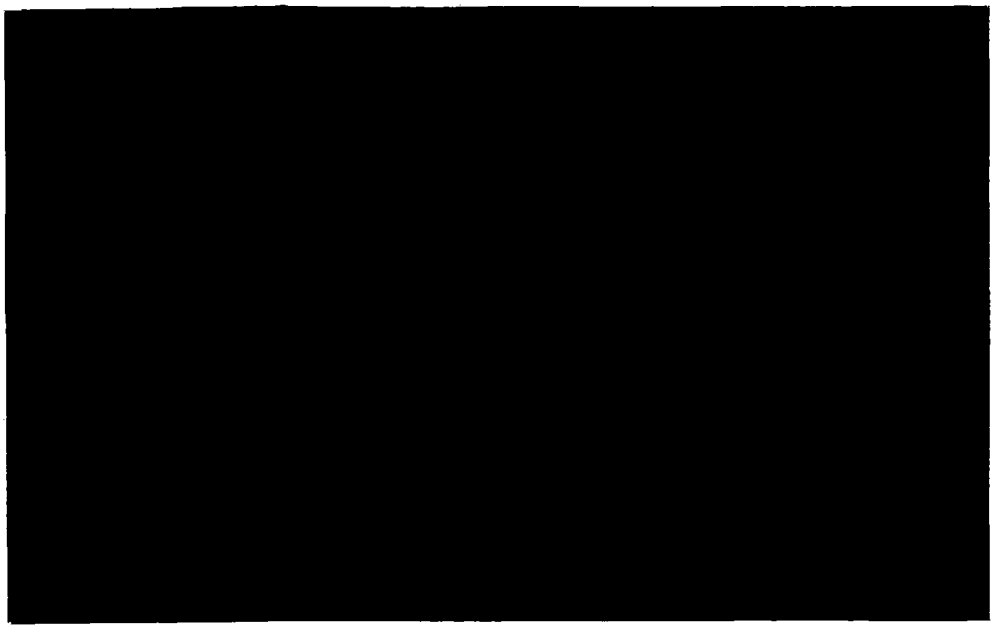


Arbeitsberichte der Schweizerischen Meteorologischen Zentralanstalt
Rapports de travail de l'Institut Suisse de Météorologie
Rapporti di lavoro dell'Istituto Svizzero di Meteorologia
Working Reports of the Swiss Meteorological Institute

Zürich

52705

No 136

The Mobile Radiation Station of the Swiss Meteorological Office Description, Sample Results of Non-Spectral Measurements

by

Alain Heimo, Zurich
December 1985

Solar Radiation	551.521.1
Mobile station	551.507.1
Instruments for determining radiation	551.508.2

Summary

The MObile RAdiation Station MORAS of the Swiss Meteorological Office is a powerful system for the measurement of solar and sky radiation. A detailed description of the instruments is presented together with their calibration methods. Sample results of the non-spectral measurements performed during the last years are examined; daily variations and angular distributions of direct solar irradiance, global and diffuse irradiance as well as atmospheric radiance are displayed for various orientations and under different meteorological conditions.

Résumé

La station mobile de mesure du rayonnement solaire MORAS de l'Institut Suisse de Météorologie est un puissant système de mesure du rayonnement solaire direct et diffus. Une description détaillée des instruments est présentée ainsi que leurs méthodes de calibration. Un échantillon des résultats des mesures non-spectrales effectuées ces dernières années est examiné; les variations journalières et les distributions angulaires de l'irradiance solaire directe, de l'irradiance globale et diffuse de même que de la radiance atmosphérique sont rapportées pour différentes orientations et sous des conditions climatiques variées.

Zusammenfassung

Die mobile Messstation MORAS der Schweizerischen Meteorologischen Anstalt ist ein leistungsfähiges System für die Messung der Sonnen- und Himmelsstrahlung. Die Instrumente und ihre Kalibrierungsmethoden werden detailliert beschrieben. Proben der in den letzten Jahren ausgeführten, nicht-spektralen Messungen werden vorgestellt; Tagesgänge und Winkelverteilungen von direkter, globaler und diffuser Strahlung, sowie die Richtungsverteilung der spezifischen Intensität des Himmels, werden für verschiedene klimatische Bedingungen aufgeführt.

Riassunto

La stazione mobile per misure dell'irraggiamento solare MORAS, dell'Istituto Svizzero di Meteorologia, é un potente strumento per la misura dell'irraggiamento solare e atmosferico. Una descrizione dettagliata degli strumenti viene presentata, assieme ai loro sistemi di calibrazione. Vengono esaminati alcuni esempi dei risultati di misure non spettrali effettuate nel corso degli ultimi anni: variazioni giornaliere e distribuzioni angolari dell'irraggiamento solare diretto, dell'irraggiamento globale e diffuso, come pure dell'irraggiamento atmosferico vengono esposte per diversi orientamenti e condizioni climatiche diverse.

Abbreviations

MORAS	: MObile Radiation Station,
PMOD	: Physical Meteorological Observatorium Davos,
WRCD	: World Radiation Center Davos,
WRR	: World Radiometric Reference
WMO	: World Meteorological Office
IPS56	: Intern. Pyrheliometric Scale 1956

Table of contents — Pages

Introduction 1

1. Instruments 2

1.1 Historical review 2

1.2 Technical description 3

1.2.1 Mobile station MORAS 3
1.2.2 Instruments 3

1.2.2.1 Sun-tracker 3
1.2.2.2 Absolute radiometer 3
1.2.2.3 Spectroradiometer 4
1.2.2.4 Photometer D-500 5
1.2.2.5 Telescopic mast 5
1.2.2.6 Pyranometers 6
1.2.2.7 Photometers 7
1.2.2.8 Meteorological parameters - Camera 8
1.2.2.9 Calibrations 8

1.2.3 Data acquisition system - Computer 11

1.3 Data transfer - Databank MORLIB 12

1.4 Installation - Operation 13

2. Non-Spectral Measurements 14

2.1 Direct solar irradiance 14

2.2 Global and diffuse irradiance 18

2.2.1 Daily variation 18
2.2.2 Angular distribution 21
2.2.3 Reflected irradiance 25

2.3 Radiance 29

2.3.1 Daily variations 29
2.3.2 Angular distribution 32

3. Conclusion 36

Annex 37

References 41

Introduction

The transfer of solar radiation through the atmosphere represents one of the main physical processes that are responsible for the general circulation and the ocean currents. A detailed knowledge of the radiative processes and the radiative balance prevailing in the earth-atmosphere system is essential for the understanding of the climate and of the mechanisms of climatic changes.

The MObile RAdiation Station (MORAS) of the Swiss Meteorological Institute has been in operation for about 10 years. During the numerous measurement campaigns performed at different locations and under various meteorological conditions, an impressive material has been gathered for short-wave, non-spectral as well as spectral measurements of the solar and sky radiation at the ground.

A description of the instruments used in the mobile station is presented in the following, together with some samples of the non-spectral measurements. References to already published more detailed results are to be found throughout the text.

The author has recently published his thesis under the title

Diagnosis of the Atmosphere through Optical Measurements Performed with a Mobile Station,
Dissertation Nr. 7755,
Swiss Federal Institute of Technology, Zurich 1985.

In this study, analysis and interpretation of the spectral measurements are extensively treated, while the non-spectral measurements are quoted only for introductory and explanatory purposes. The latter results are to be found in the present report. Processing of these data follows the general research program of the Section of Technical Meteorology of the Swiss Meteorological Office.

1 - INSTRUMENTS

1.1 Historical review

In the late sixties, a concept for new measurements was developed to improve the efficiency of the Swiss Meteorological Institute in the solar radiation field in general and to establish an empirical basis for studies of the structure of the short wave solar radiation field in particular. The project was co-sponsored by the Swiss National Fund for Scientific Research. The design and realization of the station were handed over to the Physical Meteorological Observatorium in Davos (PMOD) and a first detailed description was presented at the international congress "The Sun in the Service of Mankind" held in Paris in July 1973 (1).

The trailer was manufactured by a specialized enterprise following the design drawn at the PMOD. The installation of the scientific equipment began in Davos in 1974 and the main frame of the software was developed by EPS (Elektronische Prozesssteuerung, Wil) together with the MORAS staff.

Test measurements took place in 1975 and the first relevant campaign was completed in January 1976 in Zurich. During the following years, the instrument set has been improved and extended (2, 3, 4).

The system has been in operation during numerous campaigns in Switzerland, France and Germany, gathering some 3000 simultaneous data files in different seasons and under different conditions at an altitude range of about 100 to 2700 meters above sea level.

1.2 Technical description

1.2.1 Mobile station MORAS

The trailer is a container mounted on a double axis chassis equiped with a twin hydraulic break system. Its entire weight is approximately 4 tons, with external dimensions 6.0 x 2.3 x 2.6 meters. The walls and windows are specially insulated for easier air-conditioning of the interior. A special compartment accessible from the roof of the car is reserved at the back of the station and equiped with two mobile platforms supporting the sun-trackers. Electricity is provided usually from the public network or, if necessary, from a mobile generator (3 x 380 Volts, 10 Amps). A truck is needed for the transport of the system. All the service and maintenance material is stored within the car.

1.2.2 Instruments

1.2.2.1 Sun-tracker

The sun-tracker is built on an equatorial mount whose motion is controled by the quarz clock of the station. Once adjusted to the local latitude, the sun declination and the solar time, the hour angle stepping-motor receives a pulse every second. The fine adjustment is achieved with the help of a four-quadrant sensor mounted on the tracker which corrects for possible hour angle and declination deviations. Two operating modes are thus available: the active mode when the sun is shining and the passive mode for overcast conditions, the switching between the two being automatic. The intensity threshold between the two modes can be adjusted. This is very practical since it prevents the tracker from following very bright and fast moving clouds. The sun-tracker platform carries the absolute radiometer, the spectroradiometer, one photometer and one pyranometer. The complete system is usually fixed on one of the two mobile tables of the rear compartment. For special conditions, it may be set up anywhere else (the roof of a building for example), the only limitation being the length of the linking cables (100 meters for each instrument).

1.2.2.2 Absolute radiometer

The absolute radiometer integrated in the MORAS is the best and the most reliable instrument in operation. It was developed at the WRCD (5) and is a member of the new family of so-called absolute active cavity radiometers for the measurement of solar irradiance (PMO4). A detailed description of this instrument may be found in (6).

The main specifications are the following: the receiving cavity with an inverted cone is electrically heated so that a constant temperature difference is maintained between the irradiated part and the heat sink. The aperture ist alternatively closed and opened: the difference of the two electrical heating powers multiplied by the different calibration factors gives the solar irradiance with an estimated absolute accuracy of about 0.2%. The quality of such instruments have in fact allowed definition of the new World Radiometric Reference (WRR) now adopted by the WMO and which is 2.2% above the old IPS56 reference. It may also be noted that the newest generation of these radiometers (PMO6) are flown on stratospheric balloons and rockets for an accurate determination of the solar constant (7).

In order to study the behaviour of atmospheric turbidity, a wheel supporting the classical broad band filters (OG1,RG2,RG8) and a quarz window is mounted in front of the radiometer. A simple rotation brings the different filters into optical sight. The cut-on and cut-off wavelengths of these filters were very precisely measured with a spectrometer at the Federal Institut of Technology in Zurich (fig. 1.1). Unfortunately, they have a temperature dependence of the

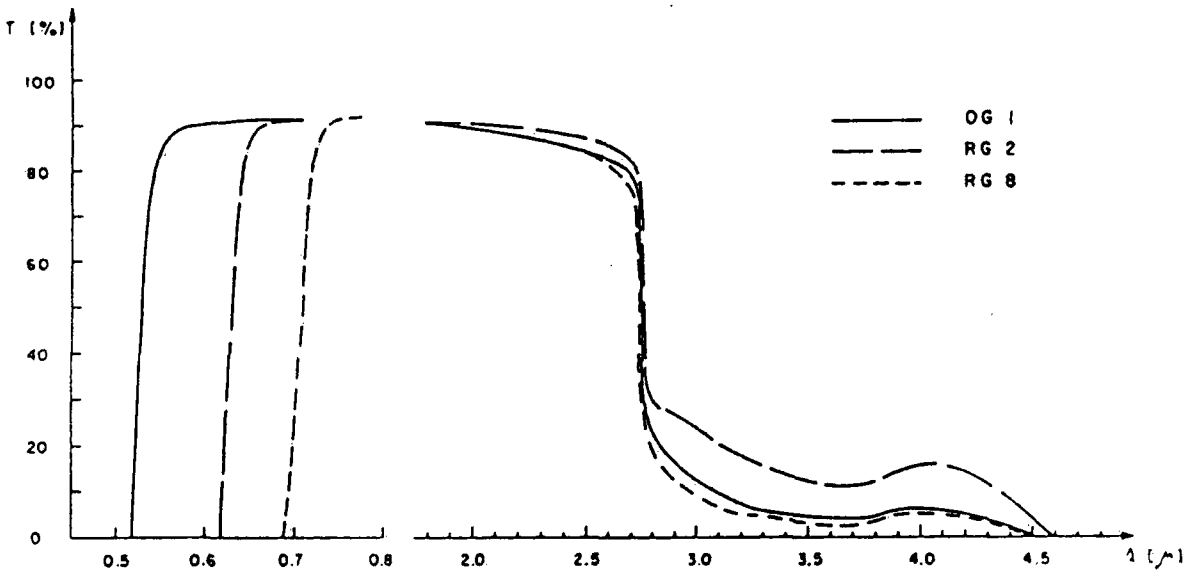


Fig. 1.1 Transmission curves of the absolute radiometer filters measured in laboratory.

cut-off which may influence the results substantially due to changes in environmental temperatures and the length of the irradiation period during the measurements: this has been taken into account for computation of turbidity from these measurements (8,9).

1.2.2.3 Spectroradiometer

The spectroradiometer operated in the MORAS is a prototype instrument developed at the WRCD (10).

The properties of this instrument are the following: a telescope of focal length 492 mm casts an image of the sun on the entrance slit (2.56 x 0.31 mm) of a double monochromator. About 1/20 of the solar disc is seen through the slit. The two successive prisms of the double monochromator are mounted on the same turntable and rotated by means of a spindle gear mechanism driven by a stepping-motor. A thermally controlled photodiode (type UV 215-B, EG+G) measures the output at the exit slit and thus the spectral intensity.

The instrument is calibrated by the method of extrapolation based on the Bouguer law and first applied by Langley in the field of solar measurements. As only the optical depth of the atmosphere is of interest, the extraterrestrial values of the intensity in relative units of the instrument (no absolute calibration) are sufficient, e.g. μA. However, these values were rather difficult to determine (Annex) as the spectroradiometer showed variations of its sensitivity due to changes of the temperature and to the position of the instrument.

Part of these problems were solved by using a separate, very stable photometer (D-500, WRCD) to take measurements at a wavelength of 500 nm through an interference filter which were used to correct the spectroradiometer (see section 1.2.2.4 and Annex).

Table 1.1 displays the wavelengths chosen for the study of aerosols, water vapour and ozone contents of the atmosphere. The half-width of the spectral bands ranges from 1.4 to 22 nm at the short (UV) to the long (near infrared) wavelengths.

λ [nm]	purpose
1030	Aerosols
863	Aerosols
822	Water vapour
781	Aerosols
633	Ozone
604	Ozone
590	Ozone
576	Ozone
554	Ozone
535	Ozone
515	Ozone
500	Aerosols
455	Aerosols
415	Aerosols
365	Aerosols
334	Aerosols

Table 1.1. Spectroradiometer wavelengths and reasons of choice.

1.2.2.4 Photometer D-500

This instrument is used to check the results of the spectroradiometer for the 500 nm channel. Its simplicity and stability dedicate it for such reference uses (11). The construction is simple: a tubus whose external aperture is sealed by a quarz window contains a set of mufflers to reduce the straylight to a negligible minimum. The light falls on an interference filter placed in front of a photodiode whose current is amplified and read by the data acquisition system. The interference filter and the diode are mounted in a copper frame which is thermally stabilized.

This instrument shows qualities which could lead in the future to the extensive use of sets of photometers instead of sensible but versatile instruments like double monochromators.

1.2.2.5 Telescopic mast

In order to perform meaningful measurements of the reflected radiation, the instruments must be used at a suitable height above the ground. This is achieved by the use of a telescopic mast which can be stretched up to 10 meters height by an hydraulic system. The base is fixed on the ground by four heavy lead blocks and the swinging of the top part is partly avoided by the use of 2 sets of 3 bracing ropes which allow a stable position of the top, even with rather strong winds.

A platform is nested at the top of the last tube and supports a second table by means of 3 electrically controlled spindle gears linked to two electrical water levels which automatically maintains the horizontal position. On this second table, a special device is mounted which rotates around the vertical axis and sustains two (up to four are possible) arms. A stepping-motor is placed at the end of each of these arms allowing rotation around the horizontal axis and holding the instruments themselves. The combined rotations around the two main axis allow a complete scan of either the upper or the lower hemisphere from a height of 10 meters.

1.2.2.6 Pyranometers

The mobile station is outfitted with 7 pyranometers developed at the PMOD (PD1) measuring the global irradiance falling on a plane surface (12, 13).

