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FIRST RESULTS OBTAINED FROM THE SWISS MOBILE SYSTEM FOR SOLAR RADIATION MEASUREMENTS

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by

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Summary

An autocar, equipped with a number of different radiation measuring instruments, constructed at the Physical-Meteorological Observatory of Davos, was operated at various locations during the last two years. By using 7 pyranometers movable with step-motors in any position this mobile system permits to determine the global radiation as falling on arbitrarily orientated and inclined plane surfaces. The direct solar radiation on normal surface is measured in the total spectrum, in the 3 broad spectral ranges of the Schott filters OG1, RG2 and RG8 and also at 12 quasi-monochromatic wavelengths. Terrain properties and cloudiness distribution are recorded by a 180° (fish-eye) camera.

By these means also the diffuse radiation flux on 77 differently orientated and tilted planes could be determined in several hundered cases for each plane. The dependence of the global and diffuse radiation intensities on solar height, atmospheric turbidity, cloudiness and on the orientation and inclination of the plane will be discussed.

The system is among others appropriate for extensive and precise calibration of solar collectors immediately at the site of their installation.

Zusammenfassung

Vor etwa zwei Jahren wurde ein (Motor-) Fahrzeug mit verschiedenen, am Physikalisch-Meteorologischen Observatorium Davos entwickelten Strahlungsmessgeräten ausgerüstet und in Betrieb genommen. Seither sind mit diesem System an mehreren Orten Messkampagnen durchgeführt worden. Zur Messung des globalen Strahlungsanfalls auf beliebig orientierte und beliebig geneigte ebene Flächen wurden sieben, mit Schrittmotoren in verschiedene Positionen gesteuerte Pyranometer verwendet. Die direkte Sonnenstrahlung senkrecht zur Strahlungsrichtung wurde im Gesamtspektrum, in den Spektralintervallen der Schott'schen Filter OG1, RG2 und RG8 und auch in 12 quasimonochromatischen Wellenlängenbereichen gemessen. Die örtlichen Terrainverhältnisse und die Wolkenverteilung am Himmel sind durch 180° (Fischaug-) Fotoaufnahmen festgehalten worden.

Auf diese Weise konnte jeweils auch der diffuse Strahlungsfluss auf 77 verschieden orientierte und verschieden geneigte Flächen in mehreren hundert Fällen pro Fläche bestimmt werden. Es werden die funktionalen Beziehungen der Globalstrahlung bzw. der diffusen Strahlung zur Sonnenhöhe, Lufttrübung und Bewölkung sowie zur Flächenrichtung und -Neigung untersucht und diskutiert.

Das fahrbare Messsystem kann u.a. zur umfassenden und präzisen Prüfung von Sonnenkollektoren unmittelbar an deren Aufstellungsort eingesetzt werden.

Résumé

Le Centre Radiométrique Mondial de Davos a développé une station mobile équipée de plusieurs instruments de mesure des radiations solaires. Ce laboratoire est opérationnel depuis deux années et a déjà effectué des mesures en plusieurs endroits. 7 pyranomètres mobiles (montés sur des moteurs pas-à-pas) permettent de déterminer le rayonnement global arrivant sur des surfaces d'orientations et d'inclinaisons quelconques. Le rayonnement solaire direct sur une surface normale est quant à lui mesuré pour tout le spectre, derrière les 3 filtres Schott utilisés habituellement en actinométrie (OG1, RG2, RG8 et quarz) et pour 12 longueurs d'ondes quasi-monochromatiques. Les propriétés du terrain et de la couverture nuageuse sont enregistrées par une caméra équipée d'un objectif oeil-de-poisson de 180° d'ouverture.

De cette façon, il a été possible de déterminer le rayonnement diffus arrivant sur 77 surfaces d'orientations et d'inclinaisons différentes lors de plusieurs centaines de mesures. L'intensité du rayonnement global et du rayonnement diffus est étudiée en fonction de la hauteur du soleil, du trouble atmosphérique, de la couverture nuageuse, de l'orientation et l'inclinaison de la surface considérée.

