle with which the shading disk subtends the sky is the same as the opening angle of the pyrheliometer as seen from the detector surface. It is also desirable that the corresponding slope angles (including the glass dome of the pyranometer) are approximately the same in the two cases. The diffuse irradiance, E_d, is calculated from the measured output U_d as

$$E_d = \frac{U_d}{r} - E_o \qquad (2)$$

where E_o is an offset in the irradiance caused by, e.g., sky cooling of the class dome, internal temperature gradients caused by different time constants from different parts of the instrument, emfs in the data acquisition system. The mean of the night-time value before and after the day of measurement is often taken as an approximation.

An error budget for E_d could as an example be estimated as in Table 1 and is calculated for 40° solar altitude and 100 Wm^{-2} diffuse irradiance. The method which was published by the International Bureau of Weights and Measures (BIPM) in 1981, is used for adding uncertainty components assuming Gaussian distribution. A clear day with low turbidity is assumed. Given standard deviations are related to mean values of irradiance.

Table 1 Example of an error budget for a pyranometer measuring diffuse irradiance

Uncertainty component	Standard deviation [%]
Uncertainty of pyrheliometer relative to WRR	0.15
Shading disk field angle relative to pyrheliometer opening	0.01
Shading disk slope angle relative to pyrheliometer slope angle	0.02
Shading disk position uncertainty max ±1° at calibration	0.03
Horizontal levelling at calibration, max. ±0.25°	0.1
Temperature uncertainty at calibration if not corrected	0.5
Cosine error at calibration if not corrected	0.5
Data acquisition uncertainty max. ±5 µV at calibration	0.05
Type A uncertainty (statistical) at calibration	0.05
Type A uncertainty at usage	0.25
Zero offset uncertainty max. ±1 Wm^{-2}	0.5
Data acquisition uncertainty at usage	0.5
Temperature uncertainty at usage	0.5
Radiance distribution dependency	0.5
RMS sum	1.26
Total uncertainty with coverage factor k=2 (about 95 % confidence level)	2.52

2.2 Global irradiance measurement using a shaded pyranometer and a pyrheliometer

The most accurate way of measuring global irradiance for clear weather conditions is to measure separately the direct component using a pyrheliometer, the diffuse component using a shaded pyranometer, and the solar zenith angle (time measurement). A modern pyrheliometer has an uncertainty on the order of only 0.3 %, if used carefully. The problem with the uncertainty in the directionality error of an ordinary pyranometer is considerably reduced in this way, because the shaded pyranometer measures only a small part of the global irradiance and the angular distribution of the sky radiance has variations that are much less than the excluded direct component at clear sky conditions.

It is therefore believed that the best way to calibrate a pyranometer for global irradiance is to measure simultaneously 1) its output U, 2) the diffuse component E_d with a shaded reference pyranometer, and 3) the direct normal component $E_{dir,n}$ with a pyrheliometer and to calculate the responsivity

$$r = \frac{U - U_o}{E_d + E_{dir,n} \cos\theta} \qquad (3)$$

where U_0 is the zero offset voltage (usually the night-time value or a value taken with a 2π sr shading device that is carefully designed for this purpose) and θ is the angle of incidence to the horizontal pyranometer.

It is very complicated to calculate the uncertainty of a pyranometer measurement of global irradiance, generally because of the many different parameters that influence the result (directionality, levelling, temperature, temperature gradient, zero offset, etc.). Therefore, we consider only the uncertainty of the responsivity r which always is measured during good, low turbidity and stable weather conditions applying well controlled procedures of measurements. Table 2 estimates the uncertainty in r when measured during the summer in Sweden at about 20 °C temperature, 40° angle of incidence and less than 20 % diffuse radiation.

Table 2 Example of an error budget for calibration of a pyranometer in global irradiance using a GRRR

Uncertainty component	Standard deviation, [%]
Uncertainty of pyrheliometer relative to WRR	0.3
Uncertainty of diffuse irradiance (above 1.26·0.2)	0.25
Type A uncertainty max. ±0.1 %	0.05
Data acquisition uncertainty max. ±5 µV	0.05
Zero offset uncertainty max. ±1 Wm^{-2}	0.15
Temperature influence ±5 °C	0.3
Solar angular dependency	0.1
Radiance distribution dependency	0.05
RMS sum	0.53
Total uncertainty with coverage factor k=2 (about 95 % confidence level)	1.06

2.3 Global irradiance measurement using a pyranometer

A pyranometer used for global irradiance measurements is usually calibrated at a selected small range of measurement conditions, a nominal condition. Also if the pyranometer is calibrated against a reference pyranometer or a GRRR system during several days or weeks, only one calibration factor (or responsivity) is given as a result representing a mean value for this period. This mean value could be corrected by the calibration institute to a nominal condition, e.g. 600 Wm^{-2}, 20 °C, 40° solar altitude at noon. Most often the user of the calibrated pyranometer uses this calibration constant for all his measurement conditions, i.e. without corrections. Generally it is not a simple task to perform corrections. For example, the temperature dependence of the pyranometer responsivity could include a temperature gradient component which generally is unknown. Table 3 is an attempt to estimate the uncertainty of global irradiance of around

800 Wm^{-2}, measured over a period of 10 minutes, on a normal clear day with low turbidity, 40° solar altitude, 0 °C temperature. A high quality pyranometer is assumed.

Table 3 Example of an error budget for global irradiance measurement using a pyranometer

Uncertainty component	**Standard deviation [%]**
Calibration uncertainty at nominal conditions	0.53
Cosine error	1
Azimuth response variations	1
Uncertainty in temperature correction	0.5
Horizontal levelling max. ±0.1°	0.1
Temperature gradients	0.5
Contamination on glass dome	0.25
Data acquisition uncertainty max. ±5 μV	0.05
Type A uncertainty (statistical)	0.1
Zero offset uncertainty max. ±5 Wm^{-2}	0.3
RMS sum	1.72
Total uncertainty with coverage factor k=2 (about 95 % confidence level)	3.44

3 The GRRR systems

The reference instruments for global radiation, the GRRRs, made by AES, DWD and SP, consist of an absolute pyrheliometer on a tracker and a pyranometer having a sun tracking shading disk, both mounted on a single unit. A data acquisition system (computer, voltmeters, multiplexers) controls the tracker, performs automatic calibration of the pyrheliometers using dc power substitution, reads and stores measurement data. Basically it is a calibration system for global irradiance according to paragraph 2.2 above and an error budget for best condition measurement would be very similar.

The measured quantities are

- Calibration dc voltage U_c over the cavity heater resistor of the pyrheliometer
- Calibration dc current through the cavity heater measured as a voltage U_R over a precision resistance R (in the control unit of the pyrheliometer).
- Calibration output $U_{c,th}$ from the thermopile of the pyrheliometer
- Output of the pyrheliometer thermopile $U_{o,th}$ when shaded and without electrical heating
- Output of the pyrheliometer thermopile U_{th} unshaded and without electrical heating
- Output voltage U_d of the shaded pyranometer
- Local mean time for calculation of the solar position (zenith angle θ and azimuth ϕ)

The calibration quantities are measured once or twice during one hour measurement periods.

The global irradiance E_g is calculated as the sum of the diffuse component E_d and the projection of the direct normal component $E_{dir,n}$:

$$E_g = E_d + E_{dir,n} \cdot \cos\theta \qquad (4)$$

A complete measurement equation is the following:

$$E_g = \frac{U_d}{r} - E_o + \frac{1}{\tau} \cdot \frac{U_{th} - U_{o,th}}{U_{c,th} - U_{o,th}} \cdot \frac{K}{A} \cdot \frac{U_r}{R} \cdot (U - \frac{U_r}{R} \cdot R_{leads}) \qquad (5)$$

τ is the transmittance of the window of the pyrheliometer.

Typically values for Hickey-Frieden type of pyrheliometers: K is a small correction factor in the order of 1.001 (instrument dependent). A is the area of the precision aperture of the pyrheliometer cavity and is $0.500 \cdot 10^{-4}$ m^2. R is 1 ohm or 10 ohms. R_{leads} is the resistance of the leads into the cavity heater and is about 0.066 ohm.

4 State-of-the-art

The aim with the GRRRs was to realize a global irradiance measurement system using the best commercially available radiometric instruments suitable for the purpose. Several manufacturers make very accurate absolute pyrheliometers but the Eppley Hickey-Frieden pyrheliometer was independently chosen for all the three GRRRs because of its availability but also for its construction that makes it suitable for relatively long measurement periods (30 - 60 minutes) between calibrations with dc power substitution.

Kipp&Zonen CM11 pyranometers were chosen in all three GRRR systems, because of the excellent cosine response. (At the time this report is written, the CM21 is probably a better choice due to its improved temperature behaviour.)

5 The intercomparison in Norrköping 1990

In subtask 9F it was agreed to verify the estimated uncertainty of 1 % for best measurements of global irradiance by direct intercomparison of GRRRs. The three GRRRs were therefore intercompared in August, 1990 at SMHI, Norrköping (longitude: -16° 15', latitude: 58° 58') and were running during days with acceptable (no rain) weather. Also the regular calibration system of SMHI, an Eppley NIP pyrheliometer and a shaded CM11 pyranometer, was included in this intercomparison.

In Table 4 the main characteristics facts of the three GRRRs and the SMHI systems and the operational parameters are displayed.

Computer controlled calibration (auto-calibration) of the HF pyrheliometers using dc power substitution was performed once every hour during minutes 0-9. For this purpose each HF was slightly modified to include a shutter and computer interfacing.

Table 4 Characteristics of the GRRRs at the intercomparison in Norrköping 1990

	AES	DWD	SP	SMHI
Pyrheliometer	HF-18747 K = 1.0007	HF-27157 K = 1.0015	HF-15744 K = 1.001	NIP-17007 8.18 $\mu VW^{-1}m^2$
Pyrheliometer window	none	quartz τ=0.933	quartz τ=0.938	yes
Auto-calibration	yes	yes	yes	no
Pyranometer	CM11-810166 4.70 $\mu VW^{-1}m^2$	CM11-820300 4.51 $\mu VW^{-1}m^2$	CM11-840552 4.65 $\mu VW^{-1}m^2$	CM11-810132 4.57 $\mu VW^{-1}m^2$
Pyranometer position	rotating w. sun	fix	rotating w. sun	fix
Pyranometer shade disk pos.	1 m	0.7 m	1 m	0.7 m
Tracker	2 axes	equatorial	2 axes	equatorial
Temperature measurement	yes	no	no	yes
Radiance distribution meas.	no	no	yes	no
Data acquisition DVM	HP3457	HP3457		HP3455
Time measurement	PC386	PC286		HP59309
Data sampling rate	6 s	6 s		6 s
Data storing rate	1 min	6 s		1 min

The DWD GRRR and the SP GRRR used a common data acquisition system as indicated in the table.

The SP system included recording of radiance distribution using a fish-eye lens and a video camera. The data are available at SP but are not included in this report.

5.1 Results of the intercomparison in Norrköping

Eight days of a total of 21 days of measurements were selected for the calculation of the final result of the comparison. On these days, August 7, 10, 20, 22, 23, 26 ,27 and 29, all participating instruments were in operation and the weather conditions reasonably good. In the figures on pages 20-35, the diffuse irradiance, the direct horizontal irradiance, and the global irradiance are displayed together with the corresponding measured value of each GRRR relative to the GRRR of SP. In these diagrams, 10 minute mean values are plotted.

In Table 5 the mean values of all measured values of global irradiance > 400 Wm^{-2} are presented. Very good agreement was achieved between the GRRRs of DWD and SP and also between the AES GRRR and the SMHI system. However, the two pairs of instruments disagreed by about 1.2 %.

Concerning the measurements of the diffuse irradiance only the AES and the SMHI instruments were in agreement (±1 % typically) while the others disagreed several percent. The spread in these measurements were higher than expected for 10 minute mean values. Systematic variations in the ratios indicate that there probably were tracking problems with the shading disk of the SP GRRR.

Table 5 Results of the comparison of global irradiance in Norrköping-1990 measured by GRRRs

Instrument	Mean value of all 10 min. mean values with global irradiance > 400 Wm^{-2} relative to the GRRR of SP	Standard deviation of the total mean value	Number of 10 min. mean values
AES	0.987	0.0008	166
DWD	0.998	0.0007	204
SMHI	0.989	0.0018	174

6 The intercomparison in Toronto 1991

Because of the relatively high fluctuations in the final results in Norrköping, it was decided to repeat the comparison. AES agreed to host this at their new radiation measurement station in Care (longitude: 79° 78', latitude: 44° 23') about 100 km north of Toronto. The main characteristics of this intercomparison are given in Table 6. Because of technical problems, all three GRRRs had to be made rather identical, having the same type of tracker, common data acquisition system and little variation in the shading devices. Weather data during the comparison are available at the AES.

Table 6 Characteristics of the GRRRs at the intercomparison in Toronto-1991

	AES	DWD	SP	SMHI
Pyrheliometer	HF-18747 K = 1.001	HF-27157 K = 1.0015	HF-15744 K = 1.001	NIP-17007 8.18 $\mu VW^{-1}m^2$
Pyrheliometer window	none	quartz τ=0.933	quartz τ=0.938	yes
Auto-calibration	yes	yes	yes	no
Pyranometer	CM11-882278 4.45 $\mu VW^{-1}m^2$	CM11-903201Q 4.74 $\mu VW^{-1}m^2$	CM11-840552 4.65 $\mu VW^{-1}m^2$	CM11-810132 4.57 $\mu VW^{-1}m^2$
Pyranometer position	rotating w. sun	rotating w. sun	rotating w. sun	rotating w. sun
Pyranometer shade disk pos.	1 m	1 m	1 m	1 m
Tracker	2 axes	2 axes	2 axes	2 axes
Temperature measurement	yes	no	no	no
Radiance distribution meas.	no	no	no	no
Other weather data meas.	yes	no	no	no
Data acquisition system	AES system at Care			
Time measurement	AES clock at Care			
Data sampling rate	6 s			
Data storing rate	1 min			

6.1 Results of the intercomparison in Toronto

The GRRRs were compared at the AES radiation measurement station at Care on July 11, 12, 15, 16, 17, 23, 24, 26, and 31. The figures on pages 36-53 show one minute mean values of the direct normal irradiance, the diffuse irradiance, and the global irradiance as well as the corresponding measured ratios of the GRRRs relative to the SP GRRR. For example, on July 11, 15.00 - 17.00, which was a very clear day, the pyrheliometers agreed very well. Only the NIP instrument of SMHI disagreed (1 %). For diffuse irradiance, the AES and SP pyranometers disagreed by almost 4 %, probably because of initial problems with the shading disks. Later on, this disagreement was generally within ±2 %. Another day with good weather was July 15, when all the instruments were operating. Again, the agreement of the pyrheliometers was on the order of the estimated ±0,3 %, except for the NIP which differed by about 1-2 % from the others. Also the agreement for diffuse irradiance was good with about ±1 % disagreement among all the systems.

An especially interesting day was July 24, a day with scattered clouds which showed very good agreement for the diffuse irradiance, but exceptionally large differences in the global irradiance (and of course, also in the direct irradiance). This is very surprising as all pyrheliometers were of the same type (except for the SMHI system) and a common data acquisition system was used which means the same time constants for all three GRRRs and also very small timing errors. In spite of these small time differences, large differences were acknowledged. The systematic behaviour of the DWD instrument relative to the SP instrument at about 12.30 hours is very strange and could have been caused by misalignment of the solar tracker.

The mean values of the comparisons from July 15, 12.00-17.00, July 16, 10.30-16.00, July 23, 12.00-16.00, July 26, 11.00-16.00, and July 31 10.00-11.30 14.00-15.30 are shown in Table 7 below.

Table 7 Results of the comparison of global irradiance in Toronto 1991 measured by GRRRs

Instrument	Mean value of 380 values in relation to the GRRR of SP	Standard deviation of the mean value
AES	0.9971	0.0006
DWD	1.0008	0.0003
SMHI	0.9882	0.0007

7 Combined results of the two intercomparisons

As mentioned above, the conditions for the intercomparisons in Norrköping and Toronto were quite different. In Toronto the weather was more suitable with several clear days. Also the usage of similar tracking disks and a common data acquisition system in Toronto made the comparison there more likely to give results of better agreement than in Norrköping.

The mean values of the final results of the two comparisons, given in Table 5 and in Table 7, show -0.8 % difference between AES and SP, -0.1 % between DWD and SP, and -1.2 % difference between SMHI and SP.

These final results, which include a broad variety in weather conditions, are very satisfactory and demonstrate clearly that measurements of global irradiance using a GRRR could be made with an uncertainty of less than 1 %. In very good weather, a 0.5 % uncertainty is more likely.

During the two intercomparisons, a very small staff operated all the systems and a full time control of the behaviour of the individual instruments was impossible. This was especially the case in Norrköping where the different GRRR systems and the NIP system were unique. On a practical use of a GRRR, at a solar collector testing facility, the GRRR will be operated with full attention during the period of measurement, which should guarantee the max. 1 % uncertainty in, for example, 1 h mean value of global irradiance.

8 Conclusions

In the first comparison, Norrköping 1990, the participating instruments had a certain variability in the four different realizations of the GRRR. Four different types of shading disks were used. Two of the pyranometers were rotated on the tracker, while the other two had a fixed position. Four different types of trackers carried the instruments and three different data acquisition systems controlled the GRRRs and collected data. This variability, reflected in the measurement results, especially for the diffuse component of the irradiance, where both randomly and systematically large differences were measured, was probably the reason why one of the true GRRRs (the NIP based system of SMHI is not a true GRRR) disagreed from the other two by -1.3 % in the final result. The corresponding disagreement of the NIP based system from these two GRRRs was only -1.1 % which must be considered as very good as the NIP pyrheliometer is not an absolute radiometer like the pyrheliometers of the GRRRs.

In the second comparison, Toronto 1991, identical trackers and shading disks were used together with a common data acquisition system and the outcome of this intercomparison was as expected: a very good agreement, ±0.15 %, for the three GRRRs and a larger deviation, -1.2 %, for the NIP based system. The latter value is almost identical with the one in the first comparison.

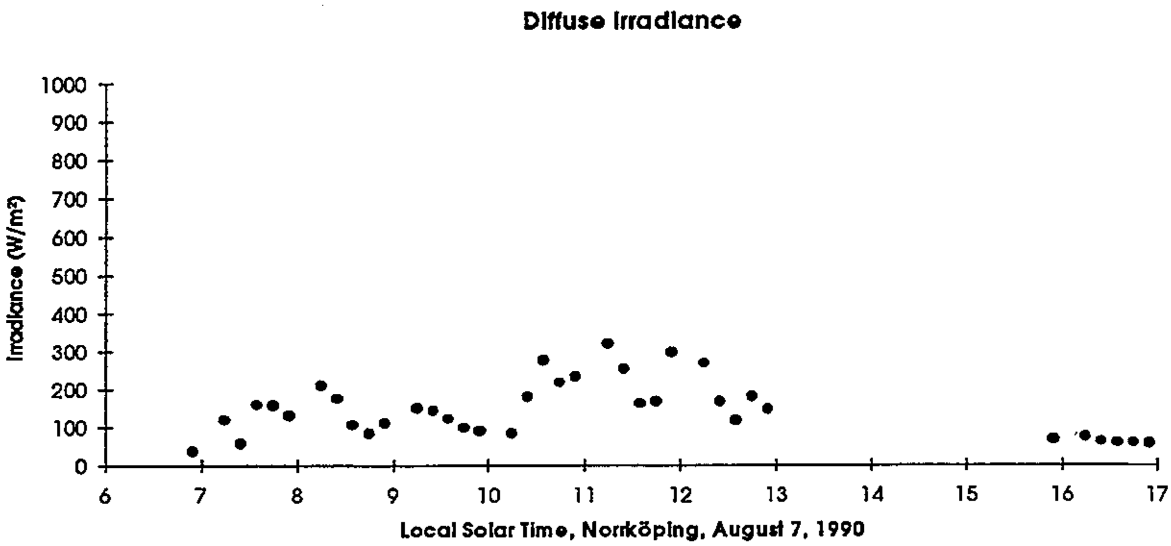
Compared to the difficulties in running four systems of this kind in parallel, especially in the first comparison, it should be much easier to set up a single well-controlled GRRR that is able to measure global solar irradiance with an uncertainty less than 1 % during clear days and stable weather conditions. The standard deviation of a 10 minutes mean value for global irradiance >400 Wm^{-2} was about 1 % in the first comparison and about 1 % for a 1 minute mean value in the second comparison. This indicates at least that a 1 hour mean value should be sufficient to achieve a 1 % total uncertainty.

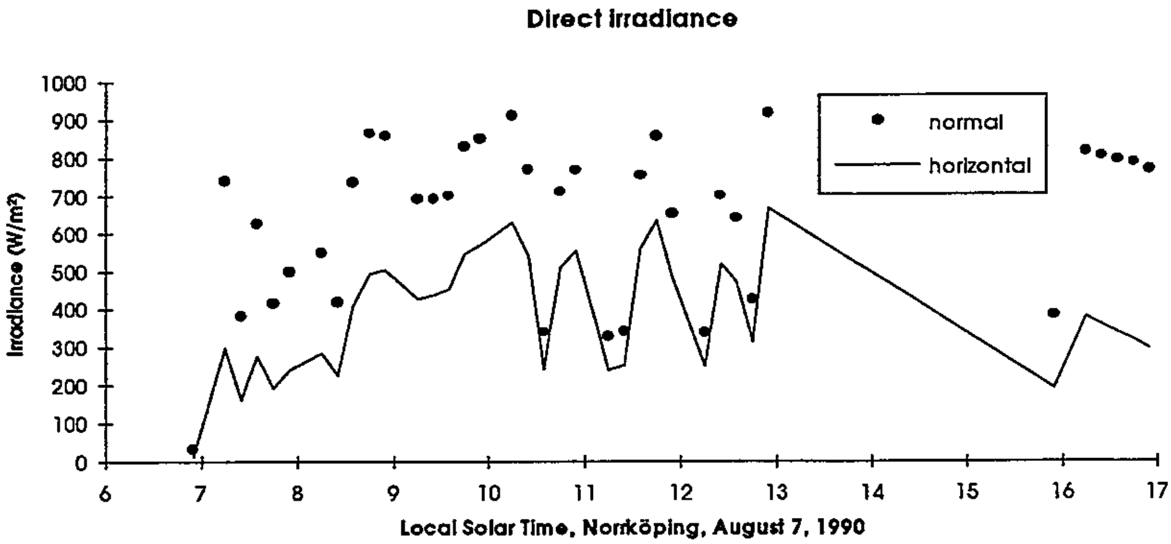
References

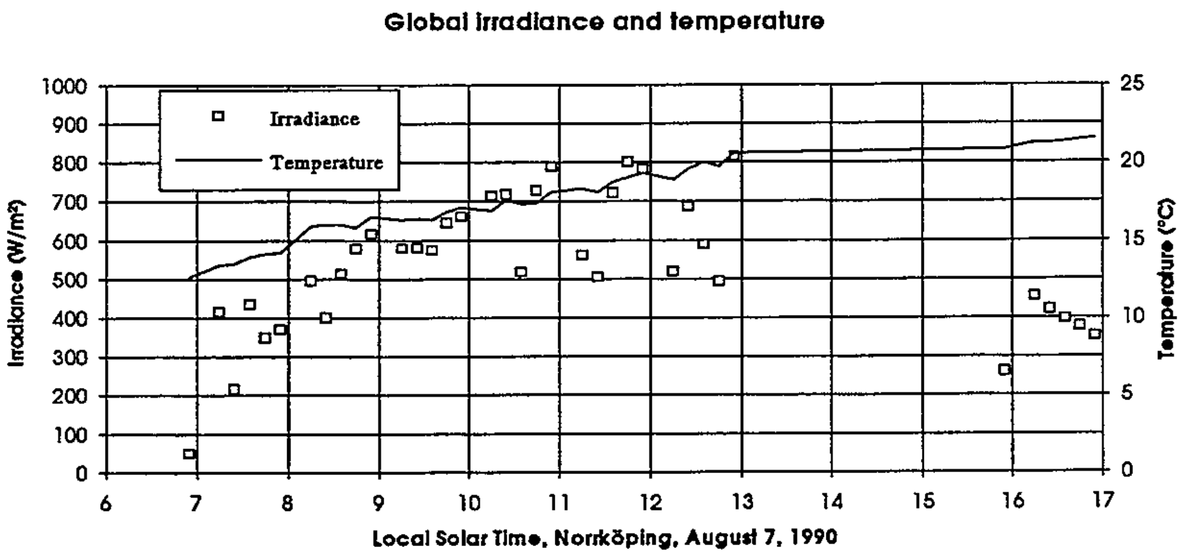
[1] Dehne K., et al, IEA Global Radiation Reference Radiometer Comparison, IPC VII, Results and Symposium, Working Report No. 162, Davos (1991), p. 85-90

Figures

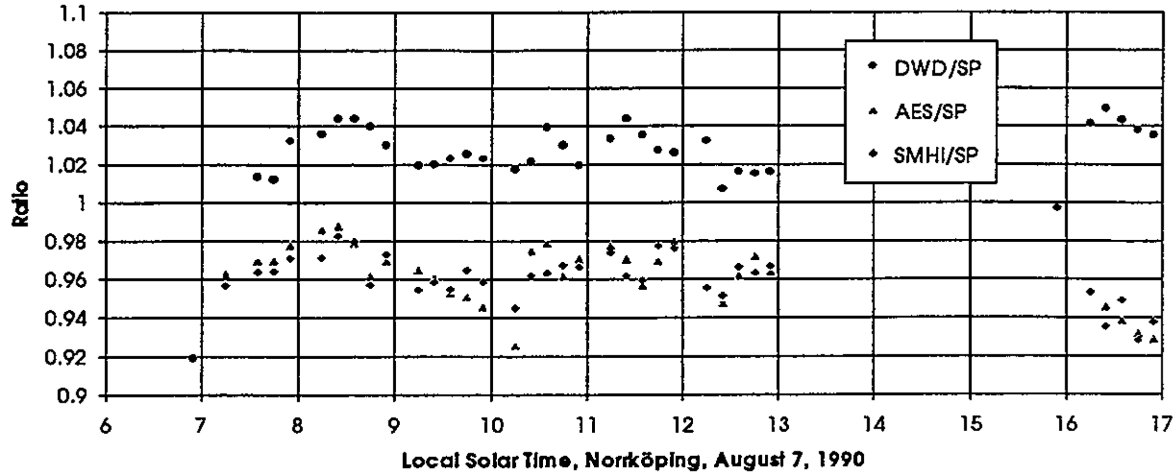
In the following figures, the measurement results of one comparison day are displayed on each opening with the irradiance conditions and the temperature on the left page. The right page shows the ratios between the irradiances (diffuse, direct and global) measured by the different systems and the corresponding ones measured by the SP GRRR system.


