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METEOROLOGICAL ASPECTS OF SOLAR ENERGY APPLICATIONS

by

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Abstract

The planet earth receives many thousand times more energy from the sun than the demand of mankind. However the areal density of the energy flux is low. On penetrating the atmosphere, direct solar intensity is reduced and its spectral composition is modified. A part of the energy reaches the ground as scattered radiation. The energy received on the earth's surface varies strongly both temporally and from site to site.

The solar energy user needs to be informed on this intricate structure of solar availability for decisions on the appropriate (economic) application technology and the selection of an appropriate site, as well as for the planning, testing and simulation of his system.

To cater for these needs solar radiation and other relevant meteorological parameters have to be measured with suitable accuracy and frequency within a station network of adequate spatial density. The data must be stored, analyzed statistically and the information (standard values for different times of day and year, frequency distributions, time share above threshold radiation levels, runs/durability statistics, combined frequencies of two and more parameters, time and frequency domain-statistics, e.g. power spectra, autocorrelation functions, etc.) presented in an applicable format. The data base generally accessible for this purpose contains long year records of conventional meteorological elements. The most common tasks are:

- estimation of missing radiation data from other meteorological parameters
- conversion of macroscale data to site specific data
- adaptation of other site's data to a site in question
- calculation of hourly values if only daily totals are recorded
- separation of direct and diffuse components if only global radiation is available
- conversion of horizontal surface radiation to inclined surface data
- calculation of spectral fractions from total spectrum measurements.

To meet specific needs, additional measurements (research projects) are recommended; these include, among others, spectral radiation as well as angular radiance distribution over the sky hemisphere.

Zusammenfassung

Die Erde empfängt viele tausendmal mehr Energie von der Sonne als der Bedarf der Menschheit ist, doch ist die Dichte dieser Energiezufuhr sehr niedrig. Die Intensität der direkten Sonnenstrahlung erleidet in der Atmosphäre Verluste und verändert ihre spektrale Zusammensetzung. Ein Teil der Strahlung wird an Luftmolekülen und Schwebeteilchen gestreut und erreicht die Erdoberfläche als diffuse Strahlung. Im Endeffekt ergibt sich eine zeitlich und von Ort zu Ort stark veränderliche Energieverteilung.

Der Solarplaner braucht Angaben über diese veränderliche Verteilungsstruktur der verfügbaren Sonnenenergie, um technische und wirtschaftliche Entscheidungen treffen zu können. Die Angaben sind Grundlage für die Wahl eines geeigneten Standortes, für die Dimensionierung und Prüfung der Anlagen sowie die Simulation des Betriebes.

Zur Befriedigung der Bedürfnisse müssen die Sonnenstrahlung und weitere meteorologische Parameter mit hinreichender Genauigkeit und Frequenz in einem genügend dichten Stationsnetz gemessen werden. Die Daten müssen gespeichert, statistisch verarbeitet, die Rechenergebnisse (Richtwerte für verschiedene Tages- und Jahreszeiten, Häufigkeitsverteilungen, Angaben über den Zeitanteil für die Ueberschreitung gegebener Schwellenwerte, Andauerwahrscheinlichkeiten, mehrvariable Verteilungen, Zeitstruktur-Statistiken wie z.B. Frequenzspektren, Autokorrelationen usw.) in andwendbarer Form bereitgestellt werden. Meistens stehen nur für die konventionellen meteorologischen Messgrössen langjährige Datenreihen zur Verfügung. Für den Meteorologen stellen sich damit diverse Probleme:

- Ermittlung fehlender Strahlungsdaten aus anderen meteorologischen Messgrössen
- Umrechnung allgemeiner Klimadaten in standortspezifische Daten
- Umwandlung von Daten anderer Standorte in standorteigene Daten
- Ermittlung von stündlichen Angaben, wenn nur Tagessummen zugänglich sind

- Trennung der direkten und diffusen Strahlungskomponenten, wenn nur die Globalstrahlung gemessen wurde
- Berechnung des Strahlungsanfalls auf geneigte Flächen aus Horizontalflächen-Strahlungsdaten
- Ermittlung spektraler Strahlungsanteile, wenn Daten nur für das Gesamtspektrum vorliegen.

Spezifische Datenwünsche können nur durch zusätzliche Messungen (Forschungsprojekte), wie beispielsweise spektrale Strahlungsmessungen, Messungen der Strahlungsdichteverteilung über das Himmelsgewölbe und anderes mehr, erfüllt werden.

Résumé

La terre reçoit du soleil une quantité d'énergie des milliers de fois supérieure à ce dont l'humanité a besoin. Cependant, la densité du flux d'énergie par unité de surface est faible. En pénétrant dans l'atmosphère, l'intensité du rayonnement solaire direct s'amenuise et sa répartition spectrale est modifiée. Une partie de l'énergie atteint la surface du globe sous forme de rayonnement diffus. La variation spatiale et temporelle de l'énergie utilisable au sol est considérable.

Pour pouvoir prendre des décisions en connaissance de cause sur la technique économiquement la plus favorable, le choix d'un site approprié, ainsi que pour planifier et essayer son système et en simuler les performances, celui qui veut utiliser l'énergie solaire doit être au courant de toutes les conditions et de tous les phénomènes qui déterminent à tout moment la quantité d'énergie solaire exploitable.

