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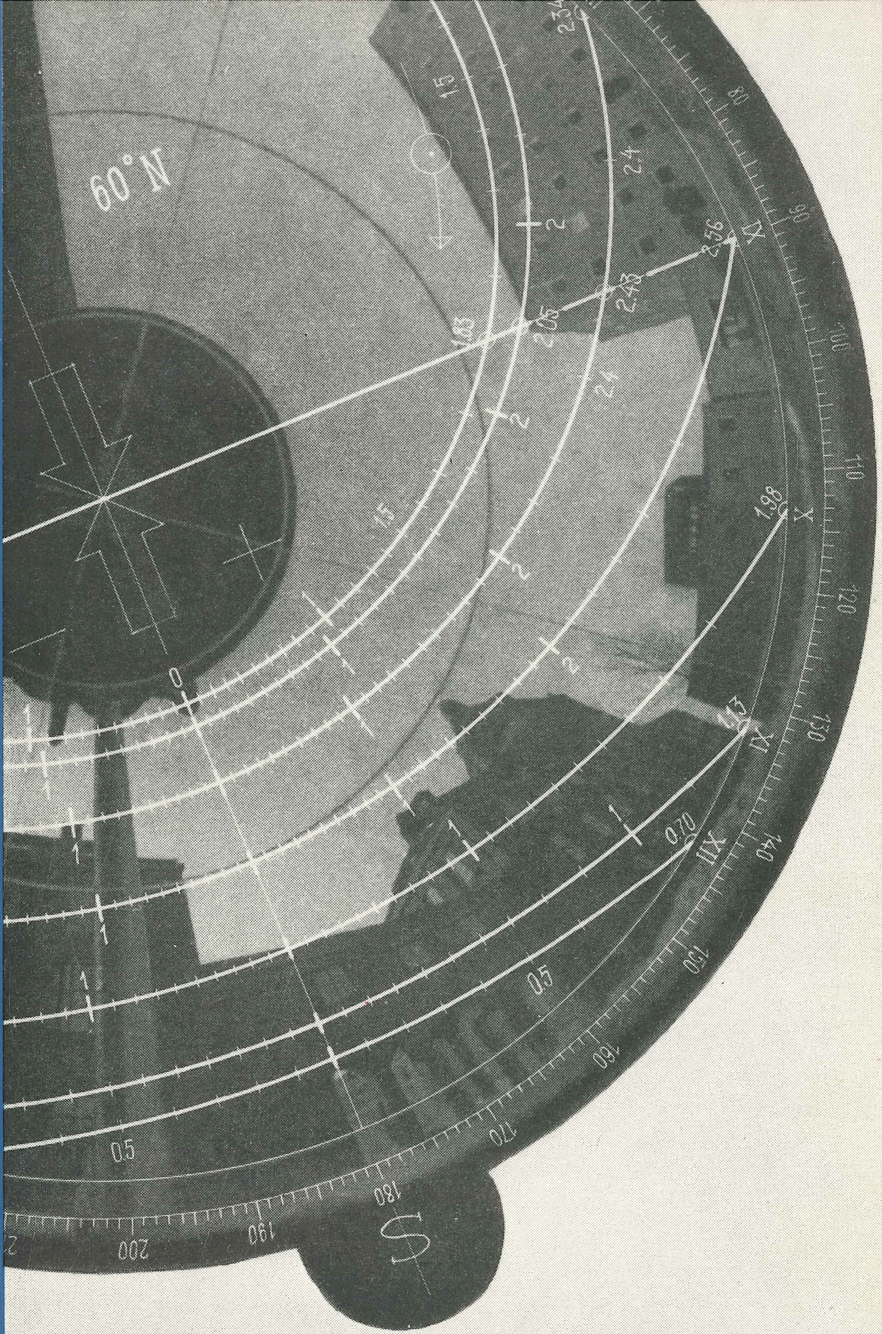

Statens
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Gunnar Pleijel:

THE COMPUTATION OF NATURAL RADIATION IN ARCHITECTURE AND TOWN PLANNING

The Computation of Natural Radiation in Architecture and Town Planning

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by

GUNNAR PLEIJEL
Architect

STATENS NÄMND FÖR BYGGNADSFORSKNING

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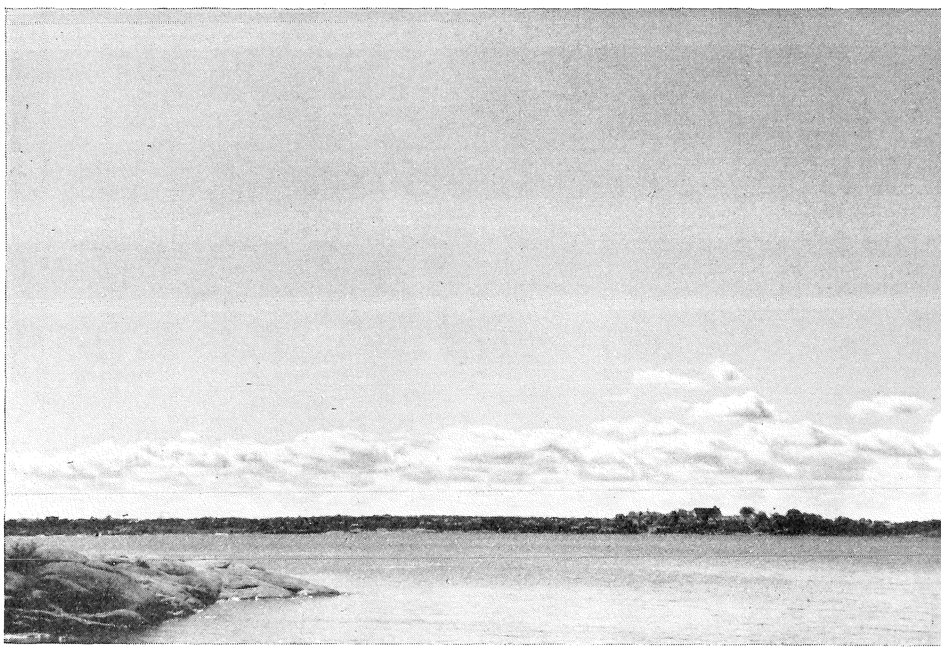

Öregrund seen from Gräsön. Observe how the low-lying cumulus clouds cease just at the limit of land and sea, and how the sky is free and clear over the water.

Victor Pettersons Bokindustri Aktiebolag, Stockholm 1954

He that observeth the wind shall not sow;
and he that regardeth the clouds shall not reap.

Ecclesiastes 11. 4.

Errata

Page 26, 6th line from top, for "constants" read "constant"
,, 28, 9th ,, ,, ,, ,, "comparision" read "comparison"
,, 43, 10th ,, ,, ,, ,, "clan" read "can"
,, 49, 16th ,, ,, bottom ,, "on" read "in"
,, 51, Caption to Table 25, "european" should be "European"
,, 63, Table 32, bottom line, for k_d read $\varkappa_k$
,, 99, Eqn 17, read $x^2 + y^2 = 8\,z$
,, 109, Figure 39, example, last line should read $= -1.46 - 0.95 =$
$= -2.41$
,, 109, Figure 41 The signs on the vertical scale should be changed (See the nomograms, Figures 42z to 46z).
,, 120, Eqn 21 should read:

$$E_x^{\triangle H} = B \times \triangle H \times \cos h \times \cos a$$
$$E_y^{\triangle H} = B \times \triangle H \times \cos h \times \sin a$$
$$E_z^{\triangle H} = B \times \triangle H \times \sin h$$

,, 120, 5th line from bottom for "22*x*" read "22*y*"
,, 127, 1st line from the top for "have the *z*-axis as centre" read "have points on the *z*-axis as centres."

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Preface

In architecture and the art of town planning, great differences are observed between the south and the north. These distinctions may arise partly from the dissimilarities in the radiation climate. On the radiation depends the temperature, to which mankind is very sensitive. The relation between architecture and radiation climate is never more evident than in the daily discussions which arise concerning illumination, fuel consumption, window design, orientation of facades, insolation through rooflights, obstructions to sunlight, etc. The fact that these problems are in most cases neglected or mishandled is due to defective knowledge about natural radiation, and also because present methods of calculation are laborious, difficult and slow. If natural radiation is to serve us to the best advantage and not cause discomfort it is necessary to realise that recourse cannot be had to tradition, for the art of building has altered a great deal in the last hundred years. Moreover it is economical to plan. It is always more costly and troublesome to rectify afterwards the result of initial neglect.