Ce système permet entre autres de procéder à des calibrations précises de collecteurs solaires in situ.

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Introduction

Meteorological services usually record at a limited number of stations the global radiation falling on the horizontal surface, at fewer places also the diffuse component separately and at a few selected sites, e.g. observatories, the direct beam intensity of normal incidence as well. Together with long year records of the sunshine duration and other meteorological quantities, these data are important for engineering applications of solar energy.

Data about vertical and inclined surface irradiation are required for solar energy utilization and also conventional heating and air-conditioning of buildings as well as daylight design. Measurements of these radiation components are sparse. The standard observations are therefore used in many cases for getting such information adopting suitable conversion methods (e.g. [1, 2]). Such computations give appropriate average values over longer time periods. For clear sky conditions the angular distribution of diffuse radiation is often assumed to be isotropic or some more refined model (e.g. [3]) is applied. Approximations of this kind are of limited value and may lead to erroneous conclusions. Short term measurements with tilted pyranometers have been made at several places (see [4, 5, 6] among others) but because of the influence of many factors a comprehensive generalization of the results has proved difficult.

In Switzerland vertical surface irradiation has been recorded since 1960 at one station to furnish engineers with suitable data. Using several years of these records empirical rules could be found relating clear sky diffuse radiation onto vertical surfaces with solar height, (wall-solar-) azimuth and atmospheric turbidity [7]. The results have been completed and applied to building problems [8, 9, 10].

This and other further experience has suggested that only a mobile equipment measuring the components of the short wave radiation field together with the relevant atmospheric and environmental parameters would permit the collection of an adequate data base at suitable locations under various conditions. The results should yield functional relationships between the instantaneous diffuse radiation on a plane of arbitrary direction on the one hand and parameters like the sun's position, air turbidity, cloudiness and terrain properties on the other. Linked with known statistics concerning these parameters, all necessary radiation data should be calculable over any integration time.

The mobile measuring system

The mobile measuring system was completed in 1974. The equipment has been described elsewhere [11]. The instruments were developed, calibrated, checked and installed by the World Radiation Centre at Davos. The photos (Figure 1) give a first impression of the system and together with the sketch (Figure 2) also a rough idea about its operation.