The receivers contain thermopiles of 60 thermoelements manufactured by copper-plating of constantan wire. The receiver surface of 25 mm diameter is blackened with Parsons Black and is covered by hemispheres of filterglass WG7 (Schott) which prevent infrared losses as well as convection effects.

The first four pyranometers are mounted on a device (called 'flower' in the following) allowing rotation around the vertical axis. Each unit itself can rotate around the horizontal axis so that a complete scan of the upper hemisphere can be achieved. Seventy seven points (directions) are measured by the four instruments within about 6 minutes.

The fifth unit is placed at the end of the first arm of the telescopic mast described in section 1.2.2.5 for the measurement of the reflected irradiance. Seventy seven points are also measured in this case but within 25 minutes as only one sensor is used for a complete scan.

The sixth pyranometer is mounted on the sun-tracker and measures the global irradiance falling on a surface constantly perpendicular to the sun (one measurement every 20 seconds, 77 times).

The seventh pyranometer usually remains in horizontal position, but can be set in any other direction for special purposes. The horizontal position is favored because of possible comparisons with the world-wide horizontal pyranometers' network. Furthermore, the 'flower's' rotation can be checked, as the first four pyranometers reach that position twice during 25 minutes. All the pyranometers take one measurement/rotation every 20 seconds. This is the result of a compromise between the time constant of this type of instrument (approximately 3 seconds to reach 1/e part of the response) and the quickest possible scan. It is actually rather optimistic to assume an accuracy better than 2-3%, especially for the rotating units which are subject to a number of possible errors, as recent international comparisons made clear. Dependance on

- temperature,
- incident angle of light relative to the instrument's axis,
- tilt angle of the instrument,
- non linearity,
- spectral absorption,
- convection effects, etc...

are common problems for users of pyranometers. There is indeed a well known difficulty to calibrate them and it looks as though there are today no satisfying existing methods, especially for tilted positions, which would produce comparable results independently of the location of the stations, if the objective is to guarantee a 2% accuracy.

1.2.2.7 Photometers

The station MORAS is equipped with a set of five photometers which are similar to the photometer D-500 (see section 1.2.2.4). They have a field of view of 4.65 degrees to allow direct comparisons with the absolute radiometer (0.00517 steradians). A filter wheel is mounted in front of the aperture and sustains up to 5 filters. The first of these filters corrects the spectral response curve of the photodiode so that a more or less flat response is obtained within the sensitivity range of the diode. This permits simulation of grey-body absorption so that comparisons with instruments like the absolute radiometer or pyranometers are possible (figure 1.2).

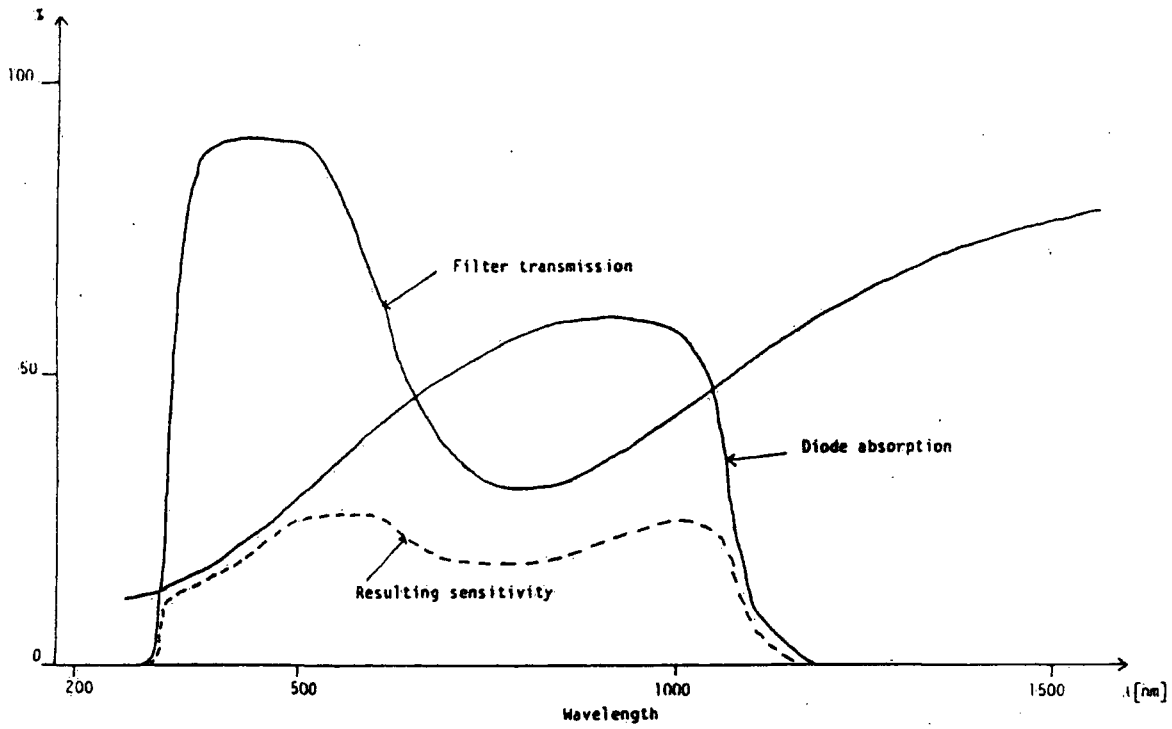


Fig. 1.2. Characteristics of diodes and filters used for the sky photometers. The resulting curve simulates a more or less flat response of the instruments.

The next three filters are interference filters (368 nm, 500 nm, 778 nm) with a half-width of about 10 nm. The last position is usually used without any filter for radiance measurements: these data could offer valuable information for photovoltaic applications.

The first four photometers are mounted on a 'flower' similar to the one described for the pyranometers, except that the instruments are much closer to each other because of the smaller field of view. The measurements can be performed much quicker as the time constant of the diodes is several orders of magnitude shorter than that of the pyranometers.

The fifth instrument is mounted at the end of the second arm of the telescopic mast and follows the same upsidedown path as the opposite pyranometer (fifth unit).

The 'flower' is rotated every four seconds and a complete scan of the upper hemisphere is achieved within 132 seconds. The fifth unit is linked to the pyranometer and performs one measurement every 20 seconds.

1.2.2.8 Meteorological parameters - Camera

Temperature, humidity and pressure are measured continuously near the station with conventional meteorological instruments. Pictures of the sky are taken during the measurements with a camera NIKON F2S equipped with a fish-eye objective of 180 degrees field of view. The camera is usually placed in the horizontal position and sees the upper hemisphere with the same angle as the horizontal pyranometer. This is a very precious piece of information for the final evaluation of the results as it allows one to see what happened during the course of the measurements. Furthermore, these pictures open the way for image processing and for precise studies of the influence of clouds on the diffuse radiation values, a procedure very useful for modeling tentatives of the global and diffuse irradiances for example.

1.2.2.9 Calibrations

Two kinds of calibration have to be used to obtain reliable results. The electronic circuits represent a variable part of the measuring chain. Indeed, from case to case, one has to cope with different amplification levels, often linked together by long cables lying on the ground, with different impedances. Temperature (the first amplification stages are usually located in the immediate neighbourhood of the instrument, that is outside), external effects (antenna, broadcasting stations) must be taken into account in the calibration. This can be solved by using a special procedure of controlled simulation of the instrument signal: the computer is given the characteristics of the sensors and sends appropriate signals (usually about 100) covering its dynamic range to the digital/analog converter. The signals are then transmitted to the nearest possible location of the sensor which is of course disconnected. A digital voltmeter reads the voltages at this point and sends them back to the computer in digital form. The response of the whole measuring chain is read as in normal operating conditions (figure 1.3). Simple regression between the two sets of points is then computed in order to yield complete scalling factors, with all possible effects integrated by the procedure (for example abnormal behaviour of one of the components).

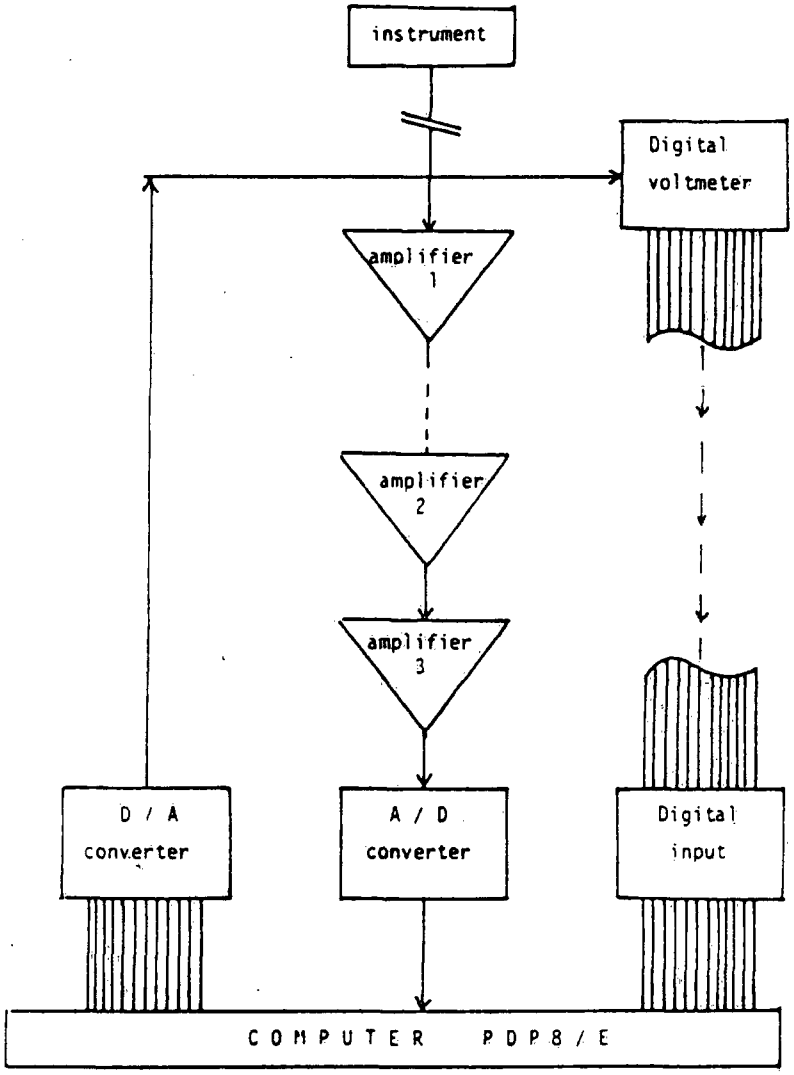


Fig. 1.3. Schematic diagram of the calibration procedure. In normal operating conditions, the instrument signals are amplified and digitalised. During the calibration, the instrument is disconnected and simulated by the computer through the D/A converter. The input voltages are simultaneously read by a digital voltmeter which transmits them to the digital input of the computer.

This calibration procedure is repeated regularly during a campaign in order to take into account possible drifts over longer periods. Direct comparisons with preceding compaigns allows one to check the state of the system, as any changes in quality can be immediately noted. It is evident that this kind of procedure is worthwhile as long as the system remains in good condition, but is not very practical for locating faulty components: in the latter case, tests at each level have to be performed. An accuracy of about 0.1% full scale is obtained, a value significantly better than the expected uncertainty of the measuring instruments.

The problem of calibrating the instruments themselves is different. As redundancy cannot be afforded, each unit is compared with the WRCD standards at least once every two years. Intercomparisons are routinely performed during the campaign to test the stability of the sensitivity ratios as damages can easily occur during transport or installation.

- The absolute radiometer is directly compared with the World Standard Group in Davos. Furthermore, it is possible at present to perform characterisation measurements of the cavity on optical benches with laser techniques, allowing for independant tests; a method particularly useful when high precision is required, for example for satellites experiments.
- The pyranometers are much more difficult to calibrate. They are usually compared directly in horizontal position with the WRCD standard, which is routinely calibrated against absolute radiometers with the shading method. Unfortunately, this requires stable atmospheric conditions, which are usually not found when desired, and very careful installation procedures. Numerous disturbing effects are possible, as noted in section 1.2.2.6. As the method can be used only for specific diffuse radiation spectral and angular distributions and a limited range of direct intensities, a possible non-linearity of the response for other intensities cannot be a priori excluded. For a given restricted range of the relevant parameters, an uncertainty of 1-2% can be expected, though this value is somehow too optimistic in the case of rotating instruments and mobile stations.
- Calibration of the spectroradiometer and the relevent problems are described in the Annex.
- As no absolute calibration was performed for the photometers, a theoretical value is computed from the design data of the optical components, the sensitivity curves of the diodes and the transmission curves of the filters. The instruments are regularly tested and compared among themselves either facing the sun or at different angles in order to compute response ratios for different intensity levels. The obtained scaling factors are tested for the grey absorption case by integrating the radiance values over the upper hemisphere and comparing the results with the diffuse irradiance on a horizontal surface measured by the seventh pyranometer. Model calculations performed with the LOWTRAN code (14) show that the missing part of the spectrum in the infrared region cover a range from 10 to 20% of the total intensity depending mostly on the water-vapour content of the atmosphere (table 1.2).

  There is, indeed, a problem of calibrating spectral instruments which are alternatively used for irradiance and radiance measurements: in the case of irradiance, apart from absolute calibration in the laboratory which are rather cumbersome and time consuming, the Langley method is certainly the most suitable. For this purpose, normal measurements sequences can be used, but, obviously, they require stable atmospheric conditions during the entire day. The radiance case is handled as described above and seems to give fairly good results as long as one is satisfied with approximate absolute values. Simple model calculations can be used in the case of interference filters (15). When only relative intensity distributions are required, direct comparisons between instruments give acceptable results.

DH/GH	Sun height [°]	Integrated value [W/m²]	Measured value [W/m²]	Corretion factor
0.12	39.8	66.1	76.4	1.16
0.19	16.4	37.8	43.8	1.16
0.20	64.6	160.2	177.9	1.11
0.31	22.9	78.0	92.2	1.18
0.41	41.1	217.4	238.0	1.10

Table 1.2. Sample results of the comparison of the irradiance values obtained by integration of the photometers' measurements and by the horizontal pyranometer's readings. GH and DH are respectively the global and diffuse irradiances on a horizontal surface and the ratio DH/GH gives an estimate of the transparency of the atmosphere.

1.2.3 Data acquisition system - Computer

The mobile station MORAS is equipped with a mini-computer for acquisition, organisation, control and a first evaluation of the data.

The instruments are connected to the station with 100 meter cables for the signal transmissions in both directions. The mobility of the system requires high quality and robustness of the whole system as the precision of the final results will only be as good as the precision of the worst part of the measuring chain. As the station is in continuous development, particular care must be taken in the choice of the different components to avoid unexpected influences of the harsh environmental conditions like vibrations during transport, quick temperature changes, etc...

1.3 Data transfer - Databank MORLIB

At the end of a compaign, all the result files (about 250 for normal conditions) are transferred to the computer of the Federal Institute of Technology in Zurich over the telephone network.

The original files are copied on magnetic tapes and archived. The data are stored in a databank system developed by J. Ruchti (EAWAG) and adapted by the author. The two main access keys to the databank are instrument type and date. Each instrument type is sorted from the results file and stored sequentially according to the daynumber and the series number within the day: this is the smallest accessible unit or 'document'. The first document on each file (instrument type-year) is however reserved for the storage of parameters like start time, scaling factors, station name , etc... , and the address of the corresponding document in order to avoid time consuming sequential readings during the retrieval of the data.

1.4 Installation - Operation

Particular care must be taken when choosing a measuring site with a mobile system to avoid the loss of valuable information through external interference. Generally speaking, when no special type of measurement is requested, the following criteria should be more or less fulfilled:

- low horizon to facilitate the evaluation of the atmosphere-ground interface for the global/diffuse radiation measurements.
- no obstacles near the station which could affect the results by exagerated reflections (white buildings) or volumes (trees),
- the albedo should be as homogenous as possible to avoid complicated reflection patterns or mosaic (middle of the sea, desert, snow, top of mountains are ideal),
- the site has to be accessible to trucks, noting that the return trip could take place under very different climatic conditions,
- if possible, electricity and telephone connections should be available, the latter especially for short term notices of rapid weather degradations by the Meteorological Office,
- the instruments should be placed as far as possible from the white trailer and out of reach of curious visitors or animals (flat roof, top of hill, ...).

Once a good location is found, the station is installed and the necessary preparation must be performed, including careful calibrations of the system, set-up and anchoring of the instruments, determination of the geographical south and pictures of the whole installation. The measurements can then begin.

2 - NON-SPECTRAL MEASUREMENTS

The present work illustrates the potential of information contained in the station MORAS. The laboratory may be used for many purposes, but mainly to display the structure of the shortwave solar radiation field and for atmospheric physics. Basically, anyone looking for an estimate of the properties of the atmospheric layer overhead, or interested in solar energy applications, or trying to develop new models for improves simulation of the radiation characteristics, could find a first answer in the potential of the MORAS station. This is a unique opportunity because of the possibility of carrying out practically all types of measurements known today in the field of short wave radiation and this with a system designed to be moved easily from one place to another. The results concerning non-spectral measurements together with many of the explanations as well as comments made in this chapter have already been presented in earlier publications and are parts of the current work of the Service (16, 17, 18, 19).