Pour répondre à ces besoins, il est nécessaire de mesurer le rayonnement solaire et d'autres paramètres météorologiques importants avec une précision et une fréquence appropriées dans un réseau de stations d'une densité spatiale suffisante. Les données doivent être archivées, faire l'objet d'une analyse statistique, et il convient de présenter sous une forme applicable les informations ainsi obtenues (valeur types pour différentes heures de la journée et différentes périodes de l'année, distributions de fréquences, distribution temporelle de l'intensité du rayonnement, statistiques concernant la durée de manifestation de certains paramètres, fréquences combinées de deux ou plus de deux paramètres, statistiques concernant l'heure et la fréquence d'occurrence, par exemple spectres de puissance, fonctions d'autocorrélation, etc.). La base de données généralement accessible à cet effet contient des relevés annuels d'éléments météorologiques classiques portant sur de longues périodes. Les tâches les plus communes sont les suivantes:

- estimation des données radiométriques manquantes à partir d'autres paramètres météorologiques
- conversion des données de grande échelle en données relatives à un site particulier
- adaptation au site considéré des données recueillies à d'autres endroits
- calcul des valeurs horaires si l'on n'enregistre que les valeurs totales journalières

- séparation des éléments "rayonnement direct" et "rayonnement diffus" si l'on ne dispose que de données sur le rayonnement global
- conversion des valeurs du rayonnement tombant sur une surface horizontale en valeurs du rayonnement tombant sur une surface inclinée
- calcul des fractions spectrales à partir des mesures de l'ensemble du spectre.

Pour répondre à des besoins précis, il est recommandé d'effectuer des mesures supplémentaires (projets de recherche), notamment en ce qui concerne la radiation spectrale et la distribution angulaire de la luminance énergétique sur la totalité de l'hémisphère céleste.

Riassunto

La terra riceve molto più energia dal sole del fabbisogno umano, però la densità di questo apporto calorico è molto bassa. Nell'atmosfera l'intensità della radiazione solare diretta subisce delle perdite e dei cambiamenti nella sua composizione spettrale. Una parte della radiazione viene dispersa da molecole d'aria e da particelle sospese e raggiunge la superficie terrestre sotto forma di radiazione diffusa. L'energia viene così distribuita in modo molto variabile, sia nel tempo che nello spazio.

Per poter prendere delle decisioni tecniche e commerciali il progettista solare abbisogna di informazioni sulla variazione della struttura di distribuzione dell'energia solare disponibile. Le informazioni servono da base per la scelta di una posizione adatta, per il dimensionamento e l'esame delle istallazioni, nonchè per la simulazione dell'esercizio.

Per soddisfare le esigenze, la radiazione ed altri parametri meteorologici devono venir misurati con sufficiente esattezza e frequenza in una rete di stazioni abbastanza fitta. I dati devono venir immagazzinati, elaborati statisticamente ed i risultati (valori orientativi per le diverse ore del giorno e diverse stagioni, distribuzioni delle frequenze, frequenze di sorpasso dei valori di soglia, durate probabili, distribuzioni a più variabili, statistiche della struttura temporale, come per esempio spettri do frequenza, autocorrelazione ecc.) rappresentati in forma adeguata. Lunghe serie di dati sono spesso disponibili solo per le grandezze meteorologiche convenzionali. Il meteorologo deve perciò affrontare diversi problemi:

- Ricavo di dati di radiazione mancati da altre misure meteorologiche.
- Conversione di dati climatologici generali in dati concernenti una stazione specifica.
- Trasformazione di dati di altre stazioni in dati per una stazione particolare.
- Determinazione di valori orari, quando sono a disposizione soltanto somme giornaliere.
- Divisione delle componenti di radiazione diretta e diffusa, quando si hanno solo dati sulla radiazione globale.
- Determinazione della radiazione su superfici inclinate, partendo dai valori della radiazione su superfici orizzontali.

- Determinazione della distribuzione spettrale della radiazione quando sono disponibili soltanto dati per lo spettro totale.

Richieste di dati specifici possono venir soddisfatte solo per tramite di misurazioni supplementari (progetti di ricerca), come per esempio misurazioni della radiazione spettrale, misure della distribuzione della radiazione sopra la volta celeste ecc.

Resumen

El planeta Tierra recibe varias veces más de energía del sol de lo que necisita la humanidad. Sin embargo, la densidad zonal del flujo de energía es pequeña. Al penetrar en la atmósfera, la intensidad solar directa se reduce modificándose su composición espectral. Una parte de la energía llega al suelo como radiación difusa. La energía recibida en la superficie de la tierra varía considerablemente tanto en el tiempo como en el espacio.

El usuario de la energía solar necesita ser informado de todas las condiciones y fenómenos que determinan en todo momento la cantidad de energía solar explotable para poder adoptar decisiones sobre la aplicación de la tecnología económicamente más favorable, para la selección de un emplazamiento idóneo, así como para la planificación, verificación y simulación de su sistema.