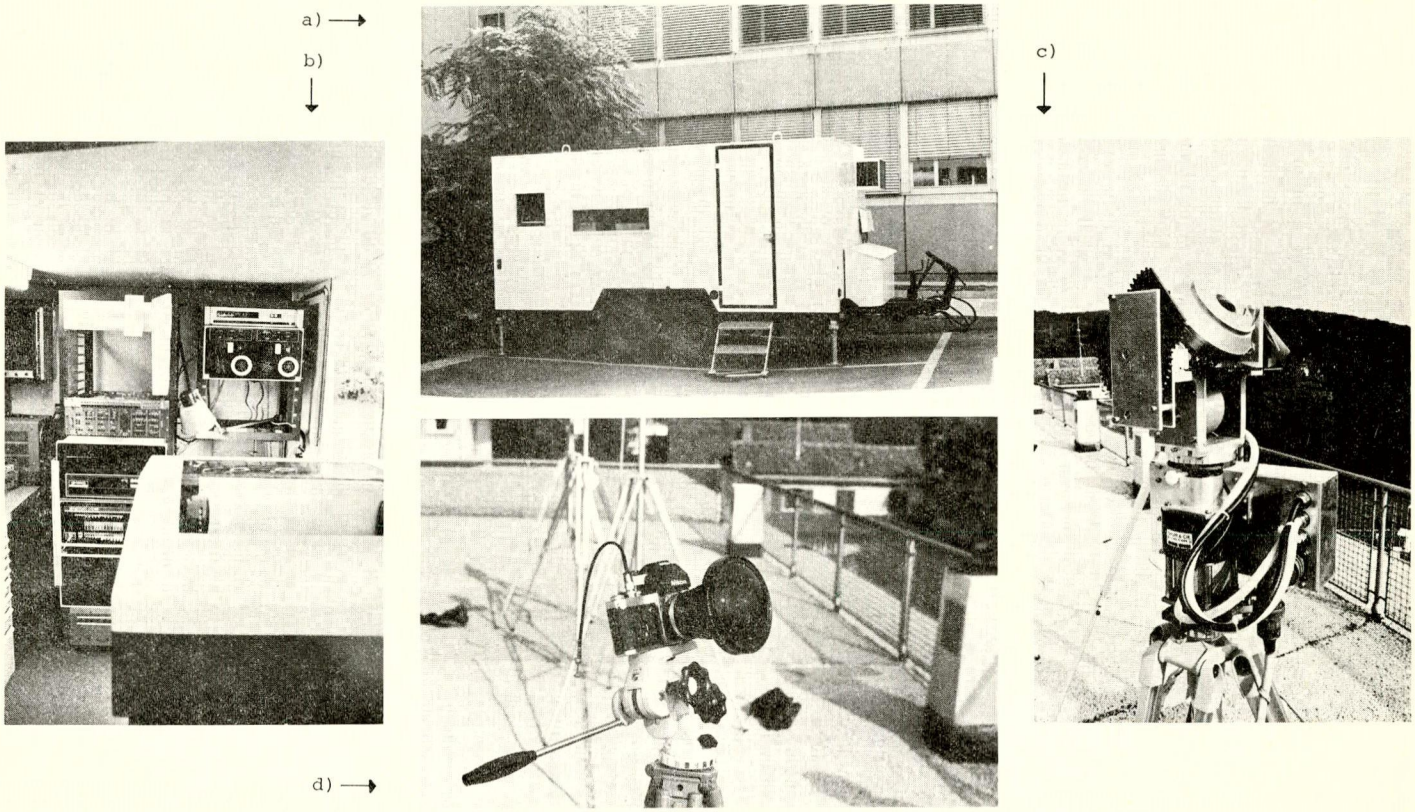


Figure 1 The mobile system for measuring solar radiation:

a) Vehicule (6,3 x 2,3 x 2,6 m, 4 tons) lodging the complete equipment
b) 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
c) One of the seven pyranometers driven by step motors in different positions
d) Fish-eye (180° aperture, linear distortion) camera for retaining state of sky and terrain characteristics

This equipment measures the direct solar radiation in the total spectrum in broad spectral intervals and also at discrete wavelengths, thus giving detailed information about atmospheric turbidity. This allows a differentiated parameterization and interpretation of the radiation field. The pyranometers S_1-S_4, measuring global radiation on plane surfaces, proceed each 20 seconds into another position; the program of the movement sequence may arbitrarily be chosen. At present, they are driven through 77 positions involving different tilts (between 0° and 90° relative to the horizontal) and