The following is a brief description of the non-spectral results of the station, which are more dedicated for solar radiation meteorology and its applications.

2.1 Direct solar irradiance

The direct component of the solar radiation is measured by the absolute radiometer described in section 1.2.2.2. Figure 2.1 and 2.2 illustrate its daily variations for a clear day and for cloudy conditions respectively. In the first case, filter measurements are performed and the resulting curves are plotted with the corresponding number of the filter indicated on the curve. In the second case, no filters are used. Figure 2.3. shows the difference between the two types of measurements (with and without filters) which are alternatively used during one clear day in order to demonstrate the influence of the measuring frequency. It is clear that part of the information, that is the small and rapid variations of the atmospheric transparency, is lost when measuring with filters. This phenomenon is further illustrated on figure 2.4 where a photometer equiped with the correction filter (section 1.2.2.7) is placed on the sun-tracker and measures parallel to the absolute radiometer but with a higher frequency (solid curve). The radiometer values are quadratically interpolated (broken curve) and the quality of the interpolation can in this way be well demonstrated. These results show that much care must be taken when using interpolated values of the direct irradiance for further computings of the diffuse irradiance, especially in the case of rapidly varying cloud cover.

The case of figure 2.1 is also of interest as it shows distinctly a destabilisation of the atmospheric transmission at about 0930 (solar time) approximately. This may be explained by:

- convection due to high surface temperature (summer),
- pollution coming from the neighbouring town of Zurich,
- take-off and landing of military jet planes from the nearby airport, as the jets were flying directly above the instruments and thus leaving clouds of exhaust gases.
- precondensation of water-vapour.

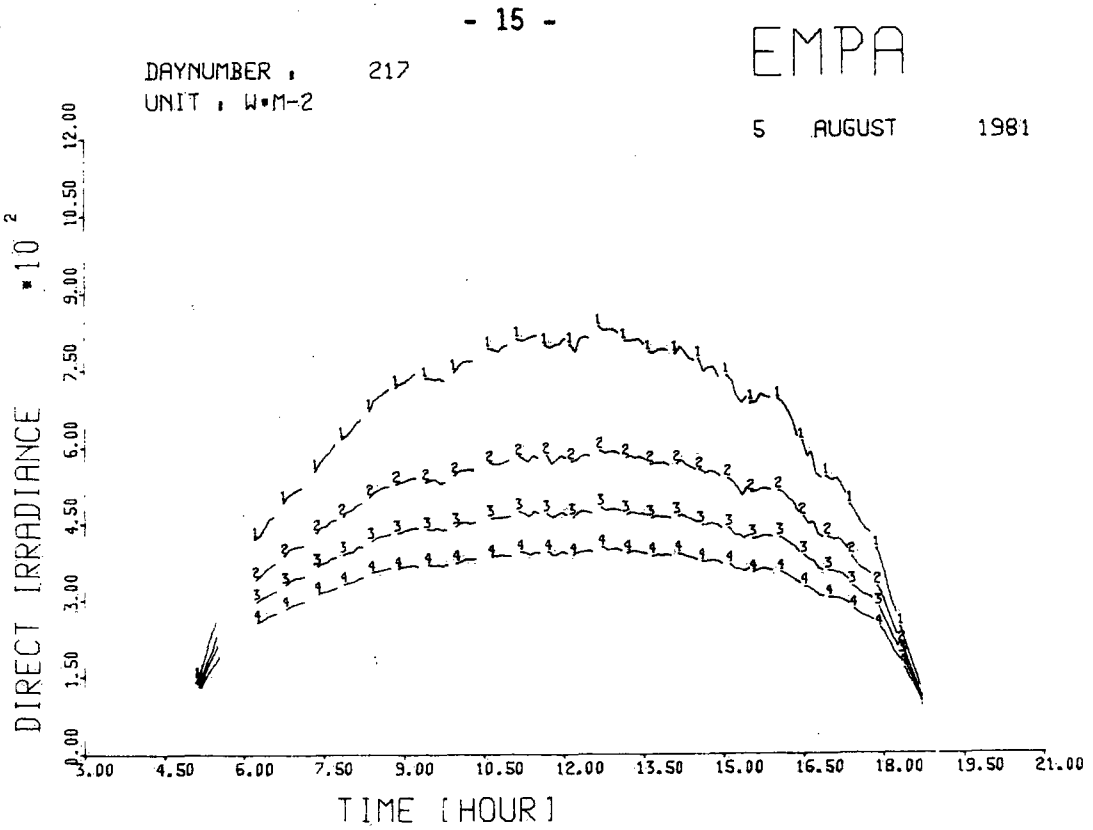


Fig. 2.1. Daily variation of the direct irradiance. The signature of the curves represents the number of the filter (see text). Local mean solar time is used.

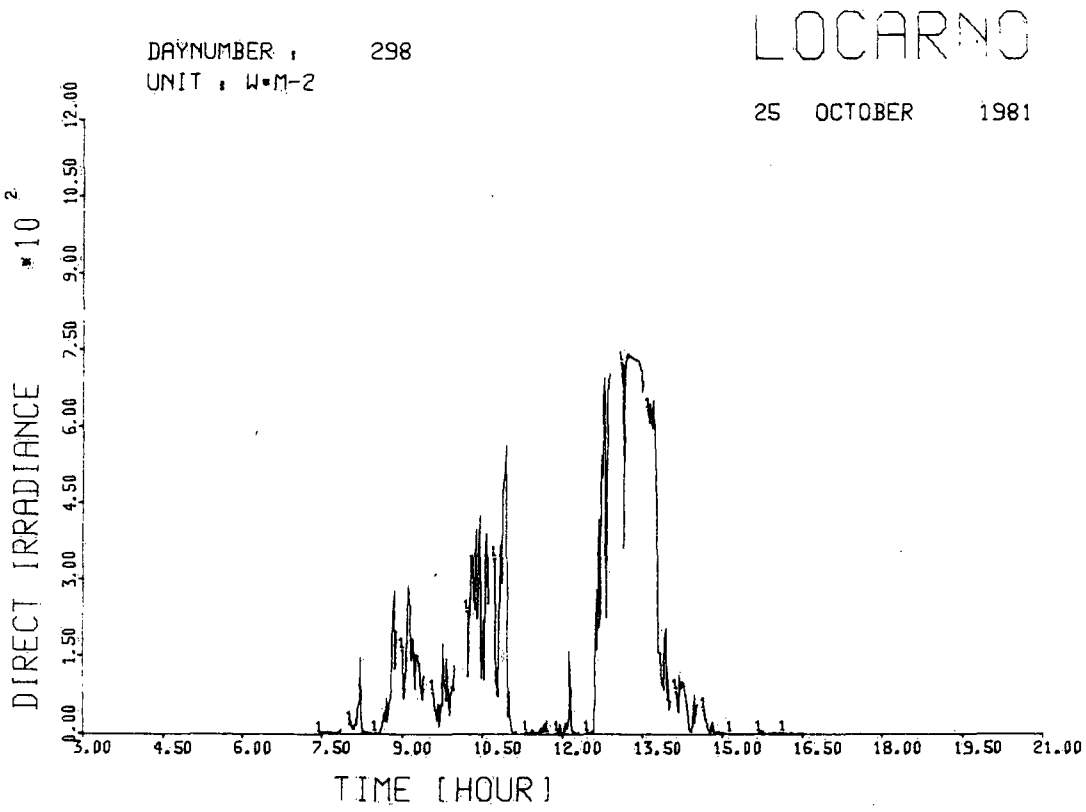


Fig. 2.2. Same as fig.2.1, but for cloudy weather. Only the first filter position (no filter) is used.

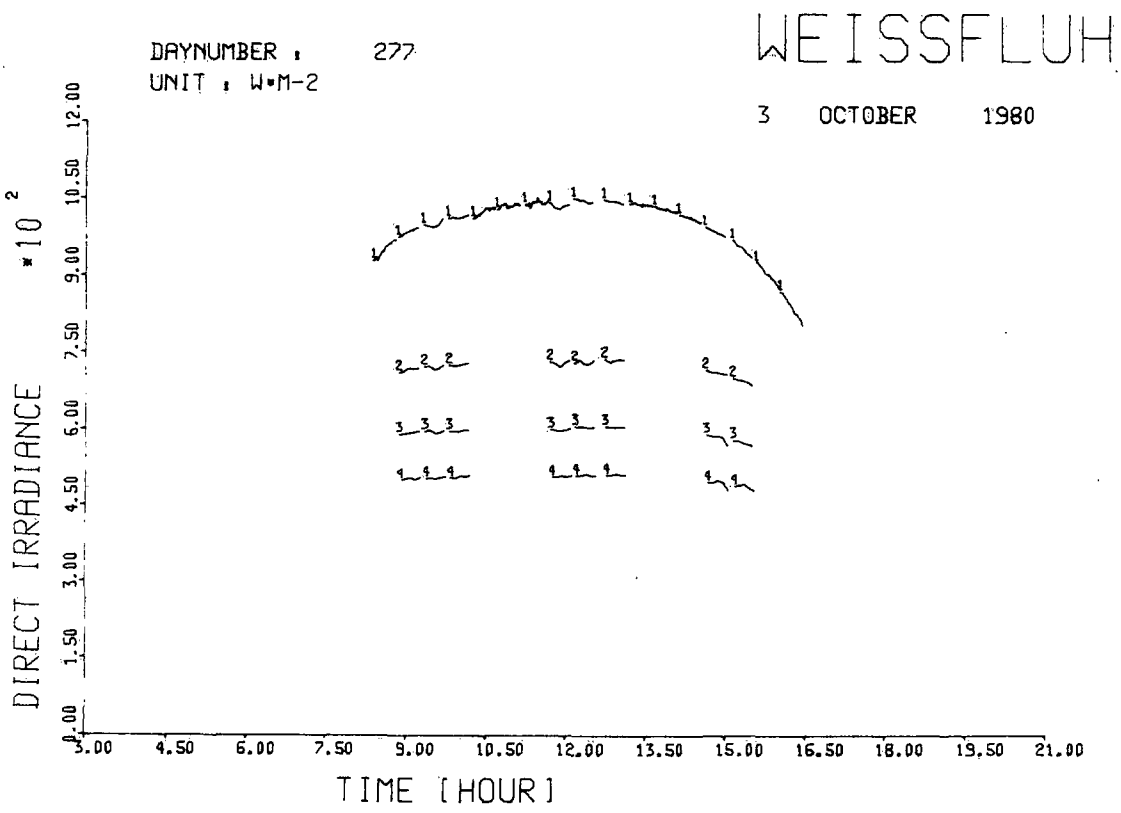


Fig. 2.3. Daily variation of the direct irradiance. Measurement with and without filters are alternately performed (see text). Local mean solar time is used.

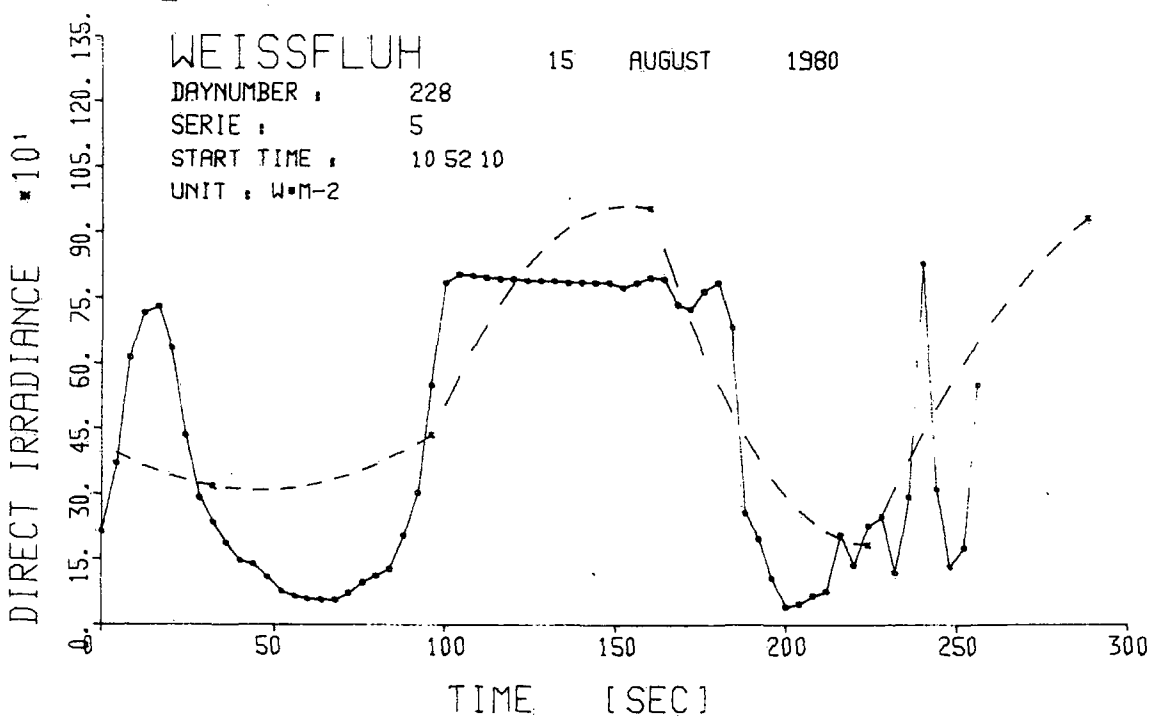


Fig. 2.4. Comparison between direct interpolated irradiance (broken curve) and intensity measured by a photometer (solid curve) equiped with the correction filter. The differences in intensities are due to the reduced spectral range of the photometer and the lack of accurate calibration.

Only a thorough spectral study of this phenomenon could bring a possible adequate and detailed explanation as presented in the publication mentioned in the introduction.

The above examples show that measurements of the direct irradiance give a good idea of the stability of the atmosphere, but one has to be particularly careful when interpolating between the values. Figure 2.2 illustrates that in the case of strong variations, for which the instrument's time-constant is very long, it can be very difficult to draw precise conclusions and to try to compute further variables. For clear sky conditions however, important information can be derived about the aerosol content of the atmosphere as presented in (20).

2.2 Global and diffuse irradiance

Section 1.2.2.6 gives a technical description of the different pyranometers used in the mobile station MORAS. The possibilities of operation and measurements are numerous:

- the first 5 pyranometers are mobile and allow study of the daily variations of the global and the reflected irradiances for different orientations,
- the frequency of the measurements can be changed at a given position by changing the sequence of orientations,
- the pyranometers 6 and 7 which measure every 20 seconds without any rotation (apart from the sun-tracker) can be used to assess the short time irradiation changes,
- the diffuse irradiance corresponding to each orientation can be calculated from the global and the direct solar irradiances.

Different sources of error must be kept in mind:

- position of the instrument (mechanical failure),
- sensitivity changes with time,
- orientation of the instrument,
- time constant effects during rapid changes of intensity,
- for the diffuse component, errors due to interpolation of the direct irradiance.

Some of the above mentionned error sources are inherent to all radiation measurements, but may cancel if integration over longer time periods is performed (hourly, daily values).

2.2.1 Daily variation

Figures 2.5 and 2.6 illustrates the daily variations of the global irradiance for different orientations. The symbols used are presented in the following table:

Fig. 2.5 - 2.7			Fig. 2.6 - 2.8		
Symbol	Azim.	Zen.	Symbol	Azim.	Zen.
o	0	90	o	0	90
Δ	90	90	Δ	0	75
+	180	90	+	0	60
×	270	90	×	0	39
6	sun track.		◇	0	18
7	-	0	↑	0	0

Table of azimuth and zenith angles

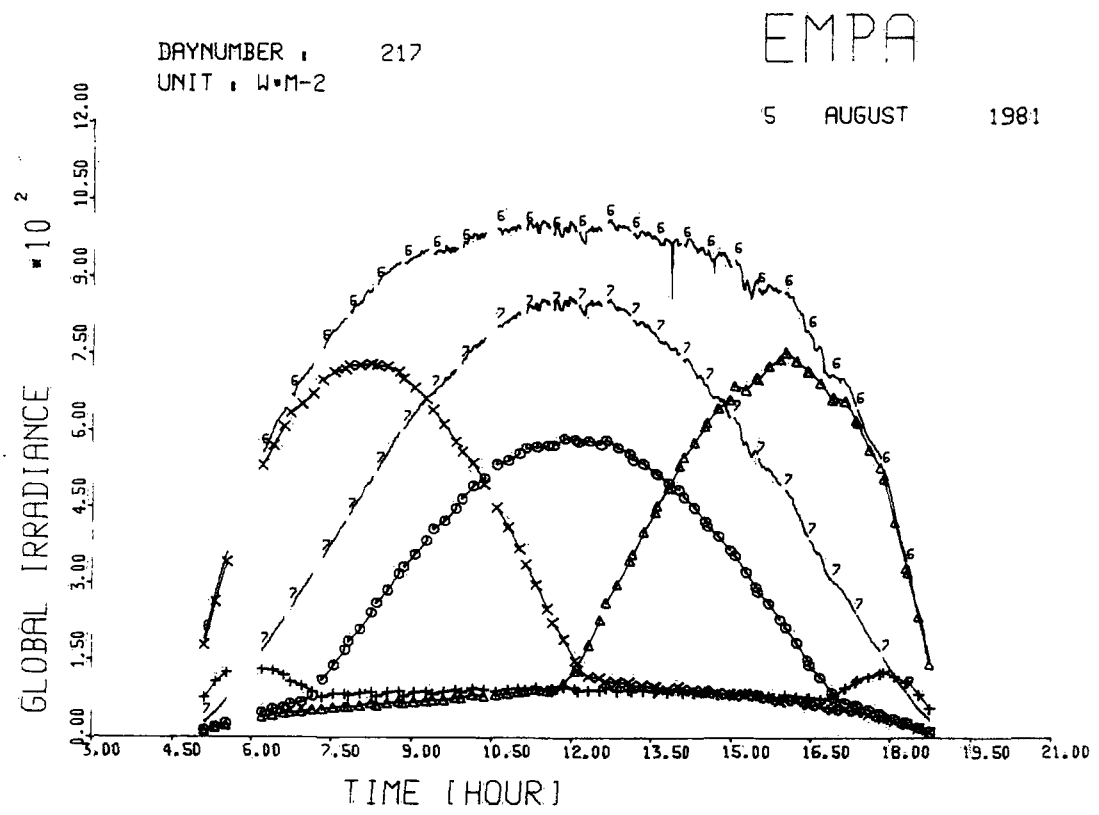


Fig. 2.5. Daily variation of the global irradiance on different surfaces (see text). Local mean solar time is used.