Diffuse irradiance
Irradiance (W/m²)
Local Solar Time, Norrköping, August 7, 1990

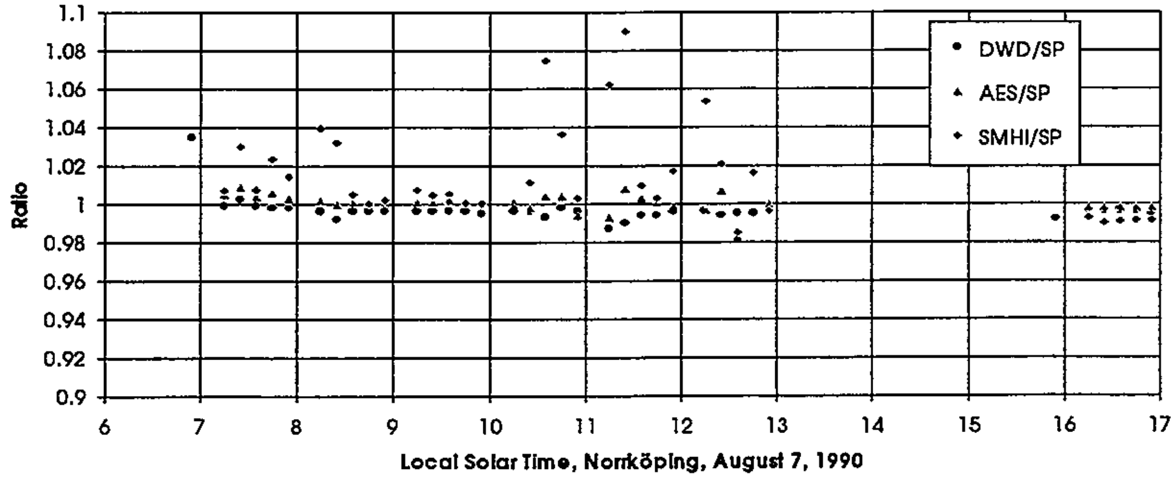

Direct irradiance
normal
horizontal
Irradiance (W/m²)
Local Solar Time, Norrköping, August 7, 1990


Global irradiance and temperature
Irradiance
Temperature
Irradiance (W/m²)
Temperature (°C)
Local Solar Time, Norrköping, August 7, 1990

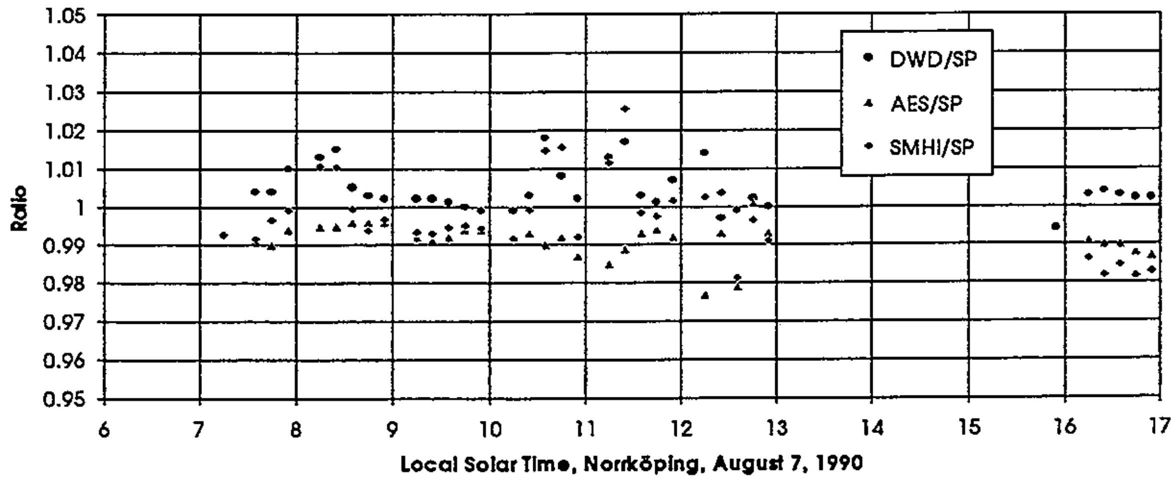
GRRR ratios for diffuse irradiance

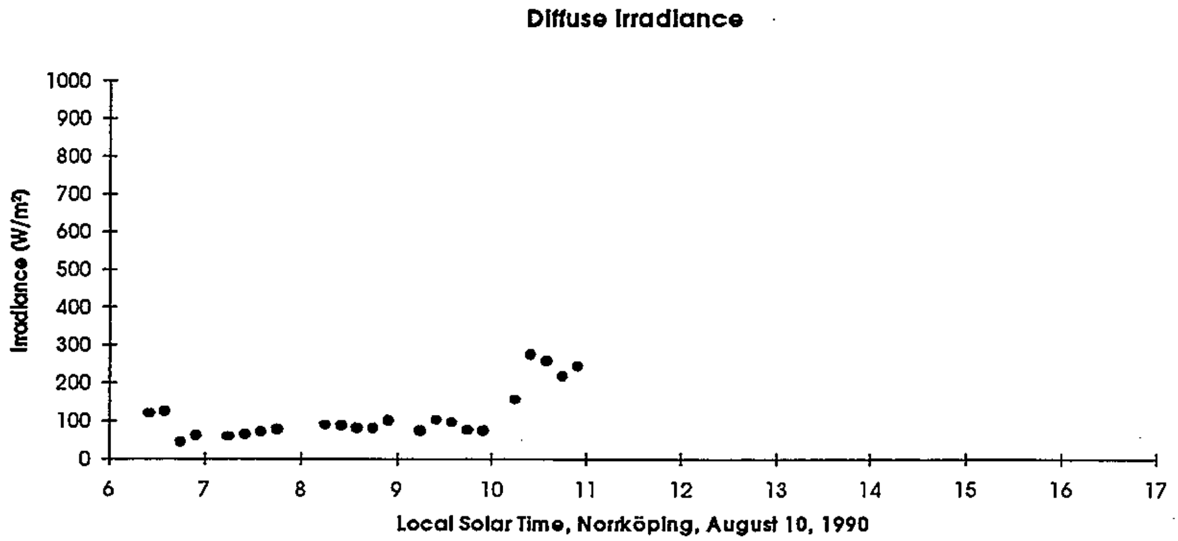


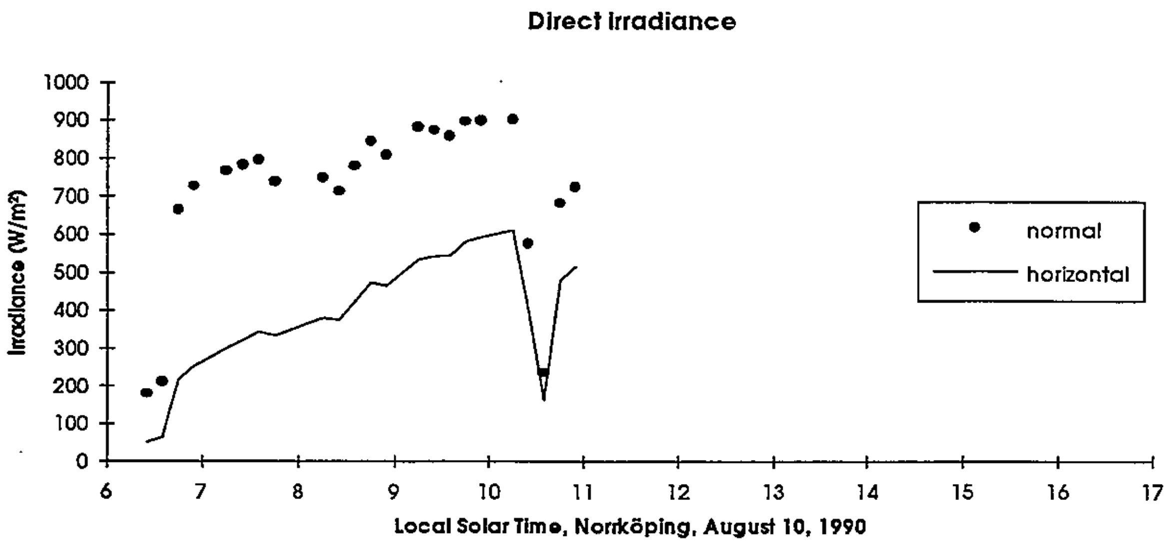
GRRR ratios for direct irradiance

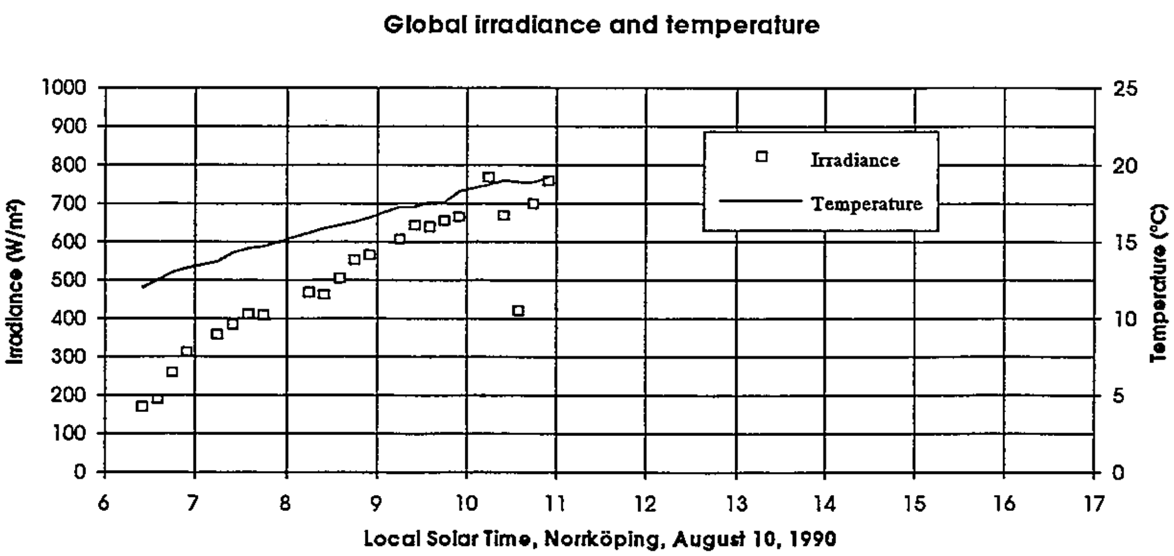


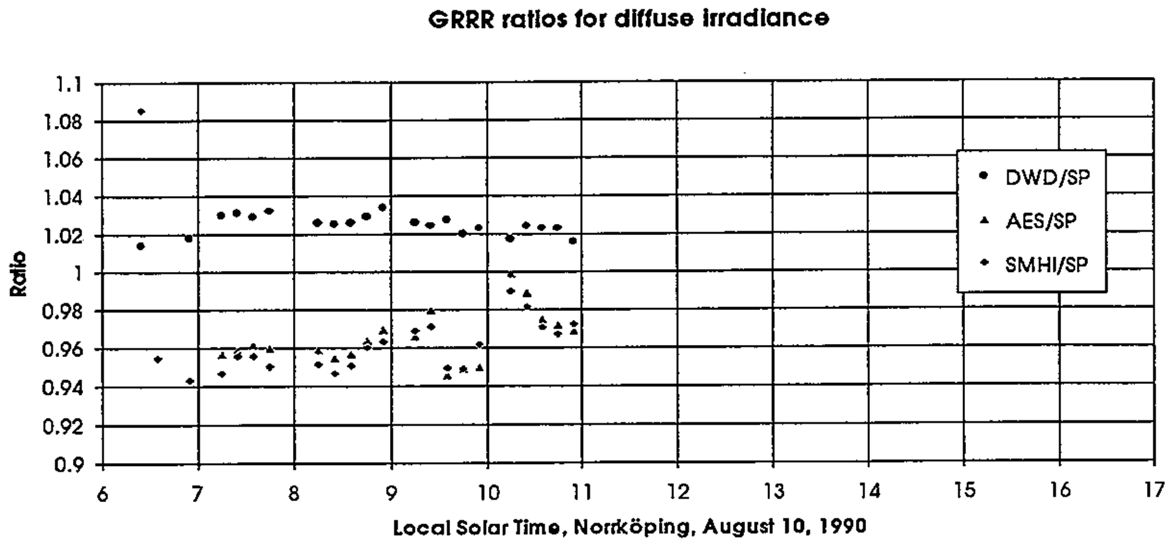
GRRR ratios for global irradiance

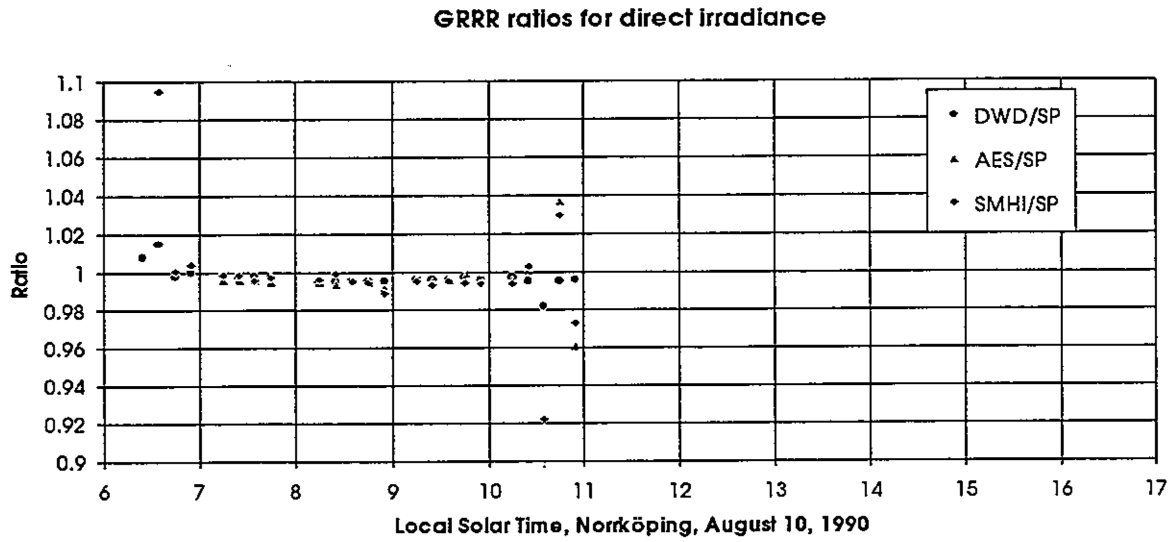


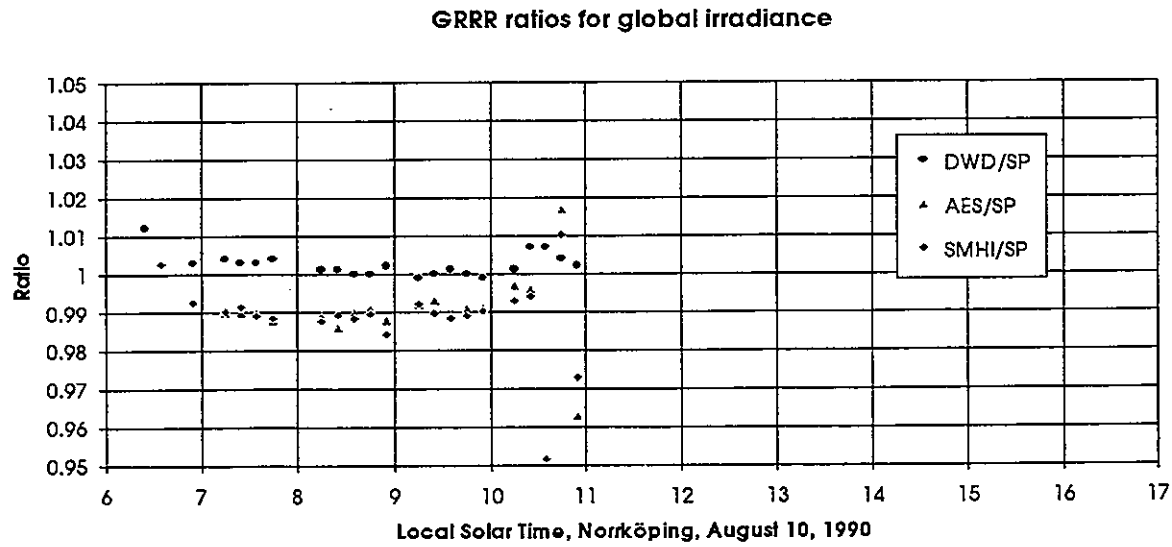

Diffuse irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 10, 1990

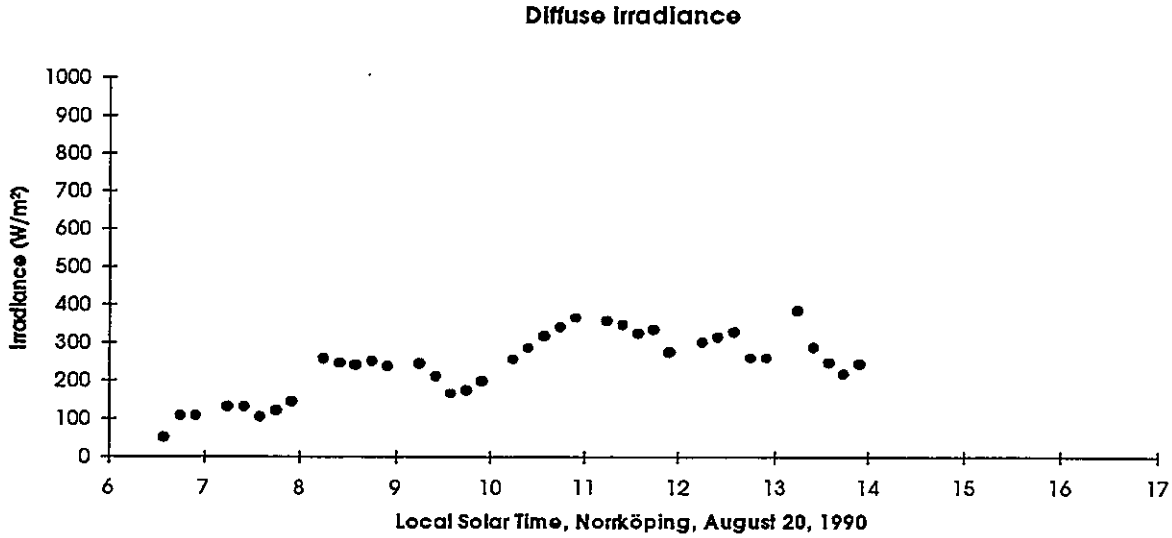

Direct irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
normal
horizontal
Local Solar Time, Norrköping, August 10, 1990

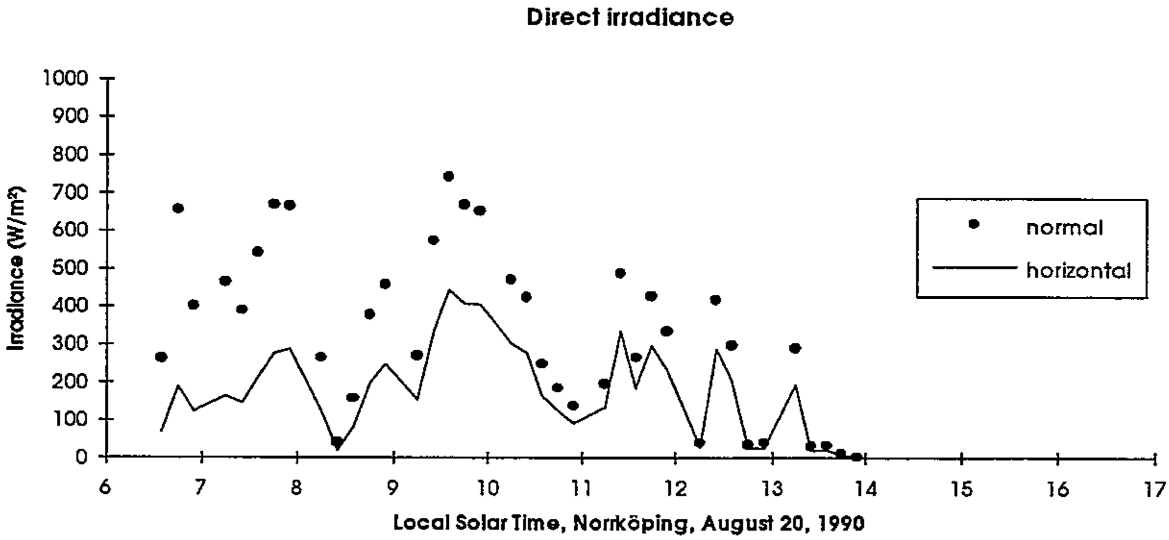

Global irradiance and temperature
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
Temperature (°C)
25
20
15
10
5
0
Irradiance
Temperature
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 10, 1990

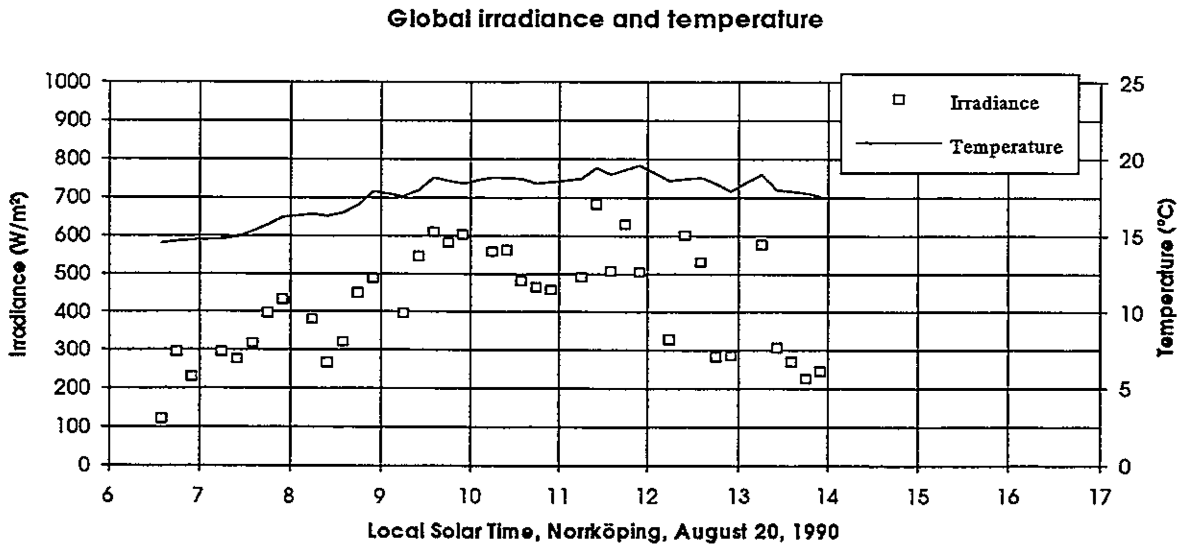

GRRR ratios for diffuse irradiance
Ratio
Local Solar Time, Norrköping, August 10, 1990
DWD/SP
AES/SP
SMHI/SP

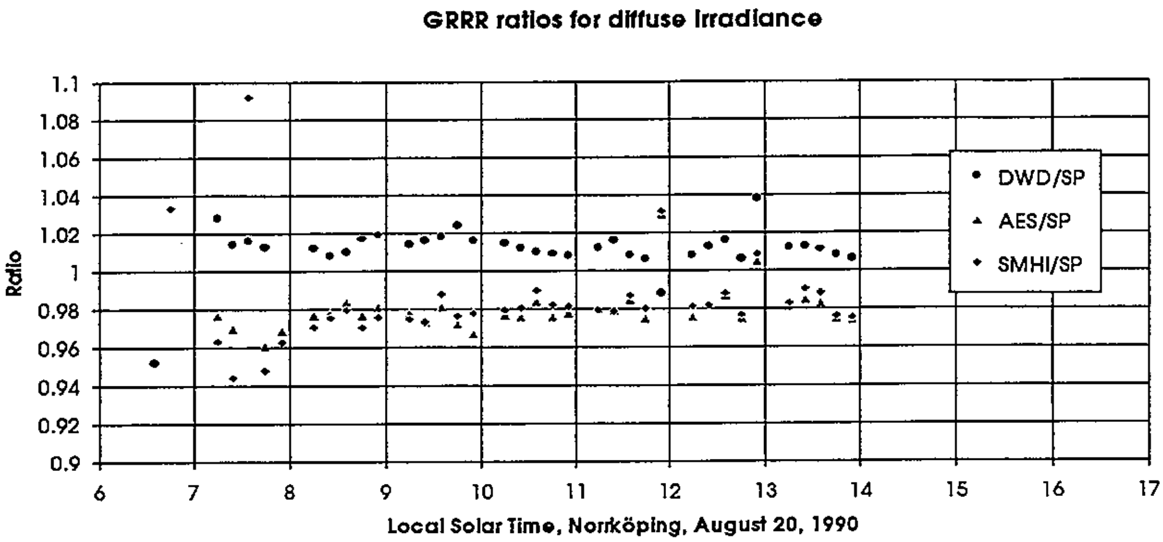

GRRR ratios for direct irradiance
Ratio
Local Solar Time, Norrköping, August 10, 1990
DWD/SP
AES/SP
SMHI/SP

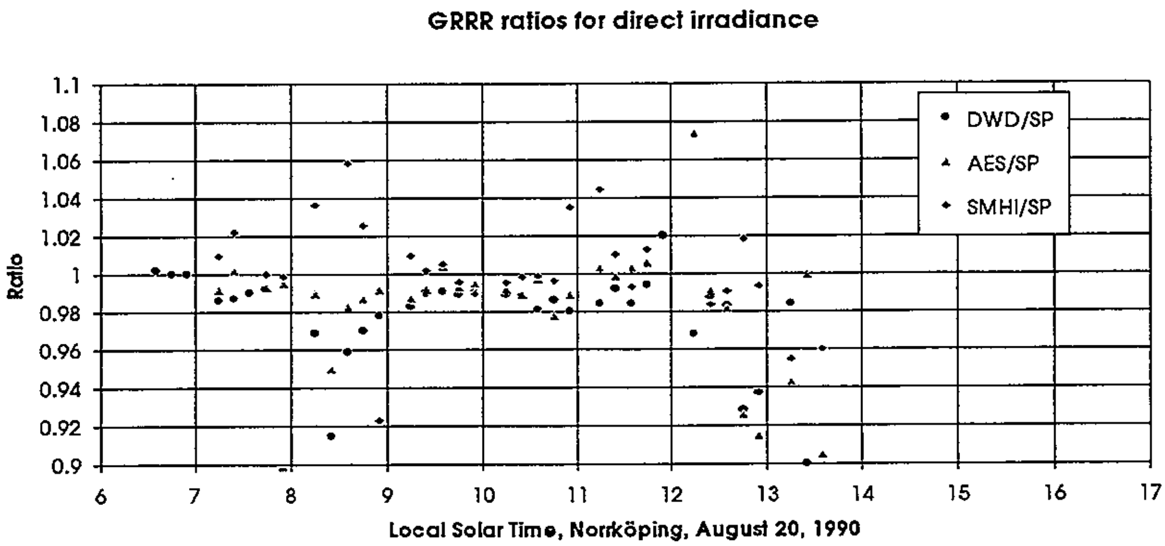

GRRR ratios for global irradiance
Ratio
Local Solar Time, Norrköping, August 10, 1990
DWD/SP
AES/SP
SMHI/SP


Diffuse irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 20, 1990


Direct irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
normal
horizontal
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 20, 1990


Global irradiance and temperature
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
Irradiance
Temperature
Temperature (°C)
25
20
15
10
5
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 20, 1990


GRRR ratios for diffuse irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 20, 1990
DWD/SP
AES/SP
SMHI/SP