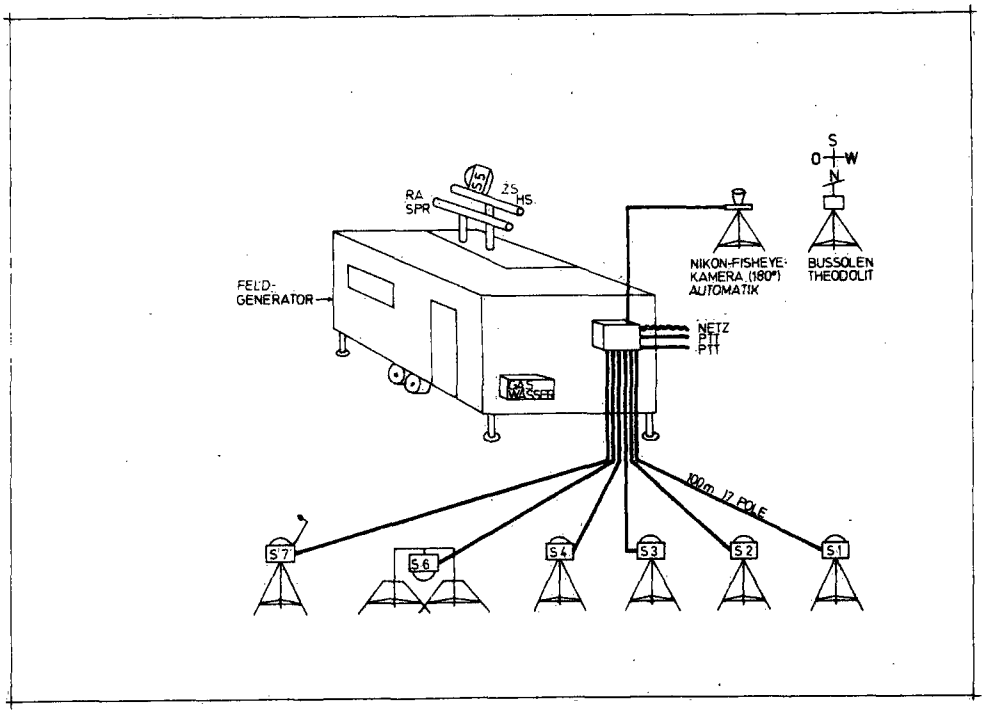


Figure 2 Sketch illustrating the operational grouping of the instruments:

- 6 pyranometers (S_1-S_4, S_6 and S_7) connected to the car with 100 m cables (17 poles) and movable mounted on step motors to orientate and tilt them in any position
- 1 absolute radiometer (RA) fitted with conventional Schott filters (Quarz, OG1, RG2, RG8), 1 spectroradiometer (SPR) measuring at 12 different wavelengths; these two instruments together with a further pyranometer (S_5) are mounted on an automatic sun-tracker emerging from the interior over the car's roof
- 1 circumsolar spectrophotometer (ZS) and 1 sky photometer (HS) are not yet ready for operation
- 1 theodolite is used if orientation according to the sun is not possible due to overcast sky
- 1 Nikon F2S camera with a fish-eye objective controlled automatically
- Other instruments besides these are foreseen.

different directions in about 6 minutes (see Figures 3 and 4 later) The 4 x 77 single measurements are usually averaged in one serie covering a time interval of about 26 minutes. Small aperture scanning devices, still under construction, will provide amongst other information, data about the intensity density distribution over the sky hemisphere. The system will collect information from the whole sphere of 4π steradians.