The theoretical methods of calculation of radiation from sun and sky which have been available up to the present, are of little use in architecture and town planning. Until recently the principal interest has been in the physical, meteorological and horticultural problems, which are all quite different from the architectural problem. The chief distinction is that the architectural problem must take into account the effect of screening by surrounding objects. In the centre of a town this screening can be considerable.

In the architectural problem the distinction must be made between solar radiation and the diffuse radiation from the sky. The sun is in effect a mobile, practically punctiform radiator, which moves across the sky during the course of the day, and radiates first the one facade, and then the other. The sky, on the other hand, can be regarded as an effectively uniformly radiating vault, from which the radiation during the course of the day merely increases and decreases. Methods of calculation for each form of radiation must necessarily be different, and they cannot be handled as a single entity as is now customary in meteorology.

The measurements and recordings which are available can in certain cases serve as basic data, but some uncertainty arises when this data is used as the basis for the architectural problem. Among other things the influence of the nebulosity on radiation has not been treated in sufficient detail. One of the reasons for this study arises from the fact that agreement between calculations and recordings could not be obtained when statistics of nebulosity were employed directly in radiation calculations for Helsinki. What is required in architecture is, furthermore, average values and not radiation intensities for certain well-defined conditions, such as completely clear or fully overcast sky. Nor is there much interest in measurements taken on high mountains or in particularly clear air. The conditions in a town are often quite the reverse to the atmospheric conditions in which the measurements were taken.

Measurements and recordings which are to serve as a basis for methods of calculation must also take into account the properties of the radiation in relation to mankind, and it is these properties which must be measured and recorded in particular, and apparatus suitable for the purpose constructed. All attempts to relate the various properties have hitherto resulted in a stream of formulae, conversion factors, constants and hypotheses which only serve to confuse rather than clarify the problem. A good example of this is the fact that ultraviolet radiation, although its importance for mankind was discovered at the turn of the century, was not the subject of any attempt at measurement until recent years, and then only as a single entity from sun and sky together.

Methods of calculation for use in architectural problems demand also, distinct from problems of pure science, a certain speed in use without too great a sacrifice of accuracy. The way in which building work is now organised does not allow very much time for calculations. It is therefore important that methods which are time-consuming should be simplified as far as possible. In a town, orientations and obstructions can vary in an infinity of ways. Every such problem demands its own solution. A method which combines numerical and graphical techniques has been shown to be the best solution. The study which is presented here is a search for a universally applicable method for the calculation of the radiation from the sun and the sky, specially directed towards architecture and town planning, but it may also have other applications.

The meteorological basic material on which this study has been developed is above all that furnished by the measurements and recordings made by Professor Harald Lunelund at the University of Helsinki in parallel with his teaching work. They constitute a unique and rich source of information without parallel here in the North. There is much to be gained there for those who are interested in the radiation problem.

A grant for the investigation was made by the Swedish State Technical Research Council and the Swedish State Committee for Building Research. The translation into English was made by Dr. R. G. Hopkinson of Abbots Langley, England. To these I wish to express my sincere thanks. I wish, however, above all to express my gratitude to my wife, who has devoted the whole of her spare time during the last year to the preparation of the manuscript of this work.

General Introduction

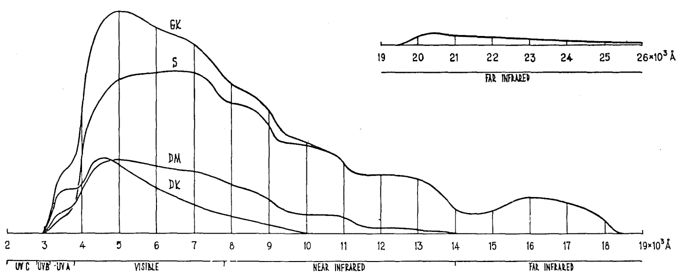


Fig. 1. Spectral composition of global radiation for clear sky (GK), solar radiation (S), radiation from clear sky (DK), and from cloudy sky (DM), all calculated for a horizontal plane with free horizon. The curves apply to a solar elevation of about 30° above the horizon. The following sources have been employed in the construction of the curves: Gage (26), International Critical Tables (35), Büttner (11), Nessi and Mouret (67), and Lunelund (56). The horizontal scale gives wave-length.

The Compass of Natural Radiation

The radiation from sun and sky which will be discussed here lies in the spectral region which comprises that called optical radiation. This extends from a wave-length of 40 Å(ngström units) to a wave-length of 2×10^6 Å, that is 0.2 mm. The lower end of this region borders on that of X-rays, the upper on radio waves.

The optical radiation region is divided into three main divisions: the ultra-violet, the visible, and the infra-red regions. Each of these regions is again divided into smaller parts. The region of shortest wave-length is called the extreme ultra-violet and this extends from 20 Å to 2,000 Å, then next comes the UV-C region from 2,000 Å to 2,800 Å, the UV-B from 2,800 Å to 3,150 Å and the UV-A from 3,150 Å to 3,800 Å. Then follows the visible region which is divided into the spectral colours from violet, 3,800 Å, through blue, green, yellow and orange to red at the extreme end of the visible spectrum, 7,800 Å. From thence extends the infra-red region, that lying nearest the visible being called the near infra-red and extending from 7,800 Å to 14,000 Å. The other part is called the far infra-red which extends from 14,000 Å to 0.2 mm. Then come the radio waves.

The natural radiation from sun and sky begins in the ultra-violet in the UV-B, and finishes in the far infra-red about 25,000 Å. See fig. 1. It is necessary to distinguish, however, between the sun radiation and the radiation from the clear sky. These supplement one another so that the radiation on a horizontal plane during the course of the day is generally of the same spectral composition. The radiation from a cloudy sky accords in its composition with the combination of sun and clear sky. The radiation on a horizontal plane has therefore generally about the same spectral composition whether the sky is clear or cloudy (28, 31, 81).

The sun radiation considered alone begins in the spectrum at a wave-length of about 3,000 Å in the UV-B. This lower boundary varies with the height of the sun. The lower the sun in the sky, the more is the spectral distribution shifted towards the long wave-lengths. When the sun is lower than 15° above the horizon no radiation is received in the UV-B region. The limit has shifted to the UV-A. The maximum of the solar radiation distribution lies in the visible region at about 5,000 Å to 6,000 Å that is, in the yellow-green. The upper limit is not so sharply marked as the lower limit but it lies at about 25,000 Å in the far infra-red.

Radiation from the clear sky is well represented in the ultra-violet. The lower limit coincides with that of sunlight but the maximum lies at a shorter wave-length, about 4,500 Å in the blue-violet. The upper limit is about 10,000 Å in the near infra-red near the limit of the visible spectrum (29).

The radiation from the cloudy sky is a combination of solar radiation and radiation from the clear sky. It therefore begins at about the same point in the ultra-violet, has its maximum at about 5,000 Å and its upper limit at about 14,000 Å.

The infra-red radiation of a wave-length longer than 25,000 Å will not be discussed here.

The Value to Mankind of Natural Radiation

Radiation is a pre-supposition for all organic life on the earth, for it maintains the temperature at a suitable level. This temperature is, however, very different in different parts of the globe, being dependent on a different supply of radiation energy per unit horizontal area. The greater the distance from the equator, the less is this energy. At the equator the energy level is about 1,500 Mcal per square metre per year, whereas at the 60th parallel it has decreased to about 700 Mcal per square metre per year, that is to say almost one half. This does not mean, however, that the same relation holds for other surfaces, for example, vertical surfaces. At certain times of the year the radiation on some surfaces can be stronger at the 60th parallel than at the equator, for example, on a vertical surface orientated towards the south, at the spring or autumnal equinoxes (73).