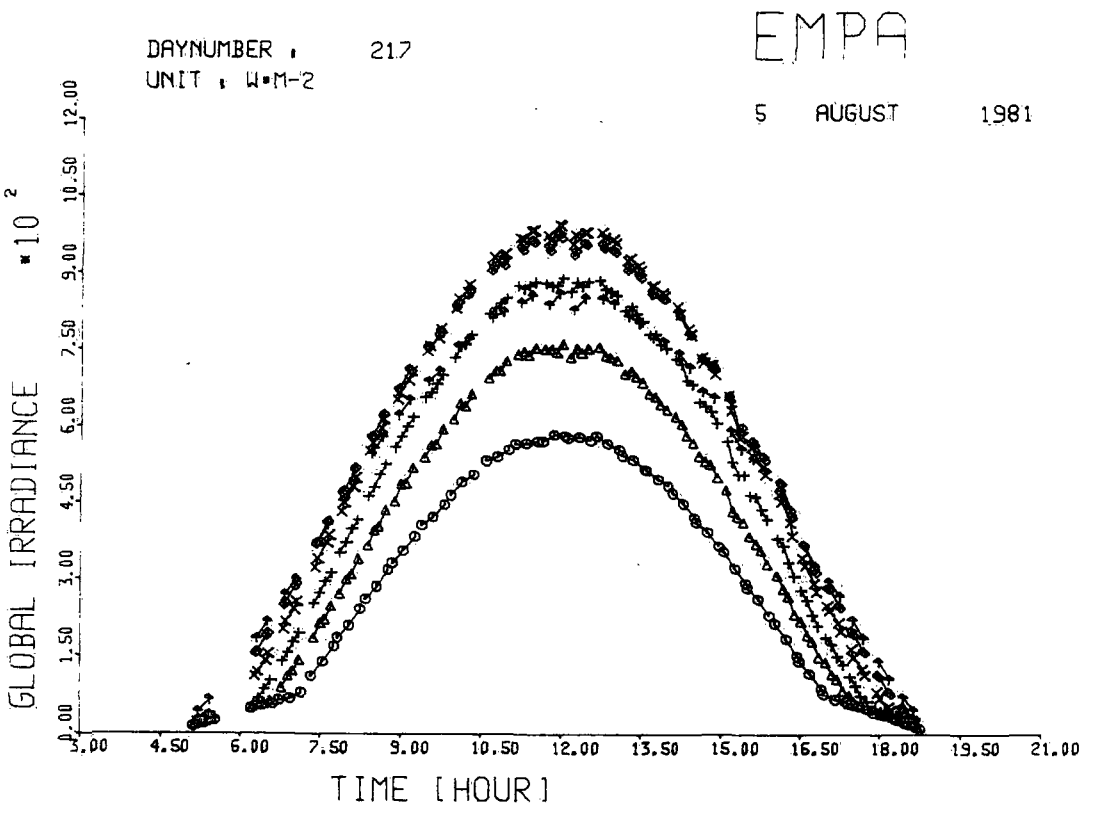


Fig. 2.6. Daily variation of the global irradiance for south oriented surfaces with different inclinations. Local mean solar time is used.

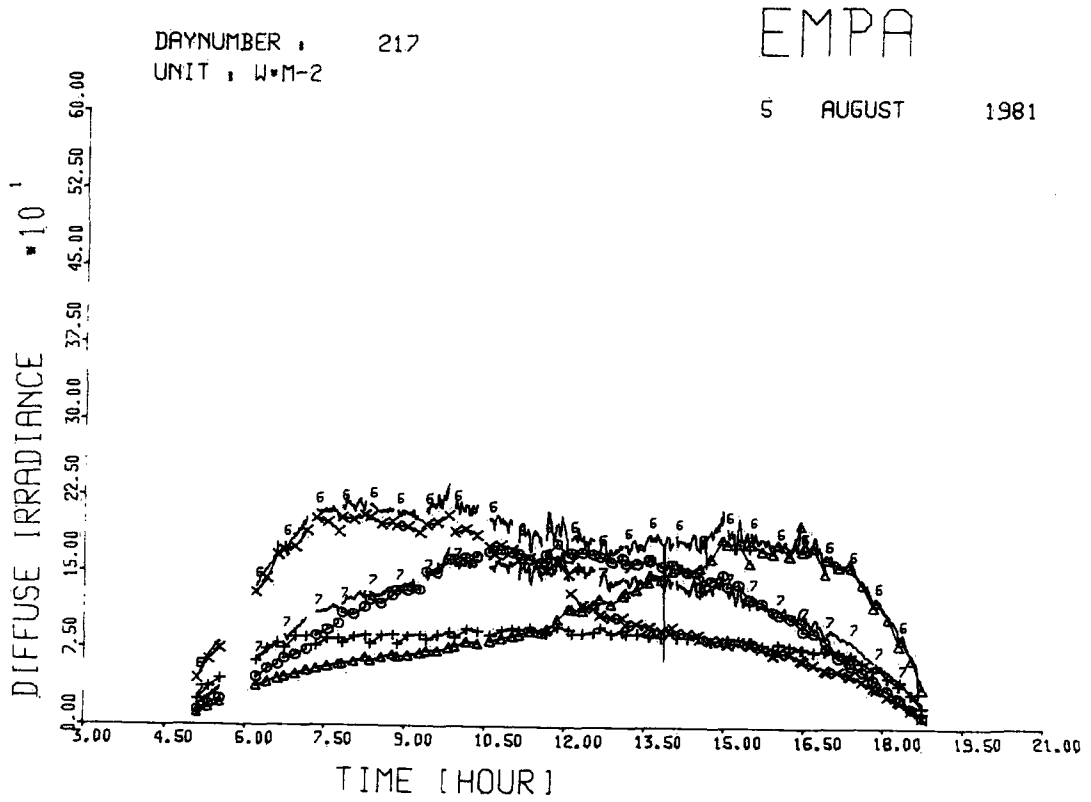


Fig. 2.7. Daily variation of the diffuse irradiance on different surfaces (see text). Local mean solar time is used.

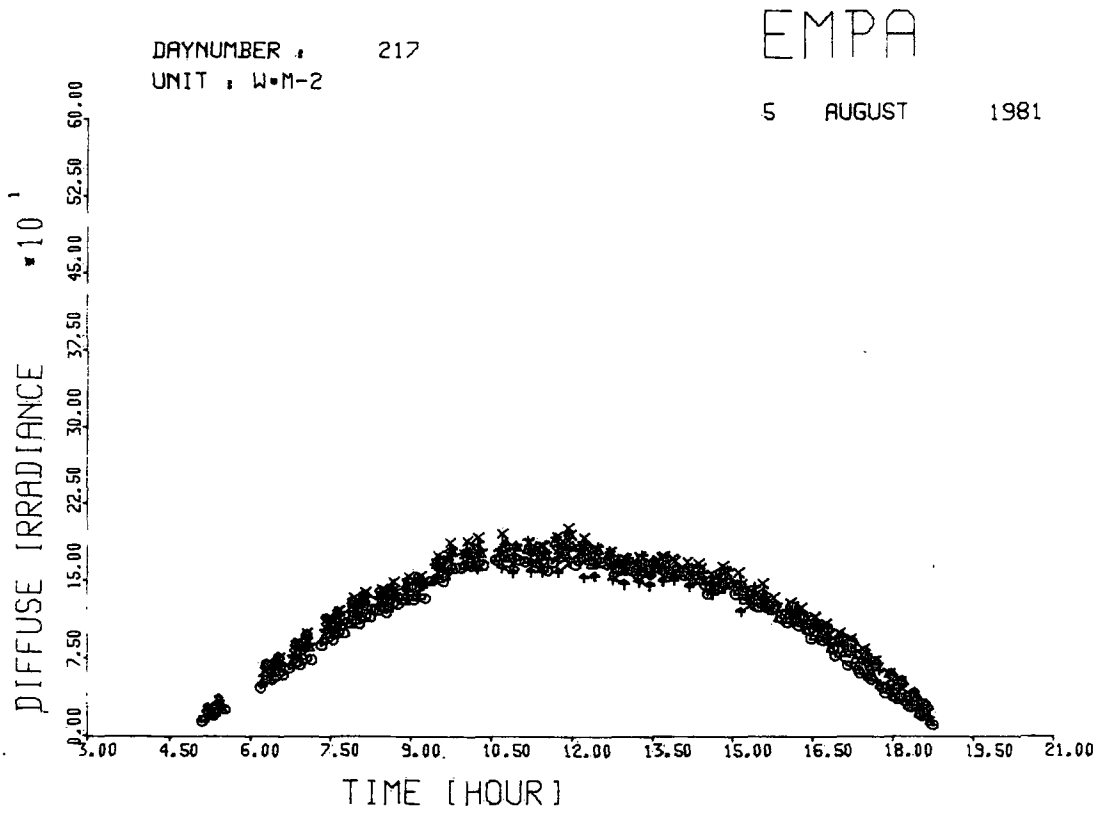


Fig. 2.8. Daily variation of the diffuse irradiance for south oriented surfaces with different inclinations. Local mean solar time is used.

As mentioned earlier, the results for any orientation can be evaluated if not directly, then through interpolation (linear, quadratic, spline, etc...).

Figures 2.7 and 2.8 present the diffuse radiation component computed from the above examples with the following formula:

$$D_i = G_i - I \cdot (\sin h \cdot \cos \nu + \cos h \cdot \cos A \cdot \sin \nu)$$

where

Di = computed diffuse irradiance,

Gi = measured global irradiance with orientation i,

I = measured direct irradiance,

h = sun elevation.

ν = zenith angle of the instrument

These four figures show that most of the variations come from the direct component of the irradiance which mainly determines the shape of the curves. The variations of the diffuse component are relatively small and, thus, the assumption of an isotropic distribution is satisfactory in most cases. For detailed studies however, the influences of the aureole around the sun, of the distribution of the cloud cover in amount and type and of the albedo of the surrounding landscape has to be taken into account and can be derived from the measurements. This means that for many applications where time-integrated values are required, knowledge of the characteristics of the direct irradiance is sufficient for deriving statistical values of fair quality with the diffuse component approximated by mean values (through yearly statistics of the turbidity for example). Furthermore, recent studies (21) demonstrate that the "best" way to obtain values of the three variables (global, direct, diffuse) is to measure the direct and the diffuse components and compute the global irradiance. Past and recent publications show that the inclusion of the non-isotropic diffuse component leads to better results in the modeling of the global irradiance, e.g. for applications to shade ring corrections. The results obtained with the MORAS can help to check and improve the models. Furthermore, the accurate measurements of diffuse irradiance yield interesting results concerning its dependance on the turbidity and the cloud cover.

2.2.2 Angular distribution

As mentioned above, the angular distribution of the global and diffuse irradiance is very important. Figure 2.9 represents the "instantaneous" (1 scan = 6 minutes) distribution of the global component measured by the pyranometer 'flower' and figure 2.10 of the computed diffuse intensity. The isolines are drawn through 3-dimensional quadratic interpolation without any kind of smoothing. Figure 2.10 shows that indeed the diffuse component is quite isotropic but also that there are features which have to be taken into account for accurate modeling. Figure 2.11 gives a time series of a whole day to illustrate the daily variation of the isoline gradient as a function of the sun elevation and the state of the atmosphere. It is also interesting to note that for overcast skies (8/8) or in the case of fog, the intensity maximum tends to creep toward the zenith (figure 2.12).

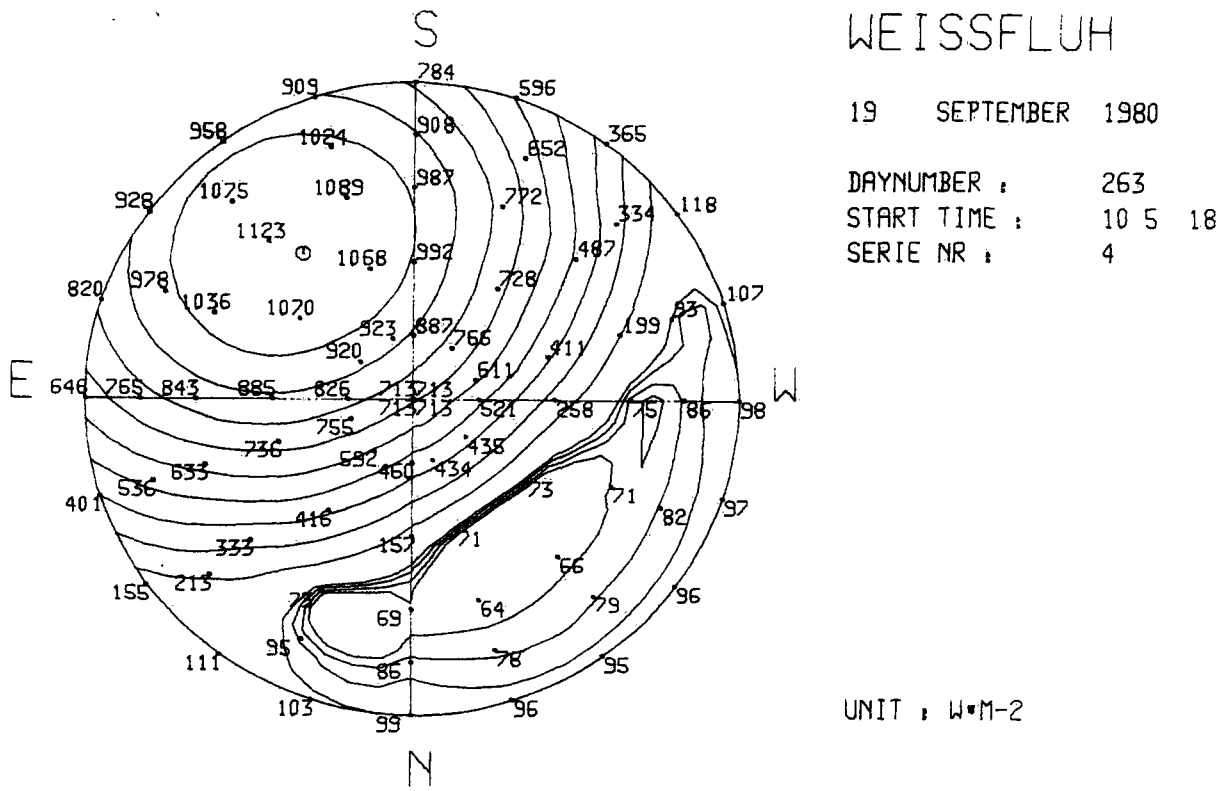


Fig. 2.9. Angular distributin of the global iradiance. The isolines are plotted every 10 W/m^2 up to 100 W/m^2 and every 100 W/m^2 above.