GRRR ratios for direct irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
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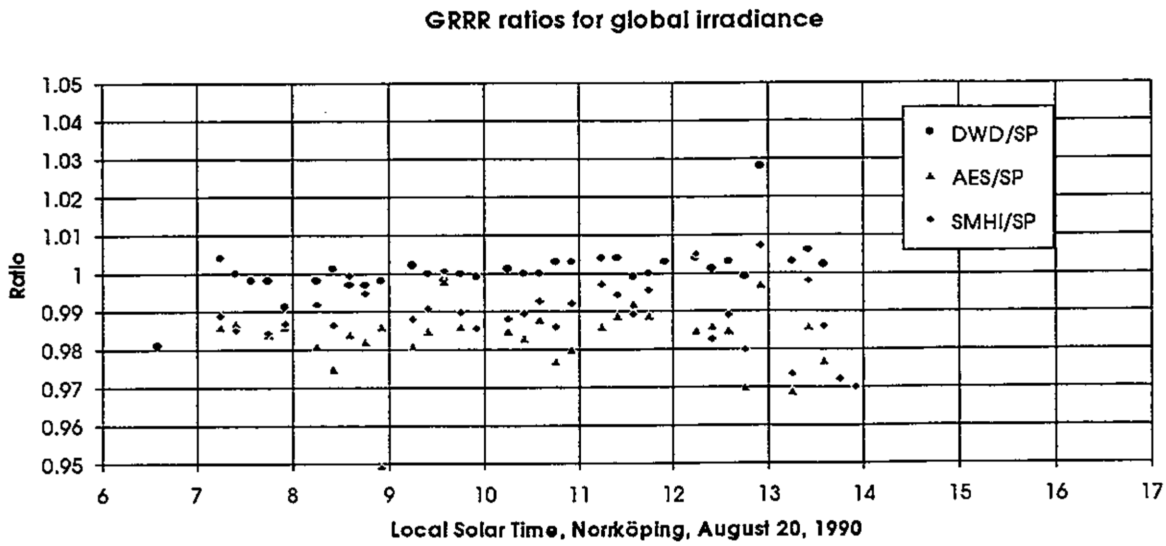
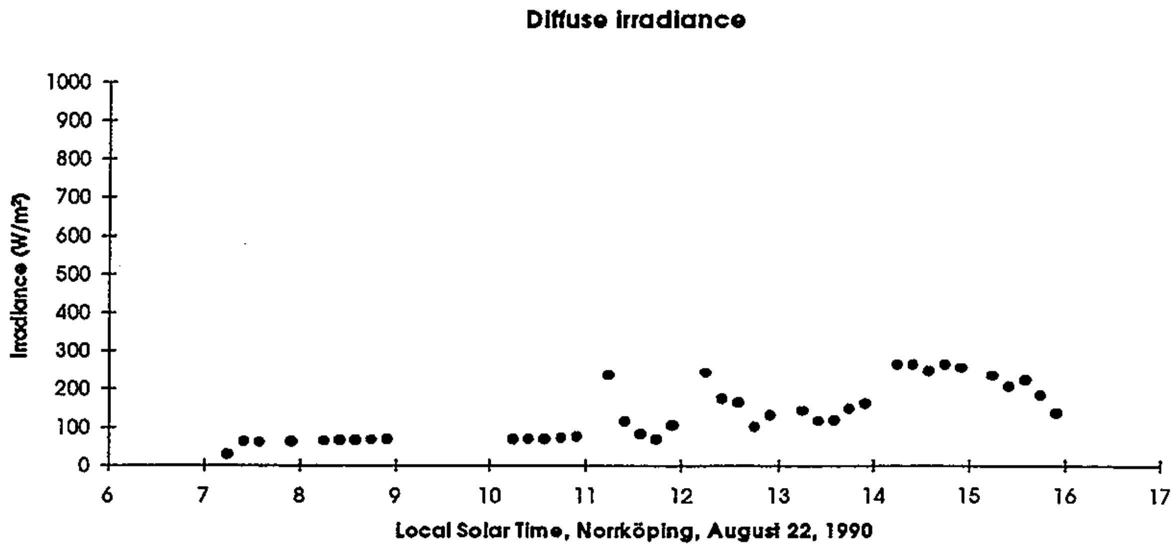
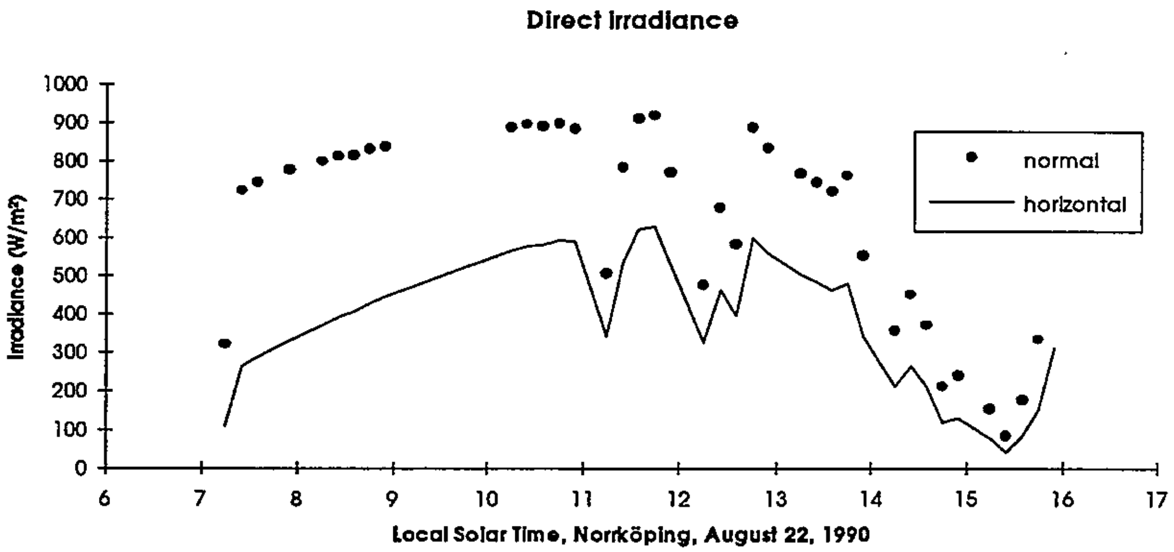
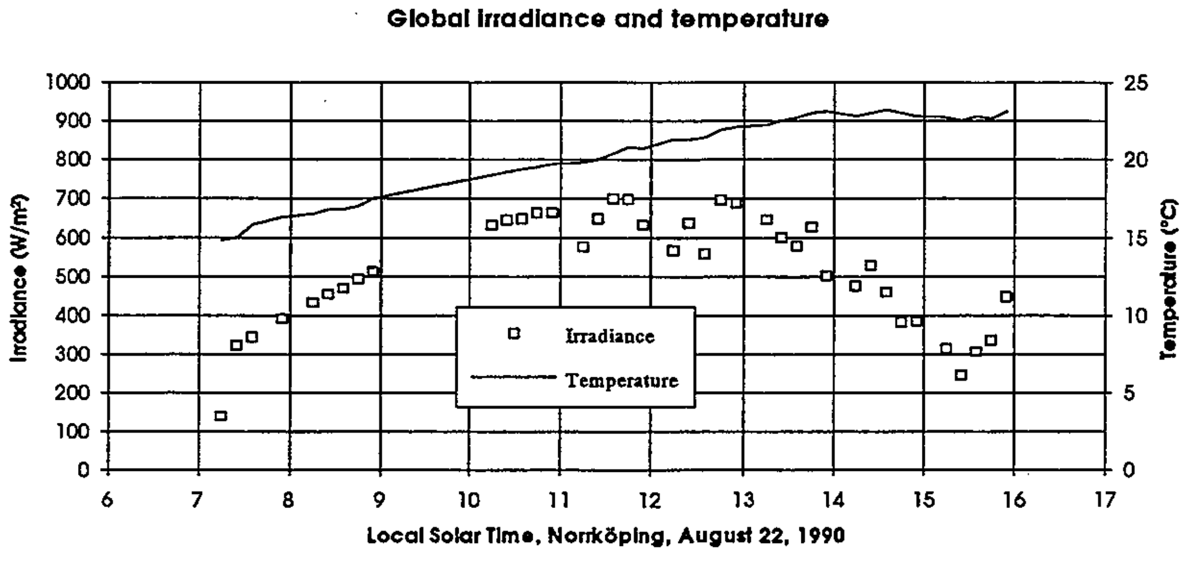
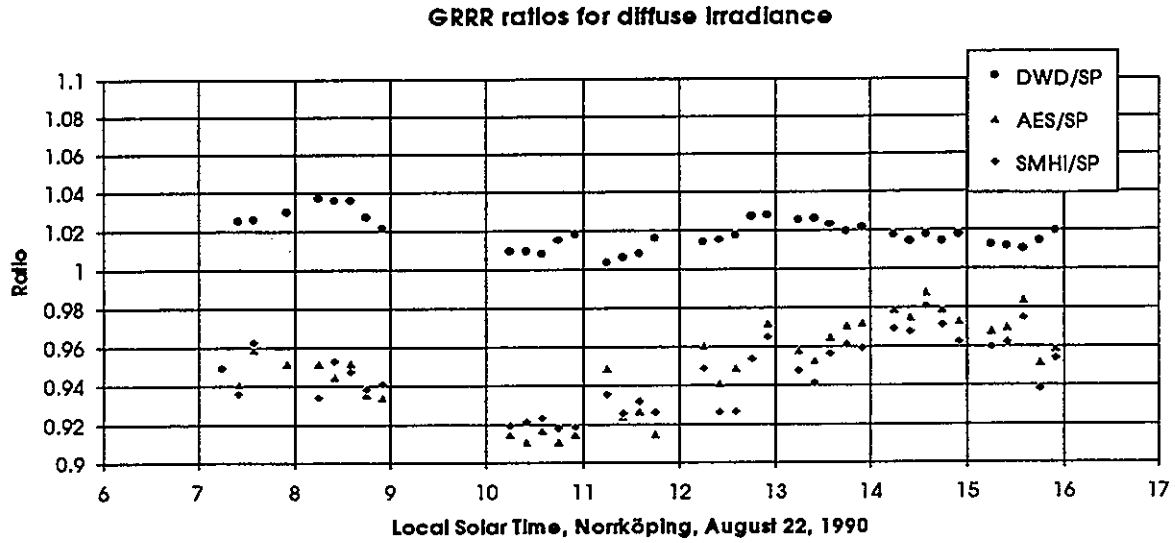
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 20, 1990
DWD/SP
AES/SP
SMHI/SP

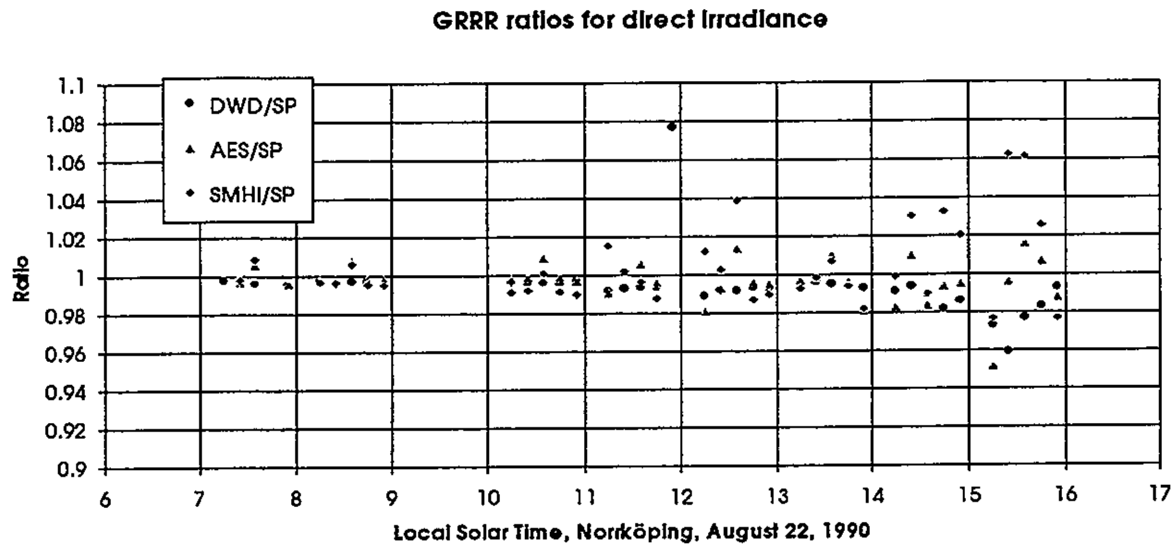

GRRR ratios for global irradiance
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 20, 1990
DWD/SP
AES/SP
SMHI/SP

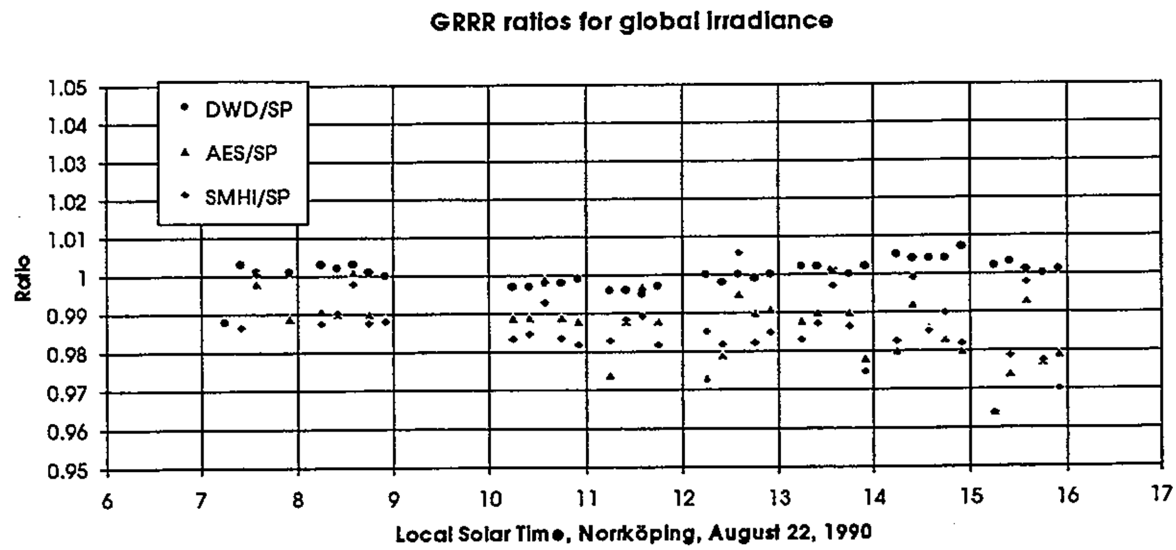

Diffuse irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 22, 1990

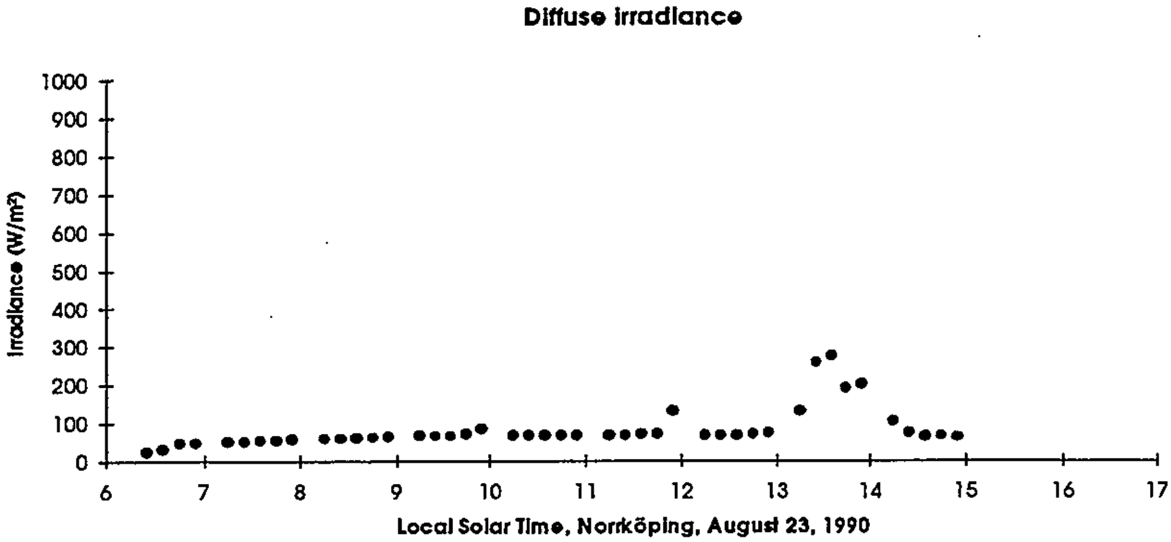

Direct irradiance
Irradiance (W/m²)
normal
horizontal
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 22, 1990

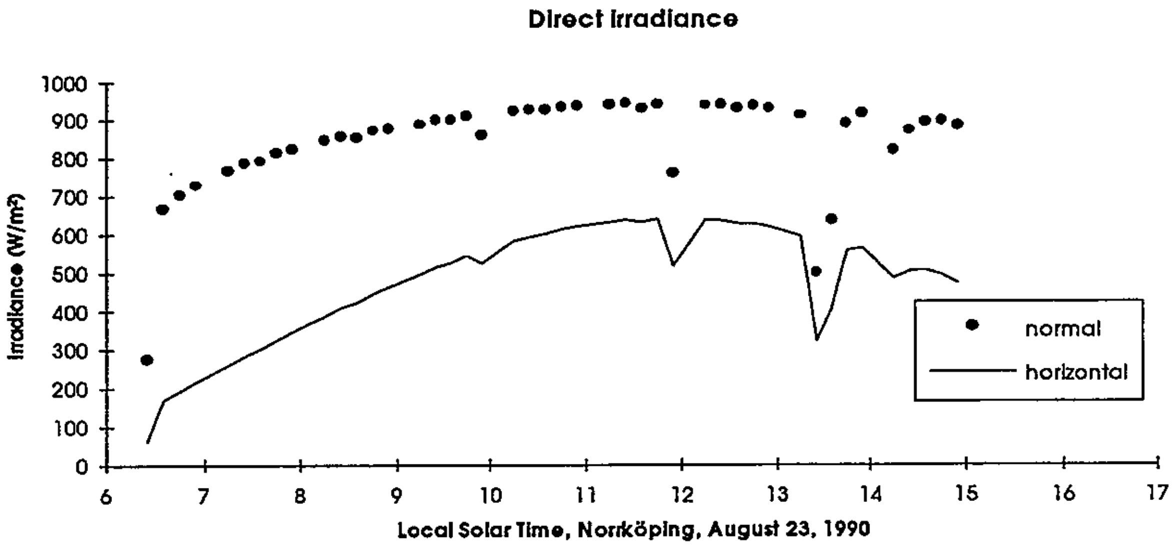

Global irradiance and temperature
Irradiance (W/m²)
Temperature (°C)
Irradiance
Temperature
1000
900
800
700
600
500
400
300
200
100
0
25
20
15
10
5
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 22, 1990

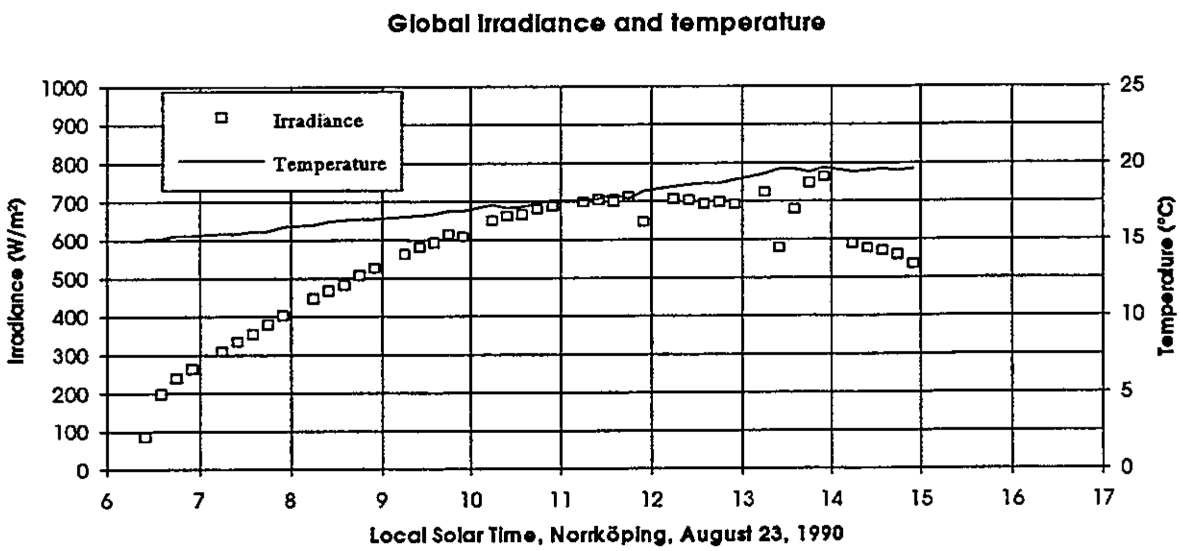

GRRR ratios for diffuse irradiance
DWD/SP
AES/SP
SMHI/SP
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 22, 1990

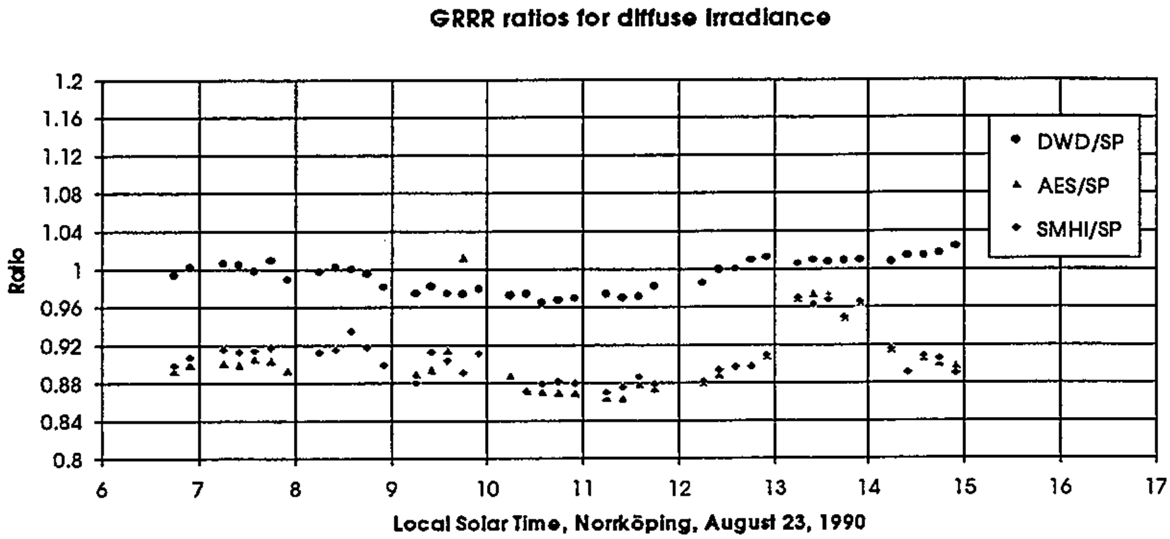

GRRR ratios for direct irradiance
DWD/SP
AES/SP
SMHI/SP
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 22, 1990

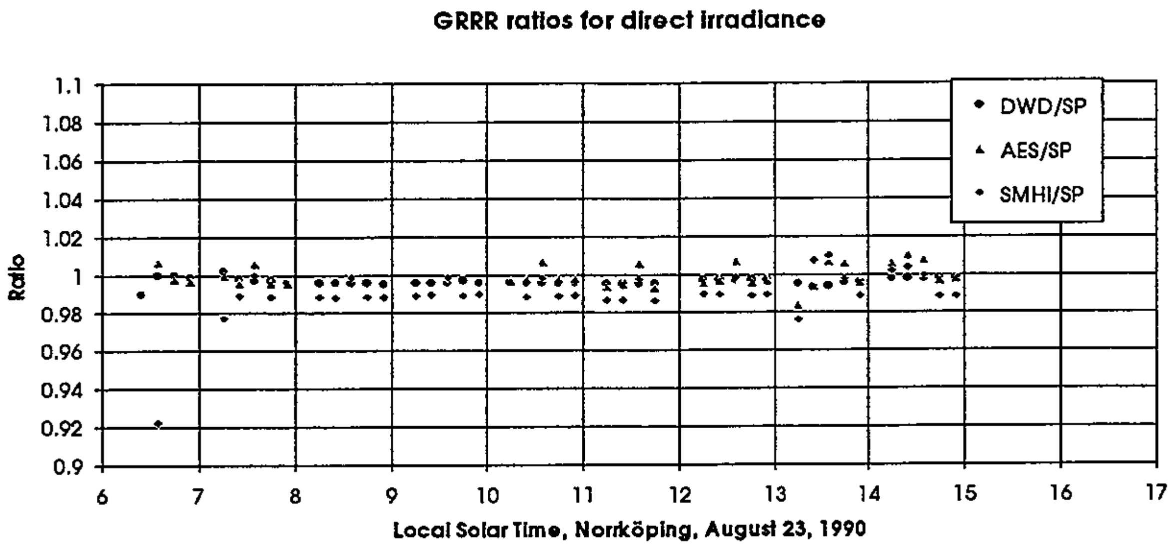

GRRR ratios for global irradiance
DWD/SP
AES/SP
SMHI/SP
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 22, 1990

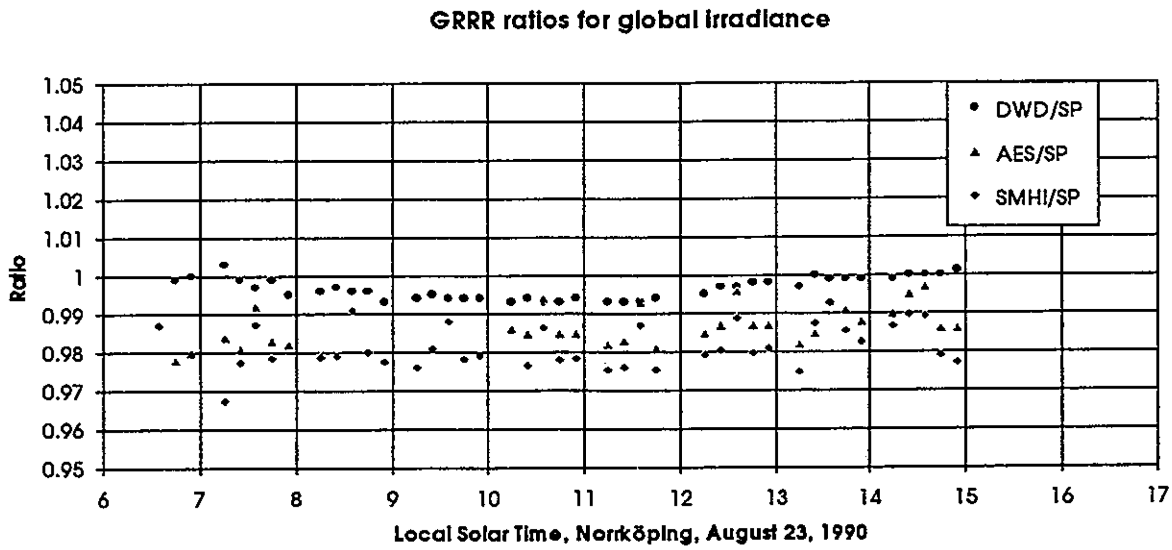

Diffuse irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 23, 1990

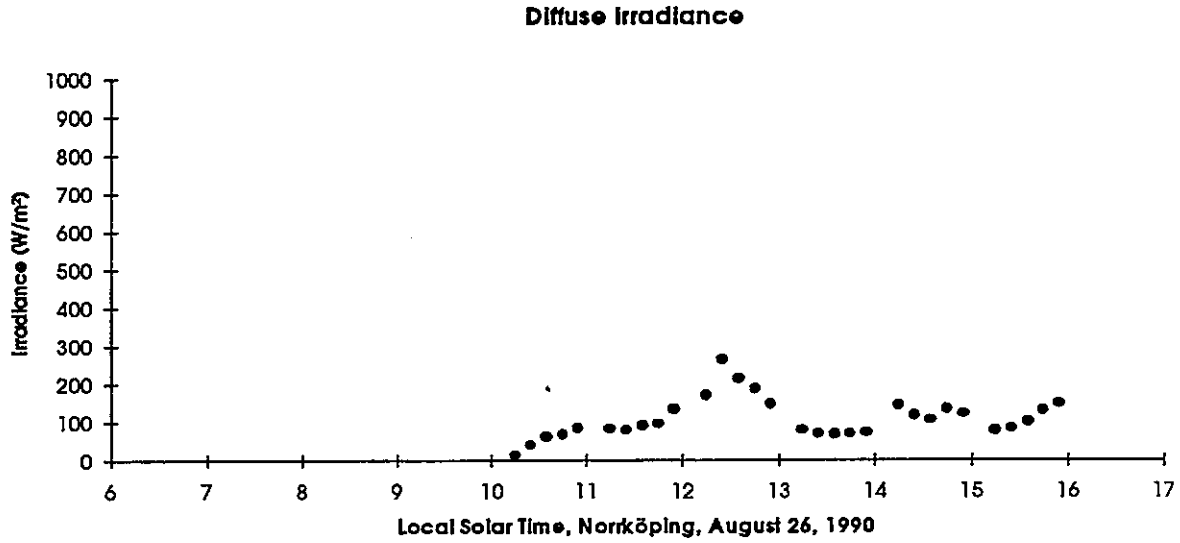

Direct irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
normal
horizontal
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 23, 1990

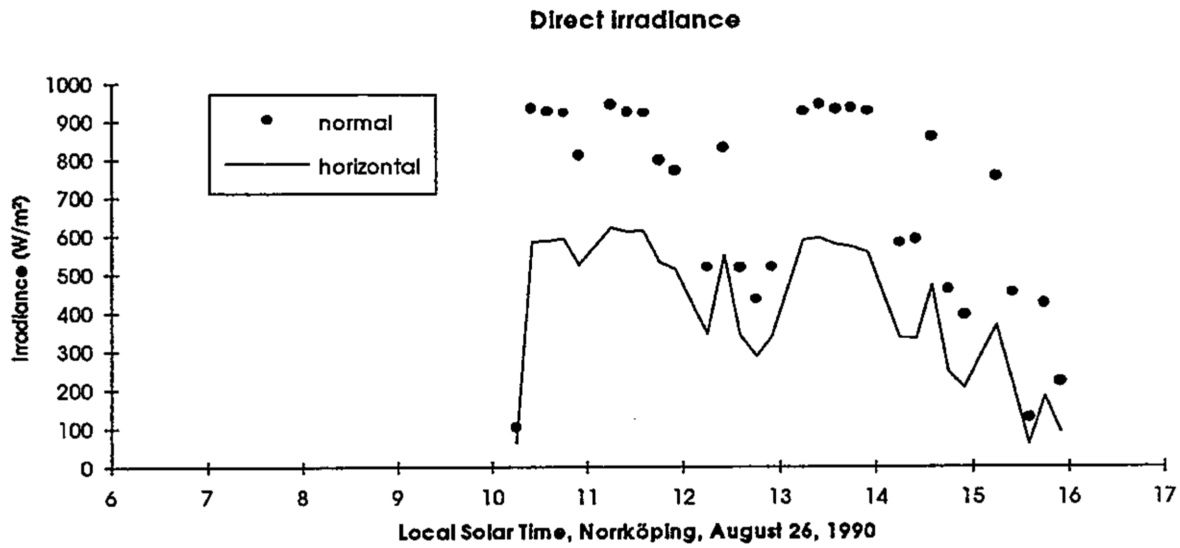

Global irradiance and temperature
Irradiance
Temperature
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
Temperature (°C)
25
20
15
10
5
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 23, 1990

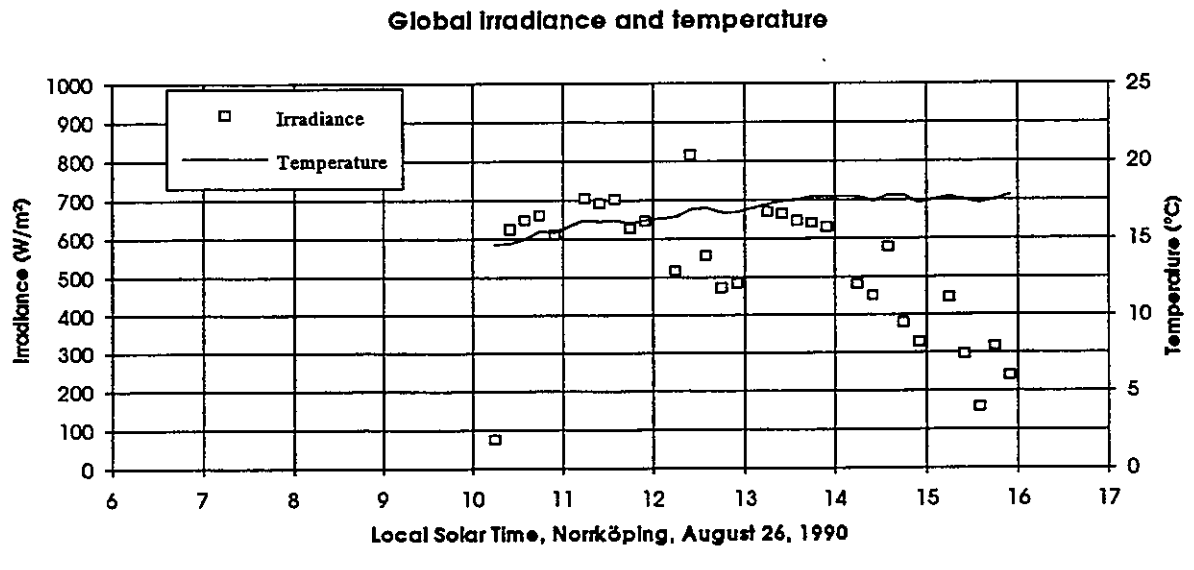

GRRR ratios for diffuse irradiance
Ratio
1.2
1.16
1.12
1.08
1.04
1
0.96
0.92
0.88
0.84
0.8
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 23, 1990
DWD/SP
AES/SP
SMHI/SP