In the tropics the radiation during the day is so strong that special protective measures must be taken to avoid over-heating, whereas in the temperate climate it is very necessary during the winter to supplement the sun's supply of warmth artificially in order to maintain the temperature at a suitable level indoors. Public health requirements in Sweden demand a temperature of +18° C in dwelling houses. Consequently in both the tropics and in temperate climates it is essential to take measures to smooth out the variations in the energy supply. It is necessary in the devising of such measures to have a detailed knowledge of the radiation in all its daily and yearly variations, and also to know the effects of the protective measures. It is also necessary to take into consideration other climatic factors and the claims of a suitable climate from the medical standpoint.

In this country there is, during a large part of the year (September to May) a marked lack of warmth which must be supplemented by artificial heating. This gives rise to considerable expense and sometimes also to anxiety as to how sufficient energy can be provided. But in fact we employ only an insignificant amount of the natural radiation. We put our confidence in the energy which is stored up in coal, oil and wood. No rational employment of the heating properties of the sun's radiation has yet been planned. Buildings in the United States of America, where attempts have been made to employ solar energy for the heating, have not yet found any follow-up in our country, for it is considered that we have insufficient energy available from the sun. This is wrong. Even if we cannot employ solar radiation during the darkest winter, nevertheless during the spring and autumn the radiation is strong enough to enable us to make use of it. Even if the heating problem cannot be completely solved as a whole by solar energy, nevertheless a large part of the necessary energy for heating can be derived in this way.

On the other hand, even in this country, there is a problem of over-heating. In factories with unsuitable roof fenestration the temperature in summer can be so high as a result of solar heat penetration through the window, that work is impossible unless special protective measures are taken. Unfortunately these measures are often of a provisory character, to the detriment of the economy, the protective effect and the appearance of the localities. The measures should be taken against over-heating at the same time as the building is designed so that they can be both economical and adapted for their purpose. But this demands a special knowledge of radiation and calculating methods which are easy to handle.

The radiation from sun and sky affects also to a considerable degree the problem of town planning. Access to the sun in dwelling areas is necessary, certainly during suitable times of day. This is not only a problem which concerns the orientation of facades. Houses over-shadow one another and cast shadows on children's playgrounds or on the benches for old people. It is desirable that the necessary measures should be taken initially at the design stage in order to avoid bad planning. Systematic investigations should be undertaken in order to obtain knowledge of the best ways in which the radiation problem in town planning can be solved.

Radiation also has other virtues than heating. The most important of these are the visual sensation which results from the spectral region between 3,800 Å and 7,800 Å, and the direct medical value of radiation in the ultra-violet region UV-B. The first of these serves us for lighting and the second has a fundamental influence on our health.

The sun as a light source is infinitely superior to all light sources with which artificial lighting concerns itself. We need only imagine that the sun was absent in order to realise its value to us from this point of view. Daylight is, however, periodic and therefore it has to be supplemented when it is insufficient. During the daytime it should, however, be used to the best advantage and only in exceptional cases replaced by artificial light. Such an employment of daylight demands, however, special planning and that in its turn demands a knowledge of the sun and sky as light sources.

We do not receive daylight free, however. Its employment indoors is linked up intimately with the heating problem becauses windows insulate badly from the cold. But this radiation which gives us light through the window also gives us heat at the same time. It is sometimes not clearly understood that daylight becomes heat when it is absorbed. The energy balance of the window comprises as well, not only heating intake and radiation of heat out of the window, but also the problem of supplementing daylight with artificial light. Economic calculations demand a detailed knowledge of heating and lighting from sun and sky and also the characteristics of the window in relation to both these forms of energy. With respect to this see the bibliography: *Cadiergues* (12), *Kreuger* (43), *Pleijel* (73, 74, 75).

Every work place should be assured of sufficient daylight illumination. A considerable amount of work has been done to establish a standard for illumination for work. In order to establish comprehensively suitable standards it is necessary to have a knowledge, not only of the medical and hygienic problems but a knowledge of the light variation during the day and during the year. Once these standards are established, methods of calculation are then demanded so that in the course of the design it can be established that the daylight will meet the demands of the standards. Methods of calculation must be both simple and easy to handle if they are going to find universal application.

The realisation of the importance of ultra-violet radiation to humanity derives from the opening of the twentieth century. Sun-therapy was well known to the ancients but they did not know of ultra-violet radiation and of its specific value.

At about the turn of the century the influence of sunlight on rickets was observed and this was paralleled by clarification of its relation with the substances now called vitamins. Vitamin D is formed in the skin under the influence of radiation in the UV-B range and this vitamin has a decisive influence on the calcium balance in the body. As a result special lamps, quartz lamps, were made which produced radiation in the UV-B region. The advertisements for these lamps have certainly been guilty of over-statement. As a result of the existence of these lamps it has almost been forgotten that nature supplies the same radiation free. The lamps have been thoroughly investigated as regards their properties, whereas investigations of sunlight and skylight are conspicuous by their absence. It has therefore been difficult to derive material for this present investigation of variations in ultra-violet radiation.

In our country which lies so far north, these actinic radiations are lacking in winter. It is therefore justifiable during this season to attempt to supplement this lack artificially, but during the spring, summer and autumn the natural radiation can very well be employed. This must however be done out of doors, on the balconies, the streets or flat roofs. The window glass at present available does not let in the important part of the radiation, consequently this does not penetrate into the house. None the less it is considered of importance that we should provide ourselves with the knowledge of how much of these radiations reach us, and especially the extent of this penetration in heavily built-up areas.

The ultra-violet radiation in the UV-B region has another effect on humanity, which is more readily observed. It causes sunburn (solar erythema) and the brown pigmentation which accompanies it. The importance of this effect has not yet been fully clarified. But since the antirachitic effect of radiation coincides almost exactly with this erythemal effect, this latter can be taken as a measure of the biological value of the radiation. *Ronge* (79) has given a summary of the biological effect of radiation.

Three qualities of natural radiation have been selected here for treatment on the basis of their importance for human beings according to the above findings. They are:

1. Heating effect
2. Lighting effect
3. Erythemal effect

The heating effect derives from the whole radiation from the shortest to the longest wave-length. When rays are absorbed they change to heat energy and this effect can therefore be measured in calories. This will be called *heat radiation* below and since it embraces the total radiation, it will be indicated by tE for the *heat radiation density* and tQ for the *quantity of heat radiation*.

The light effect (visibility) results from that part of radiation which lies between 3,800 Å and 7,800 Å. The visual response to this radiation cannot be expressed directly in terms of energy units, but the radiation must first be

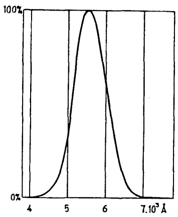


Fig. 2. Sensitivity curve of the light-adapted eye to radiation of different wave-lengths, according to Commission Internationale de l'Eclairage (CIE) (17, p 67).

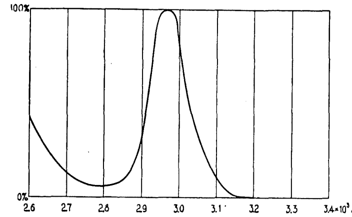


Fig. 3. The erythemal sensitivity of the skin to radiation of different wave-lengths, according to the Commission Internationale de l'Eclairage (CIE) (18, p 625).

modified by the spectral sensitivity of the light-adapted eye. See Fig. 2. For each wave-length the value of the radiation must be multiplied by the corresponding visual sensitivity. The sum of these products is called the illumination and is measured in lux. The light units have been standardised by international agreement. The term *light radiation* will be used here, indicated by *vE* for the *illumination* and *vQ* for the quantity of light, or *luminous energy*.

The erythemal effect results from the radiation in the UV-B region of the spectrum. American sources have proposed (49) that a system of units should be derived similar to that described above for light (see below Page 36). Since, however, the measurements which form the basis of these investigations are not expressed in these units, but in watts/unit area, it has been decided to use these latter units here. The term *erythemal radiation* will be used here for this part of the energy spectrum, indicated by the symbol *eE* for the *erythemal radiation density* and *eQ* for the *quantity of erythemal radiation*.

The Attenuation of Solar Radiation in the Atmosphere

From the study of solar radiation at different altitudes of the sun and at different heights above sea level it has been possible to calculate how strong is the normal heat radiation if the effects of the earth's atmosphere are neglected and the distance to the sun is considered constant. This is called the solar constant and its value is 1.164 Mcal/m²h.