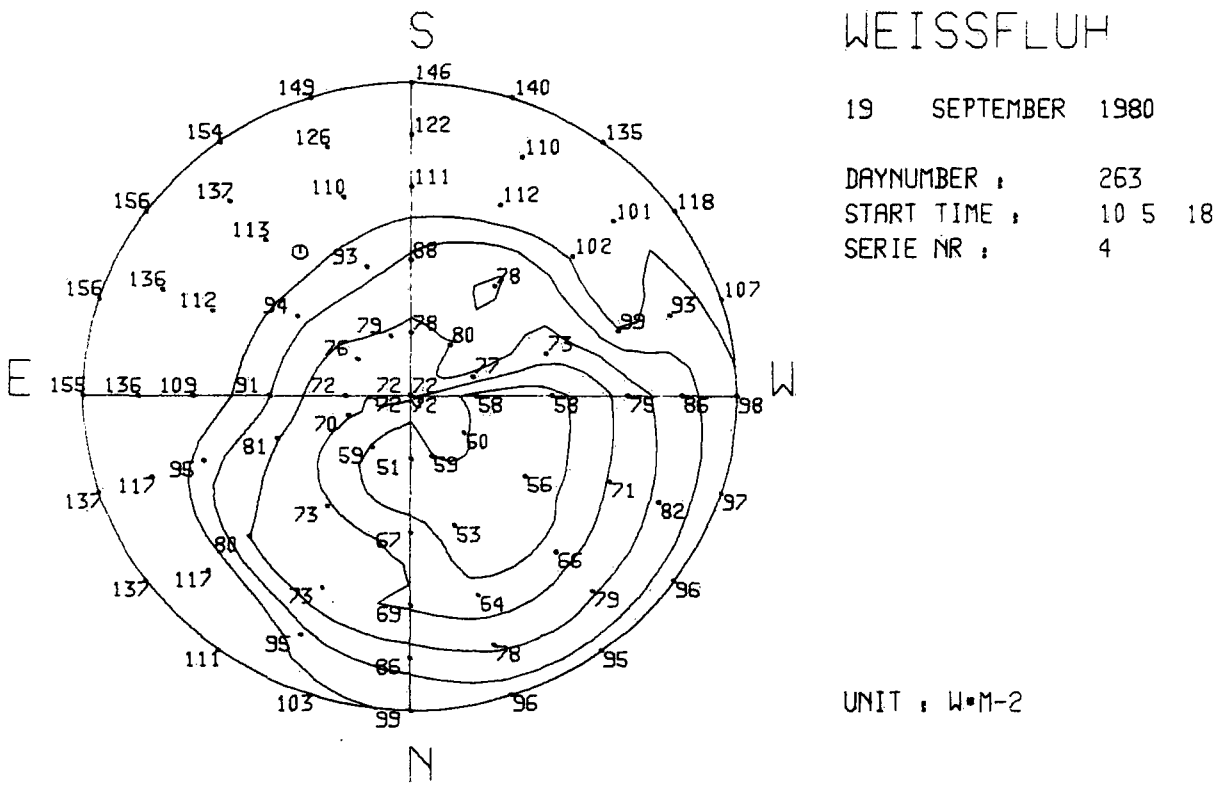


Fig. 2.10. Angular distribution of the computed diffuse irradiance. The isolines are plotted in the same way as for fig. 2.9.

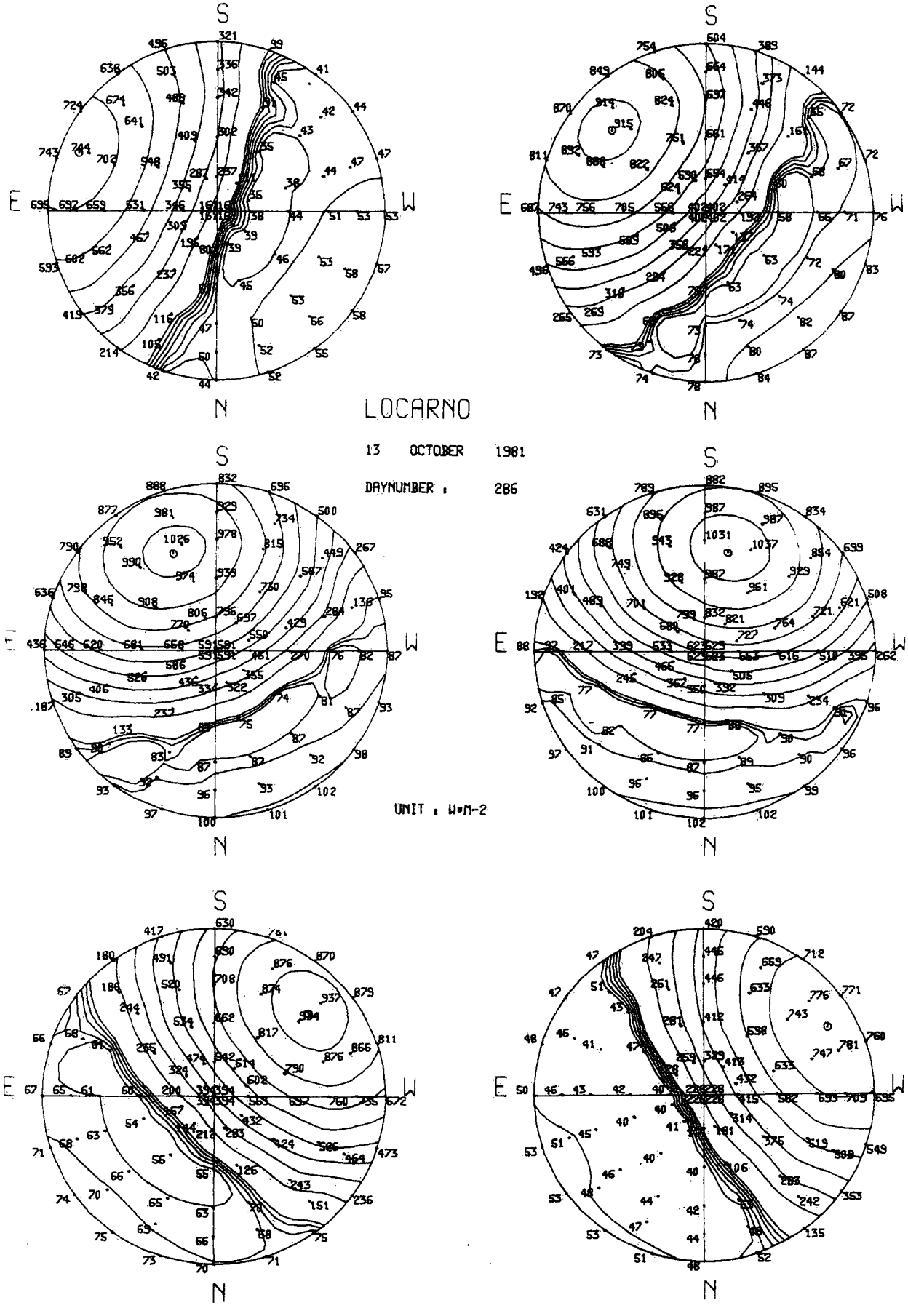


Fig. 2.11. Daily variation of the angular distribution of the global irradiance.

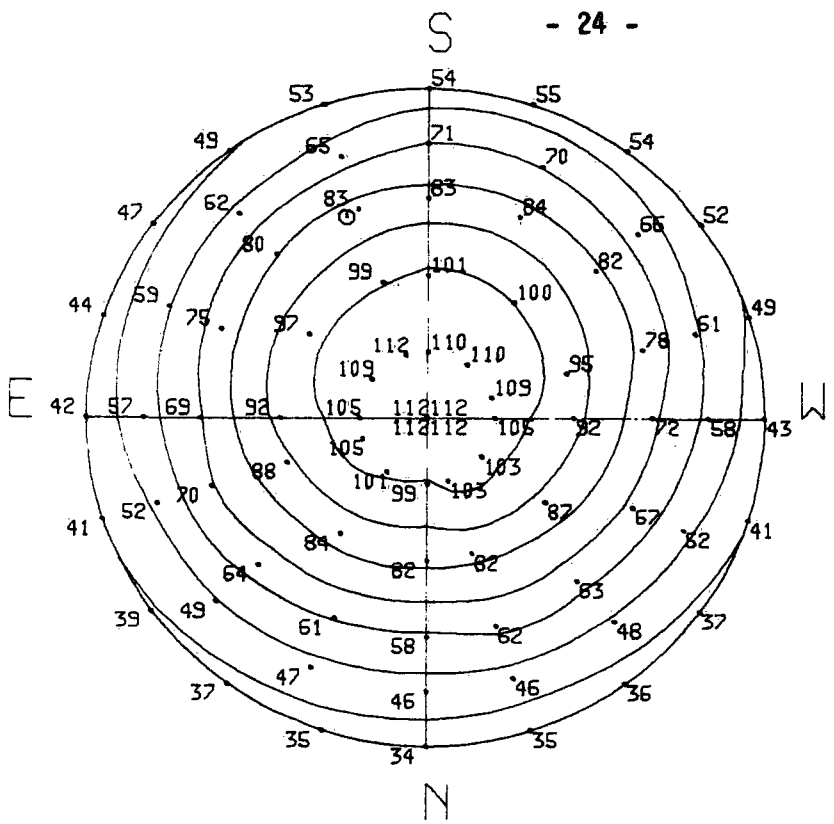


Fig. 2.12. Angular distribution of the global irradiance for overcast sky.

Figures 2.5 to 2.11 suggest another way of illustrating this behaviour and its physical basis: the behaviour of the global and the diffuse components as function of the cosine of the angle between the sun and the instrument normal for clear sky conditions is shown in figure 2.13 for the global irradiance and in figure 2.14 for the diffuse (different scales !!). The importance of the direct irradiance is obvious as is the weak variations of the diffuse component. For varying cloud cover conditions, the picture looks somewhat different (fig. 2.15 and 2.16), but still indicates that the direct part is most important.

The pictures for clear weather conditions are usually easy and straightforward to interpret. Clouds lead to an evident complication of the problem and only integrated values over time are meaningful. Nevertheless, basic understanding needed to interpret the statistics will only be obtained from instantaneous measurements such as shown above.

2.2.3 Reflected irradiance

Measurements of the reflected radiation are performed with the instruments described in section 1.2.2.5, 1.2.2.6 and 1.2.2.7. Global irradiance in this context is defined as the radiation falling from 2π steradians on a surface having the sensor's orientation. The reflected diffuse irradiance is obtained by substracting the component of the projected direct radiation.

Typical results are shown on figures 2.17 and 2.18. The first plot for the reflected global irradiance contains the obvious influence of the direct irradiance on the gradient of the isolines. The second figure gives information about non-homogeneities of the albedo, as seen from a rather short distance (10 meters height). This kind of result is characteristic of a particular site and these data can only be generalized with great care unless the site was specially chosen because of the homogeneity of the ground surface. Nevertheless, the possibility of studying the spatial distribution of the instantaneous measurements over the whole sphere is an essential piece of information to constrain modeling methods. Systematic measurements of the albedo of different surfaces and their non-homogeneous characteristics due to effects such as specular reflection would provide much information about the main reflecting materials (grass, concrete, snow, water, etc...) and could be used to understand better the mosaic albedo seen by airplanes or satellites.

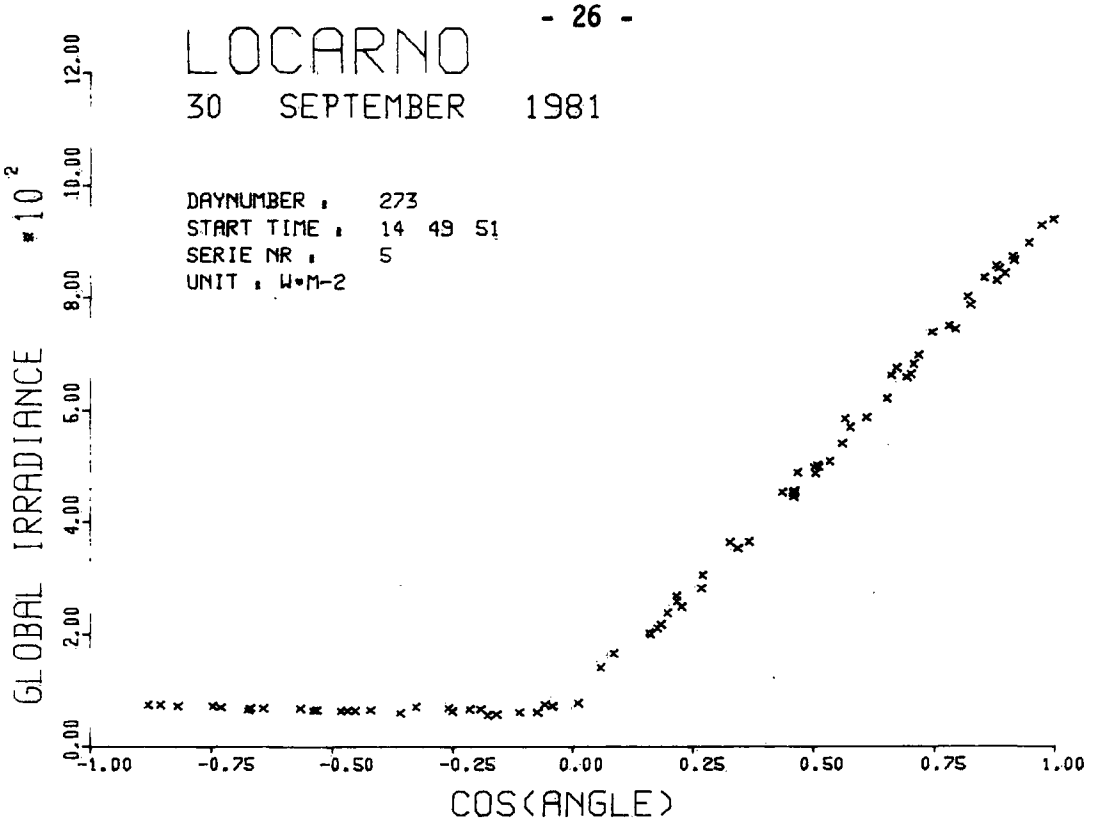


Fig. 2.13. Global irradiance as a function of the cosine of the angle between the direction of the sun and the pyranometer optical axis.

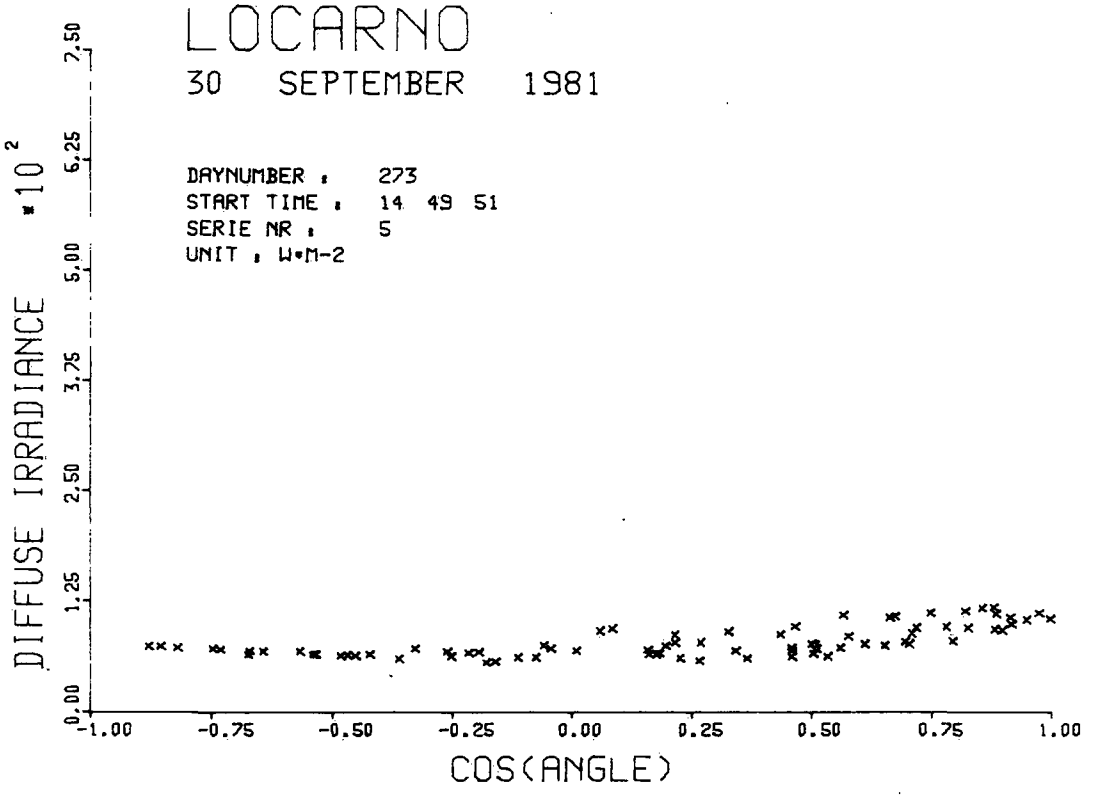


Fig. 2.14. Same as fig. 2.13 for the computed diffuse irradiance.