Para atender estas necesidades, es necesario medir la radiación solar y otros parámetros meteorológicos pertinentes con la debida precisión y frecuencia en una red de estaciones de una densidad espacial adecuada. Los datos deben ser archivados y analizados estadísticamente, y la información así obtenida (valores tipo para diferentes horas del día y diferentes períodos del año, distribuciones de frecuencia, distribución temporal de la intensidad de la radiación, estadísticas relativas a la duración de manifestación de ciertos parámetros, frecuencias combinadas de dos o más parámetros, estadísticas relativas a la hora y frecuencia de ocurrencia, por ejemplo espectros de potencia, funciones de autocorrelación, etc.) debe presentarse en forma aplicable. La base de datos generalmente accesible para este fin contiene registros anuales de elementos meteorológicos clásicos para largos períodos. Las tareas más comunes son las siguientes:

- estimación de los datos radiométricos que faltan a partir de otros parámetros meteorológicos;
- conversión de los datos macroescalares en datos relativos a un emplazamiento determinado;
- adaptación al emplazamiento en cuestión de los datos de otros lugares;
- cálculo de los valores horarios si solamente se registran valores totales diarios;
- separación de las componentes "radiación directa" y "radiación difusa" si sólo se dispone de datos sobre la radiación global;
- conversión de los valores de radiación sobre una superficie horizontal en valores de radiación sobre una superficie inclinada;
- cálculo de fracciones espectrales a partir de medidas del conjunto del espectro.

Para atender necesidades específicas, se recomienda que se efectúen medidas adicionales (proyectos de investigación), por ejemplo en lo que respecta a la radiación espectral y a la distribución angular de la radiancia sobre la totalidad del hemisferio celeste.

1. THE POWER OF THE SUN

The sun radiates energy at the rate of $3{,}85 \cdot 10^{23}$ kW into space. From the mass and structure of the sun it can be assumed that this energy output will be sustained for 10^{11} years. At a distance of $1{,}5 \cdot 10^{8}$ km, the planet earth receives outside of its atmosphere only $4{,}6 \cdot 10^{-10}$ of this power. Related to unit surface this gives the so called "solar constant". From measurements at high altitudes values between 1353 and 1394 Wm^{-2} have been obtained; 1373 Wm^{-2} is recommended as the most probable value [1]. Compared with other natural energy sources this amount is high; geothermic energy, convective heat of volcanoes and hot springs together with the energy of tides amount only to about 0,0002 of the extraterrestrial solar energy [2]. Moreover, this energy is many thousand times more than the demand of mankind.

2. INTERACTIONS WITH THE ATMOSPHERE

The extraterrestrial patterns of incoming solar energy are modified by the atmosphere. A part is reflected into space, particularly from clouds, while another part is absorbed by atmospheric gases, clouds and other suspended particles. The remainder reaches the ground partly as direct and partly as diffuse radiation, both of which vary with time of year, time of day as well as with geographic latitude. Apart from the primary astronomic factors, these variations are caused by non periodic influences: due to the changing weather, the intensity, direction and spectral composition of radiation components exhibit marked differences both temporally and from site to site.

For clear sky conditions, air molecules, turbidity and water vapour are the dominant parameters which reduce direct solar energy on penetrating the atmosphere at different incident angles. Computations are in good agreement with measurements if turbidity data are available. Turbidity decreases with altitude above sea level (see fig. 1) and with distance from cities and industrial plants. The so called "turbidity coefficient" may show differences of up to 2 powers of ten between different climatic regions as well as for different weather conditions at some sites. As turbidity increases, the loss of direct radiation is partly compensated for by a simultaneous increase of diffuse radiation.

The main influence on radiation comes from the clouds. When the sun is shaded, direct radiation vanishes to zero. On the other hand, diffuse sky radiation is generally augmented by increasing cloud amount and decreases only when the sky is almost overcast.

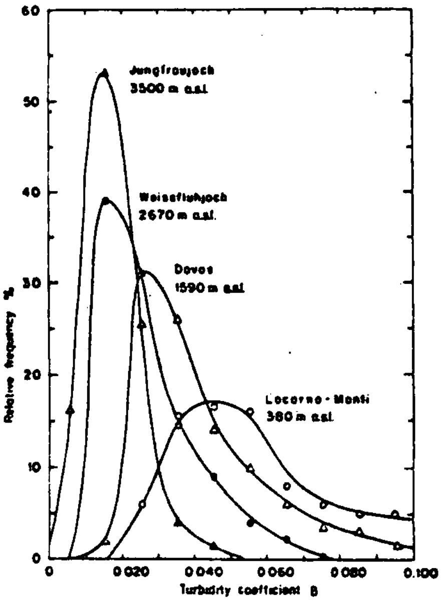


Fig. 1 Frequency distribution of the turbidity coefficient for stations at different altitudes a.s.l. in the Swiss Alps.