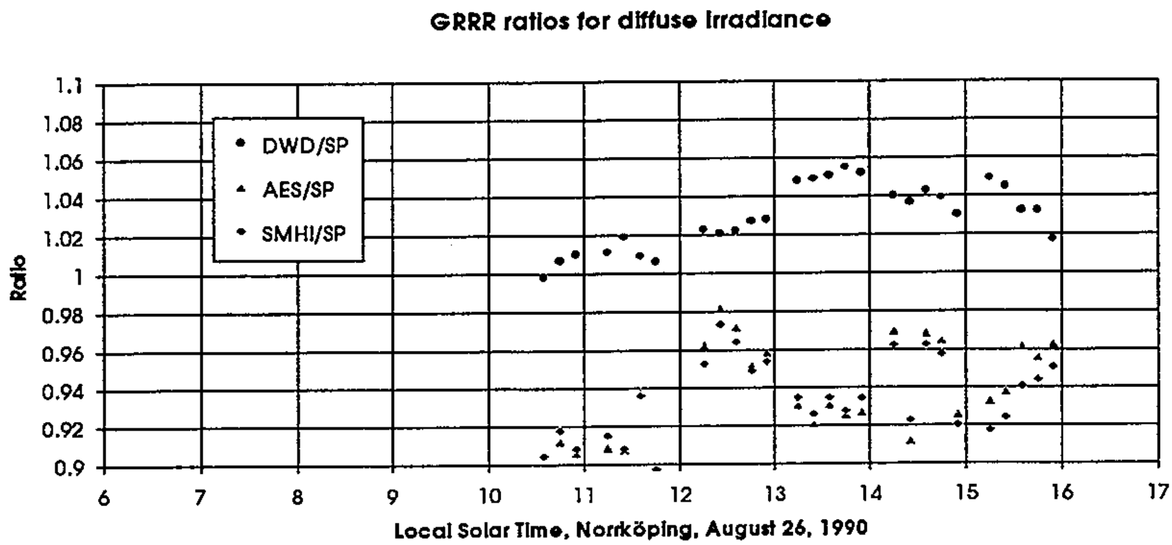

GRRR ratios for direct irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 23, 1990
DWD/SP
AES/SP
SMHI/SP

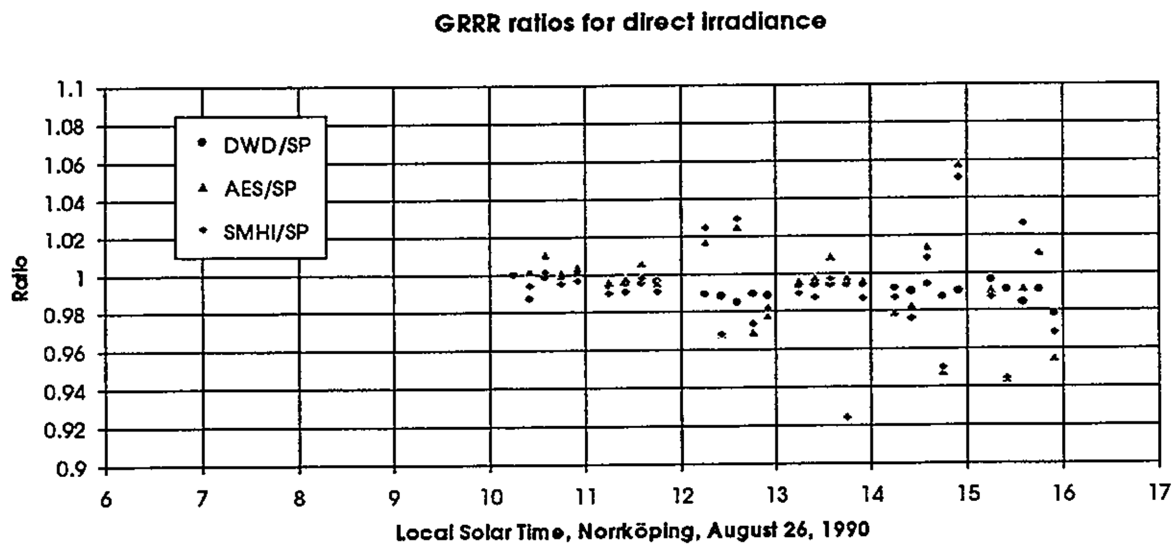

GRRR ratios for global irradiance
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 23, 1990
DWD/SP
AES/SP
SMHI/SP

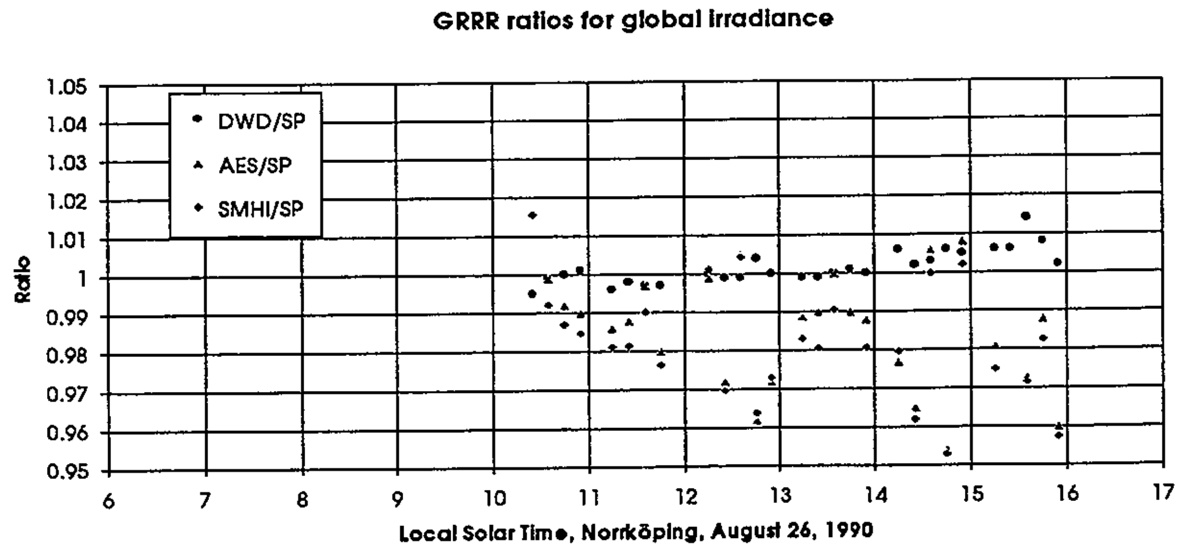

Diffuse irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 26, 1990

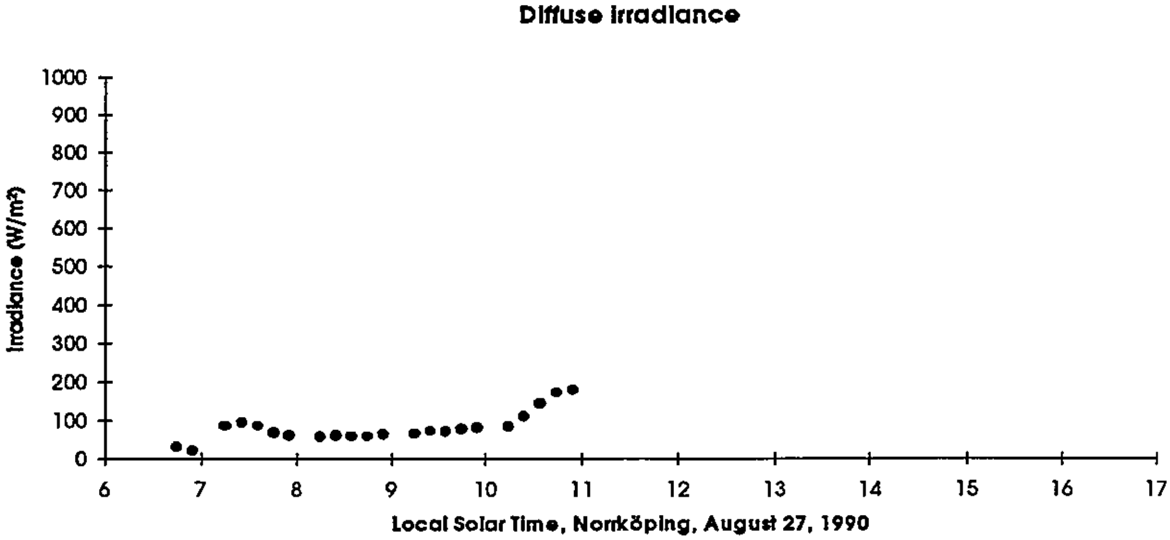

Direct irradiance
Irradiance (W/m²)
normal
horizontal
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 26, 1990

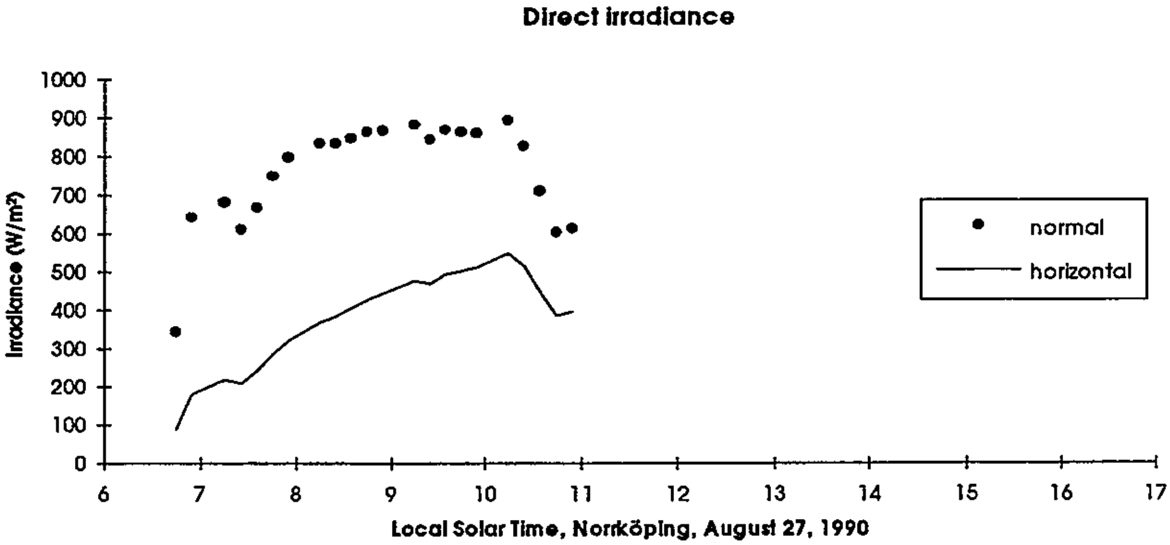

Global irradiance and temperature
Irradiance (W/m²)
Temperature (°C)
Irradiance
Temperature
1000
900
800
700
600
500
400
300
200
100
0
25
20
15
10
5
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 26, 1990

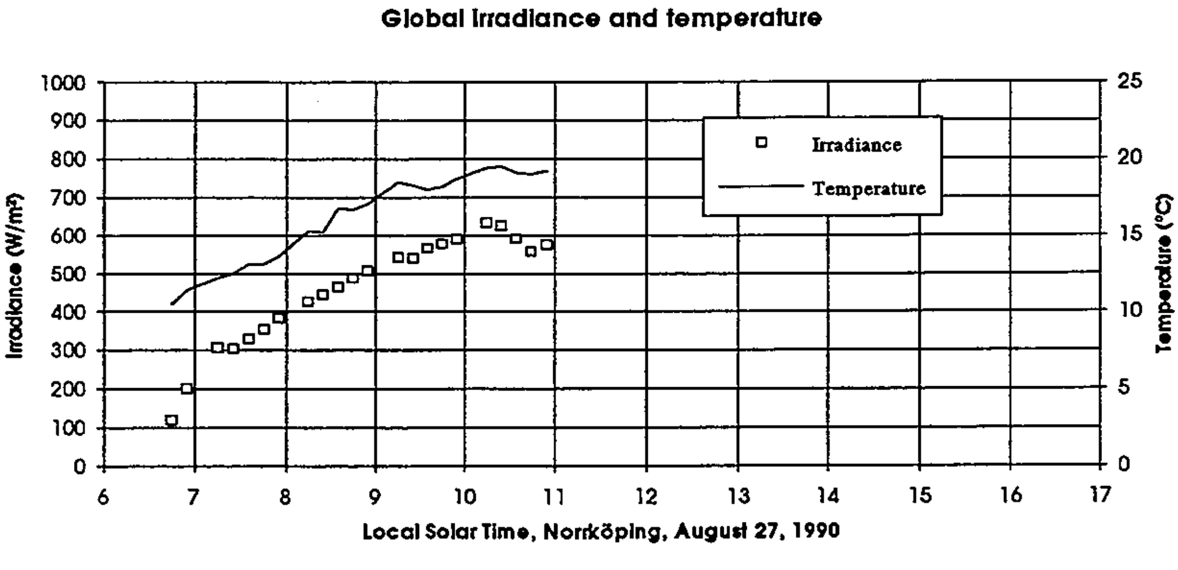

GRRR ratios for diffuse irradiance
Ratio
DWD/SP
AES/SP
SMHI/SP
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 26, 1990

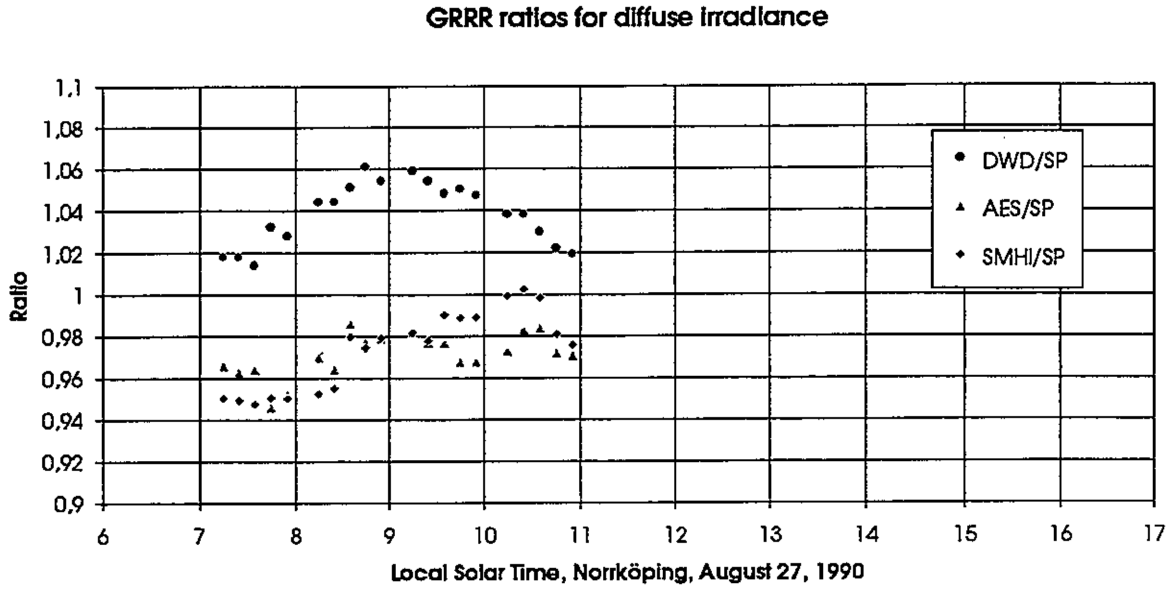

GRRR ratios for direct irradiance
Ratio
DWD/SP
AES/SP
SMHI/SP
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 26, 1990

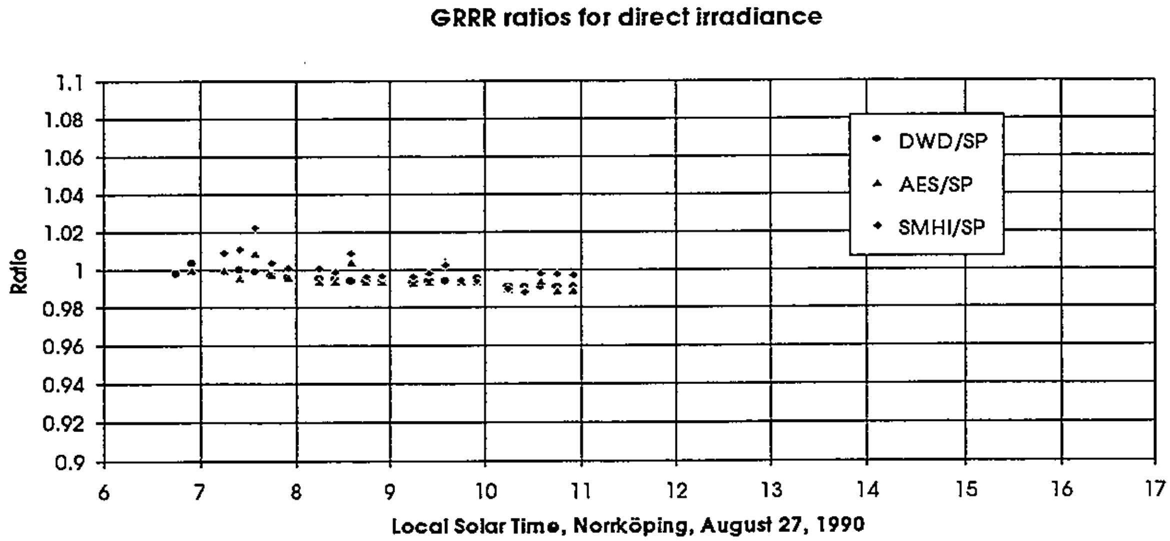

GRRR ratios for global irradiance
Ratio
DWD/SP
AES/SP
SMHI/SP
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 26, 1990

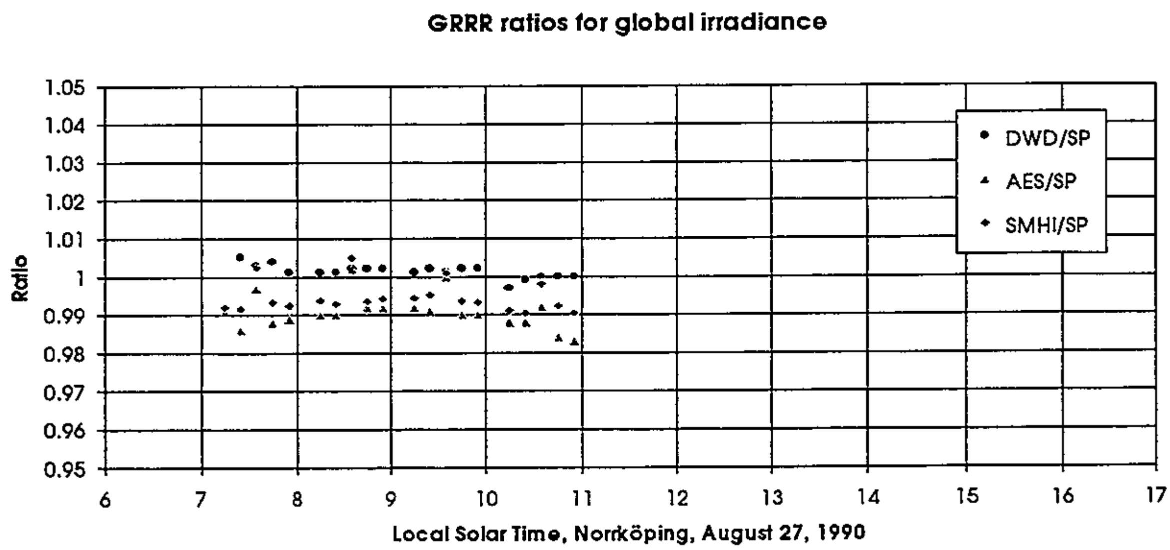

Diffuse irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 27, 1990


Direct irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
6
7
8
9
10
11
12
13
14
15
16
17
normal
horizontal
Local Solar Time, Norrköping, August 27, 1990


Global irradiance and temperature
Irradiance (W/m²)
Temperature (°C)
1000
900
800
700
600
500
400
300
200
100
0
25
20
15
10
5
0
6
7
8
9
10
11
12
13
14
15
16
17
Irradiance
Temperature
Local Solar Time, Norrköping, August 27, 1990


GRRR ratios for diffuse irradiance
Ratio
1,1
1,08
1,06
1,04
1,02
1
0,98
0,96
0,94
0,92
0,9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 27, 1990
DWD/SP
AES/SP
SMHI/SP


GRRR ratios for direct irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
6
7
8
9
10
11
12
13
14
15
16
17
Local Solar Time, Norrköping, August 27, 1990
DWD/SP
AES/SP
SMHI/SP


GRRR ratios for global irradiance
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
6
7
8
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10
11
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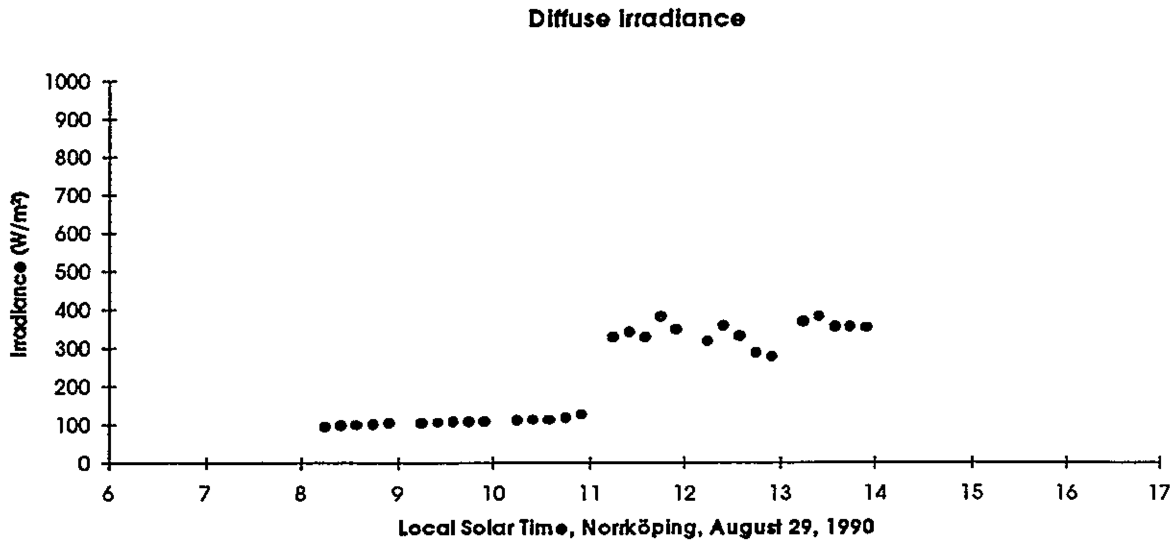
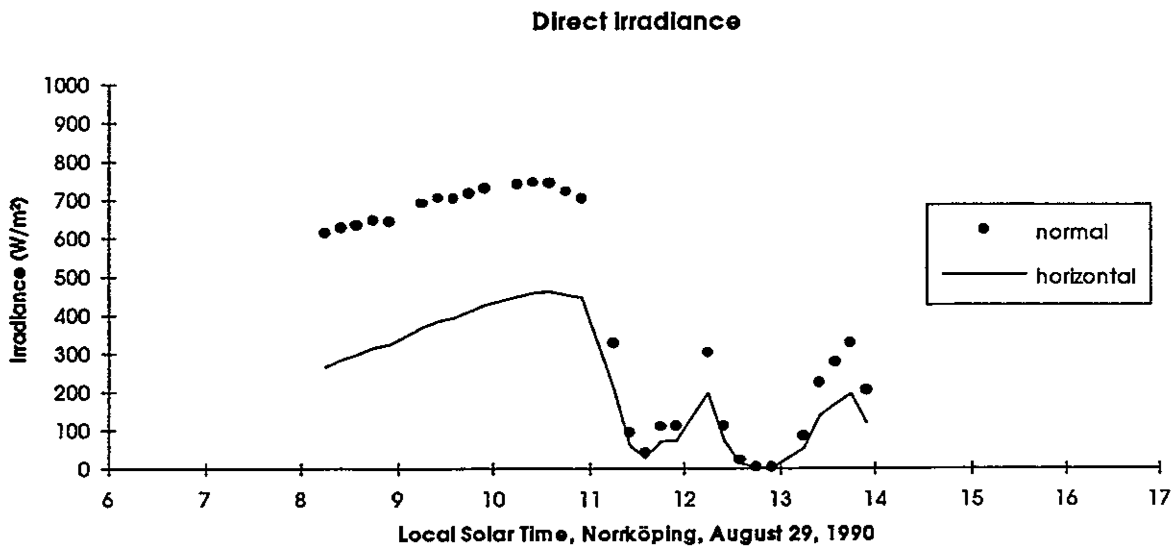
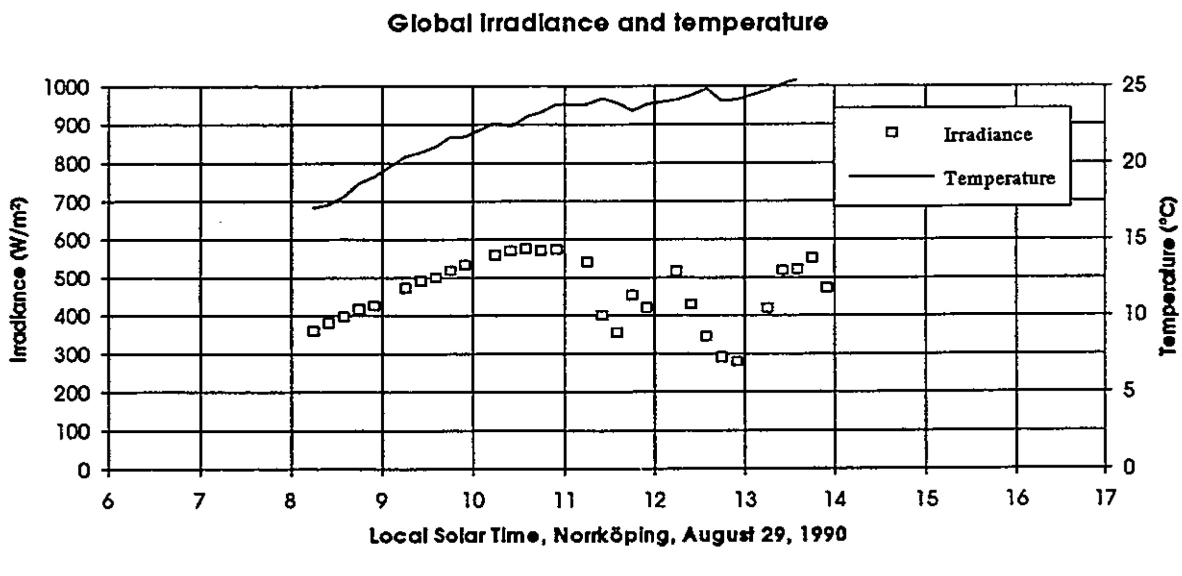
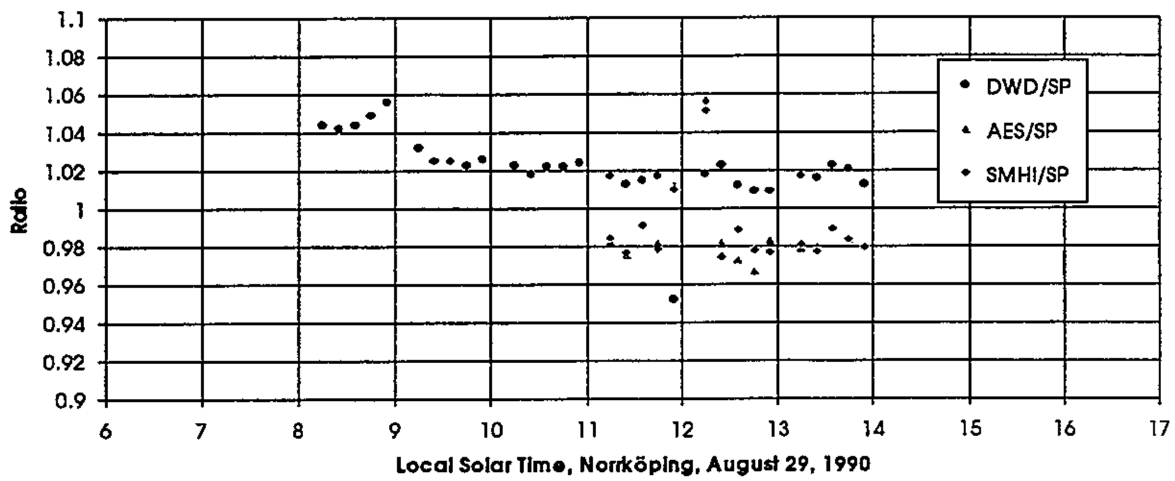
13
14
15
16
17
Local Solar Time, Norrköping, August 27, 1990
DWD/SP
AES/SP
SMHI/SP


Diffuse irradiance
Irradiance (W/m²)
Local Solar Time, Norrköping, August 29, 1990