When solar radiation penetrates the atmosphere it is attenuated through absorption and extinction (dispersion). On high mountains the traverse through the atmosphere is less than at sea level and consequently radiation is stronger on the mountains than in the lowlands. When the sun stands high in the sky the path through the atmosphere is shorter than when it stands low, and consequently radiation is stronger in the first case than in the latter. The approximate relative air path $m = 1/\sin h$. The normal radiation value E_o^S can be expressed by the following equation:

$$E_o^S = E^S \cdot (\tau)^m \quad \text{eqn 1}$$

where E^S = the solar constant, τ = the transmission factor of the air, m = the relative air path (in relation to the vertical air path).

The absorption is not the same for all wave-lengths but the irregularities manifest themselves in the form of troughs in the spectral curve. See Fig. 1. The different constituents of the atmosphere absorb different spectral regions. Water vapour (H_2O) and carbon dioxide (CO_2) absorb chiefly the infra-red, whereas the visible radiation and the ultra-violet are almost unaffected. It follows from this that the heat radiation is affected by the humidity of the atmosphere. During the winter the water-vapour content is not great and consequently heat radiation is stronger than during the summer when the water-vapour content is greater.

The ozone (O_3) in the atmosphere absorbs chiefly in the ultra-violet region. The ultra-violet radiation from the sun in the UV-B region has been calculated to be 6 W/m^2 without the atmosphere (13). The attenuation through the ozone in the atmosphere reduces this to $\cong$ 0,9 W/m^2 when the sun is at zenith. The ozone content of the atmosphere varies and the erythemal radiation consequently varies closely in proportion. The ozone content is greater in the spring than in the autumn and also greater in the morning than in the afternoon. Consequently the erythemal radiation is stronger in the autumn than in the spring and stronger in the afternoon than in the morning.

The extinction is also not the same for different wave-lengths but it is more regularly distributed than the absorption. It is inversely proportional to the fourth power of the wave-length (Rayleigh's Law). In the violet part of the visible spectrum at a wave-length of 4,000 Å it is about 9 times stronger than in the red part of the spectrum at a wave-length of 7,000 Å. This explains the well-known phenomenon that the sun becomes redder the lower it stands above the horizon. It also explains the blue colour of the clear sky.

Since the attenuation of radiation on account of absorption and extinction is different for different parts of the spectrum it follows that the variation of heat radiation, light radiation and erythemal radiation will be different for different altitudes of the sun. Each of these radiation effects must be considered independently and no simple relation is found between them. The least attenuation occurs to the heat radiation, rather more to the light radiation, and the greatest to the erythemal radiation. The latter almost disappears when the sun is about 15° or less above the horizon. The distribution of solar radiation in the different spectral regions is such that about half of the sun's radiation falls in the visible region but only about one per cent in the ultra-violet.

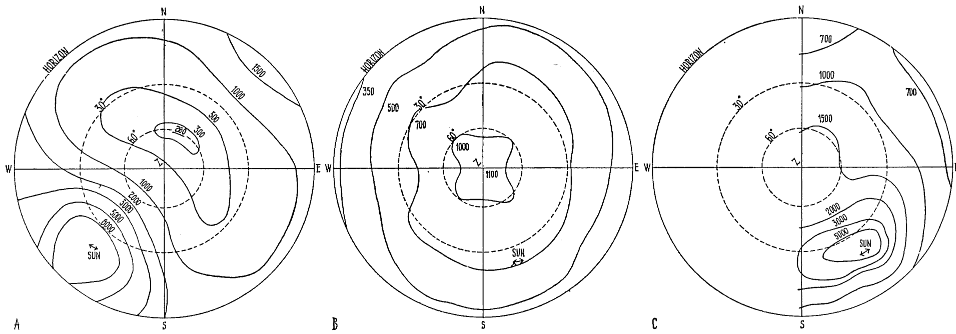


Fig. 4. Sky brightness distribution according to measurements by Hopkinson (32) in Stockholm 1953. A. Blue clear sky, 2 October 1953, 14.00—14.25 clocktime, (14.25—14.50 solar time). B. Heavy cloud, individual clouds visible, 6 October 1953, 9.40—9.57 clocktime. (10.05—10.22 solar time). C. Gathering clouds, sun intermittently covered, north sky stable, south-east sky unstable, 6 October 1953, 9.05—9.15 clocktime, (9.30—9.40 solar time). Unit 1 foot-lambert.

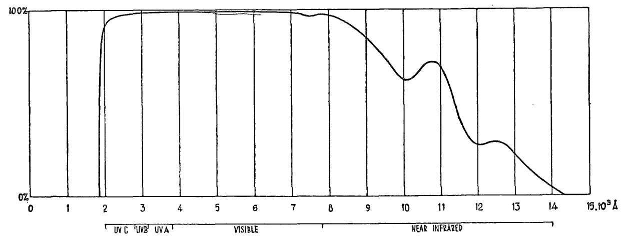
Radiation from the Sky

According to records made in Helsinki by *Lunelund* (57) the diffuse horizontal radiation from the sky forms about 40 per cent of the global (sun and sky). The contribution of the diffuse radiation can therefore not be neglected.

Radiation from the clear sky arises from extinction. According to Rayleigh's law this becomes greater for the shorter wave-lengths and, as has already been pointed out, has its maximum at about 4,500 Å in the blue violet. Cloud diffuses light radiation almost equally for all wave-lengths and so there is no marked colour of a cloudy sky as there is of the clear sky.

Radiation from the clear sky is not equally distributed over the sky vault. The heat radiation has been investigated by *Peyre* (70) and the luminance has been studied by *Kimball and Hand* (41) for Washington and by *Hopkinson* (32) for Stockholm, see Fig. 4. The distribution is very similar for heat and light. The measurements show that the brightness of the sky is composed chiefly of two parts. One of these parts has a brightness which is concentrated around the sun. The brightness decreases with the angular distance from the sun. The second part has its maximum at the horizon and this brightness decreases with the angular elevation. When these two are combined they result in a minimum at a compass point opposite to that of the sun and approximately at right angles to the direction of the sun. See Fig. 4 A and *Pokrowski* (77). The luminance of the overcast sky is greatest at the zenith and decreases towards the horizon so that the horizon luminance is only about one third of that in the zenith. See Fig. 4 B.

Fig. 5. The transmission of a layer of distilled water, 1 cm thick (35). The horizontal scale gives wave-length.



There are data for some broken cloud conditions, see Fig. 4 C, but in daylight technology there is a pressing need to record how the radiation distribution from the sky varies with cloudiness. Such data are of great importance for economic calculations because such calculations are carried out with average values during some long period, for example, average values for one month.

Luckiesh (54) has measured the erythemal radiation distribution from the clear sky and found that this has about half the value at the horizon that it has in zenith. Data are lacking, however, to show what is the distribution for an overcast sky but it is likely that the distribution is the same as that for the light radiation, for the cloud appears to act only as a diffusing filter.

The Transmission of Cloud and the Reflection Factor of Ground

A question which is of considerable significance from the climatological viewpoint is the influence of cloud on radiation from sun and from the clear sky. To begin with it can be established that distilled water has very low absorption in the ultra-violet as well as in the visible spectral region whereas the absorption is much greater in the infra-red region. See Fig. 5. *Lunelund* (56) states for the heat radiation 24 % transmission for nebulosity 10 and for light radiation 30 %. According to *Büttner* (11) the transmission by cloud of erythemal radiation is however significantly higher than of light radiation. For a nebulosity of 10 he gives a transmission value of 23 % for heat radiation, 36 % for light radiation and 42 % for erythemal radiation. This high transmission figure for erythemal radiation is confirmed also by the measurement of *Ives and Gill* (36) obtained in American towns. The transmission of cloud can be calculated from their figures as being 42 % for the erythemal radiation and 30 % for light radiation. This latter value compares well with *Lunelund's* measurements (56). For two towns, New Orleans and Los Angeles, which were not included in the above figures, values as high as 86 % for erythemal radiation and 67 % for light radiation were obtained. These high values must be due to cloud formations of a special kind or the presence of highly reflecting surfaces in the terrain around these towns (see below). The figures do however confirm that the transmission through cloud is greater for erythemal radiation than for light radiation.