First results

Several expeditions in 1975 and 1976 covering different locations

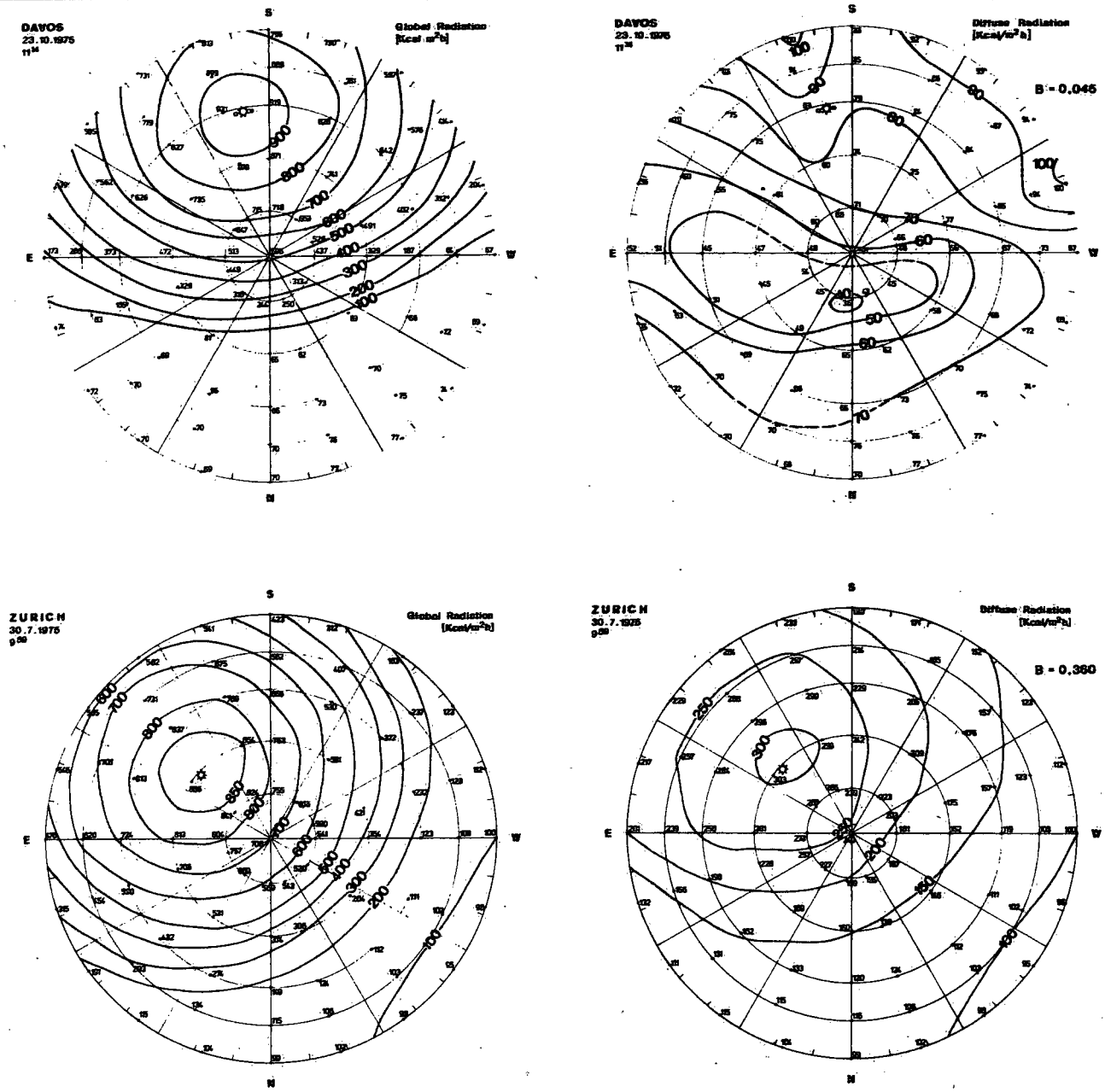
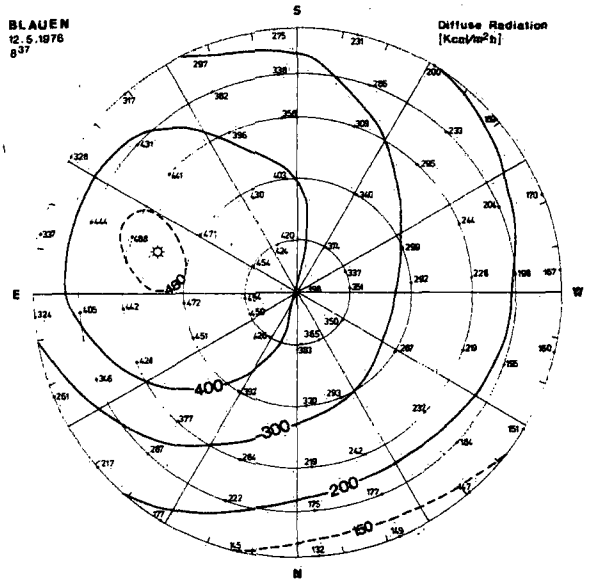
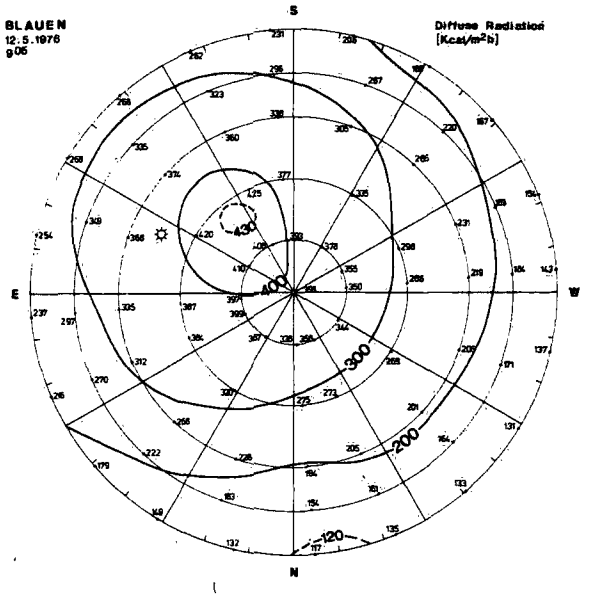