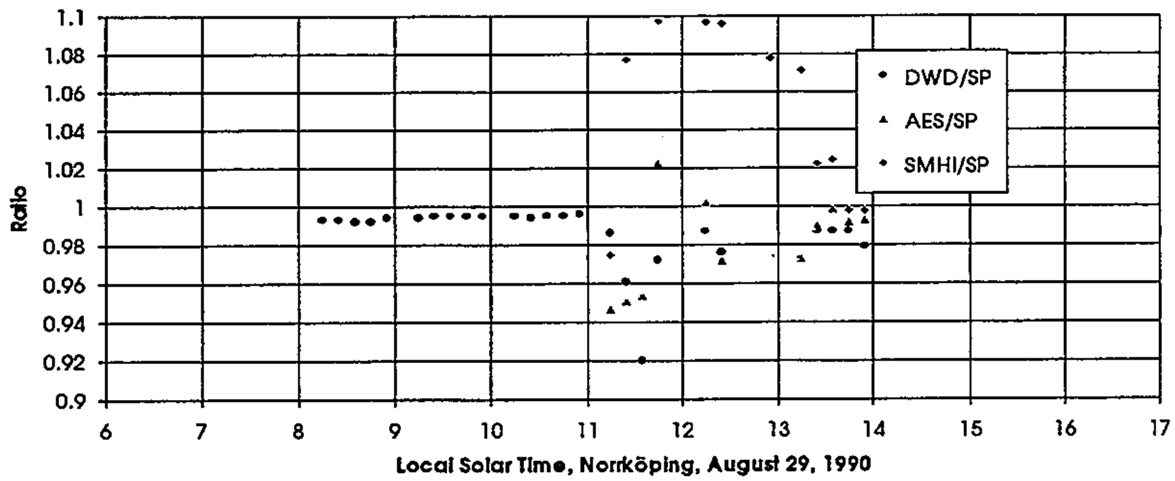

Direct irradiance
Irradiance (W/m²)
normal
horizontal
Local Solar Time, Norrköping, August 29, 1990


Global irradiance and temperature
Irradiance (W/m²)
Temperature (°C)
Irradiance
Temperature
Local Solar Time, Norrköping, August 29, 1990

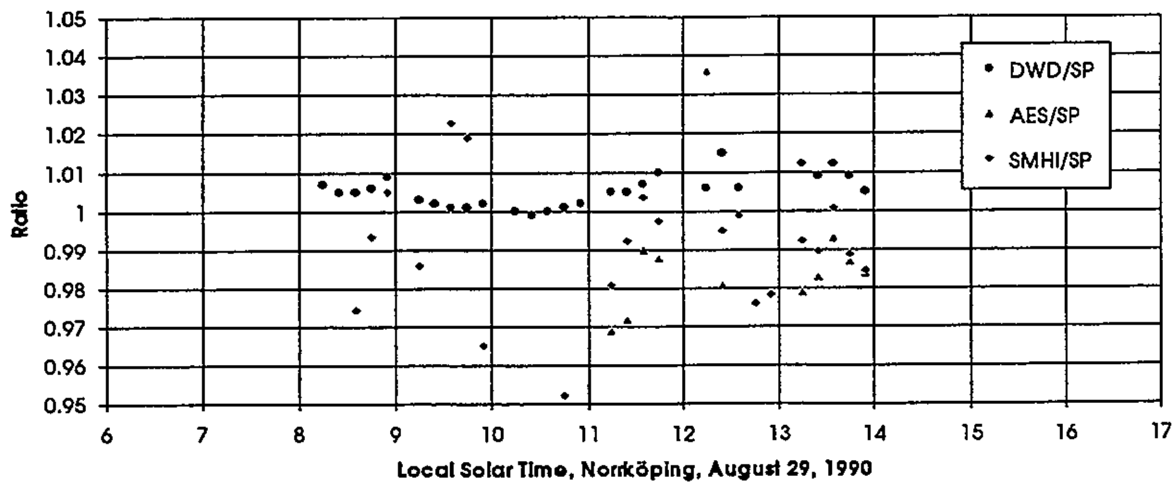
GRRR ratios for diffuse irradiance

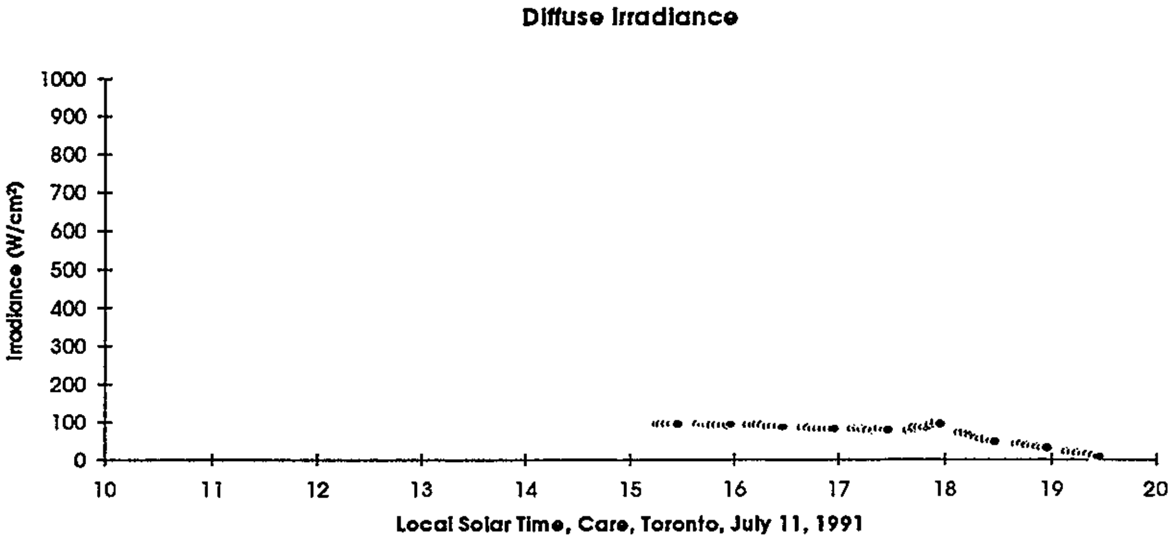


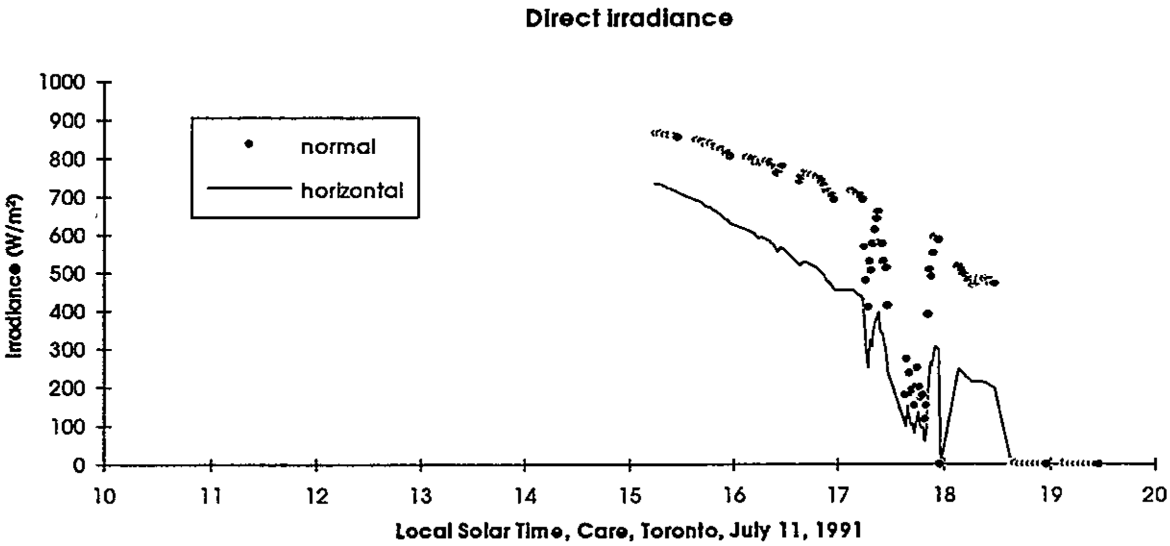
GRRR ratios for direct irradiance

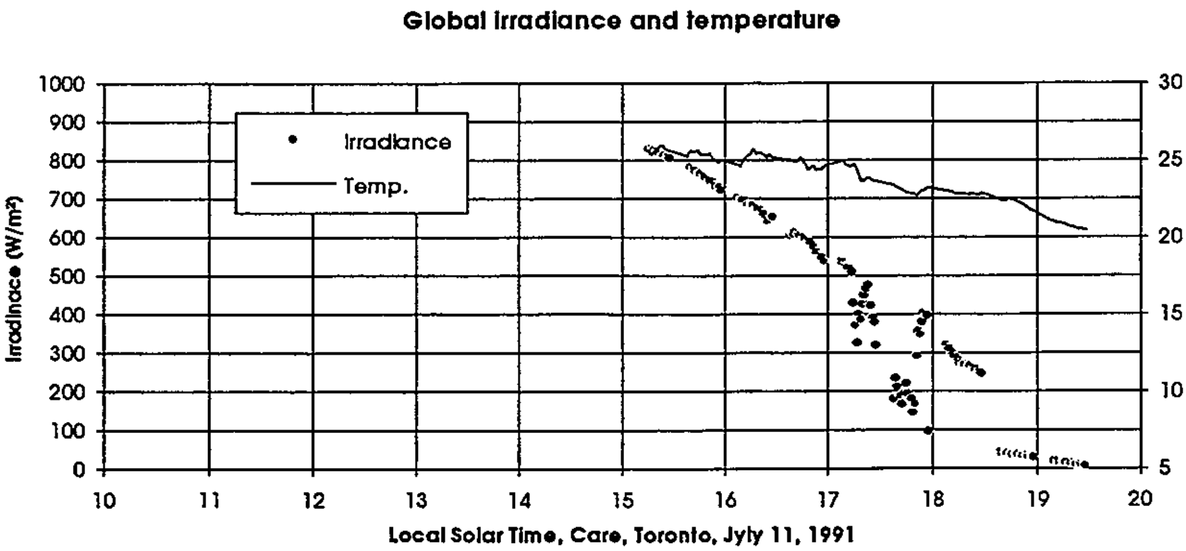


GRRR ratios for global irradiance




Diffuse Irradiance
Irradiance (W/cm²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 11, 1991


Direct irradiance
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
normal
horizontal
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 11, 1991


Global irradiance and temperature
Irradinace (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
Irradiance
Temp.
30
25
20
15
10
5
10
11
12
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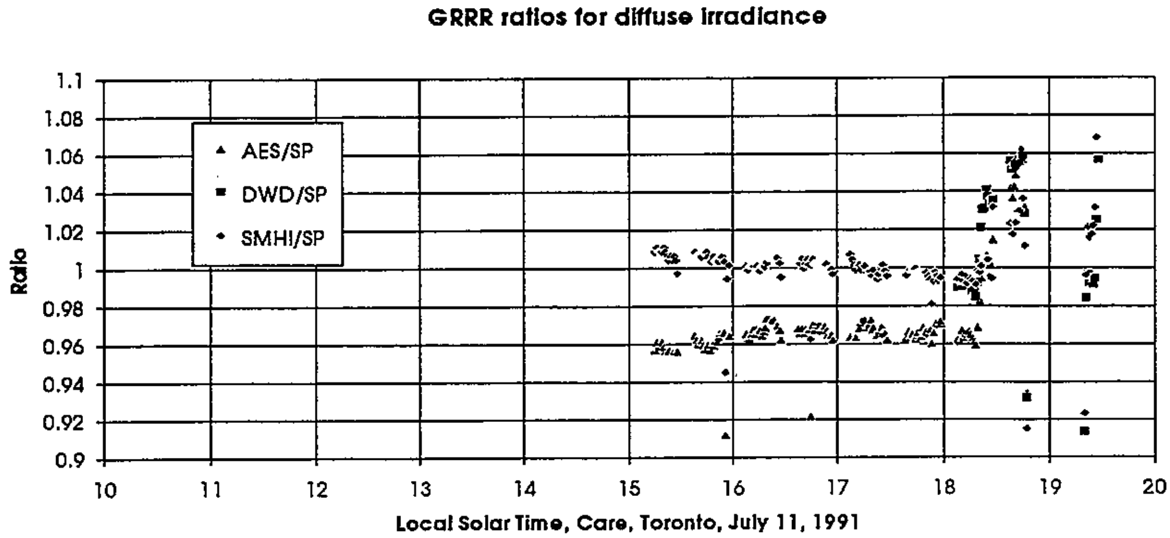
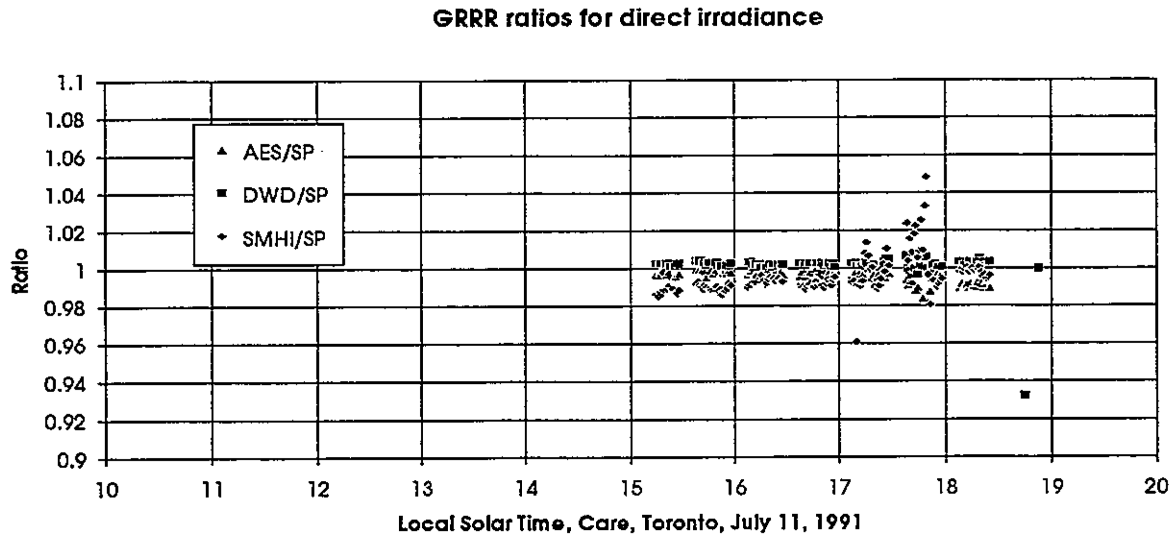
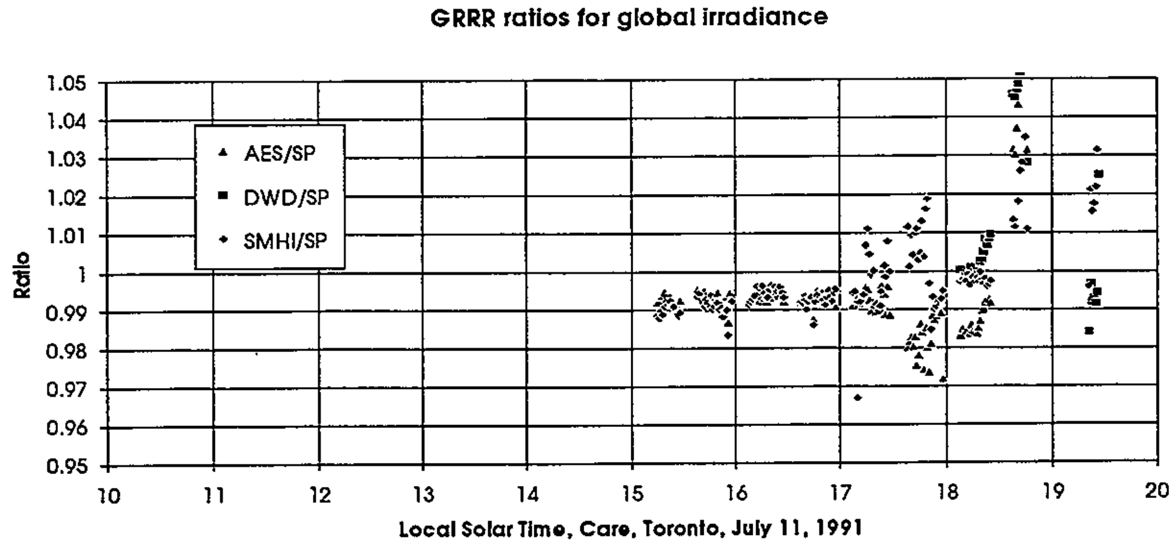
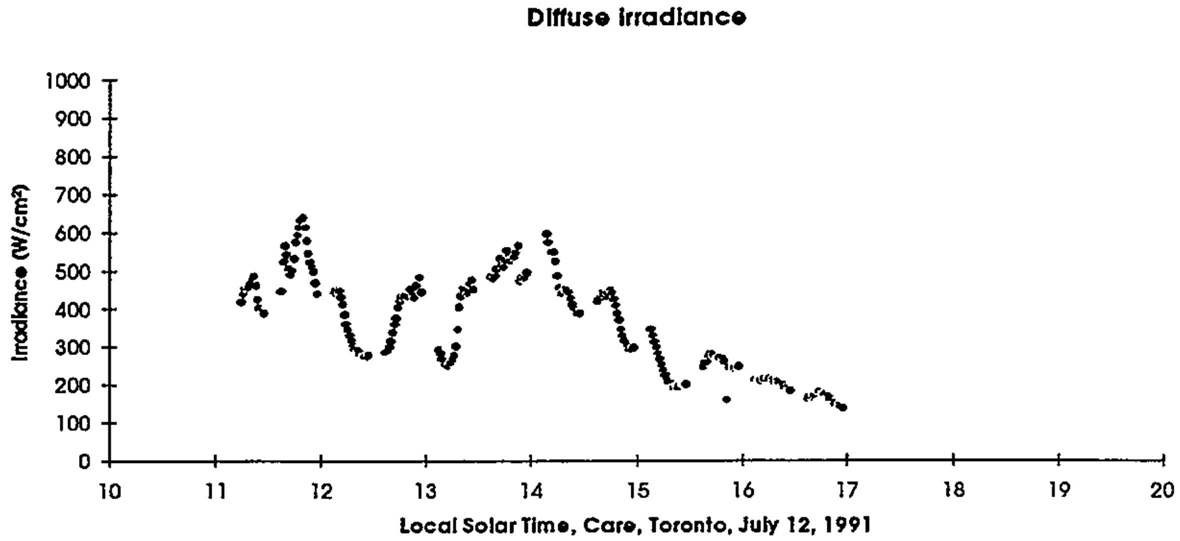
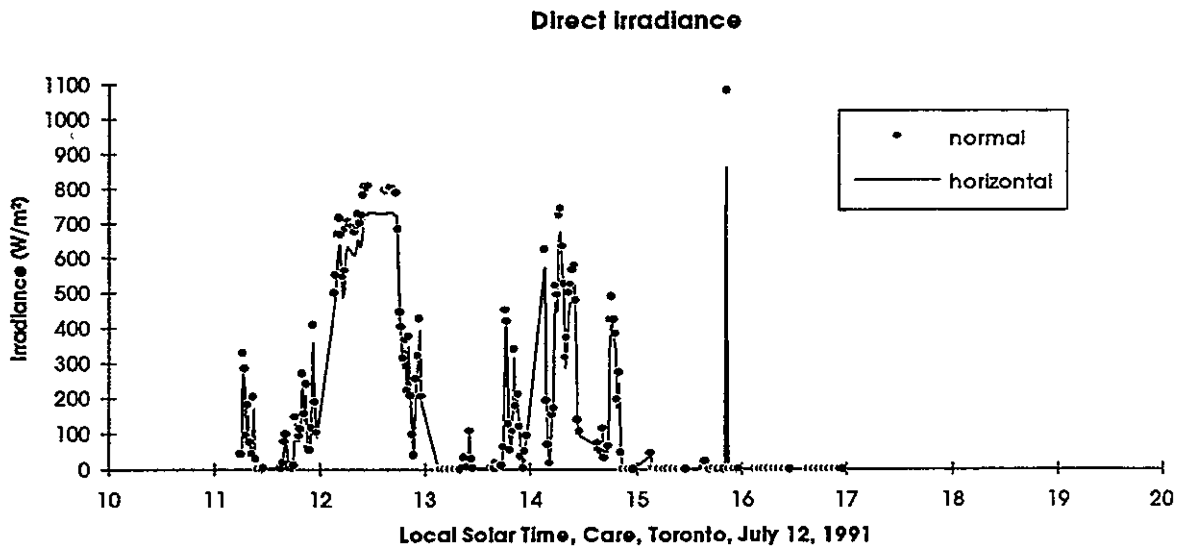
19
20
Local Solar Time, Care, Toronto, Jyly 11, 1991

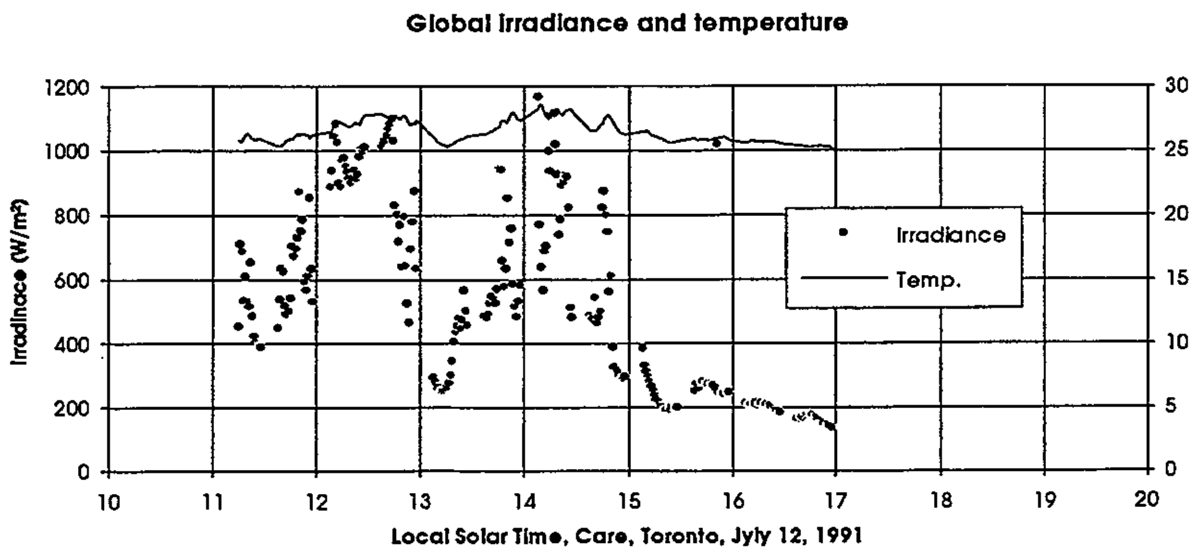

GRRR ratios for diffuse irradiance
AES/SP
DWD/SP
SMHI/SP
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 11, 1991


GRRR ratios for direct irradiance
AES/SP
DWD/SP
SMHI/SP
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 11, 1991

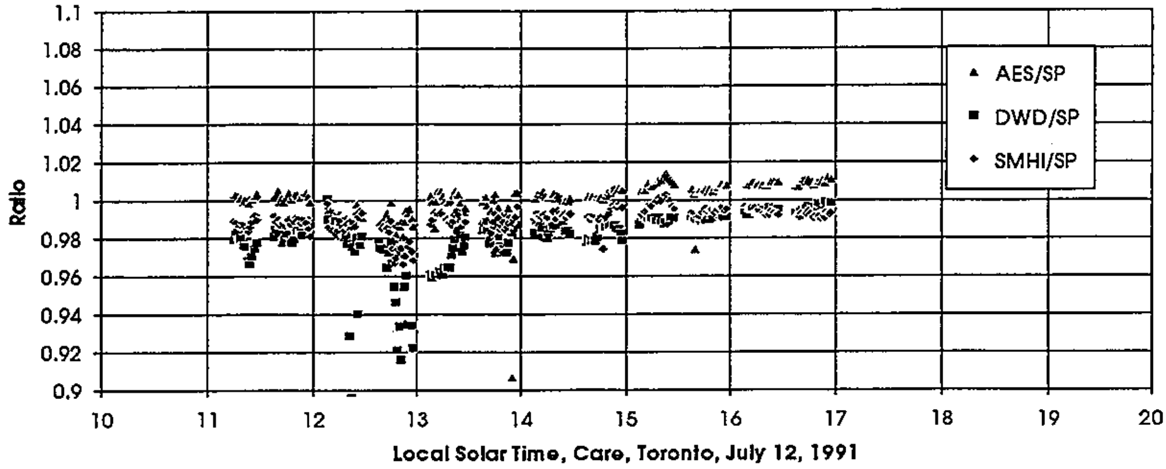

GRRR ratios for global irradiance
AES/SP
DWD/SP
SMHI/SP
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 11, 1991


Diffuse irradiance
1000
900
800
700
600
500
400
300
200
100
0
Irradiance (W/cm²)
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 12, 1991

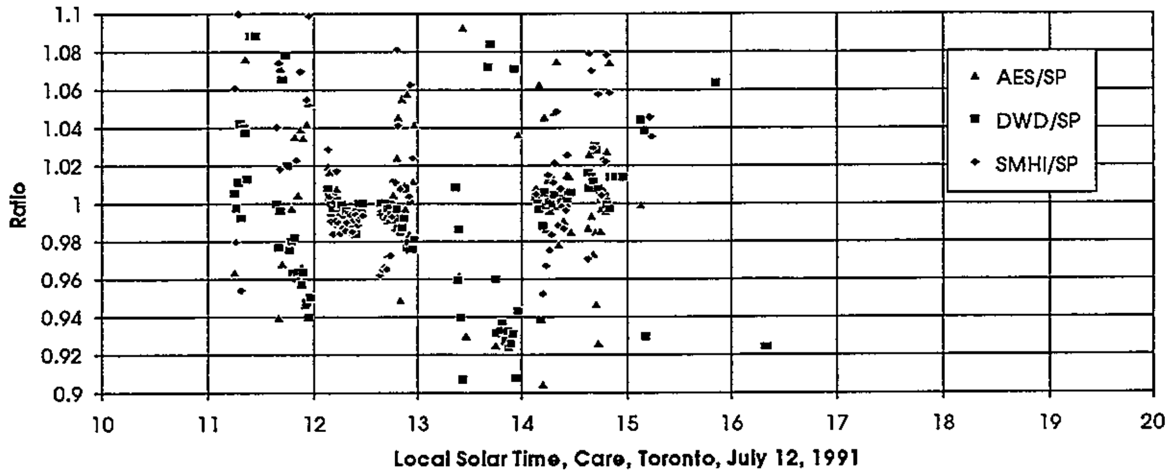

Direct irradiance
1100
1000
900
800
700
600
500
400
300
200
100
0
Irradiance (W/m²)
normal
horizontal
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 12, 1991


Global irradiance and temperature
1200
1000
800
600
400
200
0
Irradiance (W/m²)
30
25
20
15
10
5
0
Irradiance
Temp.
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 12, 1991