Kalitin (38) has studied the influence of the type of cloud and the degree of nebulosity on the illumination from the sky. High cloud and medium high cloud increase the illumination considerably with increasing degree of nebulosity, whereas the illumination with low types of cloud is to a large extent independent of the degree of nebulosity. In relation to the clear sky almost all types of cloud exercise a strengthening influence on the illumination with high solar altitudes but it is only the high types of cloud which do this for lower solar altitudes.

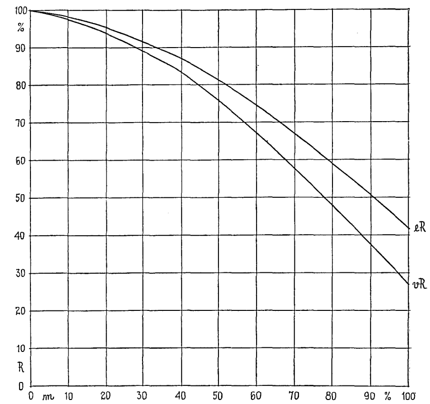
In snow covered terrain it is necessary to take into account the influence of the snow covering on the radiation. Snow is an extraordinary reflector for erythemal as well as light and heat radiation from sun and sky. The reflection factor for heat radiation is given by *Lunelund* (56) as 82 % for freshly deposited snow. *Büttner* (11) gives 89 % for heat radiation and 85 % for ultra violet radiation. *Ångström* (97) gives 69.5 % for heat radiation. In the same investigation he has also studied theoretically the influence that a snow covering can have on the horizontal radiation. With clear sky the influence on heat and light radiation is not so great, an increase of about 20 %, but for erythemal radiation this increase is 50 % because of the stronger extinction of these short-wave radiations by the atmosphere. For a cloudy sky with its strong reflection for all wavelengths the radiation on the horizontal plane can be doubled for all three types of radiation. *Kalitin's* (38) investigation of the radiation in Slutsk gives also information about the effect of a covering of snow on radiation both from a clear and from an overcast sky. For a clear sky he gives an increase of between 11 and 28 %. For an overcast sky the increase depends very much on the particular type of cloud, for high clouds the maximum lies at about 100 %, whereas low cloud formations show a greater increase with a maximum of about 184 %.

Luminous Efficiency

The ratio between the illumination and the heat radiation from the same radiation source is usually called the *luminous efficiency* of the radiation. This factor has not only a theoretical value but can also be used as a factor to calculate the illumination from the heat radiation. Existing measurements or recordings of the heat radiation can consequently, by the use of this factor, be used to calculate the light radiation. This applies only, however, to mean values. The luminous efficiency varies from place to place, depending on the differences in the radiation climate.

The luminous efficiency is important to the building technician for another reason. He can evaluate different radiation sources from the point of view of illumination. In order to obtain the dimensions of fenestration from the illumination standpoint it is necessary for him to know how much heat will penetrate the windows from the incident radiation. If one wishes to illuminate locally to a high level without a corresponding heating effect it is necessary that the

Fig. 6. Relative illumination (vR) according to *Aurén* (4) and relative erythemal radiation (eR) as functions of the cloudiness (m).



radiation should have a high luminous efficiency. If one wishes to employ the radiations for heating also, a light source can be chosen with a lower luminous efficiency.

Relative Radiation

The relationship between the average illumination on a horizontal plane with unobstructed horizon and given nebulosity and corresponding illumination with fully clear sky is called the *relative illumination* corresponding to that nebulosity. From his recordings *Aurén* (4) has calculated a curve of the relative illumination as a function of nebulosity for Stockholm. This is shown in Fig. 6. *Lunelund* (56) has done the same for Helsinki and found a curve very like that of *Aurén*. If one assumes that the relation between the reflection and absorption of cloud for erythemal radiation and the reflection and absorption for visible radiation is constant for all degrees of nebulosity, a similar curve can be constructed for the erythemal radiation. With a transmission of cloud to erythemal radiation of 42 % for nebulosity 10, see above, the curve for relative erythemal radiation on Fig. 6 is obtained.

Radiation Measurements

Heat and Light Radiation

Different measuring instruments have been used for different purposes. For heat radiation it is usual to measure the heating effect of the radiation either by measuring heat expansion or using the thermoelectric effect. The instruments which are of importance for this work will be described together with the measurements.

The normal heat radiation of the sun has been an object of measurement on many occasions in Sweden. *Westman* (88) has measured the solar radiation at Upsala during the year 1901. He used a compensation-pyrheliometer designed and constructed by *K. Ångström* (101). *Westman's* measurements give the yearly average values for different solar altitudes expressed in kcal/m²h. These are shown in Table 1 and Fig. 14. In connection with these measurements, *Aurén* (6, Page 21—22) has pointed out that the year 1901 was unusually sunny in Upsala, consequently *Westman's* measured values may lie above the mean level. Later *Westman* (93) also measured the solar radiation in the coastal belt of the Baltic Sea. These measurements are generally lower than the Upsala values.

Table 1. Perpendicular (normal) heat radiation from the sun (tE) as a function of solar altitude (h), according to measurements made by Westman at Upsala in 1901. Unit 1 kcal/m²h.

h	6°	15°	24°	33°	42°	51°
tE	378.6	594.6	683.4	737.4	772.2	791.4

During the years 1909—22 *Sjöström* (82) obtained measurements of solar radiation in Upsala, and *Ångström* (100) made similar measurements in Stockholm during the years 1930—36. Neither of these series of measurements has been produced in such a form that they can be applied directly to the present problem. *Funke* (25) measured the radiation in Abisko during the year 1914.

There are no published recordings of solar radiation separately in Sweden. Since the summer of 1951, however, such records have been in progress at the

Swedish Meteorological and Hydrological Institute in Stockholm. These will, in time, be very valuable for researches in building technique.

The global heat radiation on a horizontal plane with unobstructed horizon has been measured in Stockholm. This work was got under way by *Ångström* in 1922 (98) and has now become a standard routine at the Met. Institute. In many local and foreign publications, *Ångström* refers to the experience which has been derived from these measurements, among which references (99) gives the fullest detail. The measuring instrument is a pyranometer of his own construction. It consists of four metal strips, blackened with platinum black, of which two are subsequently painted white with zinc oxide. All four strips are placed horizontally in the same plane, one black and one white alternately. The black strips absorb almost the whole of the radiation from sun and sky whereas the white strips reflect the greater part. This occurs almost equally over the whole solar spectrum. There is a temperature difference between the black and the white strips which is greater the stronger the radiation. This temperature difference is recorded by thermocouples placed at the back of the strips. The thermocouples are connected to a recording galvanometer which records a measure of the strength of the radiation. Two types of the instrument are employed, one with a translucent de-polished opal glass disc, and the other without. In the latter case, a hemispherical glass screen protects the light sensitive element against injury and also against radiation of longer wave-length than 30,000 Å.

The investigations of *Köhler* (46) point out that the opal glass gives the pyranometer a hypersensitivity to infra-red radiation and at the same time a considerable cosine error. The arrangement without opal glass shows none of these errors to any considerable degree.

Table 2. Monthly totals and yearly totals of the global heat radiation (tQ) on a horizontal plane according to recordings in Stocksund (near Stockholm) during the years 1935—42. Ångströms' pyranometer with opal glass disc (A). Aurén's solarimeter (B). Unit 1 Mcal/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
tQ A	8.3	20.2	56.4	90.3	127.3	138.0	128.0	98.8	65.2	30.2	10.0	5.3	778.1
tQ B	7.7	19.5	52.7	88.0	130.0	142.0	126.2	96.4	63.8	29.0	9.2	4.4	678.9

Table 2 shows the average values of the recordings during the year 1935—42, in Stocksund (near Stockholm).

Aurén has similarly registered the global radiation on a horizontal plane with a solarimeter of his own construction during the year 1935—42 (5, 6, 7) and with a potassium photo-cell during the year 1928—37 (3, 4, 6).

Aurén's solarimeter (5) employs a de-polished opal glass to trap the radiation.

This constitutes the lid of a metal box which contains three blackened copper plates of which one is exposed to the radiation from the opal glass disc through a diaphragm. The two other metal plates are protected from the radiation from the opal glass. The temperature difference between the irradiated and the non-irradiated metal plates is measured thermo-electrically and this gives a measure of the radiation on the opal glass disc. The arrangement can be provided with a filter. Recordings of radiation have been made with such an arrangement and are shown in Table 2.