Figure 3

The dependence of the global (on the left) and simultaneous diffuse (on the right) radiation on plane surfaces on the surface's angular position for clear alpine air at Davos (above) and for a very turbid atmosphere at Zurich (below). Schuepp's [12] turbidity coefficient B is 0,045 and 0,360 respectively. The diffuse radiation maxima differ by about a ratio of 3, while those for the global fluxes (in opposite sense) by few percents only. The sky is free of clouds in both cases. Patterns are symmetrical to the sun's vertical, only the diffuse field pattern for Davos seems to be disturbed by the effects of the surrounding mountains. Of course the limits of instrumental accuracy also play their part in this case.





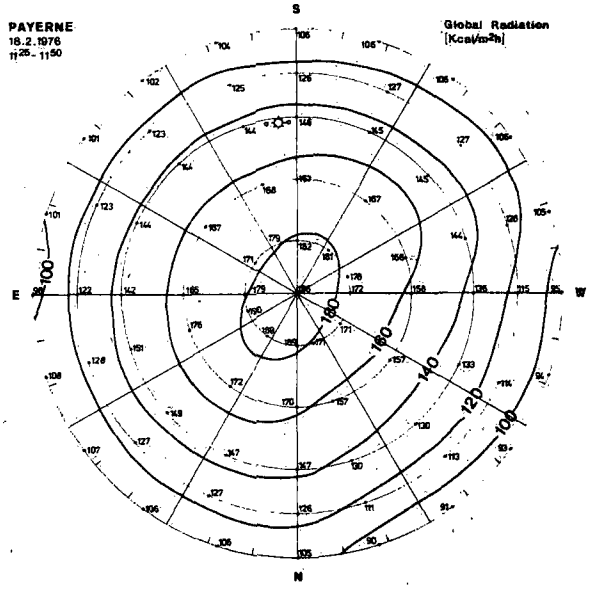


Figure 4 Distributions of the diffuse radiation presented like Fig. 3 but for

- (above) 6/10 cohesive stratocumulus covering the western half of the sky, the sun's surrounding being free of clouds but hazy. The patterns still show maximum for surface facing the sun.
- (centre) 9/10 stratocumulus of bright luminous appearance covering also the sun and its surrounding. The intensity curves are not now centered around the sun but are shifted towards the zenith.
- (below) all-enveloping fog showing good zenithal symmetry of the pattern. Absolute values and also intensity gradient are much reduced when compared with the two examples above (attention: different gradations).