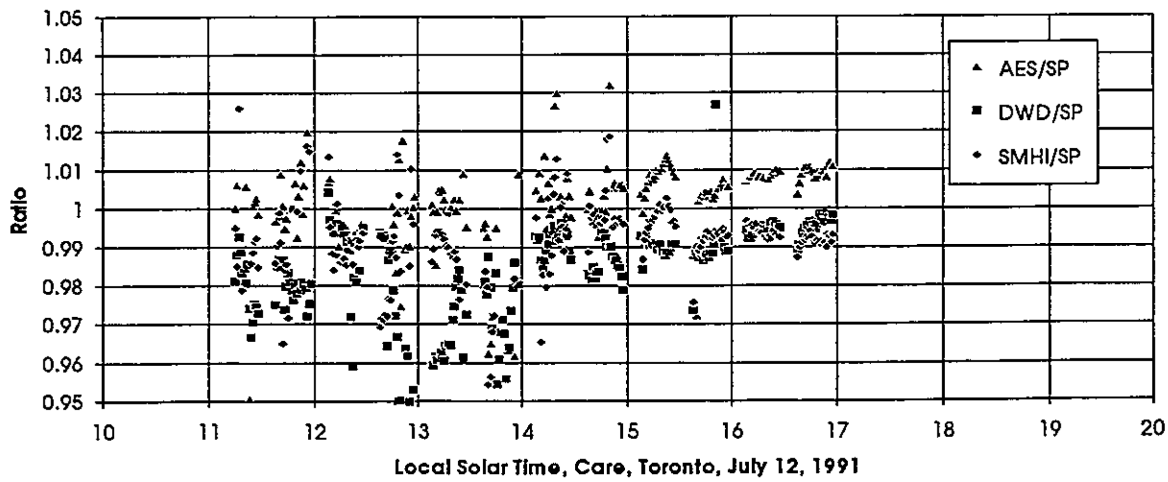
GRRR ratios for diffuse irradiance

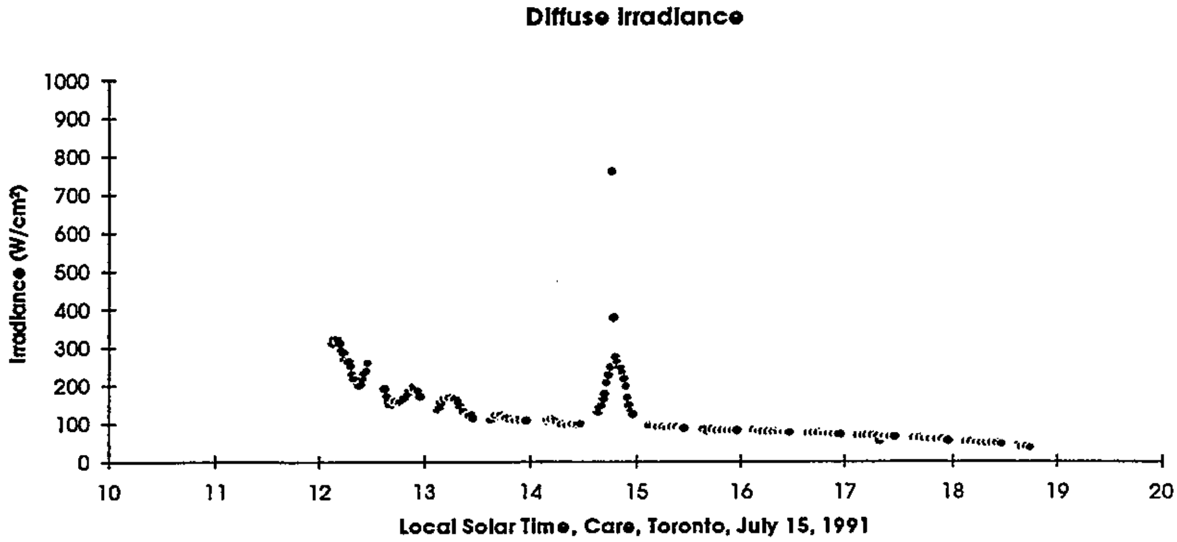


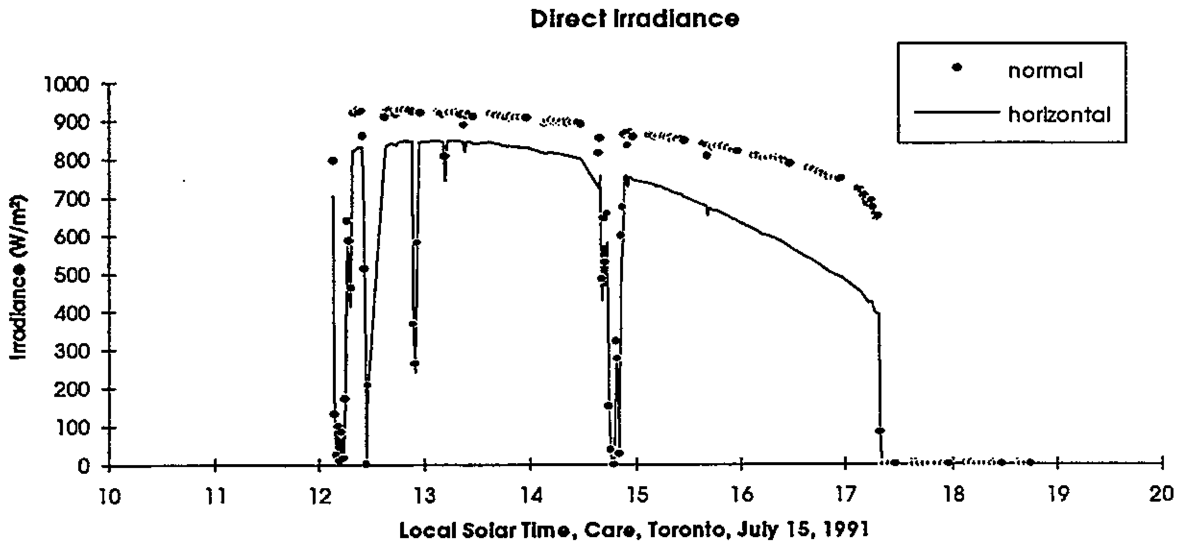
GRRR ratios for direct irradiance

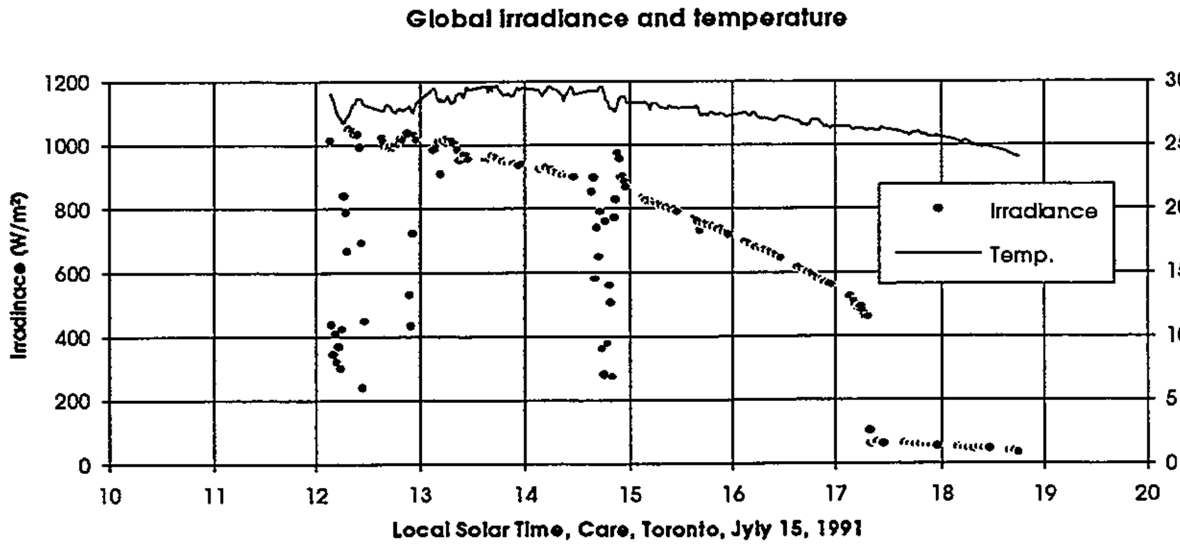


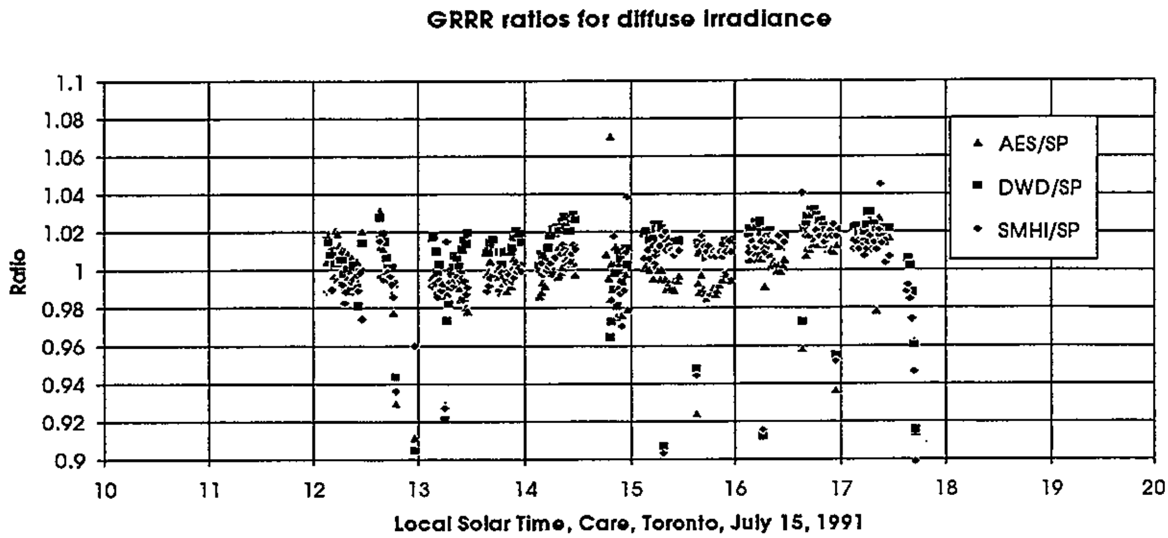
GRRR ratios for global irradiance

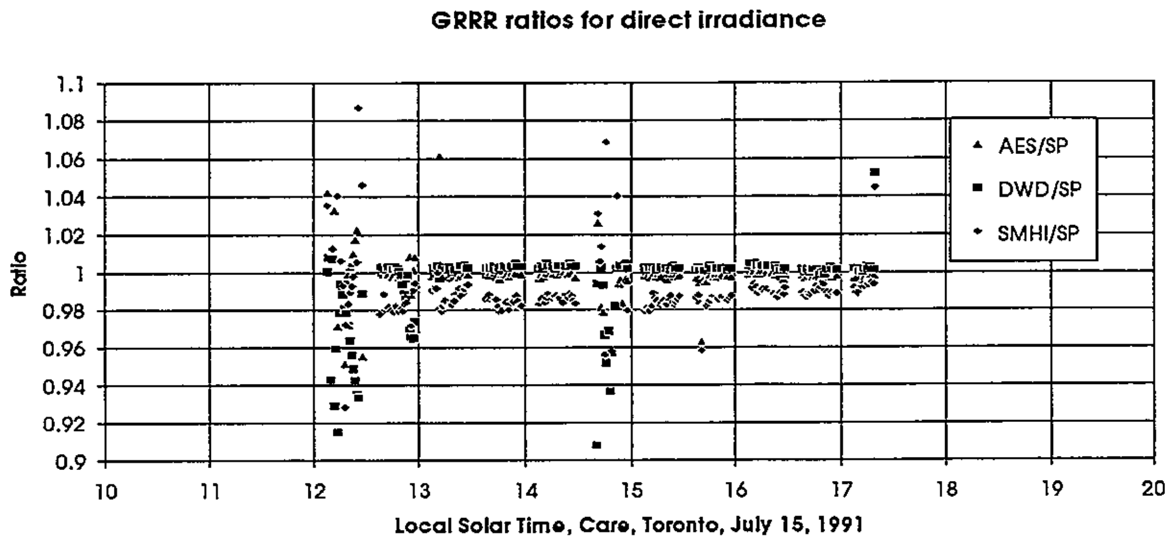


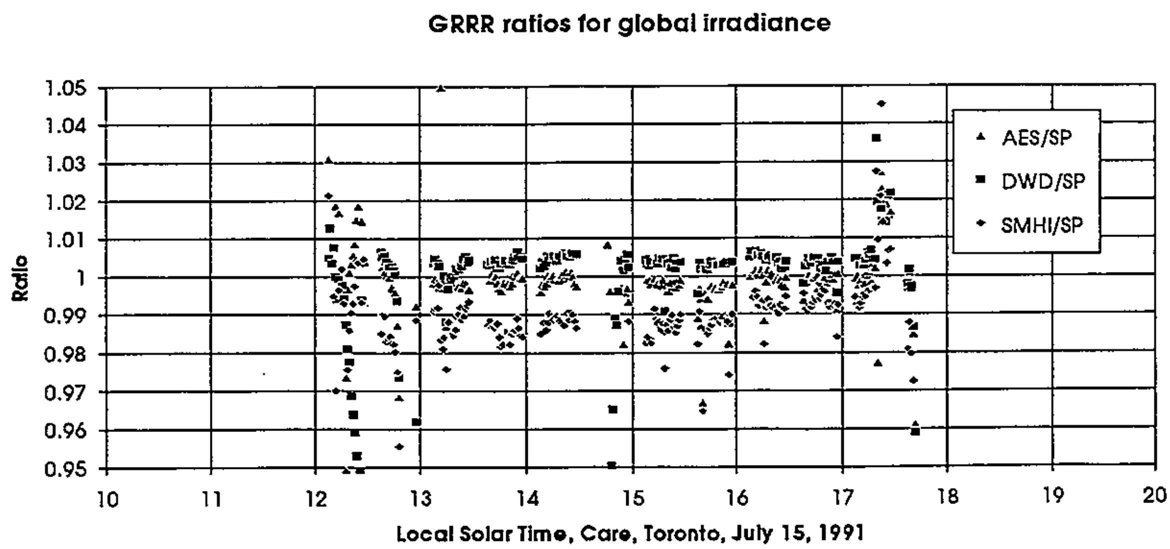

Diffuse Irradiance
Irradiance (W/cm²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 15, 1991

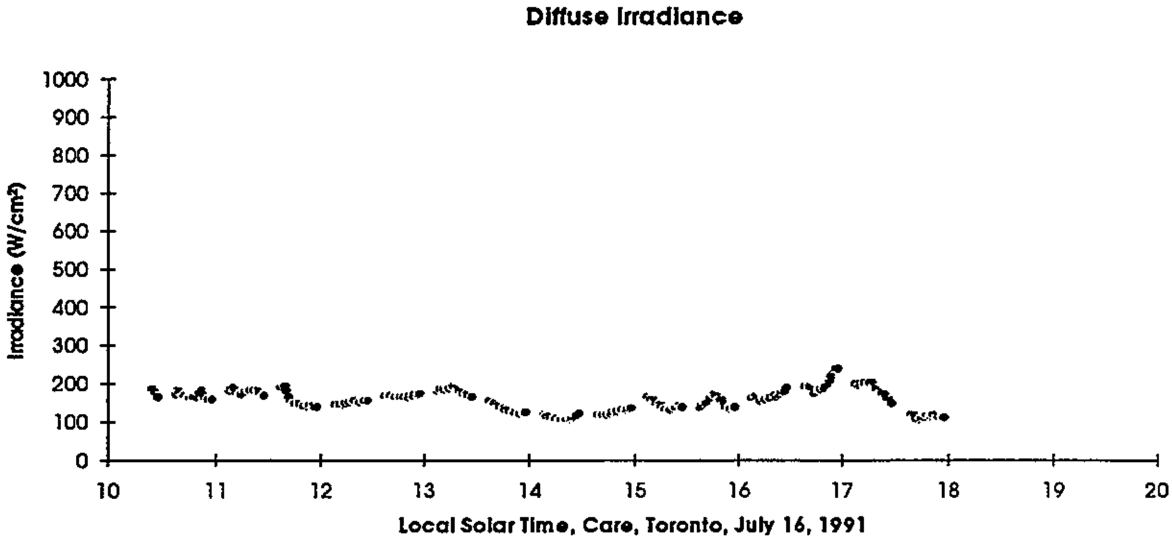

Direct Irradiance
normal
horizontal
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 15, 1991

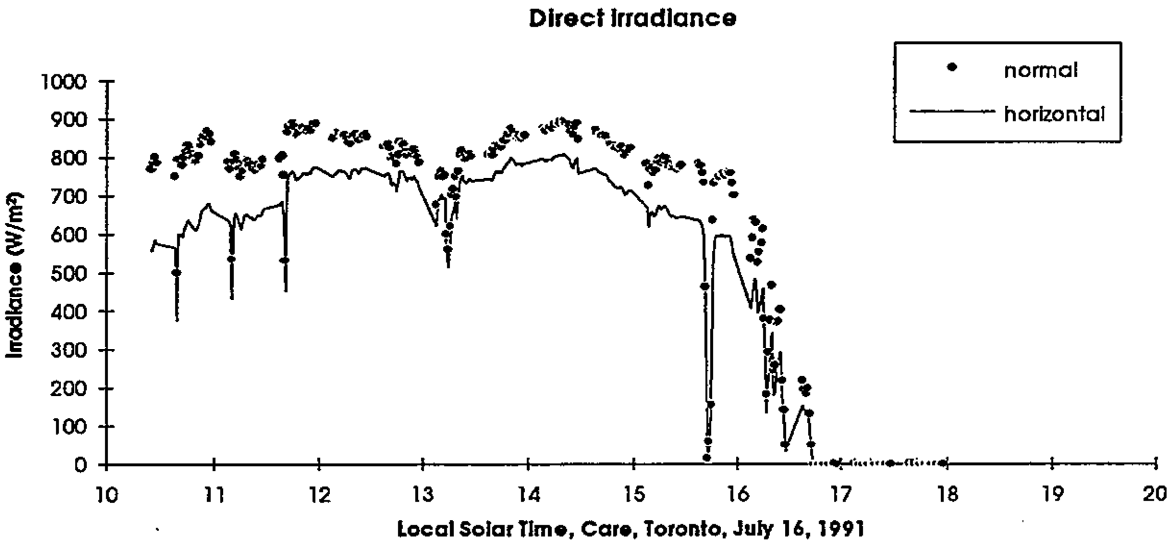

Global irradiance and temperature
Irradince (W/m²)
1200
1000
800
600
400
200
0
30
25
20
15
10
5
0
Irradiance
Temp.
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 15, 1991

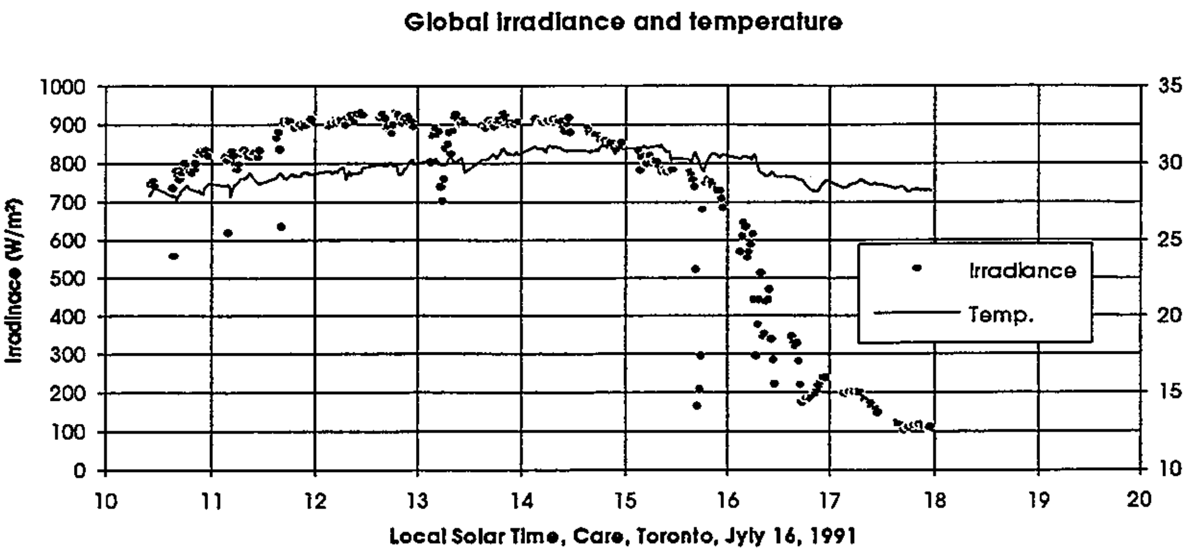

GRRR ratios for diffuse irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
12
13
14
15
16
17
18
19
20
AES/SP
DWD/SP
SMHI/SP
Local Solar Time, Care, Toronto, July 15, 1991

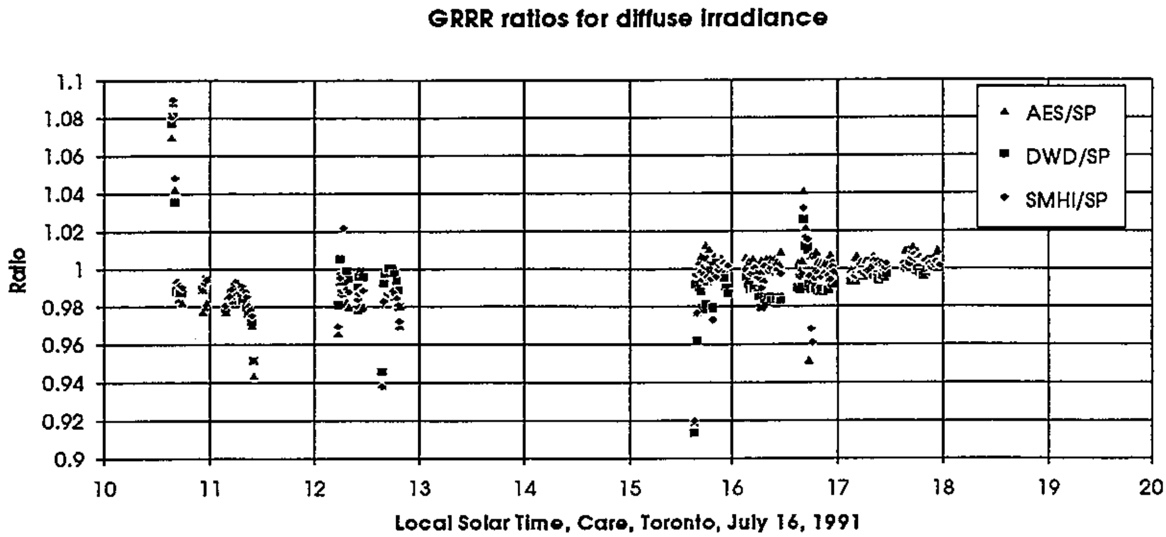

GRRR ratios for direct irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
12
13
14
15
16
17
18
19
20
AES/SP
DWD/SP
SMHI/SP
Local Solar Time, Care, Toronto, July 15, 1991

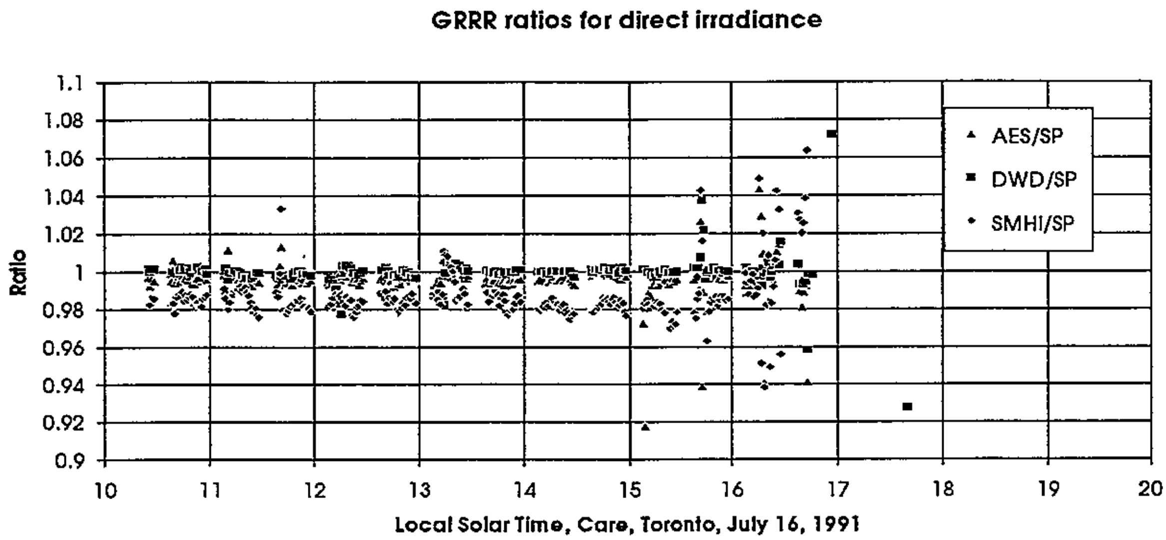

GRRR ratios for global irradiance
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
10
11
12
13
14
15
16
17
18
19
20
AES/SP
DWD/SP
SMHI/SP
Local Solar Time, Care, Toronto, July 15, 1991


Diffuse Irradiance
Irradiance (W/cm²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 16, 1991


Direct Irradiance
normal
horizontal
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 16, 1991


Global irradiance and temperature
Irradinace (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
35
30
25
20
15
10
Irradiance
Temp.
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 16, 1991


GRRR ratios for diffuse irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 16, 1991
AES/SP
DWD/SP
SMHI/SP


GRRR ratios for direct irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
12
13
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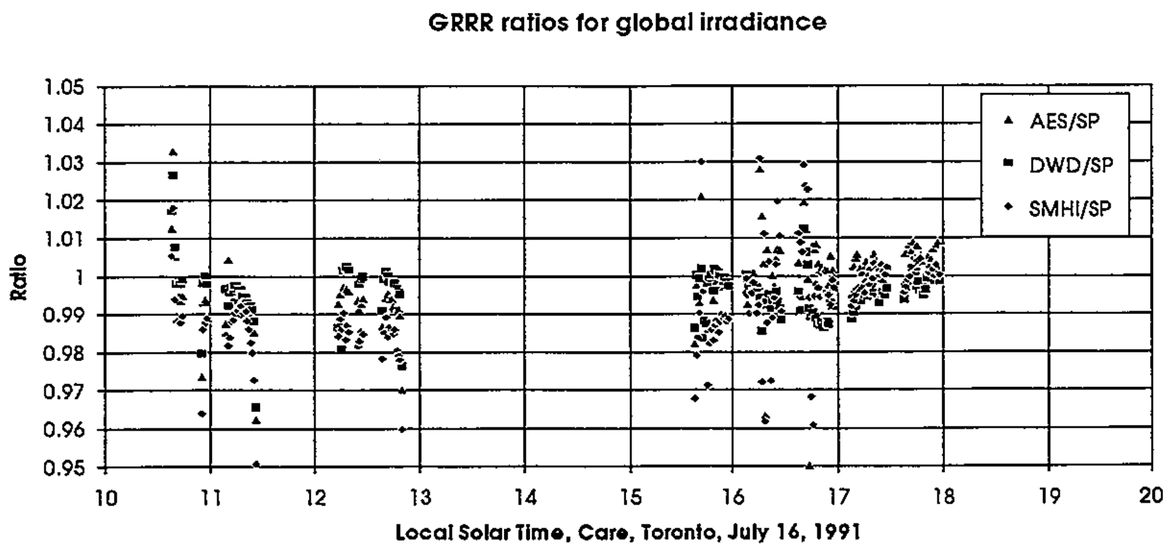
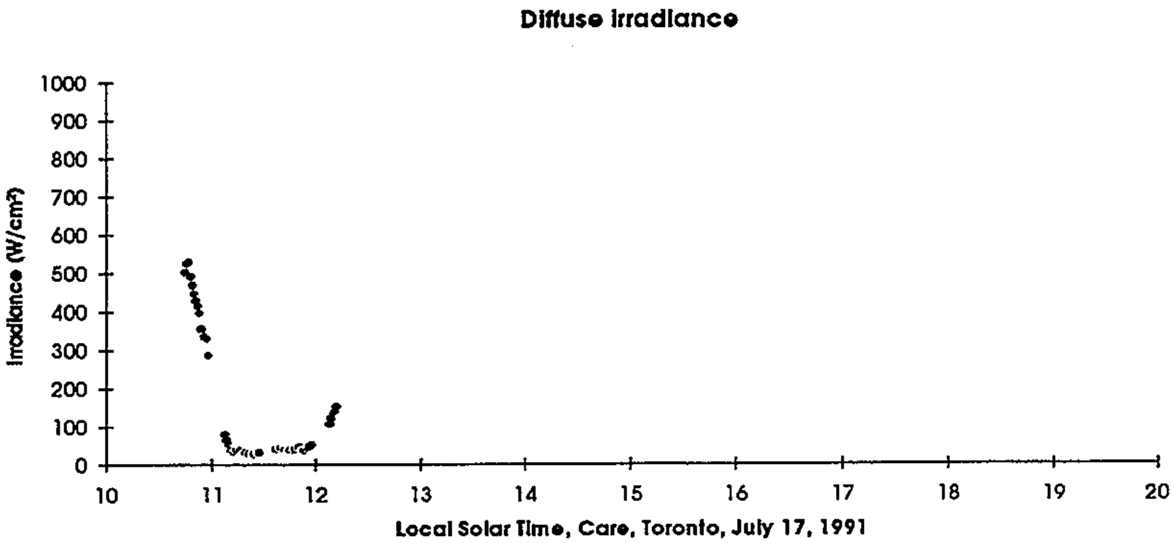
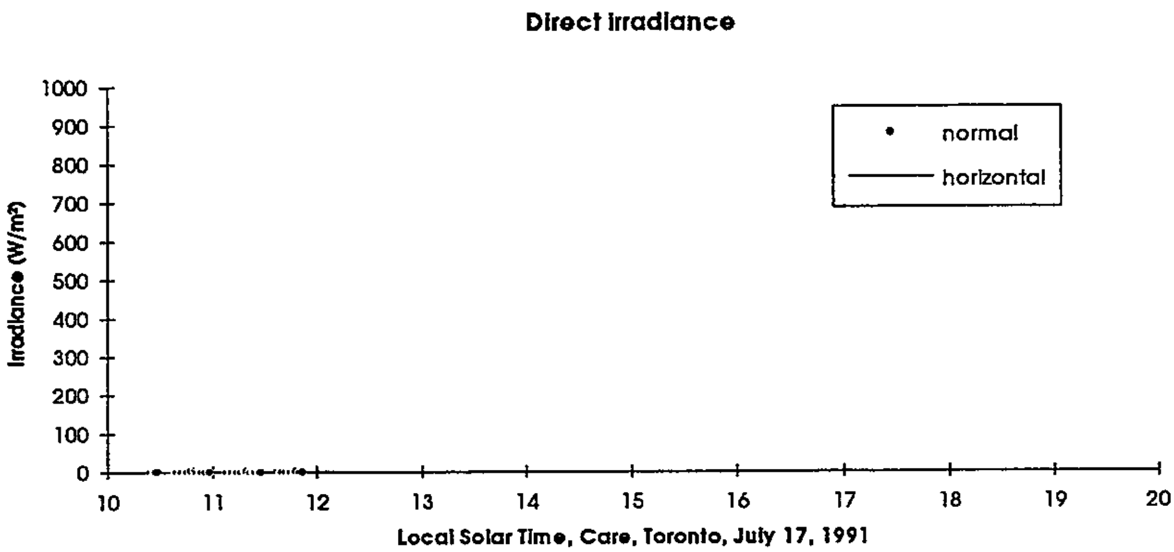
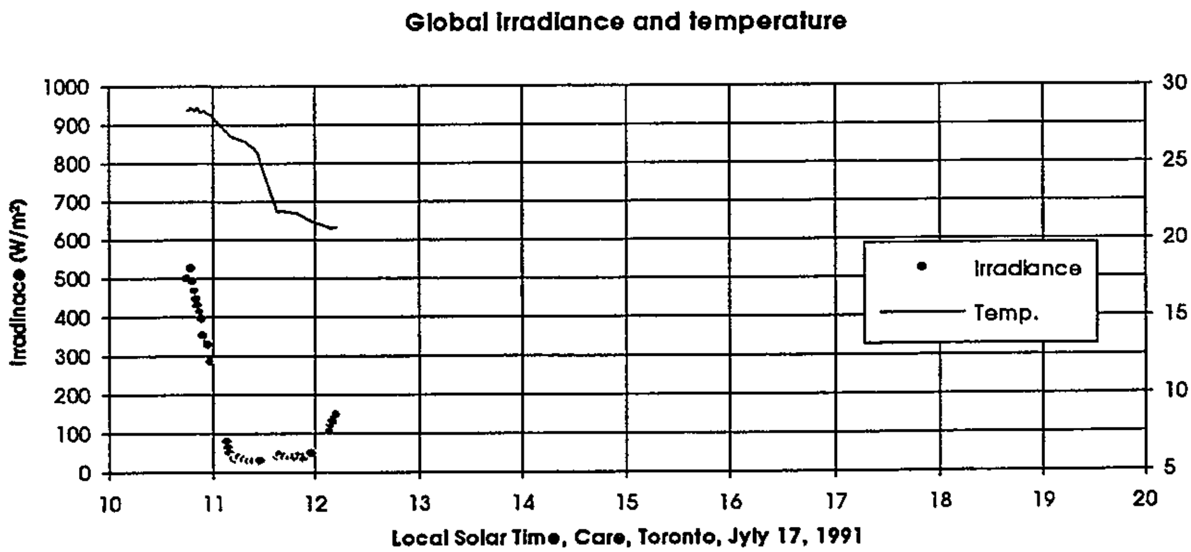
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 16, 1991
AES/SP
DWD/SP
SMHI/SP