The potassium photo-cell has been used in conjunction with a filter in order to measure the radiation in the visible region. *Aurén's* measuring equipment (3) was constructed in the following way: —

The photo-cell was placed in a box, in the upper side of which was fixed horizontally an opal glass plate de-polished on both sides. This served as a radiation trap and irradiated in turn the photo-cell in the box. Between the opal glass and the photo-cell was placed a filter (Schott GG11, 5 mm). Unfortunately *Aurén* did not specify in any of his publications the spectral sensitivity of his apparatus. *Lunelund* (56, Table 42) has, however, making use of measurements with a visual photometer (Bechstein) established that the potassium photo-cell, when provided with a suitable filter, will record, without serious error, values of illumination level.

Aurén has reported the results of the recordings with the potassium photo-cell in terms of a special unit, the E_s-unit. This unit is the global illumination on a horizontal plane with unobstructed horizon, with a completely clear sky, and with a solar altitude of 45 degrees. He has shown that this illumination remains extremely constant at least here in the North. This may perhaps be because the air is unusually clear and free from solid particles which have a considerable absorption over the whole solar spectrum. Using *Lunelund's* conversion factor 1 E_s-unit $= 77 \times 10^3$ lux, it is possible to calculate E_s-units in lux. See also Page 27.

The luminous energy measure $E_s h$ is obtained by multiplying by the time units. The equivalent illumination measure is kilolux-hours (klxh) or megalux-hours (Mlxh). Some of the results of *Aurén's* measurements will be clear from Table 3.

Table 3. Monthly totals and yearly total of the global illumination (vQ) on a horizontal plane according to Aurén's recordings in Stocksund (near Stockholm) during the years 1928—37. Potassium photo-cell with filter. Unit 1 Mlxh.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
vQ	0.93	2.47	6.55	10.00	16.73	19.23	18.26	13.75	8.29	3.63	1.09	0.52	101.4

In the calculation methods to be described here the solar radiation has been separated from the diffuse radiation from the sky. The above recordings are concerned with sun plus sky radiation and consequently they cannot be used directly for the calculating methods under consideration. They can, however, be used as a check on the results which are obtained with the methods.

Lunelund (57) has measured sun and sky radiation in Finland in a manner which is quite suitable for these studies of radiation in relation to building technique. Measurements which he made are briefly as follows: —

The measurements of heat radiation were initiated in 1922. At first they were concerned only with measurements of solar radiation employing a bimetallic actinometer. This instrument was used later for a check on the recordings which began in 1926. At first only the direct solar radiation was recorded with a Gorzynski pyrheliograph, an instrument which measures heat radiation by a thermoelectric technique and which is synchronised with the sun by means of a clockwork movement. Apertures are placed at different distances from the thermoelement in order to ensure that the diffuse radiation is screened off.

Later recordings were commenced of the global as well as the diffuse radiation on a horizontal plane. Two Ångström pyranometers were used for this investigation of the above-mentioned type, without the opal glass plate, coupled to a recording galvanometer. The pyranometer for the diffuse radiation was provided with a screening ring to screen off the direct solar radiation.

Of *Lunelund's* recordings those which were taken during the years 1928—35 (57) have been used below to establish the calculating method. Table 4 has been derived from the results of these recordings.

Table 4. Monthly totals and yearly totals of heat radiation (tQ) from the sun (S), from the sky (D), and global heat radiation (G) on a horizontal plane according to Lunelund's recordings in Helsinki 1928—35. Gorzynski's pyrheliograph (S), Ångström's pyranometer (D and G). Unit 1 Mcal/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
S	1.2	7.0	27.5	45.4	76.3	97.0	88.8	56.8	30.0	10.6	1.6	0.7	445.8
D	4.8	13.0	28.9	40.4	46.3	50.8	51.1	42.1	28.1	14.5	5.3	2.5	324.2
G	6.0	20.0	56.4	85.8	122.6	147.8	139.9	98.9	58.1	25.1	6.9	3.2	770.0

This table shows amongst other things that the heat radiation on a horizontal plane is greater from the sky than from the sun during six months of the year. During the whole year 42 per cent of the radiation comes from the sky and 58 per cent from the sun.

Tables 26 and 35 show in greater detail the average values taken over 10-day periods for each hour, the normal radiation from the sun as well as the diffuse radiation on a horizontal plane.

Lunelund has also studied separately the heat radiation on clear days and on cloudy days and in the first case he has separated the solar radiation from the diffuse radiation (56). See Table 5. It can be seen from this table that the percentage proportion of the global radiation on the horizontal plane which comes from the clear sky increases with decrease in the sun's altitude whereas the radiation from the cloudy sky remains fairly constants in one quadrant for all altitudes of the sun. See also Fig. 7.

Table 5. Heat radiation on a horizontal plane (tE) with unobstructed horizon expressed as a function of the altitude of the sun (h). Global radiation with clear sky (GK), radiation from the sun alone (S), radiation from a clear sky alone (DK), radiation from an overcast sky (DM), and percentage relation between sky radiation and global radiation with a cloudy (DM/GK) and with a clear sky (DK/GK). Unit 1 kcal/m²h and percentage.

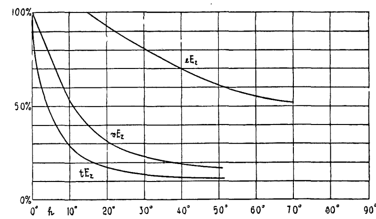
h	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
tE GK	46	111	184	260	334	411	478	534	598	660
tE S	25	79	145	214	284	357	419	470	529	586
tE DK	21	32	39	46	50	54	59	64	69	74
tE DM	14	29	44	65	83	98	109	125	134	155
DK/GK	45.7	28.8	21.2	17.7	15.0	13.1	12.3	12.0	11.5	11.2
DM/GK	30.4	26.1	23.9	25.0	24.9	23.8	22.8	23.4	22.4	23.5

Measurements of the illumination from sun and sky in Helsinki were begun at the same time as the measurements of the heat radiation (55, 56). The measurements were commenced using a Weber photometer, but during the same year recordings were also begun with a potassium photo-cell. The recordings were checked now and then with a Bechstein photometer. It is chiefly the recordings which will be used here.

The Bechstein photometer is a subjective photometer (visual photometer) of the following construction:— In one half of the visual field is seen a de-polished opal glass which is illuminated by the sun and/or sky and in the other half is seen another opal glass illuminated by a standard lamp. This latter illumination is controlled by means of an aperture so that both halves appear to have equal brightness. The calibration of the aperture enables the illumination level of the first glass to be read off. This instrument enables measurements up to 500 lux to be obtained directly, but by use of an ancillary component with a filter values up to 100,000 lux can be measured. Such levels are necessary in the measurement of daylight and sunlight.

The recording apparatus was of almost the same construction as *Aurén's*, see Page 24. The photo-cell was coupled to a recording galvanometer. Between the opal glass and the photo-cell was placed a yellow filter (Schott P 5899).

Fig. 7. Radiation from the clear sky expressed as a percentage of the global radiation on a horizontal plane with a clear sky. tE_z = heat radiation, after Lunelund (56), vE_z = illumination, after Lunelund (56), eE_z = erythemal radiation, after Luckiesh (54). Vertical scale = percent, horizontal scale = solar altitude in degrees.



No spectral sensitivity curves for this recording apparatus have been published, but the check with the Bechstein photometer may be taken as quite satisfactory to permit the recordings to be expressed in lighting units. In his publications *Lunelund* usually expresses his measurements in E_s-units, but these are not suitable for use in lighting technology, particularly as other units are already in use, and so the recordings have been converted by means of *Lunelund's* own factor:

$$1\ E_s\text{-unit} = 77 \times 10^3 \text{ lux.}$$

Table 6 can be derived from *Lunelund's* recordings of the illumination in Helsinki. If these recordings are compared with those of *Aurén* for Stockholm in Table 3, it is found that the yearly values correspond very well, whereas the distribution over the year is somewhat different. Helsinki has a somewhat lower quantity of light during the winter than has Stockholm, due to the greater nebulosity at Helsinki during this season.