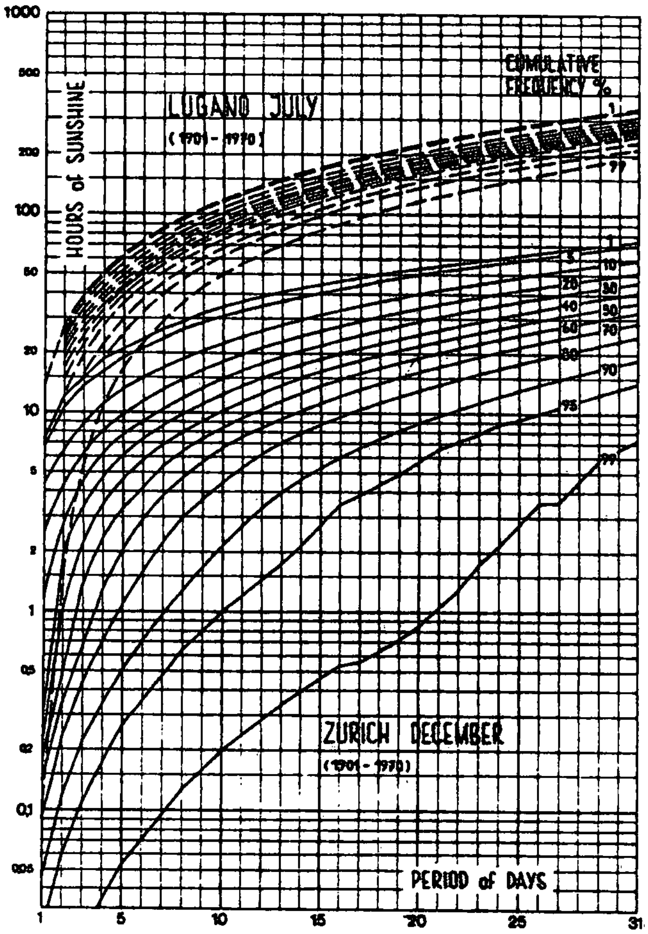


Fig. 2 Cumulative frequency distribution of sunshine hours accumulated over consecutive days for Lugano, July and Zurich, December.

3. DATA NEEDS FOR ENERGY UTILIZATION

Solar availability thus shows a complex statistical structure and therefore it is a correspondingly difficult task to present suitable data for planning of energy applications. By grouping the different application forms a useful survey of the meteorological information requirements may be prepared. These requirements include not only radiation parameters but also other meteorological quantities. This information should serve for planning, testing and simulation of solar systems.

For many applications hourly values of global radiation, sunshine duration and either the direct or the diffuse component are sufficient. The accuracy of the radiation quantities should be $\leq \pm$ 50 Wm^{-2} [3]. Direct measurements of short wave radiation on inclined surfaces are of advantage, otherwise approximative values may be computed (see section 5). Concerning the other meteorological parameters, hourly values of temperature, wind velocity and relative humidity satisfy most needs.

4. TYPICAL DATA SETS AND STATISTICAL INFORMATION

4.1 Sunshine duration

Sunshine is measured at a great number of stations all over the world since many years. It is the most commonly available parameter for statistical treatment. Table 1 gives a synopsis of average yearly sunshine hours $\bar{S}$ for selected stations. S/S_0 % is the relative sunshine which is a good indicator of cloudiness.

Table 1 Yearly sunshine and global radiation totals for selected stations

Location	$\bar{S}$ [hours]	$\bar{S}/S_0$ %	G_H [$kWhm^{-2}$]
Tromsö	1250		
Hamburg	1560	36	930
Zürich	1700	40	1160
Lugano	2200	54	1375
Roma	2500		1475
Tunis	2900		1714
Tamanrasset	3690	83	2300

Sunshine data may give useful information for energy storage problems. For this purpose frequency distributions of sunshine hours accumulated through consecutive 2, 3, ... 31 days have been computed for each month for several Swiss stations [4]. For example in Zurich (fig. 2) during any period of 10 consecutive days in December there is only 1 % probability to obtain altogether 33 hours of sunshine, 10 % for 22 hours,... and in the worst case (99 % frequency level) one does not have more than 12 minutes of sunshine.

Depending on the response time of the solar energy collecting system, short period fluctuations of the energy input may also be of importance. With this in mind, a minute by minute evaluation of sunshine records over many years [5] was made to compute duration-frequency characteristics of short period sunshine interruptions.

4.2 Direct radiation

Many measurements of this parameter have been made at several ground stations. Table 2 compares average 12.00^h values for altitudes of 4000 and 2000 m a.s.l. as measured in the Alps with the 2 % (very clear weather conditions) and 98 % (heavy turbidity) probability values for the Swiss lowland (400 m).

Table 2 Typical 12^h intensities of direct solar radiation in Switzerland $[\mathrm{Wm}^{-2}]$

Altitude m a.s.l.		Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
4000		1107	1140	1158	1155	1147	1139	1134	1132	1129	1115	1097	1086
2000		989	1026	1047	1036	1021	1012	1109	1013	1015	1007	975	954
400	2 %	901	961	1004	1013	1007	1004	999	990	989	966	913	864
	98 %	628	626	622	611	597	563	565	565	637	666	651	612

4.3 Global and diffuse radiation on horizontal surface

Global radiation is the most frequently measured radiation parameter. Yearly average $\bar{G}_H$ values for selected locations are given in table 1. Considering the figure 1160 KWhm^{-2} for Zurich for instance and an average efficiency typical for today's collector technology, one may expect about 450 KWhm^{-2} as yearly output of thermal energy. This has to be reduced again by about 0,3 to convert thermal energy into electrical energy. This gives roughly 150 KWhm^{-2} a year. Let us consider on the other hand a conventional power plant producing electrical energy of the order of 1000 MW. This corresponds to 8,766 · 10^6 MWh per year. To produce the same yearly energy, a solar plant of about 60 km^2 collector surface would be required. Although this computation doesn't take into account several technical problems, nevertheless it gives a quantitative indication.

Table 3 presents a survey of daily averages for different seasons at Swiss stations.