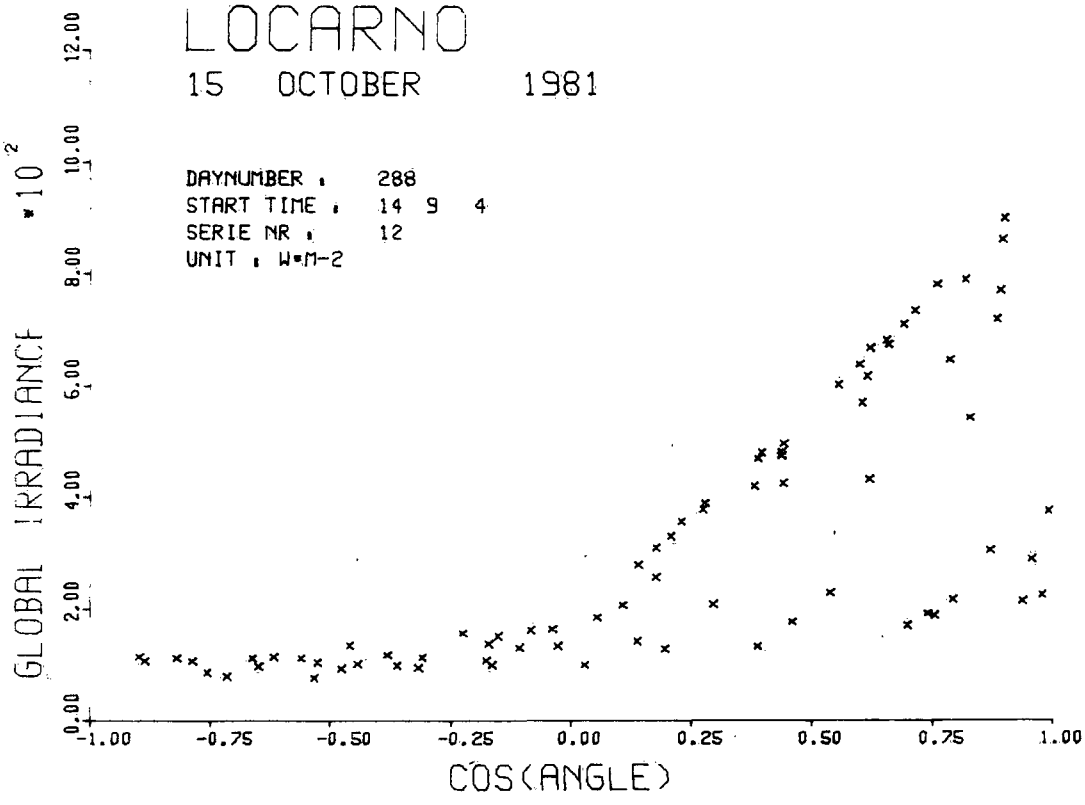


Fig. 2.15. Same as fig. 2.13 for cloudy conditions.

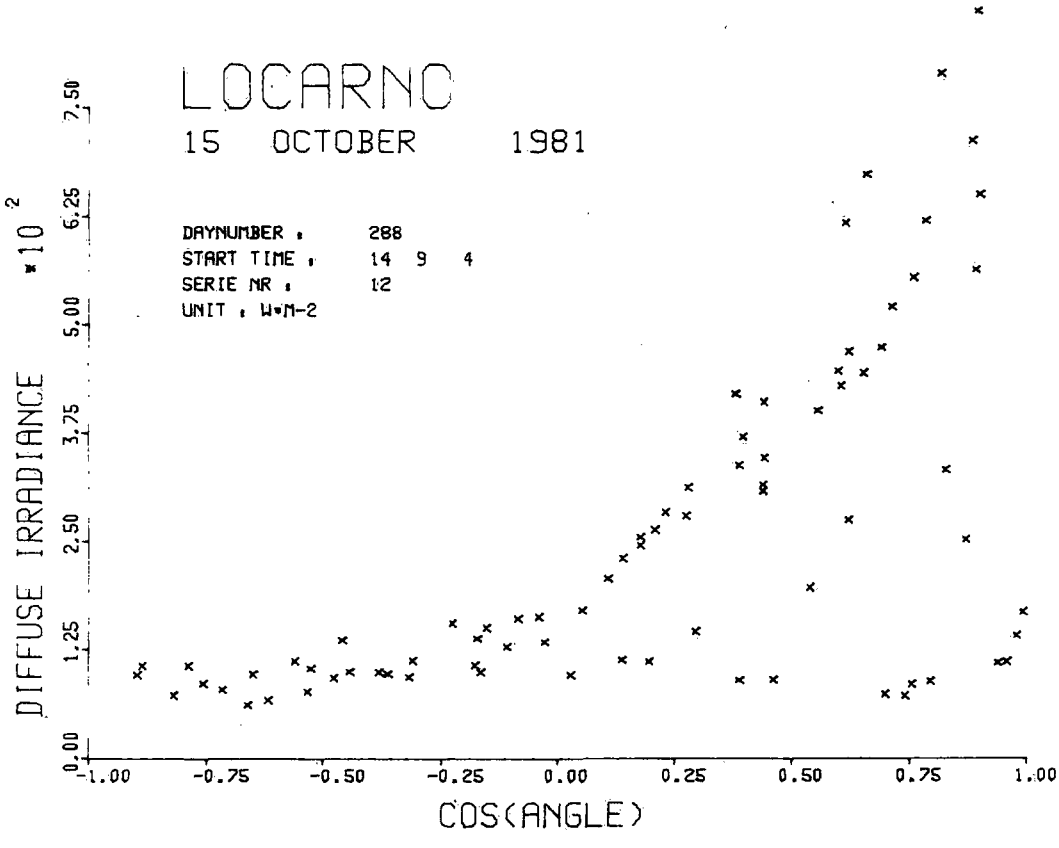


Fig. 2.16. Same as fig 2.14 for cloudy conditions.

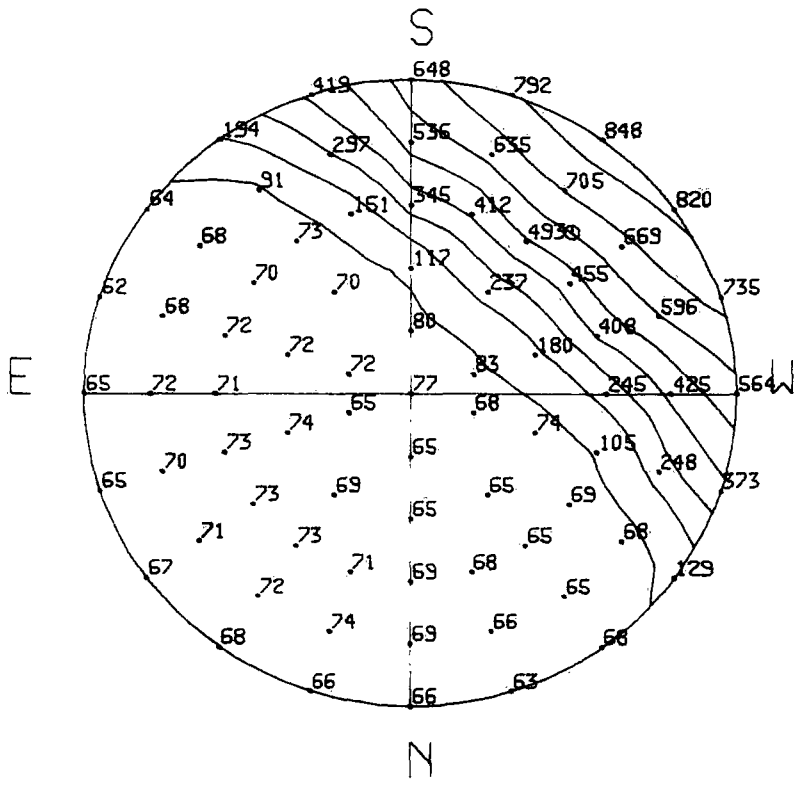


Fig. 2.17. Angular distribution of the 'global' reflected irradiance (see text for definition) measured from the 10 meters high mast.

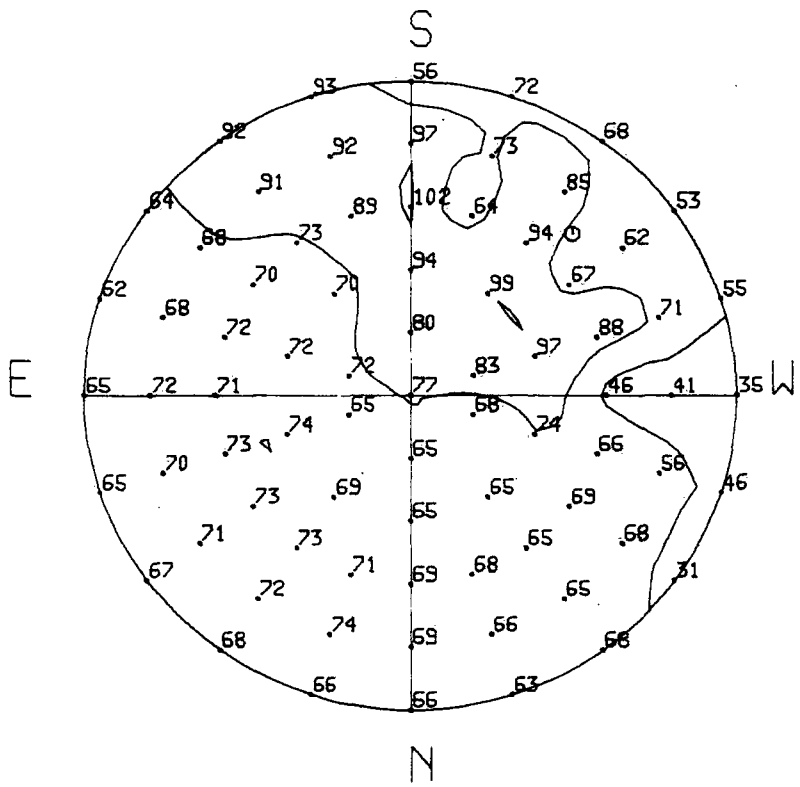


Fig. 2.18. Same as fig. 2.17 for the computed 'diffuse' reflected irradiance.

2.3 Radiance

The use of pyranometers to determine the characteristics of the radiation field gives only information about the properties integrated over 2π steradians of the atmospheric and reflected radiance. In principle, it is possible to derive the resolved angular distribution of the sky radiances from the results described above. Another possibility is to measure this parameter and to check the results with the pyranometers readings.

Sections 1.2.2.7 and 1.2.2.9 describe the type of instruments used for this purpose and the way measurements are performed. Instantaneous radiance spatial distribution can be gathered in less than two minutes as the time constant of the diodes is very short and the only constraint is coming from the mechanical elements. Only the results with the correction and with no filters are presented in the following discussion.

Comparisons between the instruments are routinely performed in order to obtain homogeneous results. As only typical values of the sensitivity, filter transmissions, etc... are used to calculate the calibration factor, its value is approximate, but typical.

2.3.1 Daily variations

Figures 2.19 and 2.20 show the daily variation of the radiance for different orientations chosen in the same way as for the pyranometers for possible comparisons. The symbols used are presented in the following table:

Fig. 2.19 - 2.21			Fig. 2.20 - 2.22		
Symbol	Azim.	Zen.	Symbol	Azim.	Zen.
o	0	90	o	0	90
+	90	90	△	0	72
×	180	90	+	0	54
◇	270	90	×	0	36
△	-	90	◇	0	18

Table of azimuth and zenith angles.

Figure 2.21 and 2.22 give the same information for cloudy conditions. This is certainly a powerful method to characterize the influence of different types of clouds on the radiance and therefore on the diffuse irradiance. Basic research with the data also includes attemps of searching for relationships between the type, amount and angular distribution of the clouds and the measured radiance and irradiance. Models using cloud observations made at airports with a high frequency in order to compute the global and the diffuse irradiances on horizontal surfaces already exist. Satellite cloud observations are also beginning to be used for that purpose with interesting results (METEOSAT). But systematic measurements of the transmission and reflection characteristics of clouds are necessary for

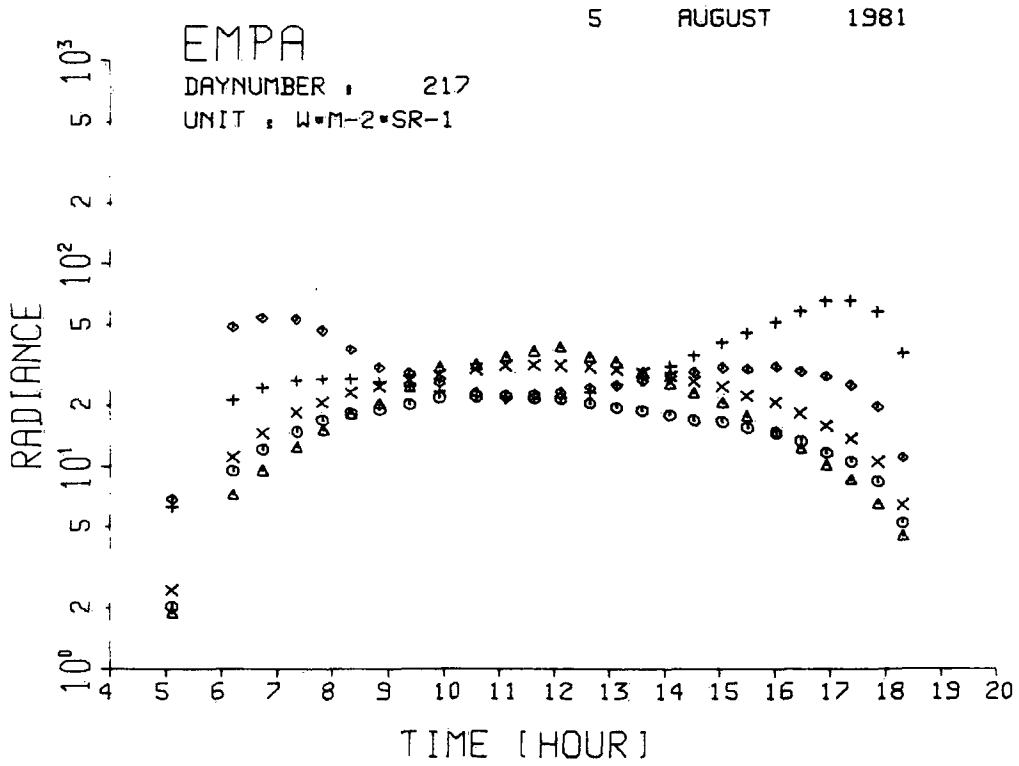


Fig. 2.19. Daily variation of the radiance measured in different directions (see text). Local mean solar time is used.

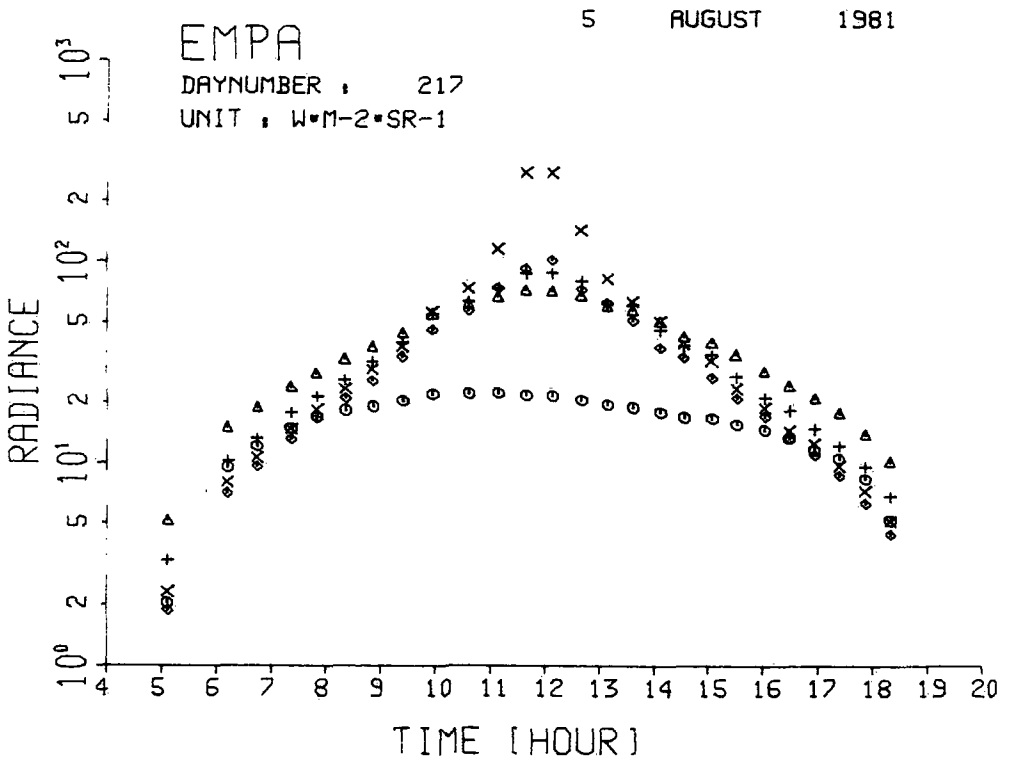


Fig. 2.20. Daily variation of the radiance measured in the south direction with different inclinations. Local mean solar time is used.