Lunelund has studied separately the illumination from the sky on clear days as well as cloudy days. In this way he has established how great a proportion of the global illumination comes from the sky on clear days. See Fig. 7. This proportion is different for different altitudes of the sun, i. e. greater when the sun lies lower. The light from the sun and clear sky have a very different spectral composition and therefore the investigation was carried out with the Bechstein photometer which could be provided with a special apparatus for screening off the direct sunlight from the opal glass.

Table 6. Monthly totals and yearly total of global illumination (vQ) on a horizontal plane according to Lunelund's recording in Helsinki 1929—33. Potassium photocell with yellow filter. Unit 1 Mlxh.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
vQ	0.59	2.19	6.60	10.30	16.32	19.77	18.87	12.85	7.48	3.21	0.82	0.38	99.35

In order to be able to carry out such an investigation with an objective instrument, for example a photo-electric cell, the spectral sensitivity of the apparatus must be the same as that of the eye. It is most unlikely that this was the case with the potassium cell which was used for the recordings. This was no disadvantage for the recordings because the spectral composition of the global illumination on a horizontal plane is very constant and independent of the nebulosity, as has been established by *Schulze* (81) and *Hull* (31).

Table 7 shows the result of *Lunelund's* studies of the illumination as a function of the sun's altitude. This table shows that the proportion of the global illumination due to the clear sky on a horizontal plane increases with the decreasing height of the sun. By comparision of Tables 5 and 7 it can be seen that the percentage illumination from the clear sky is greater than the percentage heat radiation. This is due at least partly to the fact that the whole of the infra-red part of the solar spectrum is lacking in the sky radiation, see Fig. 1.

Table 7. Illumination on a horizontal plane (vE) with unobstructed horizon as a function of the altitude of the sun (h). Global illumination from the clear sky (GK), illumination from the sun alone (S), illumination from clear sky alone (DH), illumination from overcast sky (DM) and percentage relation between illumination from the sky and global illumination with a clear (DK/GK) and with an overcast sky (DM/GK). Unit 1 klx and percentage.

h	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
vE *GK*	5.7	13.2	21.6	30.8	40.0	49.6	58.7	67.9	77.0	85.9
vE *S*	1.4	6.1	13.0	21.3	29.6	38.2	46.7	55.0	63.1	71.3
vE *DK*	4.3	7.1	8.6	9.5	10.4	11.4	12.0	12.9	13.9	14.6
vE *DM*	2.5	4.9	7.6	10.5	13.3	16.2	18.9	21.4	23.7	25.9
DK/GK	76	54	40	31	26	23	20.5	19	18	17
DM/GK	44	37	35	34	33	33	32	32	31	30

The illumination from an overcast sky is a greater percentage of the global illumination than the corresponding percentage of the heat radiation. Light radiations are transmitted more readily by cloud than are heat radiations. This is due to the fact that the infra-red part of the global radiation is partly absorbed by the water particles in the cloud, see Fig. 5.

Kalitin (38) has recorded the illumination from the sky alone during a four year period in Slutsk (1925, 1927, 1928 and 1929). The light sensitive element was a potassium photo-cell and an opal glass disc served as light receptor. Between the two was placed a filter to give the apparatus a sensitivity approximating to that of the human eye. Direct sunlight was screened off by means of a small screen rotated by a clockwork device so that a shadow was always cast on the light receptor. A calibration made with a Weber photometer enabled the recordings to be expressed in lux. See Table 8 and Fig. 21.

Table 8. Average illumination (vE) on a horizontal plane with unobstructed horizon from the sky alone, according to Kalitin's measurements in Slutsk, near Leningrad. Unit 1 klx.

Table A gives the illumination for different types of cloud covering: *AS* = altostratus, *ACu* = altocumulus, *SCu* = stratocumulus, *CiCic* = cirrus and cirrostratus, *CiCu* = cirrocumulus, *CuNb* = cumulonimbus, *St* = stratus, *Nb* = nimbus.
Table B and C give the variation of illumination with degrees of nebulosity. 0 = clear sky, the other figures (2—10) give the degree of nebulosity on the 10-point scale.

A (m = 10)

Solar altitude	7°	15°	30°	45°
AS	3.3	6.6	21.2	31.5
ACu	4.2	9.5	23.5	31.0
SCu		7.0	18.4	30.2
CiCis	4.5	7.4	16.9	24.5
CiCu	6.4	10.0	21.4	27.8
CuNb	4.6	6.0	16.9	22.8
Cu			15.0	23.0
St	2.3	4.7	12.5	18.0
Nb	1.9	4.0	9.4	13.7

B (CiCis)

Solar altitude	7°	15°	30°	45°
m 0	3.6	6.1	9.4	12.6
m 2, 3, 4	4.3	6.8	10.8	16.9
m 5, 6, 7,	4.0	6.9	13.8	15.7
m 8, 9, 10	4.5	7.4	16.9	24.5

C (CuNb)

Solar altitude	7°	15°	30°	45°
m 0	3.6	6.1	9.4	12.6
m 2, 3, 4	2.8	6.2	14.8	22.7
m 5, 6, 7	2.6	8.6	16.1	23.0
m 8, 9, 10	4.6	6.0	16.9	22.8

Lunelund has not made separate recordings of the diffuse light from the sky like those which he made for the heat radiation. Such measurements have however been obtained by *McDermott and Gordon-Smith* (20) at the National Physical Laboratory in England. The recordings took place during the period from July 1933 to October 1939. The light sensitive receptor was a potassium photo-cell with filter, coupled to a recording galvanometer. By means of a screening device one single octant of the sky at a time illuminated the photo-cell. The screening device could be turned about a vertical axis through the photo-cell so that all four octants (north-west to north-east, north-east to south-east, south-east to south-west, south-west to north-west) could each be made to illuminate the photo-cell. The results which were obtained from this recording apparatus have been employed in the present investigation for the analysis of the diffuse illumination from the sky.

Kunerth and Miller (44) have made measurements in Ames, Iowa, U.S.A. of the illumination from sun and sky on a horizontal plane with unobstructed horizon, from which they obtained lower values than *Lunelund*, about 13 % lower for global illumination. Also the percentage diffuse sky illumination from their study during clear days is lower than *Lunelund's* value and the illumination during cloudy days is about one half. The measuring instrument was a Macbeth illuminometer. This instrument operates from a comparison lamp of the normal kind but the difference from the Bechstein photometer is that measurements are made by reflection from a flat white test-plate. Figure 20 shows a curve drawn for the sun illumination and Fig. 21 gives a corresponding curve for the illumination from the sky. *Moon* (65) has calculated, in addition to the heat radiation, the illumination from the sun. The curves derived from this calculation have been drawn in on Fig. 14 and 20.

It is not advisable to compare similar measurements taken in two different places without having a detailed knowledge of the differences in climate. These latter curves have therefore been given only as an example of measurements at other places. *Moon's* heat radiation curve is calculated for an atmospheric humidity of 20 mm, which in practice is rarely reached in Sweden.

Luminous Efficiency

Lunelund has established from his recordings the luminous efficiency of global radiation on a horizontal plane with free horizon and gives the values for the different months of the year as shown in Table 9.

Tables 5 and 7 enable the luminous efficiencies of different types of radiation source to be calculated. The result will be clear from Table 10 which shows that the luminous efficiency for global radiation is effectively constant for clear as well as for cloudy skies. The luminous efficiency of radiation from the clear

Note. In the present work, all the information on luminous efficiency is calculated in terms of lmh/kcal (lumen-hours per kilogram-calorie).

Different authors employ different units. *Lunelund* uses $E_s h$ per 10 kcal/cm^2; *Kimball* uses foot-candles per cal/cm^{2}mn; *Harff* uses lux per cal/cm^{2}mn; *Atkins and Poole* use lm/W. For comparison with artificial light sources, 1 lm/W can be taken to be 1.16 lmh/kcal.