Table 3 Average daily totals of global radiation $\bar{G}_H$, 10.00-14.00 hours fraction and diffuse to global ratios for July and December at Swiss stations

Station	m a.s.l.	July			December		
		$\bar{G}_H$ kWhm^{-2}	$\bar{G}(10\text{-}14^h)$ %	$\bar{D}_H/\bar{G}_H$ %	$\bar{G}_H$ kWhm^{-2}	$\bar{G}(10\text{-}14^h)$ %	$\bar{D}_H/\bar{G}_H$ %
Zurich-Kloten	420	5,86	45	44	0,60	73	80
Locarno-Monti	380	6,53	45	40	1,30	71	44
Davos	1590	5,56	47	42	1,28	75	50
Weissfluhjoch	2670	5,11	43	--	1,57	70	--

These figures have been computed from 10 to 15 years of measurements. The year to year variation of G_H may be up to 20-30 % of the long term average depending on calendar month and location. On individual July days at Locarno-Monti G_H may be up to about 10 $KWhm^{-2}$ with the diffuse component beeing only about 15 % of this value. On average, for the whole year, diffuse radiation accounts for about 50 % of the global; at mountain stations a few % less, in the lowland a few % more. These percentages vary with season especially for Zurich due to fog in the winter months (last columns). The interdiurnal variation of global radiation is well pronounced on clear days. The table shows that a high percentage of the daily total is irradiated between 10.00 and 14.00 hours, even during the long summer days with more than 40 %.

4.4 Short wave radiation on vertical and inclined surfaces

The global radiation falling on vertical and tilted surfaces is composed of a direct solar component, a diffuse component from the sky and of radiation reflected from the ground. Measurements are sparse. The essential problem is to determine the diffuse sky and the reflected components, whereas the direct fraction may be computed by simple geometry. A good synopsis of the present knowledge in this field is given in [6].

Considering clear sky conditions, a 5 year period of measurements taken at Locarno-Monti was chosen to find empirical relationships between the ratio of vertical D_V to horizontal D_H diffuse radiation on the one hand and solar height h, surface-solar azimuth a and turbidity coefficient B on the other. Fig. 3 shows the result. D_V includes here the reflected component. It is apparent, that the often used isotropic assumption (b.e. diffuse radiation is isotropically distributed over the sky) may yield to significant errors. The results are analysed in more detail in [7].

When all days of the whole available 10 year (1963-1972) period of measurements are considered, it is useful to compute frequency distributions and to present curves for the daily variation at different frequency levels. Fig. 4 shows these results for global radiation for July and December respectively (E: East-, S: South-, W: West-, N: North-facing vertical surfaces) together with the global radiation on the horizontal (H). Curves for the 1, 10 and 50 % cumulative frequencies have been drawn, with M being the arithmetic mean in each case. One should note the differences between summer and winter, between different surface orientations, the dependence on time of day at the various frequency levels as well as the fact, that the distributions are rather skewed (50 % and M curves being separated). Whereas the 1 % curves have been drawn from sunrise to sunset, the others show only the characteristic sections of the day.

The vertical surface data have been stored as 5-minute integration step values. It was therefore possible to quantify statistically also short term intensity fluctuations. This was done by computing power spectra within the period range of 10 minutes to 20 hours. The results show characteristic differences for clear, cloudy and overcast sky conditions.

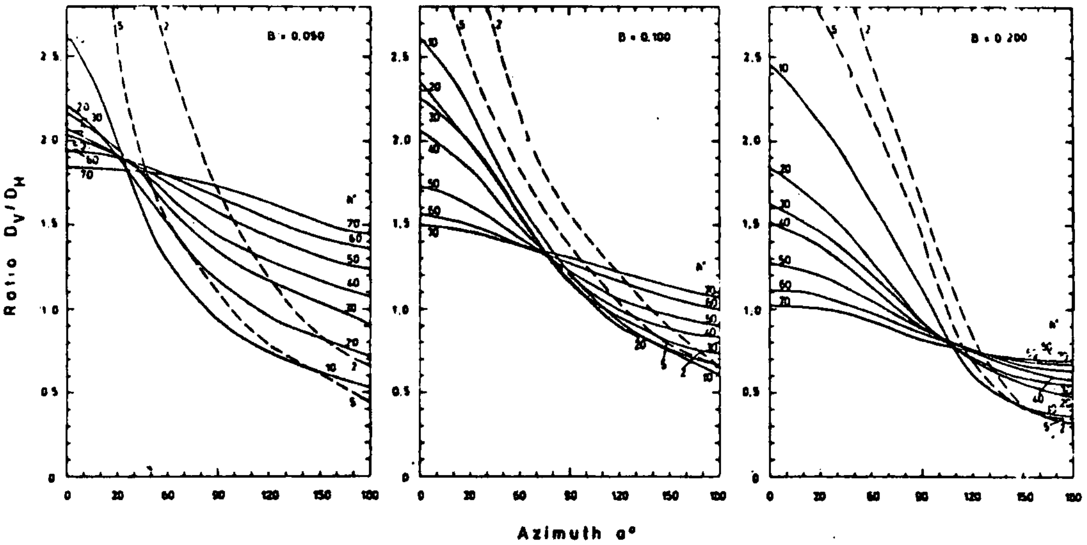


Fig. 3 Ratio D_V/D_H of diffuse radiation on vertical surfaces to that falling on the horizontal surface as a function of surface-solar azimuth a and solar height h for selected values of the turbidity coefficient B.