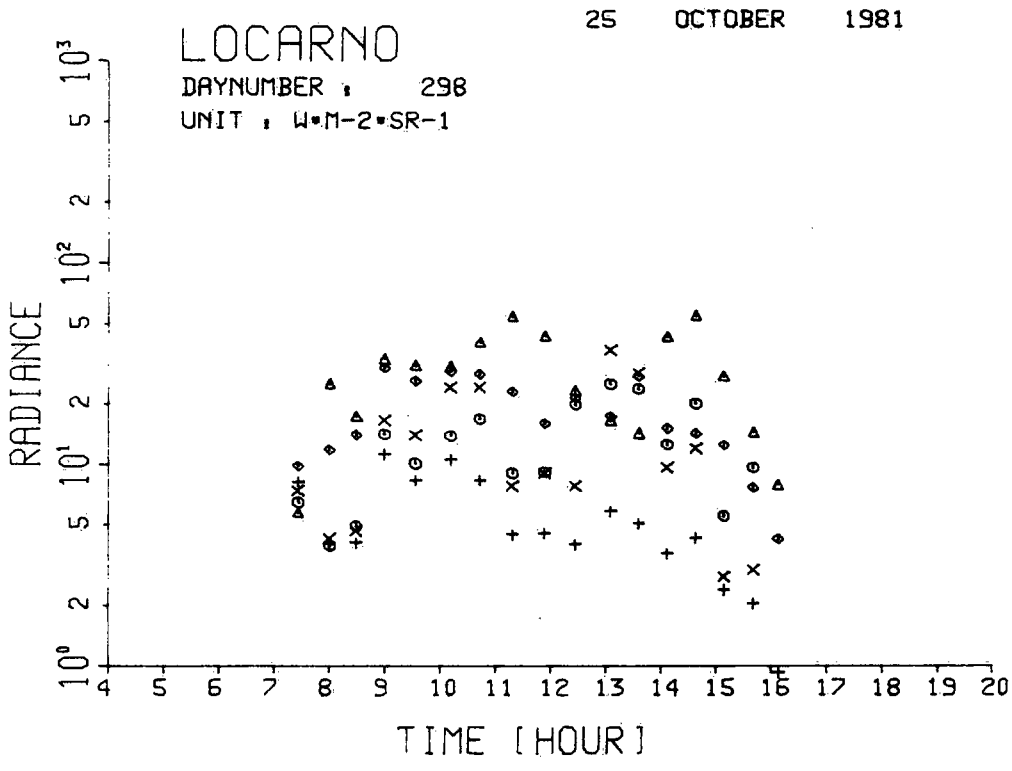


Fig. 2.21. Same as fig. 2.19 for cloudy conditions.

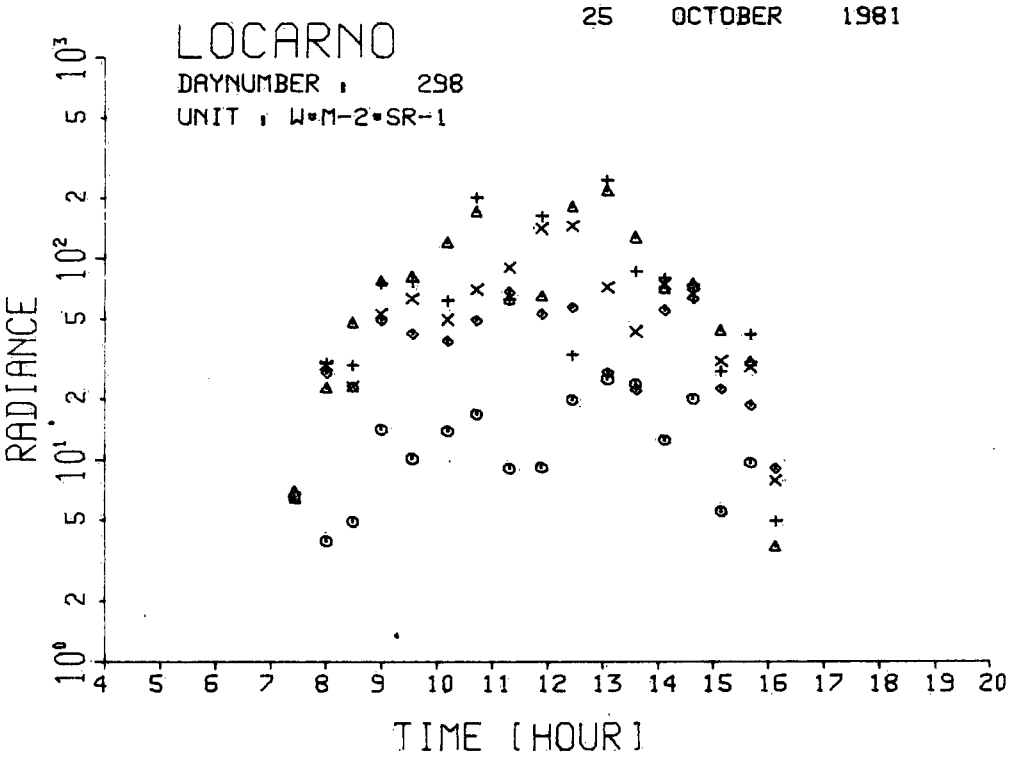


Fig. 2.22 Same as fig. 2.20 for cloudy conditions.

the improvement of the models. The basic research of the Service (17, 18) also includes correlations between zenith radiance and diffuse irradiance on the horizontal surface in order to characterise the radiance distribution from diffuse irradiance measurements only.

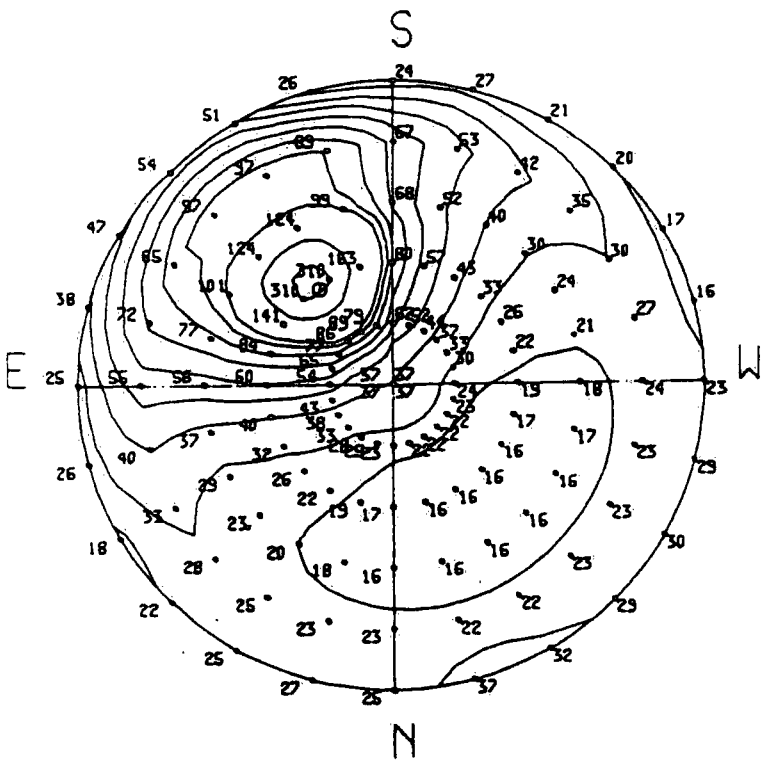
2.3.2 Angular distribution

Figure 2.23 illustrates the instantaneous radiance distribution in absolute units measured by the photometer 'flower' during one complete scan (132 seconds). The isolines are again drawn through 3-dimensional quadratic interpolation without any kind of smoothing. For comparison purposes, the measurement series chosen is the same as for the pyranometer measurements. Figure 2.24 shows the same picture but in relative units with the zenith value being chosen as reference. Figure 2.25 displays the daily variation in order to illustrate the variation of the isolines gradient as function of the sun's elevation and the state of the atmosphere. For cloudy conditions (3/8), the isolines pattern looks smoother as seen on figure 2.26.

Measurements made in the vicinity of the sun must be handled with care. The instruments have a 5 degrees solid view angle so that positions where part of the sun is seen by the diode may be influenced by straylight. Moreover, as the mechanical construction of the 'flower' leads unavoidably to some looseness in the gears, all measurements which are made within a 7.5 degrees solid angle around the sun must be considered as ill defined.

The above examples show a typical distribution pattern of the radiance with a peak around the sun and a hole in the vertical plane containing the sun at approximately a 90 degrees angle from it as one would expect from scattering theory. The isolines follow the typical bean-like shape of the radiance distribution.

Measurements made without any filter are difficult to treat, mainly because of the spectral characteristics of the diode itself. Figure 2.27 is an exemple of such kind of results and may be directly compared with figure 2.24 in order to study the influence of the different spectral sensitivity in the different regions of the sky. The possible use of this type of measurements for photovoltaic applications (solar cells) should lead to a revision of the whole data set compiled during the past few years.



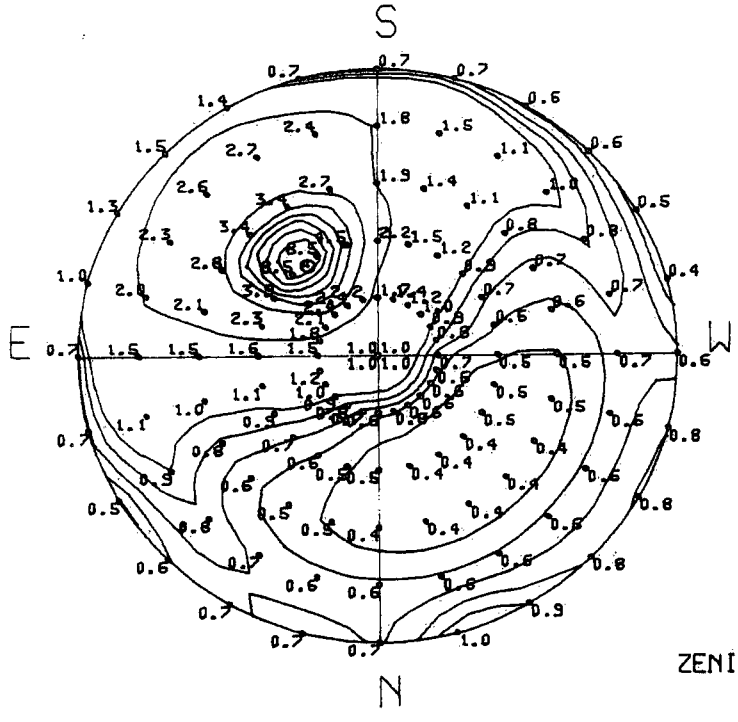
EMPA

5 AUGUST 1981

DAYNUMBER : 217
START TIME : 10 35 24
SERIE NR : 10

UNIT : W•M-2•SR-1

Fig. 2.23. Angular distribution of the radiance in absolute units.



EMPA

5 AUGUST 1981

DAYNUMBER : 217
START TIME : 10 35 24
SERIE NR : 10

ZENITH INTENSITY : 36.5 W•M-2•SR-1

Fig. 2.24. Angular distribution of the radiance in relative units. The zenith value is taken as reference.

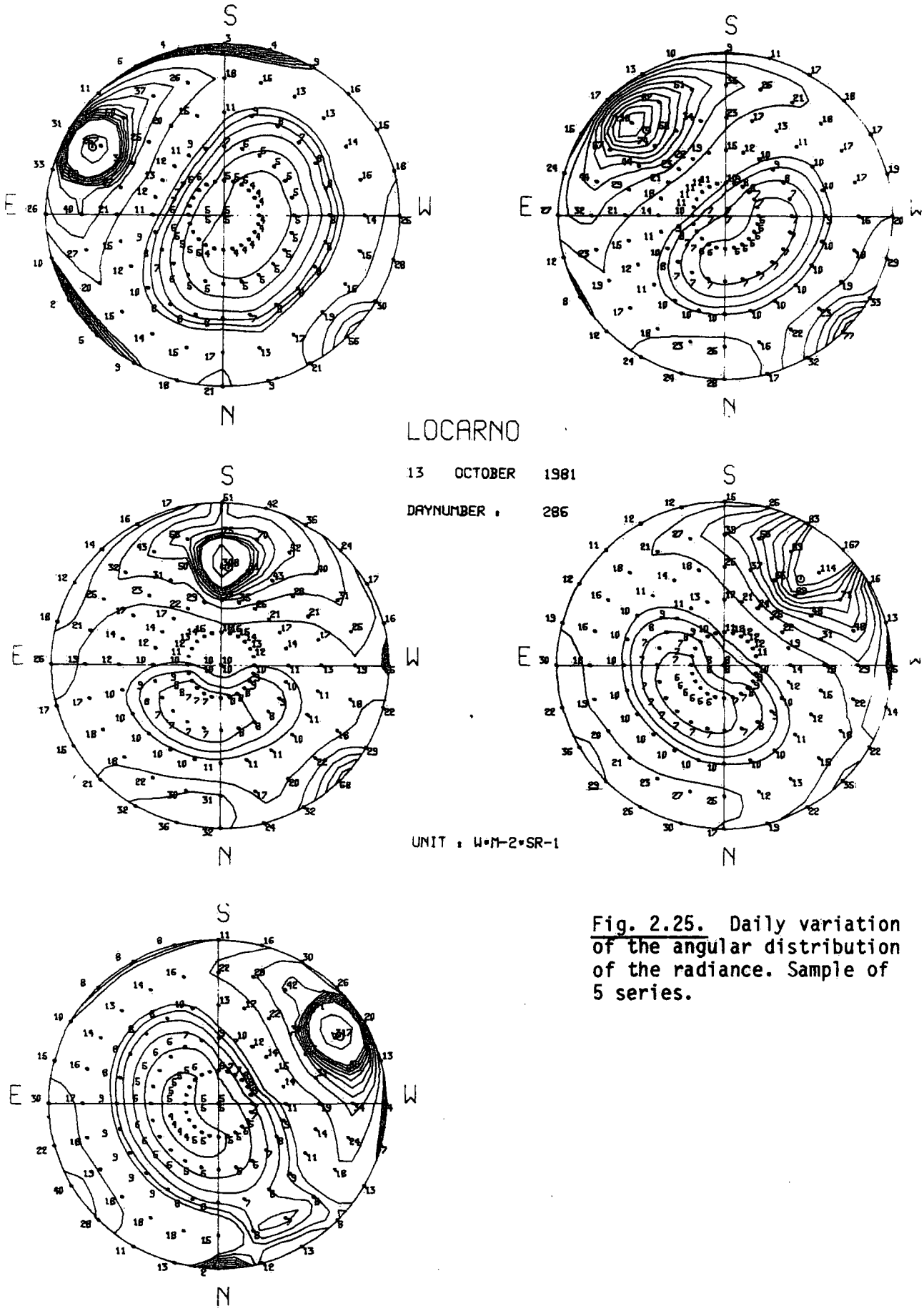
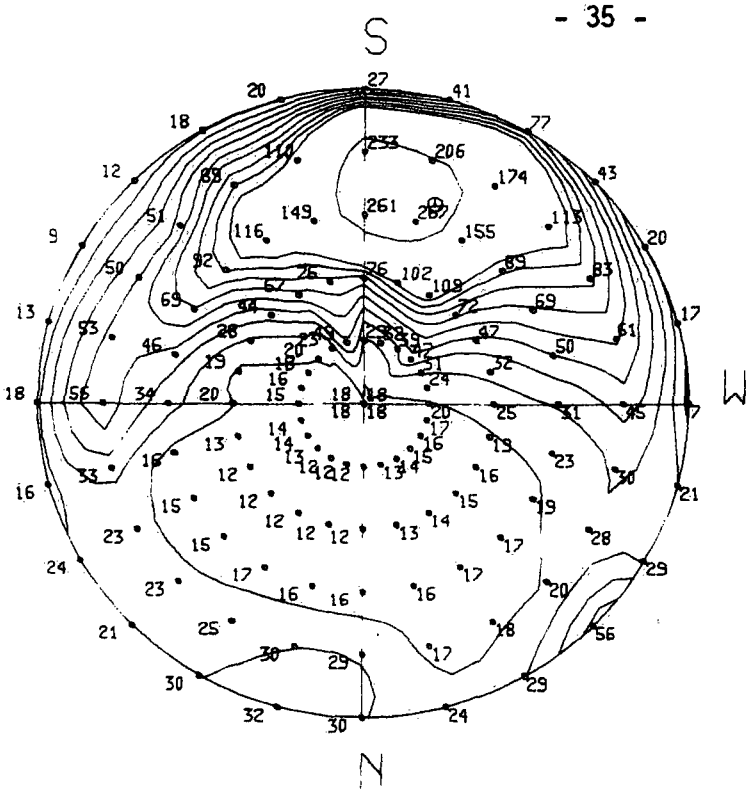


Fig. 2.25. Daily variation of the angular distribution of the radiance. Sample of 5 series.



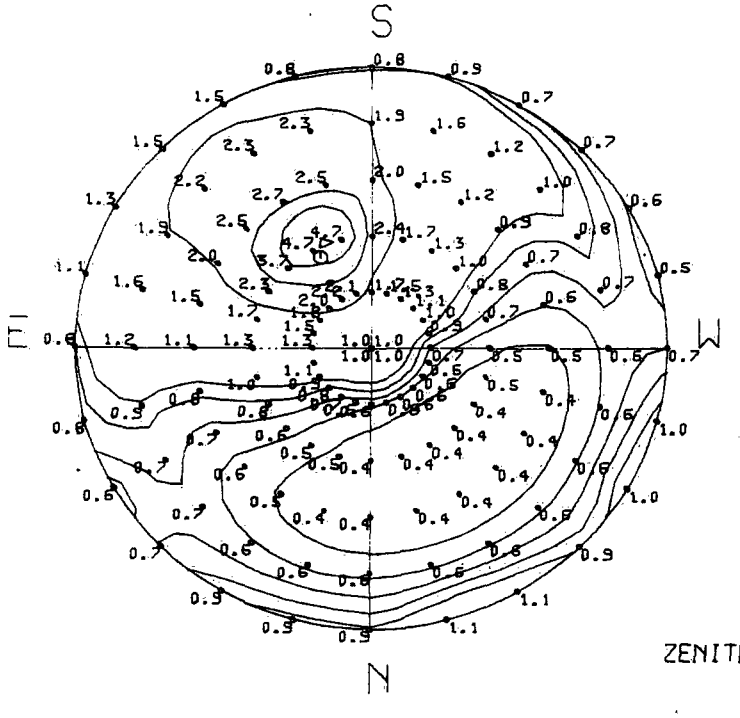
LOCARNO

25 OCTOBER 1981

DAYNUMBER : 298
START TIME : 13 5 19
SERIE NR : 10

UNIT : W*M-2*SR-1

Fig. 2.26. Angular distribution of the absolute radiance for cloudy conditions.