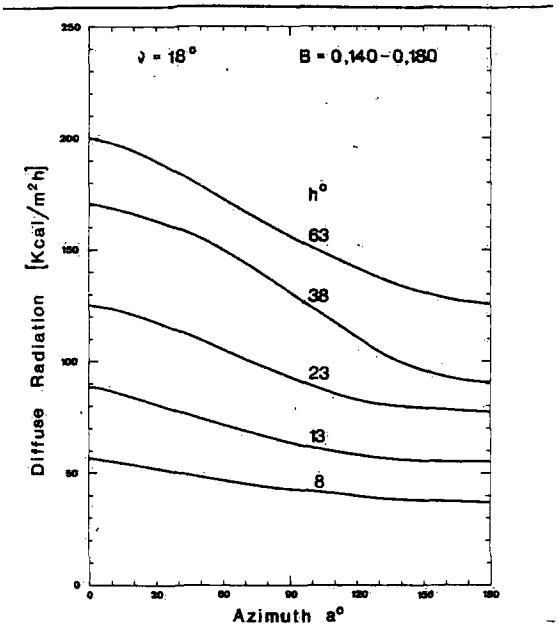


Figure 5 Variations of the diffuse irradiation on a surface inclined at 18° to the horizontal for a hazy atmosphere with the orientation of the surface for various angular heights of the sun.

situated up to 1700 m a.s.l. produced 400 series of measurements. In the following paragraphs typical examples are discussed first; the functional relationships presented thereafter are only preliminary. They may need refinement when more material is available.

Figures 3 and 4 show polar diagrams, each representing quasi-instantaneous angular distributions of the radiation intensity received by plane surfaces. The intensity value received by each (pyranometer-) surface is entered at the point where the surface's normal meets the sky dome. The coordinate grid indicates the tilt angles of the pyranometers by the circles drawn for 90 (vertical surface, border circle), 75, 60, 39 and 18 degrees and by the central point for 0° (horizontal surface) respectively. The azimuthal scale measures the orientation. The sun's position is marked by ☼ in each field. The curves of equal intensities were fitted by eye to the plotted values; attention should be paid to the different gradations. The patterns show good congruency with the simultaneous fish-eye photographic images which are not included in this paper.

Using the notation

D : diffuse radiation intensity on plane surface
h : solar height
a : azimuth between sun's direction and the normal to the surface
ν : inclination of irradiated surface to the horizontal plane
B : atmospheric turbidity coefficient

Figures 5, 6 and 7 present different three-variate sections of the five-variate relationship D = f(h, a, ν, B) valid for cloudfree sky conditions. The measurements used were taken at two places (roof of the Meteor. Institute in Zurich and open field in Payerne) located at about 500 m a.s.l. both with fairly free horizon. The effect of albedo (estimated values: 0,15 - 0,25) has not been investigated in the present studies.

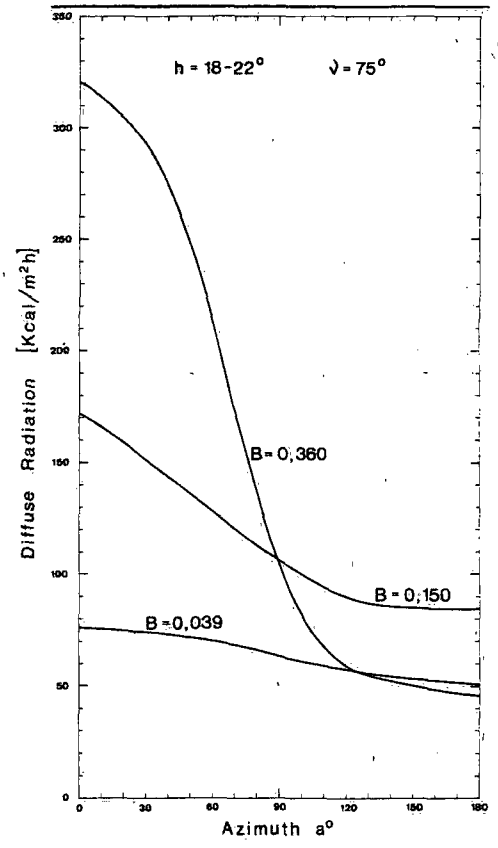


Figure 6

Diffuse irradiation of a surface of nearly optimal tilt for maximum incident energy ($h + \nu \approx 90°$ facing the sun, $a = 0°$) for different surface orientations for various air turbidities. The effect of haze is considerable: diffuse radiation may increase by a factor > 4 with change of turbidity though the angular conditions remain the same.