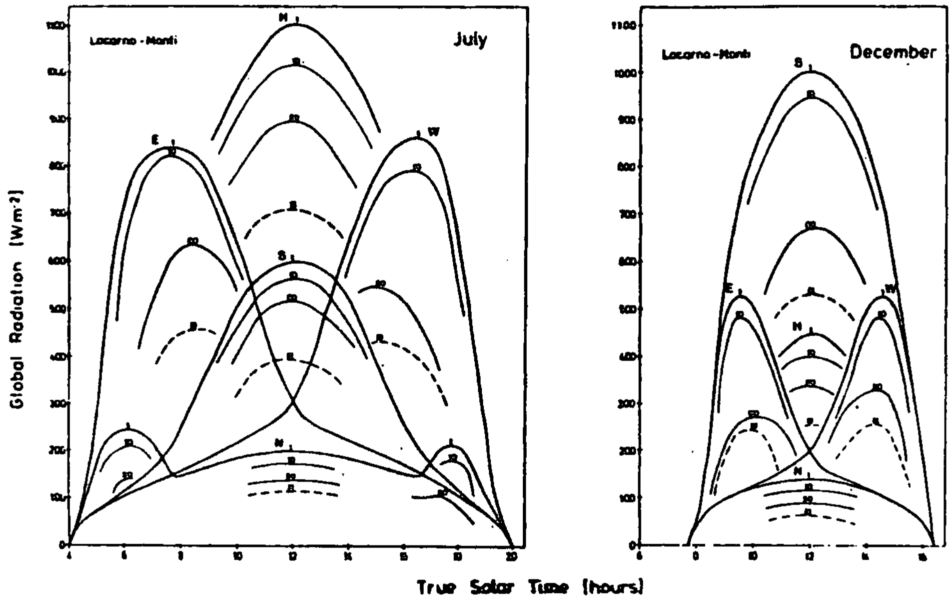


Fig. 4 Daily variation of global radiation falling on vertical and horizontal surfaces for July and December in Locarno-Monti. Curves were drawn for different percentages of the respective cumulative frequency distribution.

The radiation falling on vertical surfaces is a special case of the inclined surface irradiation problem. The dependence on the inclination angle complicates the detection of empirical relationships of the kind shown in fig. 3. In analogy to this set of diagrams, fig. 5 shows corresponding clear sky ratios for different air turbidities B and constant solar height (h = 35°). The curves have been drawn for the inclination angles (measured from the horizontal) ν = 18, 39, 60, 75 and 90 degrees [8]. The problem is further discussed in section 6.

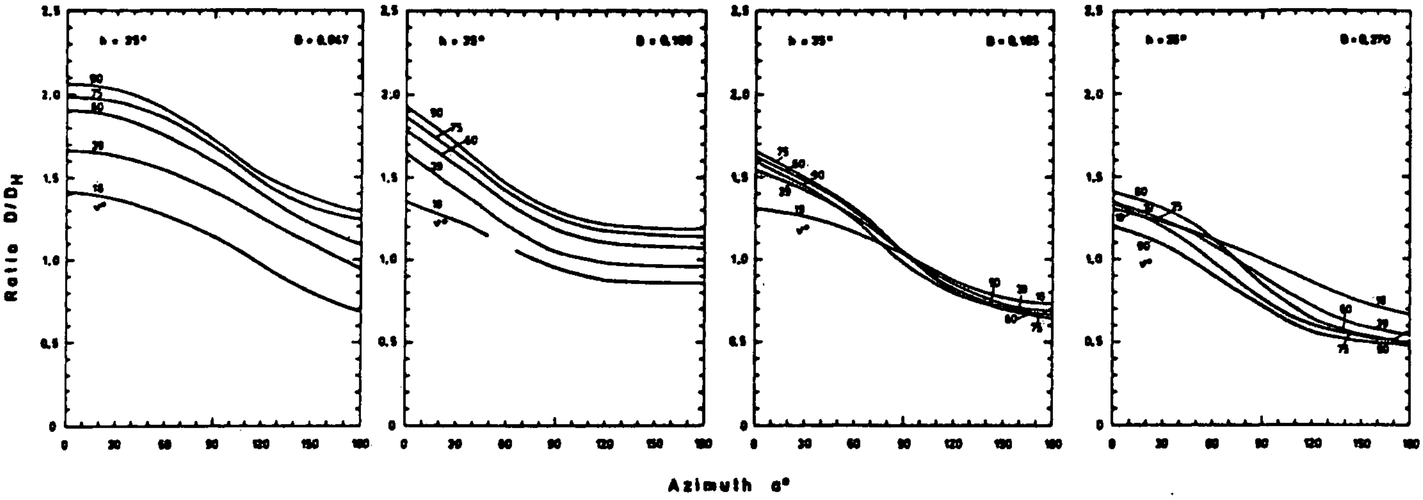


Fig. 5 Ratio D/D_H of diffuse radiation on inclined surfaces to that falling on the horizontal surface as a function of surface-solar azimuth a, inclination angle ν and turbidity coefficient B. A constant (35°) solar height h was used throughout.

5. ESTIMATION PROCEDURES

In general the lack of a suitable radiation data base causes several problems. The most typical of these are:

- estimation of missing radiation data from other meteorological parameters
- conversion of macroscale data to site specific data
- adaptation of other site's data to a site in question
- calculation of hourly values if only daily totals are recorded
- separation of direct and diffuse components if only global radiation is available
- conversion of horizontal surface radiation to inclined surface data
- calculation of spectral fractions from total spectrum measurements

In this paper these tasks cannot be treated in detail. It is evident that simple computation models may yield useful approximations only when averages over longer time periods are considered. The longer the period, the more the astronomical factors determine the radiation parameters.