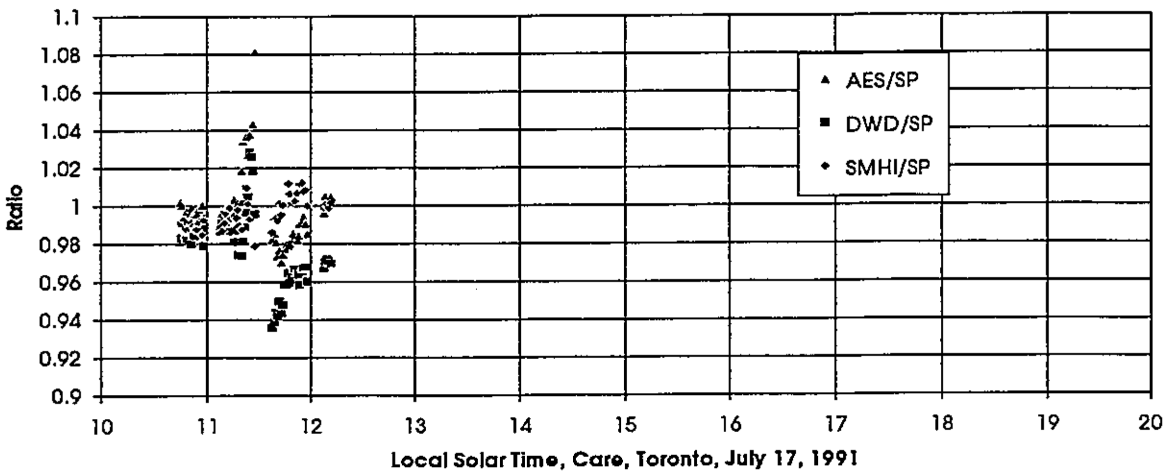

GRRR ratios for global irradiance
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 16, 1991
AES/SP
DWD/SP
SMHI/SP


Diffuse irradiance
Irradiance (W/cm²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 17, 1991

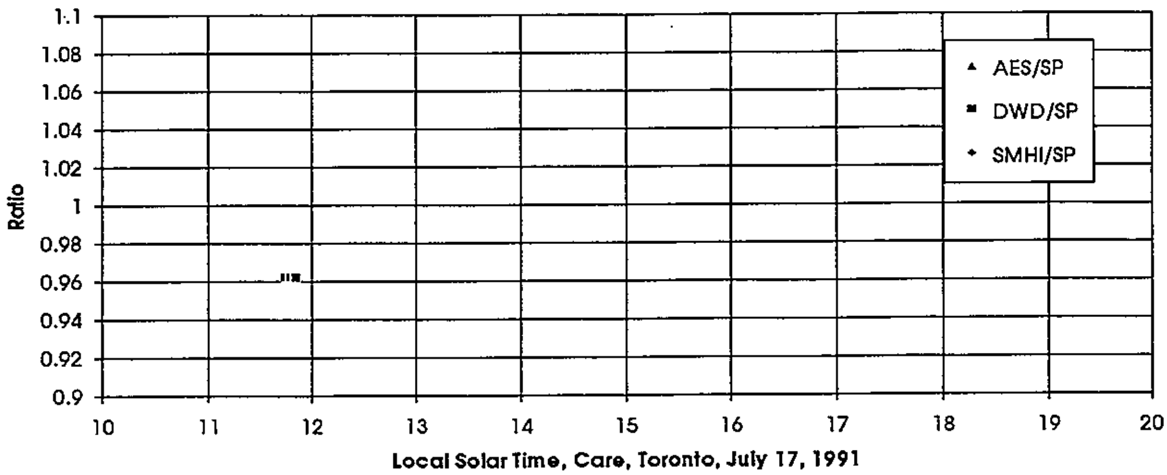

Direct irradiance
Irradiance (W/m²)
normal
horizontal
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 17, 1991


Global irradiance and temperature
Irradinace (W/m²)
Irradiance
Temp.
1000
900
800
700
600
500
400
300
200
100
0
30
25
20
15
10
5
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 17, 1991

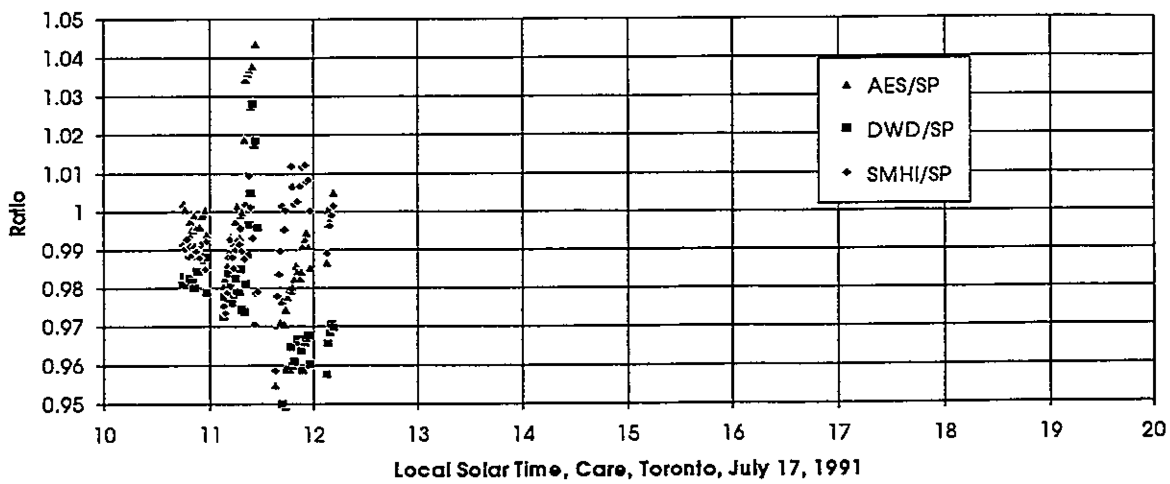
GRRR ratios for diffuse irradiance

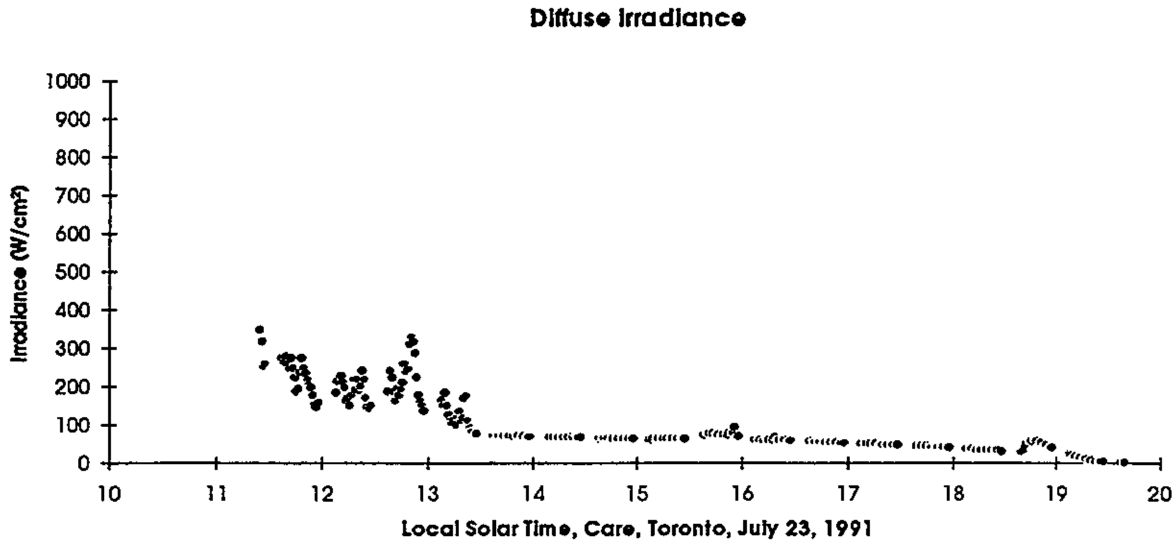


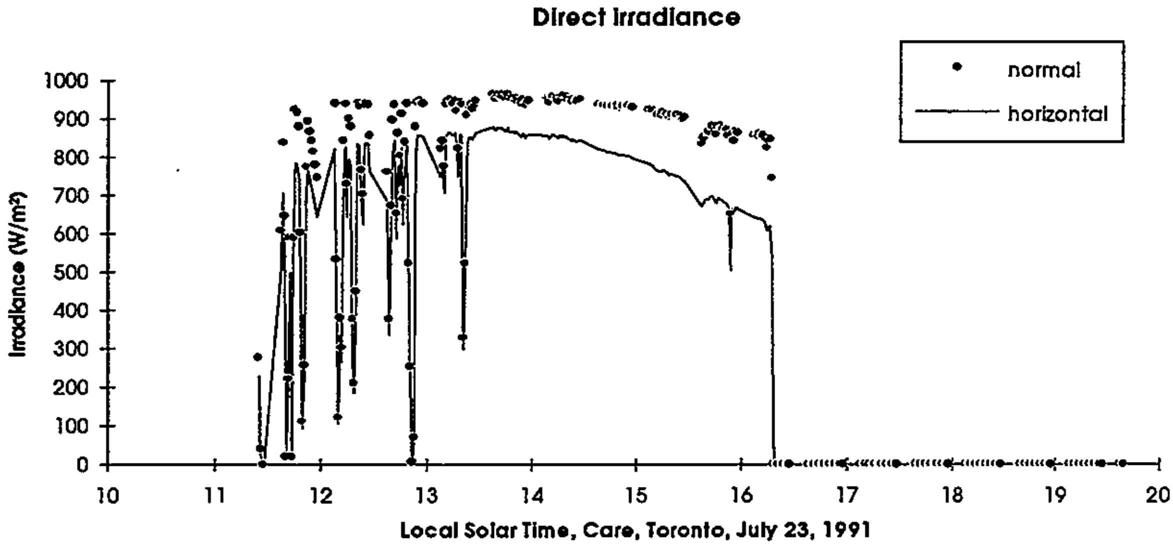
GRRR ratios for direct irradiance

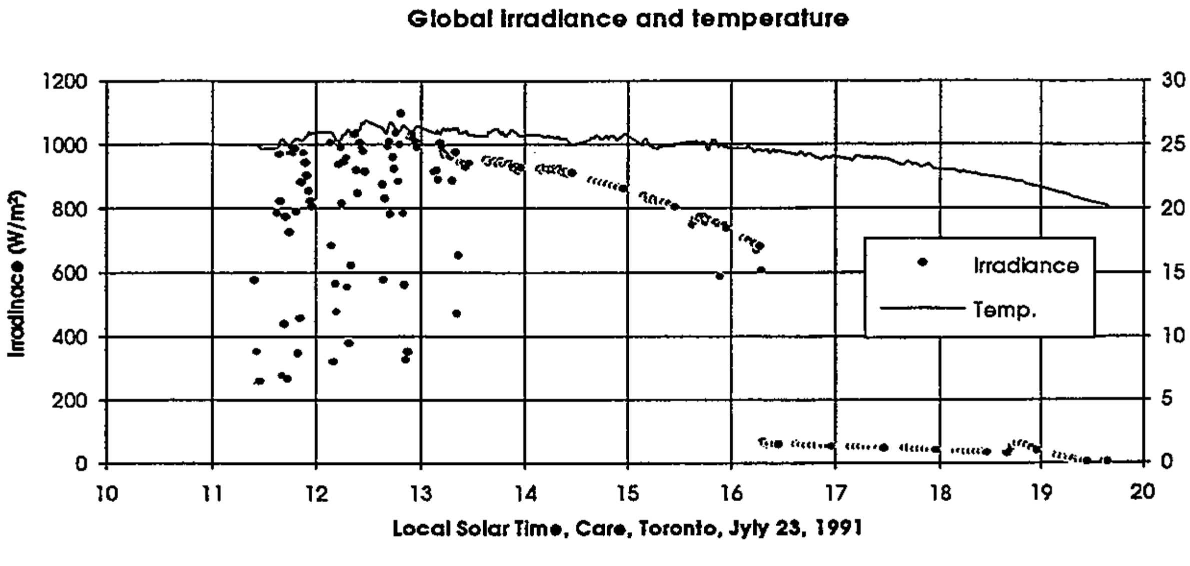


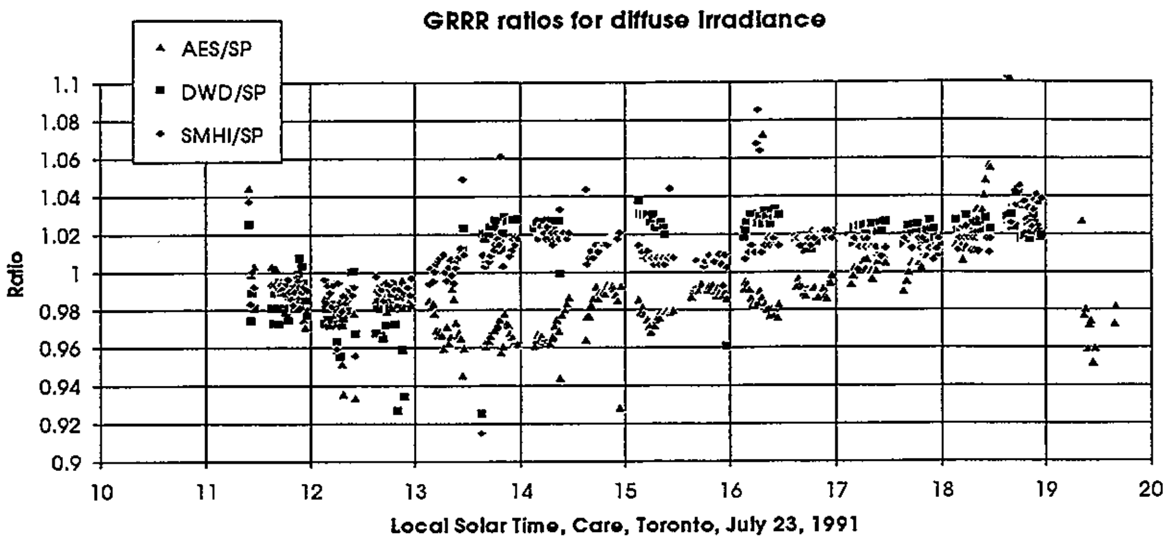
GRRR ratios for global irradiance

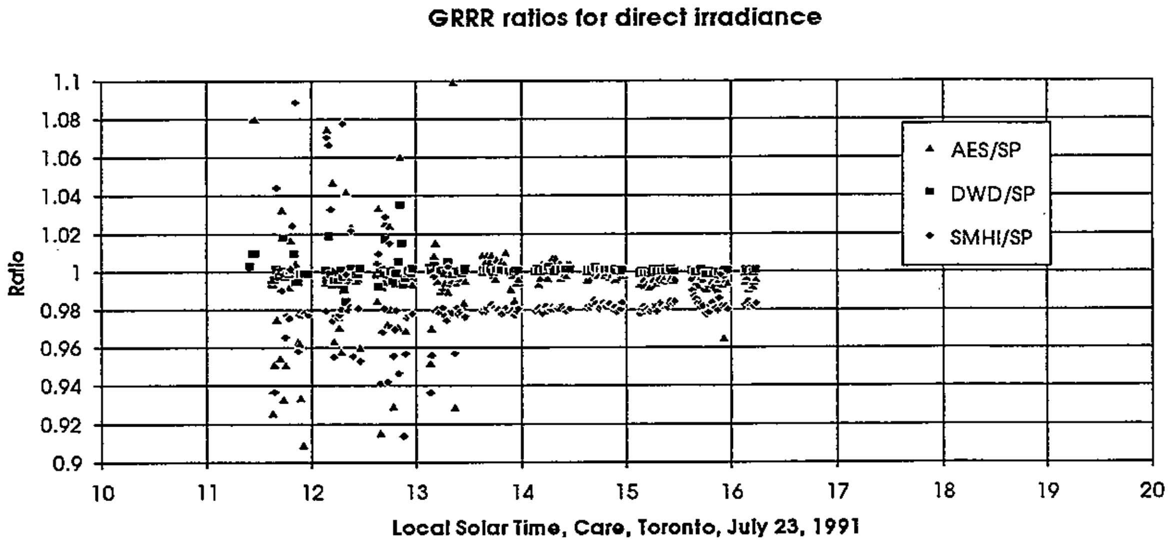



Diffuse irradiance
Irradiance (W/cm²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 23, 1991


Direct irradiance
normal
horizontal
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 23, 1991


Global irradiance and temperature
Irradinace (W/m²)
1200
1000
800
600
400
200
0
30
25
20
15
10
5
0
Irradiance
Temp.
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 23, 1991


GRRR ratios for diffuse irradiance
AES/SP
DWD/SP
SMHI/SP
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 23, 1991


GRRR ratios for direct irradiance
AES/SP
DWD/SP
SMHI/SP
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
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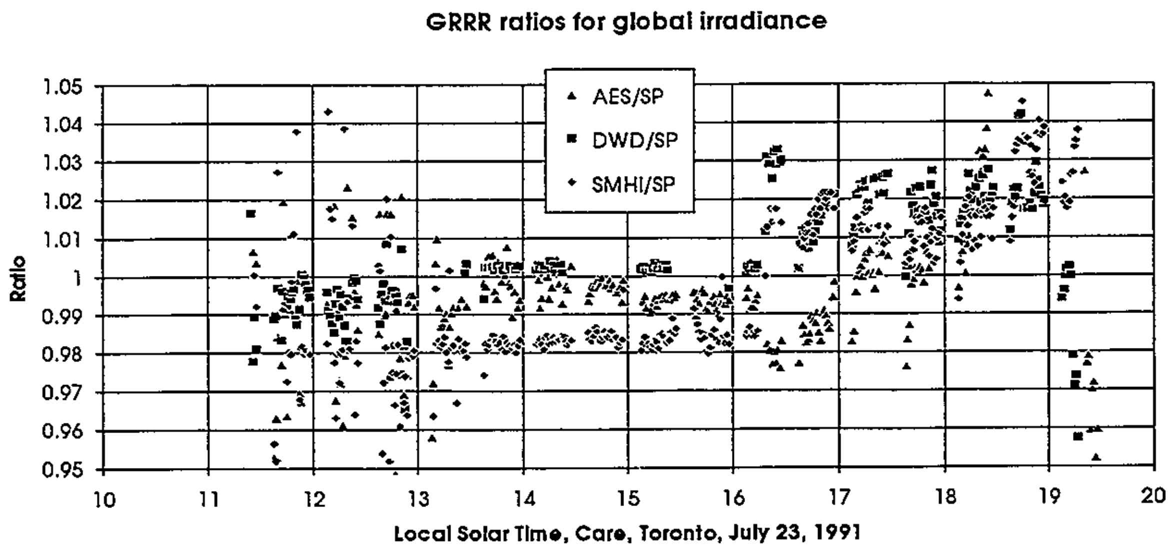
Local Solar Time, Care, Toronto, July 23, 1991


GRRR ratios for global irradiance
AES/SP
DWD/SP
SMHI/SP
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
10
11
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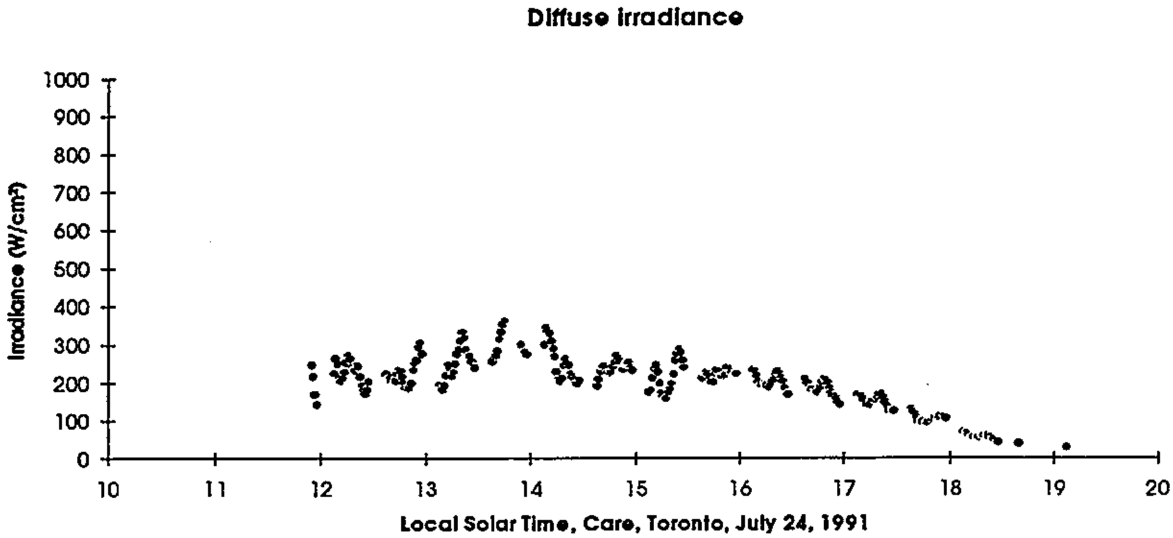
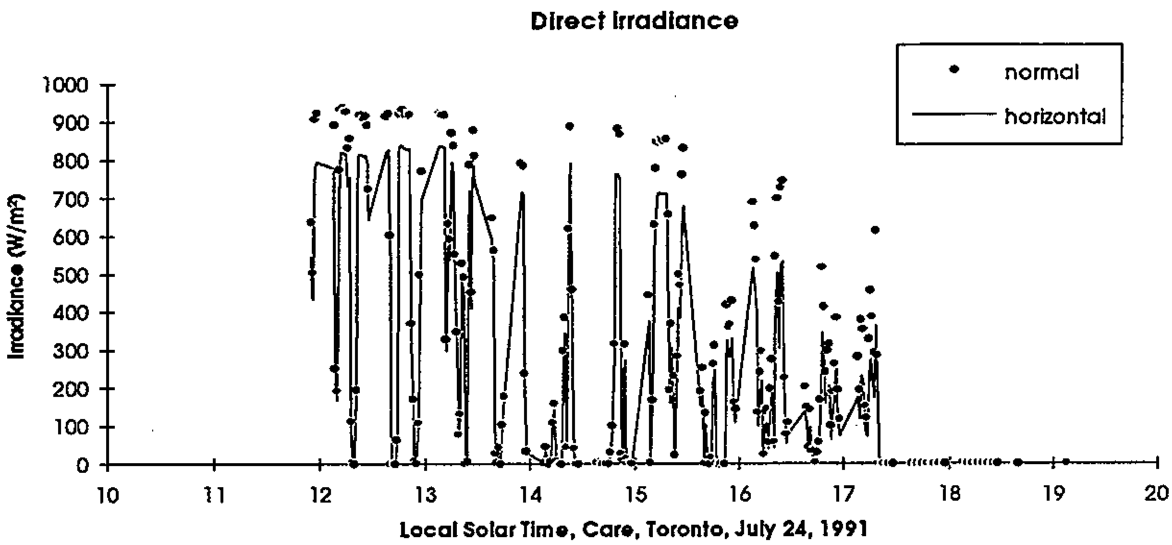
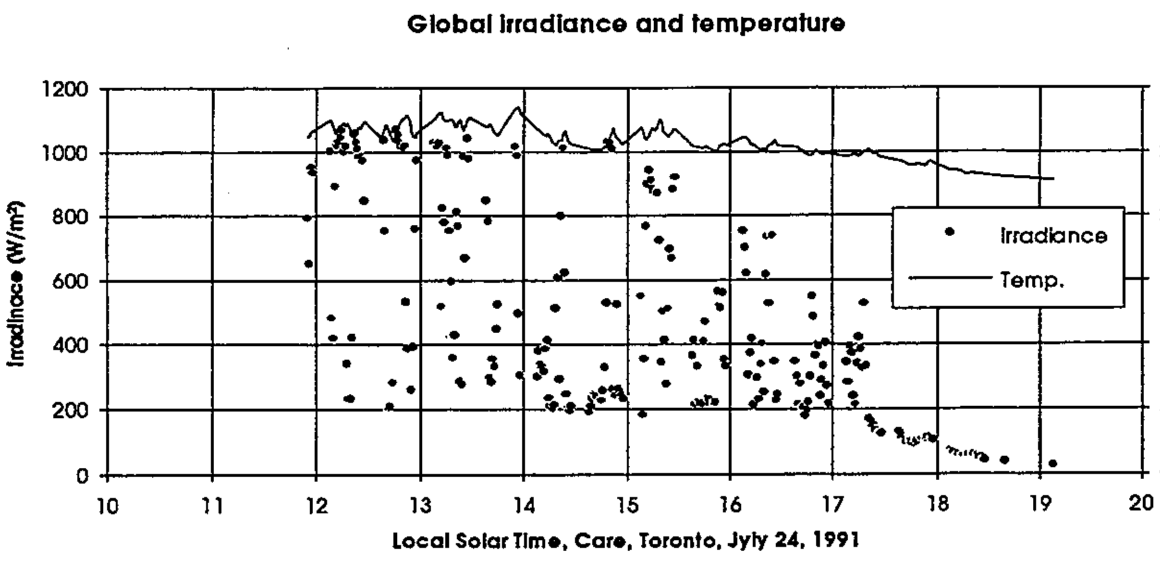
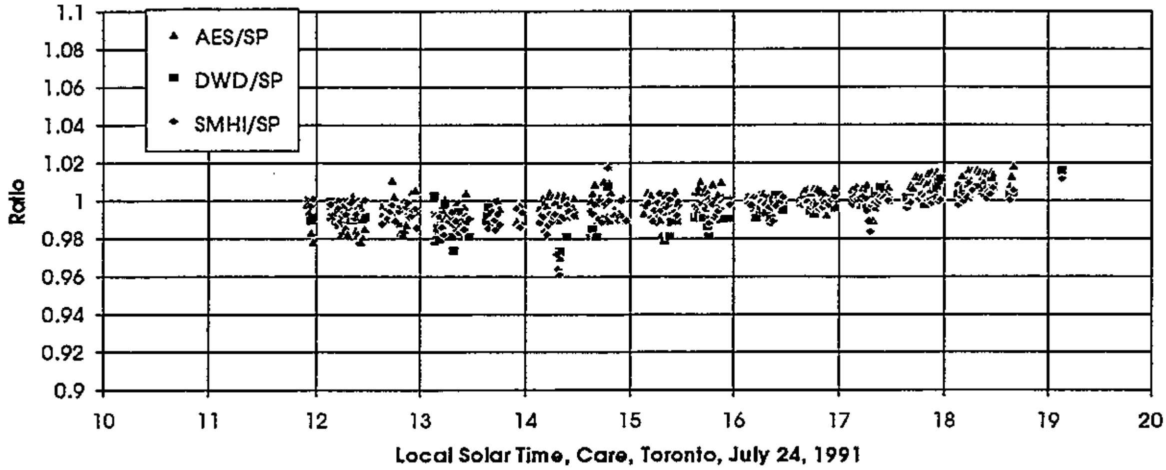
Local Solar Time, Care, Toronto, July 23, 1991


Diffuse irradiance
Irradiance (W/cm²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 24, 1991

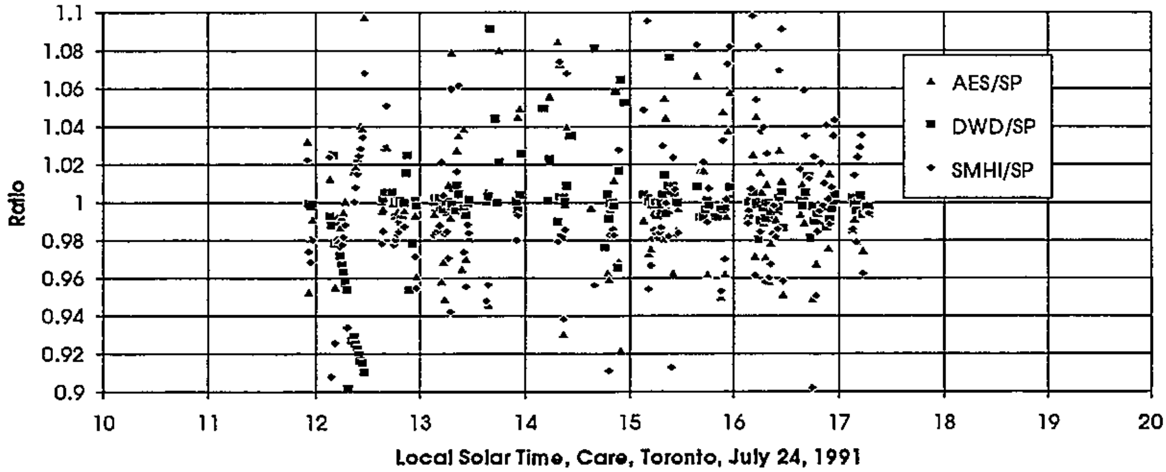

Direct irradiance
normal
horizontal
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 24, 1991