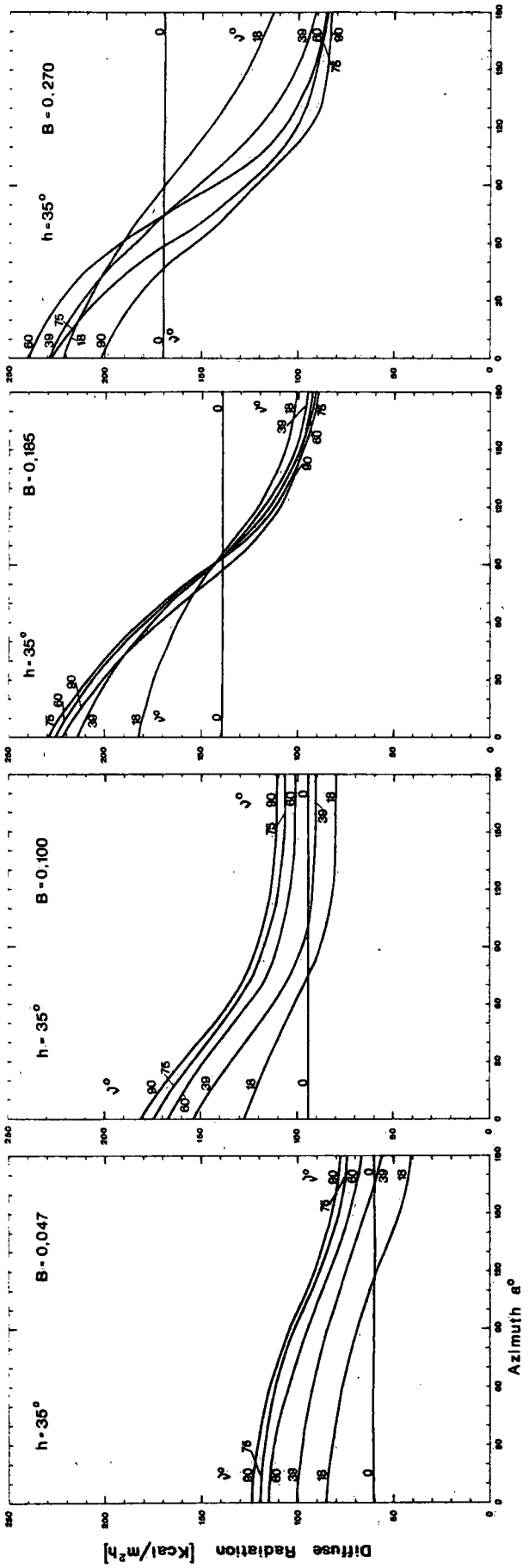


Figure 7

Diffuse radiation as a function of orientation and inclination of the irradiated surface presented for very clear air (B = 0,047) and for successively augmenting turbidities (B = 0,100; 0,185 and 0,270). The solar height is throughout constant (h = 35°). Ground reflections are included. The albedo was estimated to lie between 0.15 and 0.25.

The results for cloudless skies cover the intervals up to h = 65° and 0,030 ≤ B ≤ 0,360 respectively but, due to lack of space, Figure 7 presents the (D, a, ν) intersections only at h = 35° which remains constant for a sequence of gradually increasing B-values. It can be seen that the slope of the surface receiving the greatest diffuse solar radiation varies with turbidity. For clear conditions, a vertical surface receives most diffuse radiation from sky and ground. When B = 0,185, a 75° slope receives most diffuse radiation when facing the sun and least when facing away from the sun. The diffuse radiation on a vertical slope falls relative to the other slopes when B is high the horizontal diffuse radiation increases with increasing B. The changing hierarchy of tilt angles with respect to maximum diffuse irradiation may easily be explained as function of the other parameters if traced back to the causal effects formulated earlier [7, 13].

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