Global radiation is most often computed from sunshine duration as monthly average daily totals by using the well known linear relationship:

$$G_H = G_o \, (a + b \, S/S_o)$$

where S/S_o is the relative sunshine and G_o the extraterrestrical radiation on horizontal surface. Average diffuse ratios may be computed in a similar manner, using:

$$D_h = G_H \, (c + d \, G_H/G_o).$$

By these means, direct and diffuse components may be separated and also inclined surface averages computed, if isotropy or some adjusted model for the angular distribution of the diffuse component is assumed. Further details are discussed in [9, 10].

The areal interpolation problem is also a question of integration time. Fig. 6 shows the result of such investigations using sunshine hours measured at numerous Swiss lowland stations.

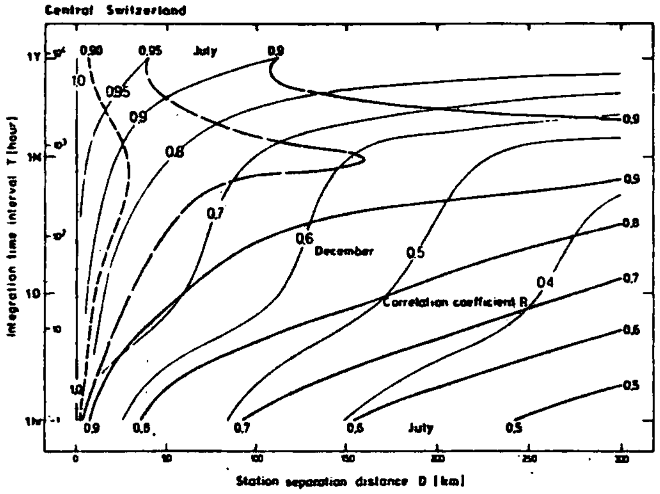
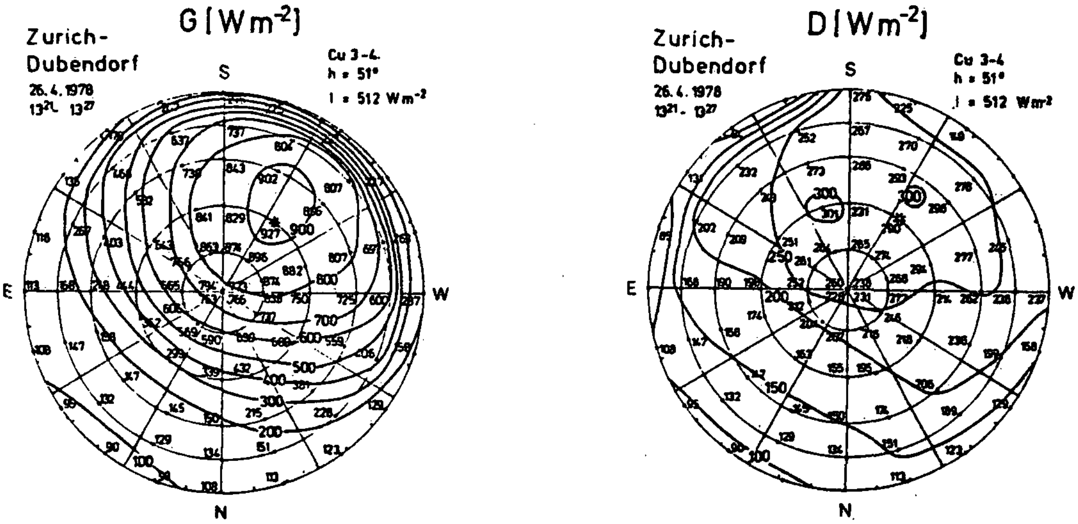


Fig. 6 Dependence of the correlation coefficient between sunshine totals of station pairs on station separation distance and integration time for July (thick curves) and December (thin curves) for central Switzerland.

6. SPECIAL MEASUREMENTS

For more sophisticated applications (research) routine measurements are usually not sufficient. To meet these demands a special mobile station has been developed [8]. The attached sheet of illustrations gives an impression of the single measuring devices as well as of the system as a whole, whereas figures 7 and 8 show typical results.



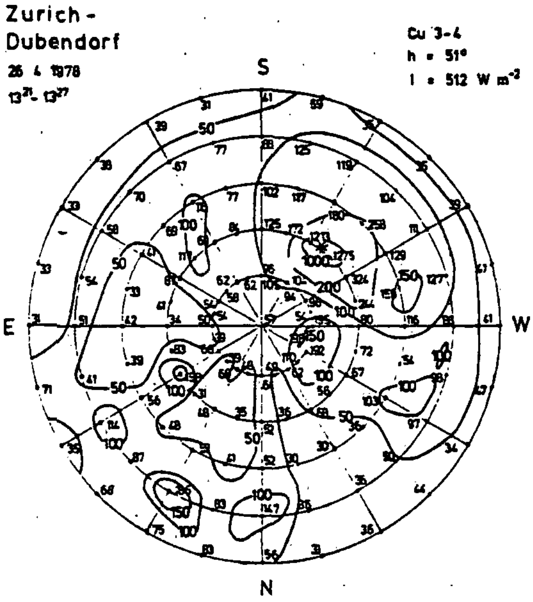


Fig. 7

Distribution of global irradiance (top left) and simultaneous diffuse irradiance (top right) as functions of orientation and inclination angles of the irradiated surface. Measurements were made with four pyranometers at 77 different positions. (Contours and measured values are in Wm^{-2}.) The polar diagram at the bottom represents the corresponding distribution of sky radiance in relative units; the instruments (see photograph) have an aperture of 5°.