Global irradiance and temperature
Irradiance
Temp.
Irradinace (W/m²)
1200
1000
800
600
400
200
0
30
25
20
15
10
5
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 24, 1991

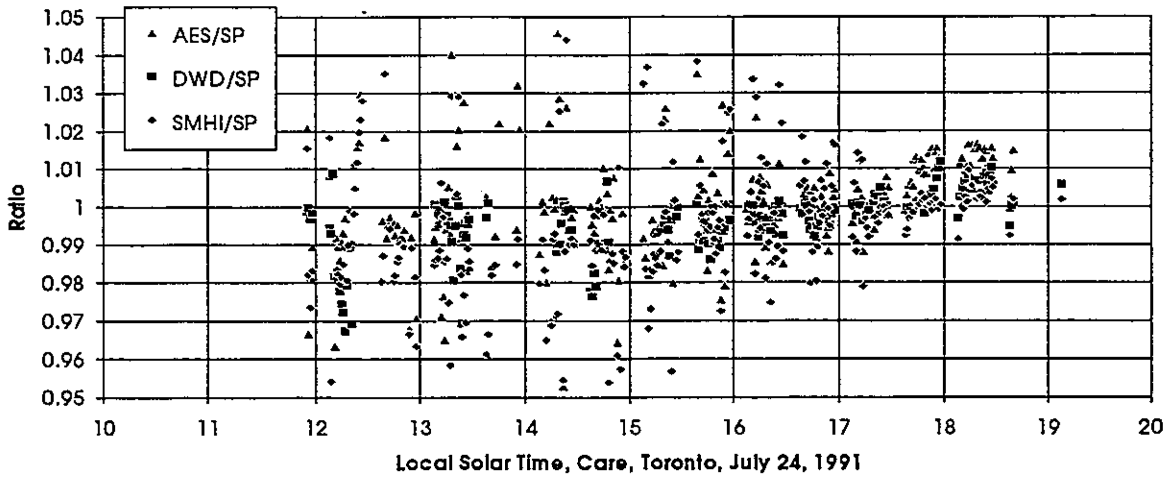
GRRR ratios for diffuse irradiance

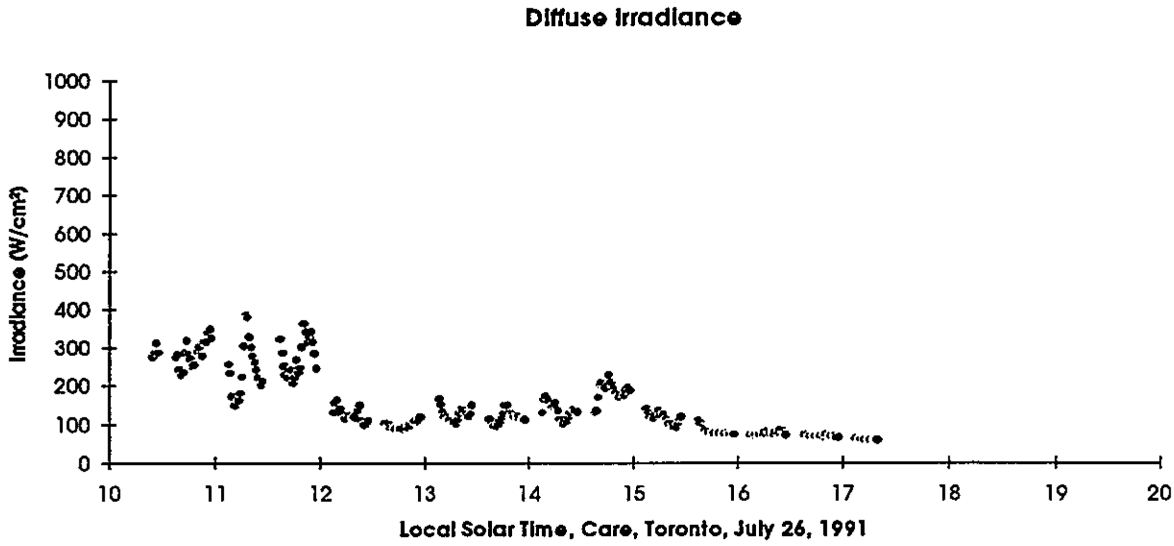


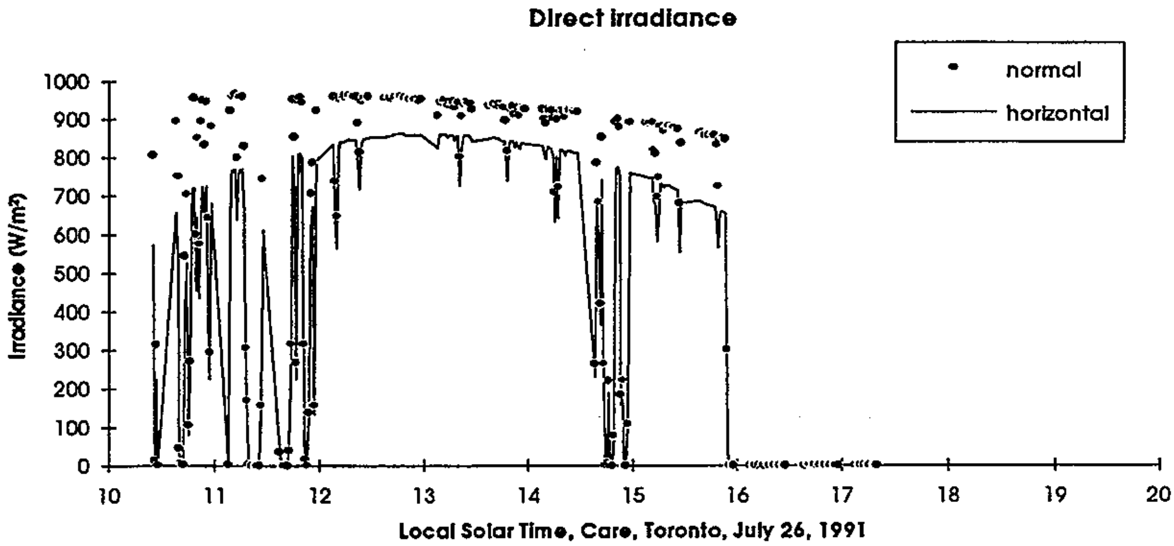
GRRR ratios for direct irradiance

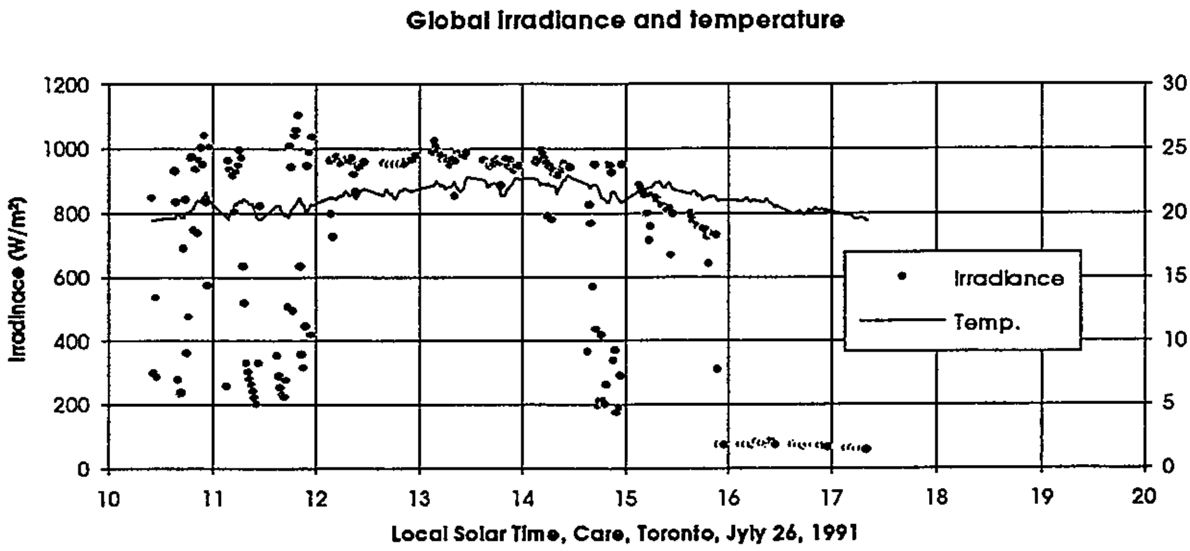


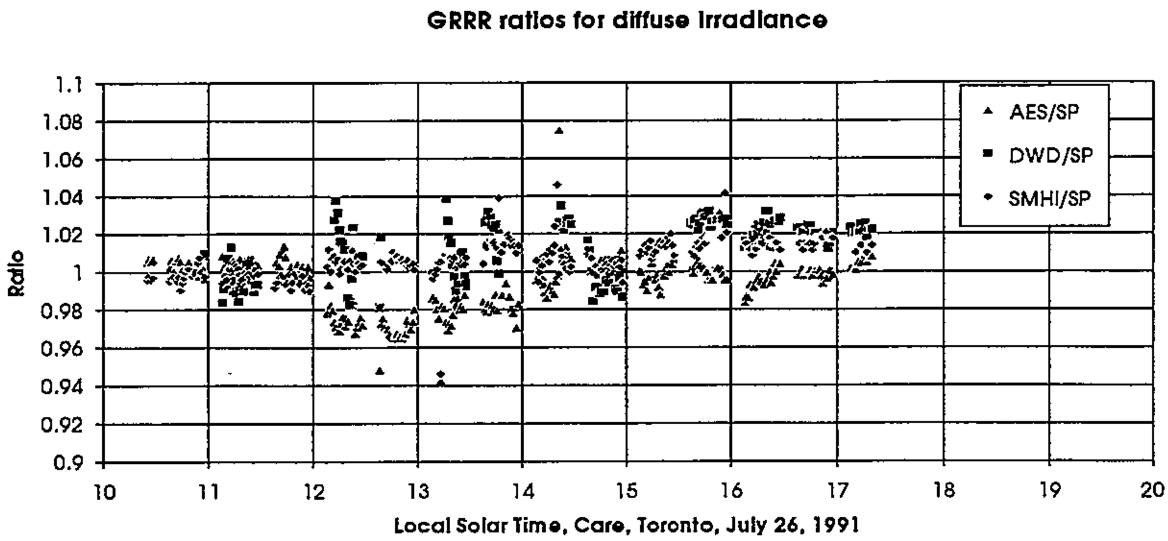
GRRR ratios for global irradiance




Diffuse Irradiance
1000
900
800
700
600
500
400
300
200
100
0
Irradiance (W/cm²)
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 26, 1991


Direct Irradiance
normal
horizontal
1000
900
800
700
600
500
400
300
200
100
0
Irradiance (W/m²)
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 26, 1991


Global Irradiance and temperature
1200
1000
800
600
400
200
0
Irradinace (W/m²)
30
25
20
15
10
5
0
Irradiance
Temp.
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 26, 1991


GRRR ratios for diffuse irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
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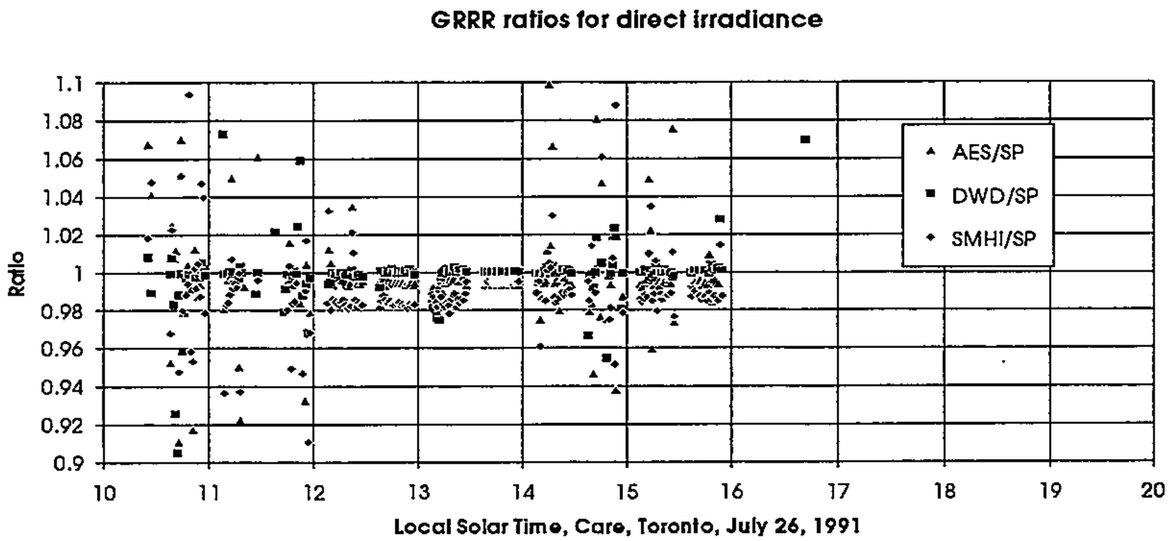
13
14
15
16
17
18
19
20
AES/SP
DWD/SP
SMHI/SP
Local Solar Time, Care, Toronto, July 26, 1991


GRRR ratios for direct irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10
11
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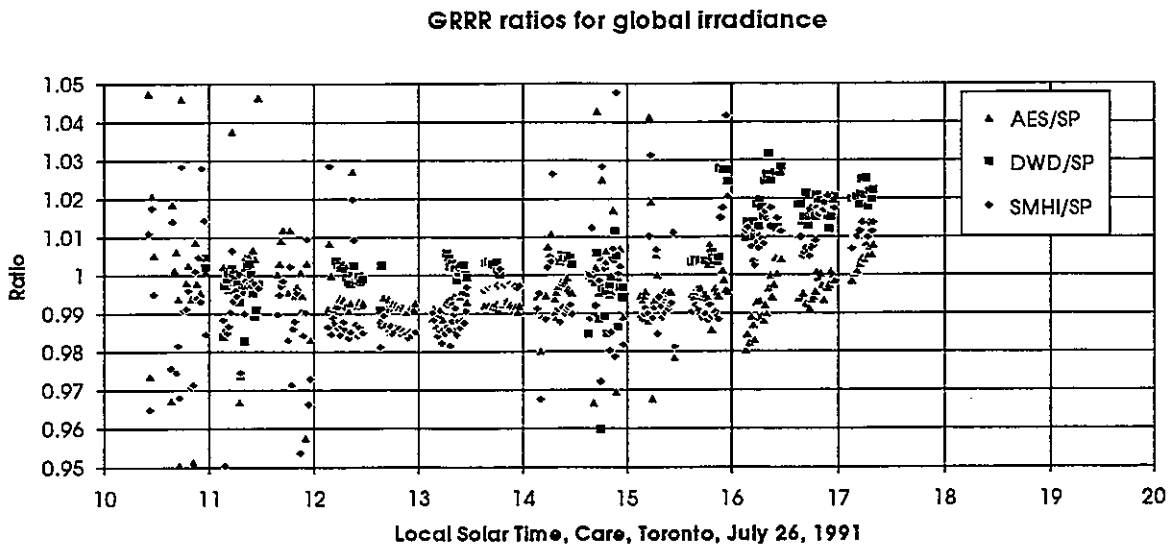
15
16
17
18
19
20
AES/SP
DWD/SP
SMHI/SP
Local Solar Time, Care, Toronto, July 26, 1991


GRRR ratios for global irradiance
Ratio
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
10
11
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13
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17
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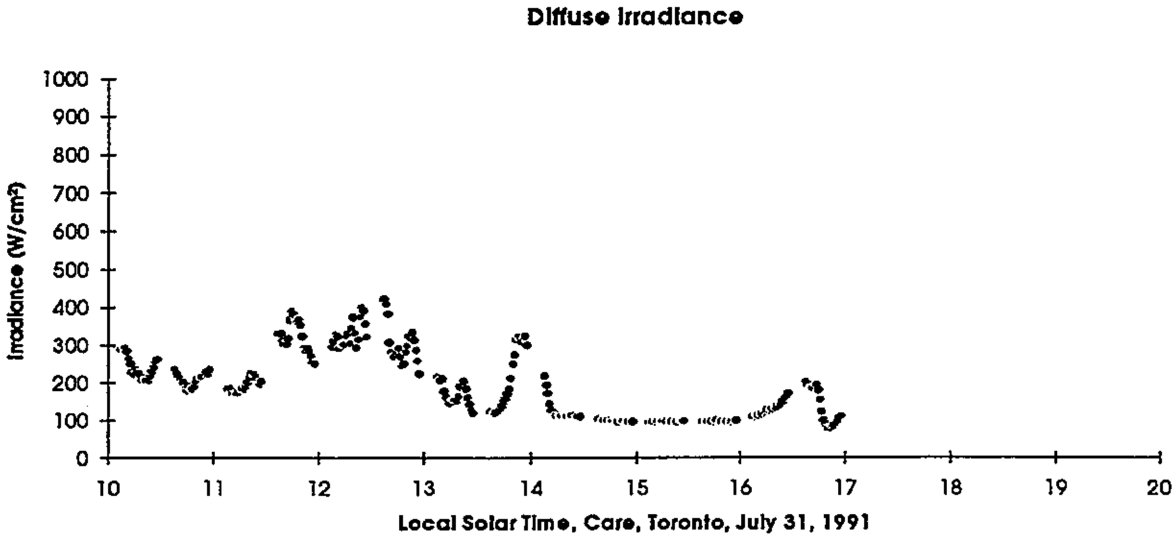
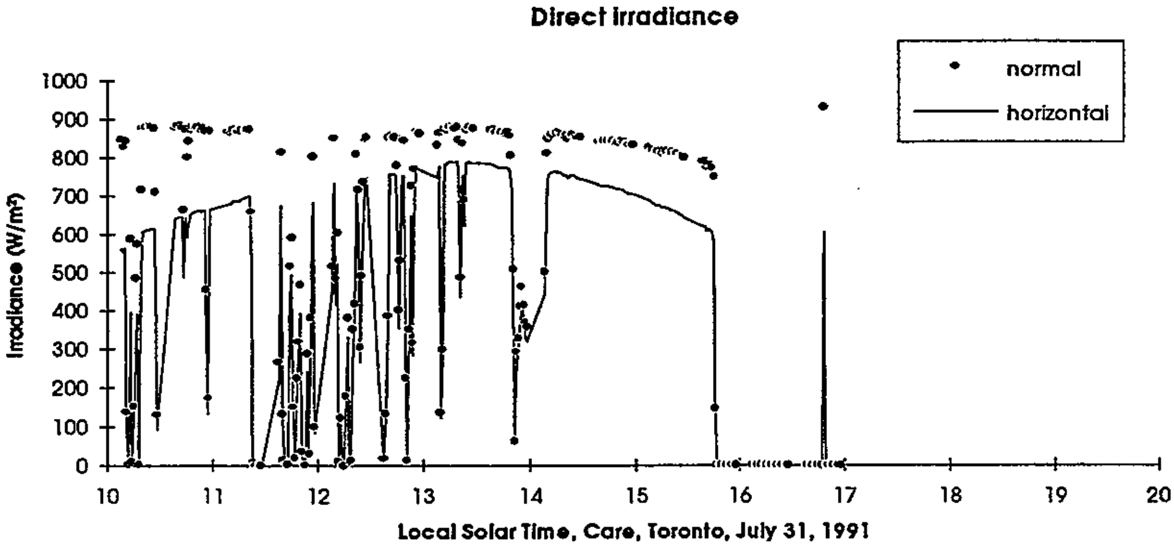
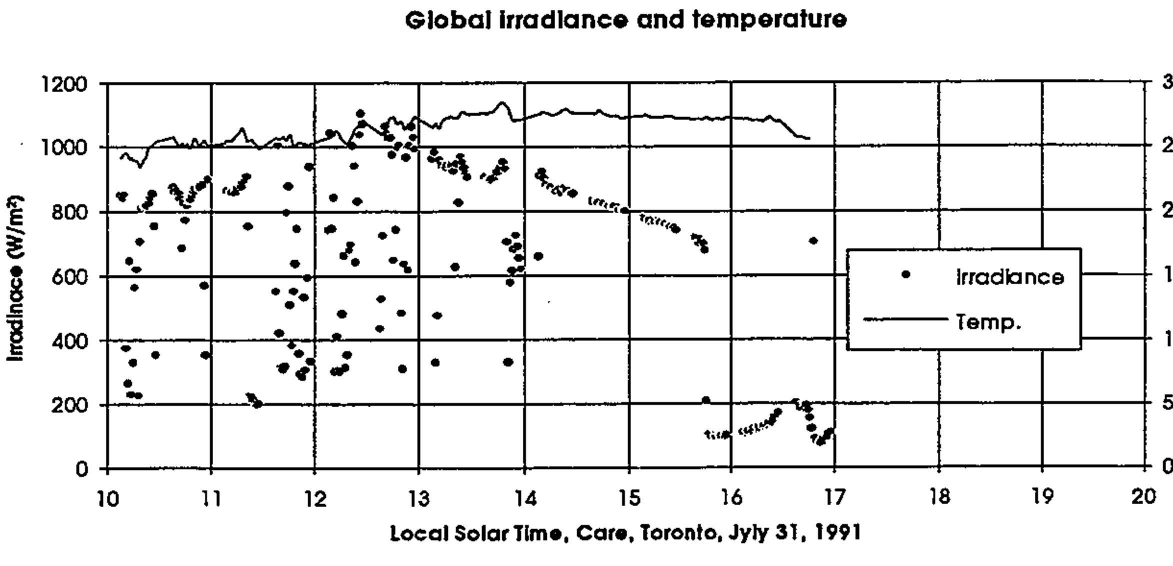
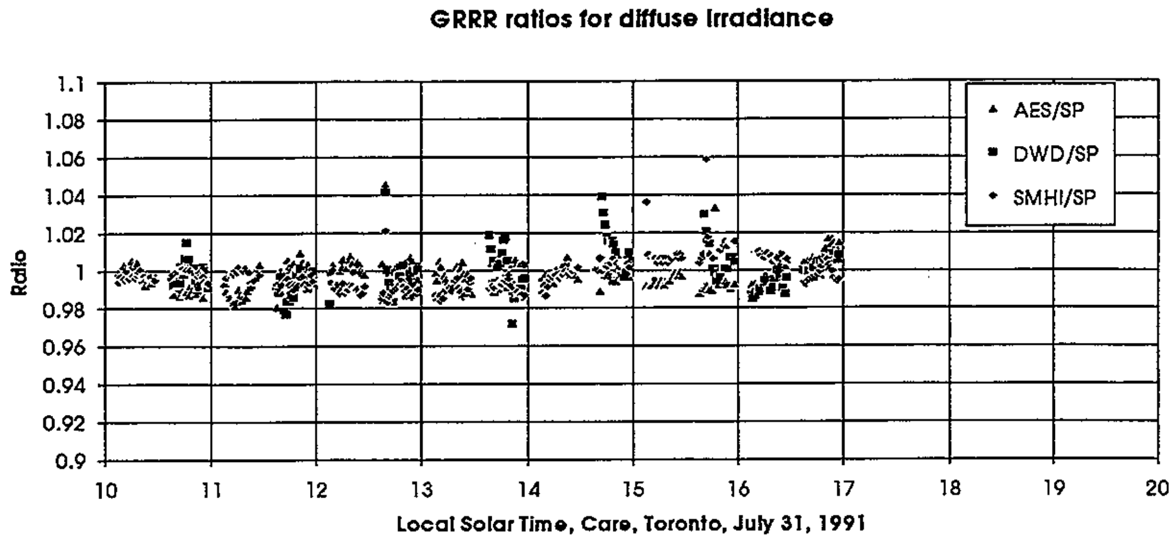
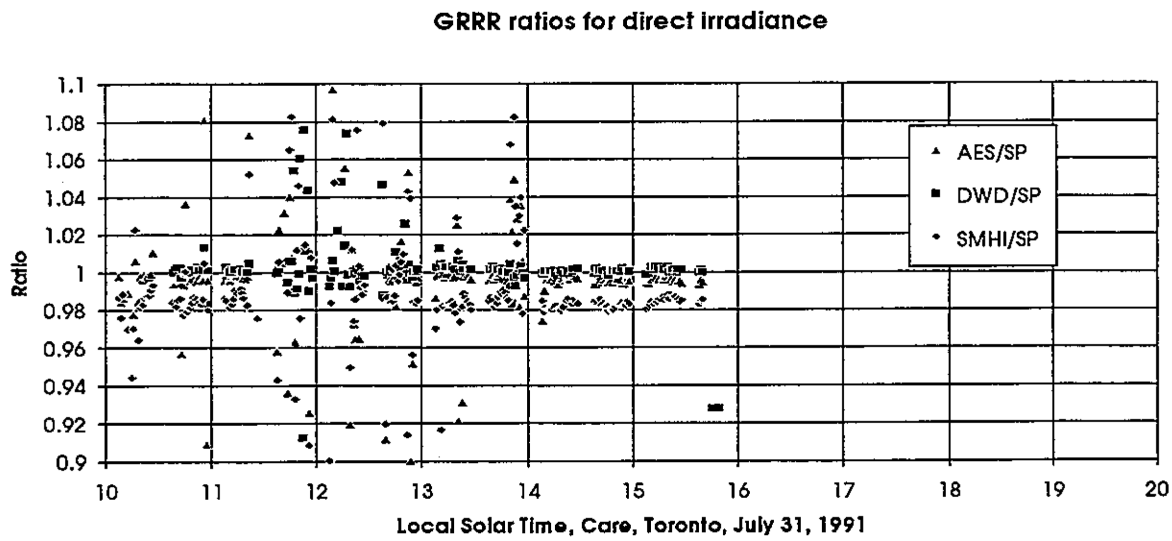
19
20
AES/SP
DWD/SP
SMHI/SP
Local Solar Time, Care, Toronto, July 26, 1991

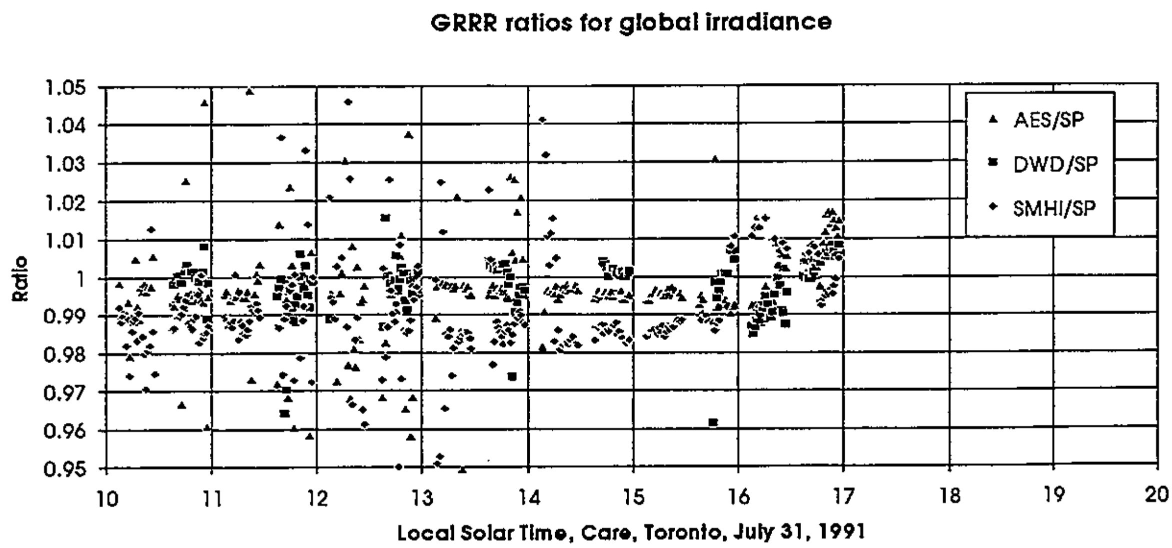

Diffuse Irradiance
Irradiance (W/cm²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 31, 1991


Direct Irradiance
normal
horizontal
Irradiance (W/m²)
1000
900
800
700
600
500
400
300
200
100
0
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, July 31, 1991


Global Irradiance and temperature
Irradinace (W/m²)
1200
1000
800
600
400
200
0
30
25
20
15
10
5
0
Irradiance
Temp.
10
11
12
13
14
15
16
17
18
19
20
Local Solar Time, Care, Toronto, Jyly 31, 1991


GRRR ratios for diffuse irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10 11 12 13 14 15 16 17 18 19 20
Local Solar Time, Care, Toronto, July 31, 1991
AES/SP
DWD/SP
SMHI/SP


GRRR ratios for direct irradiance
Ratio
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
10 11 12 13 14 15 16 17 18 19 20
Local Solar Time, Care, Toronto, July 31, 1991
AES/SP
DWD/SP
SMHI/SP


GRRR ratios for global irradiance
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1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
10 11 12 13 14 15 16 17 18 19 20
Local Solar Time, Care, Toronto, July 31, 1991
AES/SP
DWD/SP
SMHI/SP