EMPA

5 AUGUST 1981

DAYNUMBER : 217
START TIME : 10 35 24
SERIE NR : 10

ZENITH INTENSITY : 25.8 W*M-2*SR-1

Fig. 2.27. Angular distribution of the radiance measured without the correction filter in relative units. The zenith value is taken as reference.

3 - Conclusion

The characteristics of the direct solar irradiance, the temporal and angular distributions of the global and diffuse irradiance as well as of the radiance are presented together with the description of the instruments used in the mobile station MORAS.

Better models of direct, global and diffuse radiation available at any point of the earth's surface under various inclinations are required more and more. The experience gained with the use of mobile stations like the MORAS leads to the definition of both instrumental and evaluation tools in order to fulfill such a task. Furthermore, and from a more technical point of view, solar energy applications are becoming more and more important as the present fossil energy reserves are running short.

The material presented in this study indicates that mobile stations offer the possibility for short, but accurate in situ tests for interpolation between stations and for establishing more reliable constants for models.

The current system may also be considered as a valuable complement of automatic networks as it is meant to perform sample measurements of missing information and to participate in the development of new instruments of evaluation methods. It has to be viewed as a tool in constant evolution, as a mobile research laboratory.

Adress of the author:

Dr. A. Heimo
Swiss Meteorological Office
Krähbühlstrasse 58

CH-8044 Zurich

ANNEX

Calibration of the spectroradiometer

The spectroradiometer described in section 1.2.2.3 is a prototype instrument developed at the WRCD. It was first integrated in the mobile station MORAS during a measuring campaign which took place in Carpentras (France) during the summer 1977. Before that, the instrument was very carefully tested and adjusted by using, as reference, mercury and cadmium lamps as well as a He-Ne laser. Furthermore, the first extraterrestrial relative intensities of the instruments were obtained for a few clear weather days by the Langley method (extrapolation of the values read during a day to an airmass zero). The spectroradiometer was then transported with great care to the measuring site. Unfortunately, the quality of the results was catastrophic due to large instabilities in the intensity readings. The cause of this behaviour could not be found on the spot.

A further investigation performed in Davos showed that the instability was due to mechanical deformations, that is the protecting cylinder was subject to torsional constraints while following the sun on the sun-tracker. A second steel shell was then added in order to reinforce it mechanically and new adjustment and calibrations were made.

The spectroradiometer was again in operation during the summer of 1979 and measurements were performed during the next three years in Carpentras, at the Weissfluhjoch, in Davos, in Zurich (EMPA) and in Locarno. The behaviour seemed at first convincing. Good results were obtained by the Langley method. However, from the very beginning, clear deviations of the extraterrestrial values from the calibration results of the readjusted instrument (up to 20% in some cases) were registered although the stability was always acceptable during one measurement campaign. During the Weissfluhjoch campaign, the same type of deviation appeared again but with an opposite sign, which led to negative aerosol optical depths!

A new calibration made in Davos, independently of the mobile station and in the same way as the previous calibrations, resulted in the original values for the extraterrestrial intensities. The last campaign in Locarno reproduced again the Carpentras values. Fortunately, since summer 1980, the sun-photometer D-500 was borrowed from the WRCD so that comparisons of the 500 nm channel could be achieved with this reference. The slopes of the Langley plots regression lines (optical depths), were approximately the same for both instruments and the extrapolated values remained constant for the sun-photometer while showing strong deviations for the spectroradiometer from one campaign to the other.

A theoretical study of the atmospheric properties and their influence on the instrument was carried out. Dependence on temperature, relative humidity, pressure and turbidity were considered theoretically as well as experimentaly. Measurements on the optical bench in Davos using the new dye laser as reference were performed and showed that:

- the linearity of the response as function of the intensity was excellent,
- a weak wavelength displacement had taken place, but too small to explain the obvious instability.

The only possibility left was that the instrument was still suffering from some type of torsion caused by its position in the gravity field and/or by being fastened to the sun tracker. The following measurements were then performed: the whole instrument was enveloped in a polyurethane shell and covered by a third metallic tube which was itself fastened to a device allowing rotation along its own axis and around the horizontal axis. The suspension of the optical system was then almost ideal, providing, at the same time, a perfect thermal isolation. A hollow cathod lamp (22) was used as light source and fastened in front of the aperture so that it was itself rotating with the spectroradiometer. The emission line at 656 nm was taken as reference. With this construction, a complete scan over all possible positions could be realised and the results are displayed in figure A1.

A first set of measurements showed that the response was independent of the position in the vertical direction. These values were taken as reference in order to compute the relative deviations as function of the position in the gravity field. This method permitted slow variations of the intensity of the light source. An offset measurement was made before and after each sampling to compensate for possible drift of the electronic amplification. The results shown are a mean value of 10 series of scans, each value being measured 200 times in order to have a sufficient integration over the time.

The analysis of the response curves showed that the position in the gravity field was at the root of the problem together with the anchoring on the tracker which could not be neglected. Fortunately, the instrument was never displaced during a measurement campaign.

The only possible explanation of this behaviour was that the light path was very slightly shifted by the mechanical constraints which resulted in a weak displacement of the wavelength and the measurement in a wing of the entrance slit function, thus reducing the measured intensity depending on the position of the instrument. The fastening of the spectroradiometer on the sun-tracker was never recorded except for the measurements made in Davos where another type of sun-tracker was used. The variation of the extraterrestrial intensities was therefore dependent on the mechanical dressing of the sun-tracker, such information being unfortunately not registered.

The next step was to find a mathematical formulation simulating the deviations shown on figure A1. Figure A2 is a graphical representation of this modeling. The curves follow the simple formula:

$$z = C * \cos(x) * \sin(y)$$

with

z = simulated relative spectroradiometer readings,

x = elevation angle of the spectroradiometer,

y = rotation angle of the spectroradiometer around its own optical axis,

C = constant representing the mechanical constraints influence.

Fig. A3 illustrates the difference between the computed and the measured values.

Assuming that the rotation angle of the instrument is 0 degree at 1200 solar time, its values at any time during the day can be computed from the principle of the equatorial mount of the sun-tracker:

$$tg(\theta) = \frac{\sin(H)}{\frac{\sin(\psi)}{\cos(\psi)}\cos(D) - \sin(D)\cos(H)}$$

with

H = hour angle,

ψ = latitude,

D = declination angle.

The effective rotation angle is then obtained by adding the effective starting angle:

$$y = \theta + s.$$

The constand C is assumed to describe the mechanical pressure effect on the output signal. C is considered as independent of the rotation angle y.

With the use of this model, the corrected spectroradiometer intensities I_c were expressed by the relationship

$$I_c = \frac{1}{1 + C \cdot \cos(x)\sin(y)} .$$

Assuming now that the total optical depth readings of the photometer D-500 could be used as reference, the deviations between the photometric and the spectroradiometric extraterrestrial values were examined for the best weather conditions which could be found for each measuring site. The starting angle was iteratively rotated until the behaviour of the extraterrestrial values of the sprectroradiometer coincided with that of the photometer, but for a constant which was used as the mechanical pressure constant C. The results for the 3 measurements sites were:

Weissfluhjoch: C = 0.250, s = 102 deg.,

EMPA: C = 0.050, s = 260 deg.,

Locarno: C = 0.050, s = 270 deg..

A subjective look at these results suggests that the same operator did mount the instrument in the EMPA and at Locarno, while the author prepared the sun-tracker at the Weissfluhjoch, a fact which seems true as far as can be remembered!

The corrections for the complete set of available data were performed and the new extraterrestrial intensities computed. The results, though far form being ideal, were satisfying enough to use the data for further evaluation.

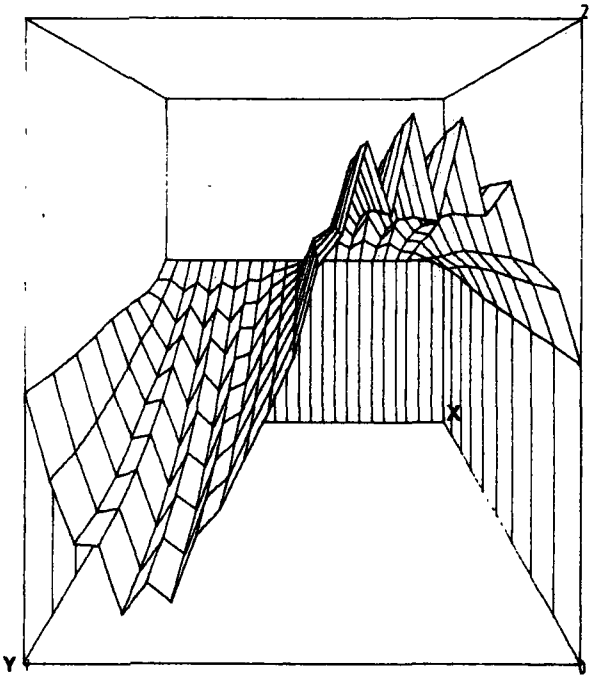


Fig. A1

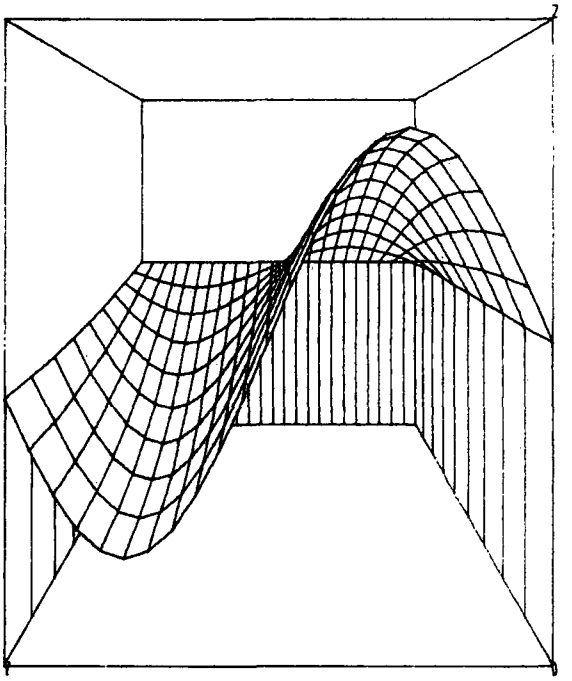


Fig. A2

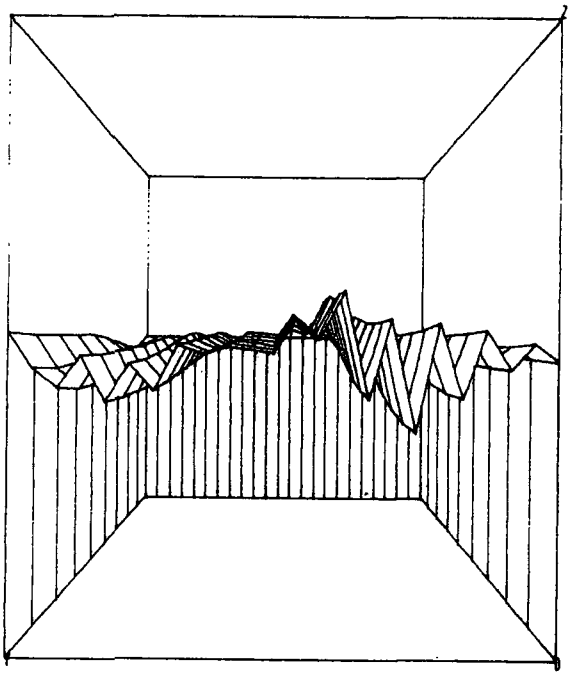


Fig. A3

Fig. A1 3-dimensional spectroradiometer sensitivity as function of the rotation angle around its own axis (y-axis) and the elevation of the instrument (x-axis).

Fig. A2 3-dimensional simulation of the spectroradiometer sensitivity following the equation

$z = C * \cos(x) * \sin(y)$.

Fig. A3 3-dimensional variations between measured (fig. A1) and simulated (fig. A2) response of the spectroradiometer

References

(1) Bener, P., Fröhlich, C. and Valko, P.
Mobile Station for Automatic Measurements of Spectral Solar and Sky Radiance and of the Fluxes of Global and Sky Radiation on Differently Oriented Planes,
International Congress "The Sun in the Service of Mankind", Paris, 1973.

(2) Heimo, A. and Valko, P.
First Results Obtained from the Swiss Mobile System for Solar Radiation Measurements,
Working Reports of the Swiss Meteorological Office, Zurich, 1976.

(3) Valko, P. and Heimo, A.
The Swiss Mobile Solar Radiation Research System.
Chapter 4, pp. 20-27 in the Task -IV/2- Handbook "Validation of the Guidelines for Portable Meteorological Instrument Packages" of the Int. Energy Agency Solar R & D Program, Washington, 1980.

(4) World Meteorological Organization
Meteorological Aspects of the Utilization of Solar Radiation as an Energy Source.
WMO Tech. Note No 172, pp 161-165, Geneva, 1981.

(5) Brusa, R.W. und Fröhlich, C.
Entwicklung eines neuen Absolutradiometers,
WRCD Technical Note No 1, 1972.

(6) Brusa, R.W.
Solar Radiometry,
WRCD Publication No 598, Dissertation ETH No 7181, 1983.

(7) Brusa, R.W. and Fröhlich, C.
Recent Solar Constant Determinations from High Balloons.
Proc. 3rd Scientific Assembly of IAMAP, Hamburg, 1981.

(8) Schuepp, W.
Die Bestimmung der Komponenten der atmosphärischen Trübung aus Aktinometermessungen,
Arch. Met. Geoph. Biokl., B1, 257 (1948).

(9) Valko, P.
Vereinfachtes Auswerteverfahren für die Schueppsche Methode zur Bestimmung der atmosphärischen Trübung,
Arch. Met. Geoph. Biokl., B11, 1. Heft , 1961.

(10) Fröhlich, C. und Bener, P.
Spektroradiometer zur Bestimmung der Atmosphärischen Trübung,
WRCD Publication no 555, 1978.

(11) Fröhlich, C.
Development of a New Sunphotometer,
WRCD Publication no 554, 1977.

(12) Die Davoser Pyrradiometer and Pyranometer vom Typ PD - Beschreibung der konstruktive Gestaltung.
PMOD, FD-D-67-02, Davos.

(13) Die Davoser Pyrradiometer und Pyranometer vom Typ PD - Beschreibung der einzelnen Empfängertypen,
PMOD, FD-D-67-03, Davos.

(14) Selby, J.E.A., Kneizys, F.X., Chetwynd, J.H. and McClatchey, R.A.
Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 4.
Air Force Cambridge Laboratories, 1978.

(15) Bird, R.E.
A Beer's-Law-Based, Simple Spectral Model for Direct Normal and Diffuse Horizontal Irradiance,
SERI/TR-215-1781, 1982.

(16) Valko, P.
Some Empirical Properties of Solar Radiation and Related Parameters.
Chapter 8 of Handbook "An Introduction to Meteorological Measurements and Data Handling for Solar Energy Applications",
Int. Energy Agency, Solar R & D Program, Washington, 1980.

(17) Valko, P.
Empirical Study of the Angular Distribution of Sky Radiance and of Ground Refected Radiation Fluxes,
Reports 1-3 within Project F of the EEC Solar Energy R & D Programme, 1981-1982.

(18) Valko, P.
Empirical Study of the Angular distribution of Sky Radiance and of Ground Reflected Radiation Fluxes.
Proceedings of the ISES Solar World Congress, Perth, 1983.

(19) Valko, P.
Format for Presentation of Data.
International Energy Agency, Solar R & D Programme, Task V, Subtask D.
Report, in press.

(20) Schubiger, F.
Ein numerisches Modell zur Bestimmung der Trübung, der Sichtweite und der Transmissionskoefficienten der Atmosphäre anhand von Breitband- und Spektral-strahlungsmessungen,
Arbeitsbericht der Schweiz. Meteorologischen Anstalt No 115, 1983.

(21) Heimo, A.
Contrôle de qualité du système RASTA,
Institut Suisse de Météorologie, 1983 unpublished.

(22) Schwarz, W.
Untersuchungen an Streuscheiben und Hohlkathoden für das Spacelab-Experiment 1 ES 016 "The Solar Irradiance from 180 nm to 3200 nm",
Diplomarbeit, Landessternwarte Heidelberg, 1979.