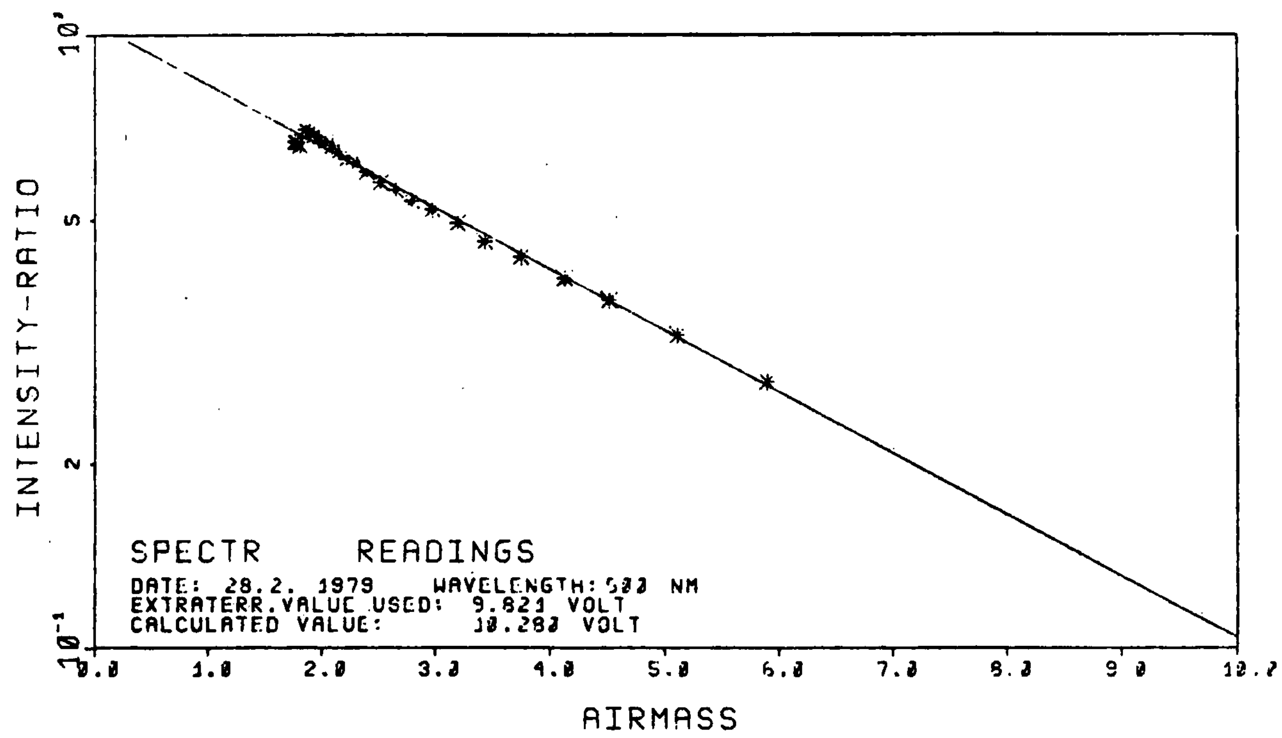


Fig. 8 Example of spectral solar intensity at 500 nm as measured with the sun-spectroradiometer (see illustration) at Davos (1590 m a.s.l.) with very clear weather. Results (in relative units, normalized to the solar constant at this wavelength) are plotted against absolute air mass m.

The pyranometer measurements used for preparing figure 7 were made under moderately cloudy sky conditions (3-4 tenths of cumuli), the solar height being 51°. The sun was not shaded by the clouds and the intensity from direct solar rays (on a perpendicular surface) was $I = 512\ Wm^{-2}$.
Results as shown here for the diffuse irradiance D (top right) have been produced over about 3 years; in total more than a thousand cases for different turbidities and different angular conditions but with cloud-free skies. These measurements were used to detect such empirical relationships as presented earlier in figure 5 for the special case h = 35°.

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#8

1. and 2. The caravan (6.3 x 2,3 x 2,6 m, 4 tons) lodging the equipment

HH4

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3. Interior view showing the Computer PDP8/E (for steering the instruments and for primary data processing) and its periphery components: magnetic tape units, line printer and plotter

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6. Side-view of the sun-tracking devices

6. Four pyroelectric detectors scan the sky (5 aperture) in 121 points in about 2 minutes

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9

4. On the car's roof four instruments are mounted on an automatic sun-tracker: pyranometer (A), pyroelectric detector (B), absolute radiometer (C) with broad band Schott-filters OGI, RG2 and RG8 and spectroradiometer (D) measuring at 16 different wavelengths

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MS

7. and 8. Four pyranometers are driven by step motors and measure in 77 different tilts and directions in about 6 minutes

^- A shading disc always occults direct s°lar beam from a fish-eye camera