Table 9. Luminous efficiency (v/t) of radiation at Helsinki during the years 1929—33 according to Lunelund (56). Unit 1 lmh/kcal.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
v/t	105	109	113	120	131	132	131	130	128	125	115	105	127

Table 10. Luminous efficiency (v/t) of different sources of radiation as function of the altitude of the sun (h). Global radiation on a horizontal plane with clear sky (GK), solar radiation (S) clear sky (DK) overcast sky (DM). Unit 1 lmh/kcal.

h	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
GK	124	119	117	118	120	121	123	127	129	130
S	56	77	90	100	104	107	111	117	119	122
DK	205	222	221	207	208	211	203	202	201	197
DM	179	169	173	162	160	165	173	171	177	167

sky is also independent of the sun's altitude. The solar radiation alone shows a luminous efficiency which decreases with the altitude of the sun. This is what would have been expected because the atmospheric scattering is greater for the visible than for the infra-red part of the sun's radiation.

The average value for the luminous efficiency of the global radiation for a clear sky (GK) is 123 lmh/kcal. This value agrees fairly well with the value of 120 lmh/kcal which *Kimball* (40) found for Washington. For a solar altitude of 65 degrees and 11.3 degrees he found the values 126 lmh/kcal and 111 lmh/kcal respectively. For lower altitudes of the sun, about 15 degrees, *Kimball's* measurements show a constant luminous efficiency which also the values in Table 10 reflect by an increase in the luminous efficiency with decreasing altitude of the sun, beginning at about 15 degrees. This is due probably to the fact that with the decreasing altitude of the sun an increasing proportion of the sky radiation is added. *Atkins and Poole* (1) have found the mean value of 125 lmh/kcal for the global radiation with a minimum of 94 lmh/kcal and a maximum of 139 lmh/kcal for low and high solar altitudes respectively. It is natural that the maximum and minimum values show a greater difference than the mean values, the agreement with *Lunelund's* measurements is otherwise very good.

The luminous efficiency of sun radiation alone decreases in a fairly definite manner with the altitude of the sun, as is shown in the table. At a solar altitude of 45° the luminous efficiency is 119 lmh/kcal, decreasing slowly to 100 lmh/kcal at 20° altitude and then more rapidly to 77 and 56 lmh/kcal at solar altitudes of 10° and 5° respectively. *Kimball* (40) has found a gradual reduction from 126 lmh/kcal at 65° altitude of the sun to 114 lmh/kcal at 11.3° altitude. *Atkins and Poole* (1) have found greater variations from their investigations, a minimum value of 41 lmh/kcal, a maximum of 139 lmh/kcal and a mean value of 105 lmh/kcal. *Johnson and Olsson* (37), who have studied the possibility of using a selenium photo-cell for the measurement of heat radiation from sun and sky, found from a theoretical calculation that the luminous efficiency of the sun should be constant between 65° and 35° solar altitude but should decrease by 25 % between 35° and 15°. *Moon* (65) has studied the luminous efficiency of the sun's radiation from a theoretical standpoint. His results give the value 120 lmh/kcal for high solar altitudes and 108 lmh/kcal with a solar altitude of 11.3°.

The luminous efficiency of solar radiation is, however, influenced markedly by the humidity of the atmosphere. With high water vapour content the luminous efficiency will be higher than when the humidity is low. This arises from the fact that the absorption of radiation by water vapour takes place especially in the infra-red region of the spectrum whereas the visible radiation is largely unaffected. The values in Table 10 are average values for the year, thus the values for the lower solar altitudes apply to both winter and summer conditions while the values for the higher solar altitudes apply only to summer conditions. The luminous efficiency values for the lower solar altitudes are influenced therefore by the lower humidity during the winter and this influence becomes greater the lower the solar altitude. It is therefore evident that the values in the table for the lower solar altitudes will be less than those of *Kimball*, which were measured during spring and summer, and than those of *Moon* which apply to a constant, relatively high humidity (20 mm). The measurements of *Atkins and Poole*, which were performed during every season, show the same tendencies as the values in the table, especially the lower luminous efficiency during the winter.

The highest luminous efficiency is shown by the radiation from clear blue sky. The mean value is 208 lmh/kcal. *Atkins and Poole* (1) give as mean value from their measurements 145 lmh/kcal but their maximum value is of the order of 183 lmh/kcal. A measurement taken immediately after sunset gave the value 152 lmh/kcal. *Lunelund's* values are probably rather too high, which may be due to the reduced sensitivity of the pyranometer to the long-wave ultra-violet (see 37, Page 15), which constitutes a considerable part of the radiation from the blue sky. Other possible sources of error can be considered, for example, the uncertainty of the measurements with the Bechstein photometer. The values in the table are evidently too high but a value of 180 lmh/kcal may be taken as a basis for calculation.

The luminous efficiency of radiation from the overcast sky appears also to be rather high. The average value from the table is 170 lmh/kcal. *Kimball* (40) gives the value of 126 lmh/kcal for the cloudy sky. *Johnson and Olsson* (37) from their recordings for overcast skies have obtained the value of about 25 % above the average value for the global radiation with the clear sky. As this latter value according to the above average figure is 123 lmh/kcal the luminous efficiency of the overcast sky becomes 154 lmh/kcal. A theoretical investigation by *Harff* (28) gave a value of 125 lmh/kcal as an average with a maximum value of 158 lmh/kcal. Since however some absorption of the infra-red will always take place during the passage of the global radiation through the cloud (see Fig. 5) the luminous efficiency of an overcast sky ought to have a value greater than that of the global radiation for a clear sky. *Lunelund* (61) states that the average value for heat radiation during overcast days is 24 % of the values for clear days and that the corresponding value for light radiation is 30 %. This value is certainly appoximate but it would give a luminous efficiency of 154 lmh/kcal. According to *Büttner* (11) these transmission values are 24 % for heat radiation and 36 % for light radiation. This gives a luminous efficiency of 185 lmh/kcal. From the above the conclusion can be drawn that the luminous efficiency of the overcast sky is very variable and has a value of about 150 lmh/kcal.

In making use of *Lunelund's* measurements a calculation factor of 1 E_s-unit = $= 77 \times 10^3$ lux has been used throughout. This value was however established subjectively which naturally gives a degree of uncertainty to the corresponding luminous efficiency. The uncertainty cannot be eliminated until illumination measurements are available from an instrument with the exact spectral sensitivity of the human eye (see Fig. 2) and which also is fully corrected for cosine error. The cosine error is discussed by *Köhler* (46) and *Pleijel and Longmore* (76).

Erythemal Radiation

The importance of erythemal radiation to humanity was discovered round about the turn of the century and consequently it has not been an object of measurement for so long as heat or light radiation. Certain difficulties arise from the small amount of the radiation in terms of energy. In addition there are advantages in having the measurements on some biological scale. These difficulties are still not overcome and investigations have therefore been especially directed towards research after suitable measuring instruments. The oldest and most often used are chemical methods, that is to say they consist of liquid or solid materials which undergo chemical changes under the influence of ultra-violet radiation. Photographic plates can be quoted as an example. These have however now been supplemented by photoelectric instruments. These can be much better adapted to a study of the biological effects of radiation and have in addition better qualities as measuring instruments than chemical methods.

Rectifier-type photo-cells can, in addition to their value for the measurement of illumination, also be employed for the measurement of erythemal radiation (62, 79), but vacuum type photo-cells are in fact most suitable for this purpose. These comprise two electrodes in an envelope transparent to ultra-violet radiation. The cathode is coated with a metallic deposit which emits electrons when it is radiated. These are captured by the anode which is given a positive po-

Table 11. Monthly and yearly totals of the global erythemal radiation (eQ) on a horizontal plane according to recordings made in Washington, U.S.A., 1941—43, by Coblentz and Stair. Unit 1 Wh/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
*e*Q	21	39	77	123	172	192	179	166	123	64	30	14	1,200

tential. A galvanometer is coupled into the circuit, its output giving a measure of the strength of the radiation. The output can be amplified and consequently very weak radiation can be measured in this way. *Rentschler* (78) has constructed a suitable measuring apparatus with such a photo-cell. *Luckiesh and Taylor* (52) have made a transportable meter and also a recording apparatus.

The cathode can be coated with different metals and in this way the photo-cell can be given a different spectral sensitivity. Further variations can be obtained by combination with suitable filters. *Rentschler* employed metallic uranium in his measuring equipment giving a maximum sensitivity at about 3,200 Ångström units. Other suitable metals for the measurement of erythemal radiation are for example cadmium, magnesium, zirconium and titanium. Potassium is most suitable for the measurement of visible radiation.

The measurements and recordings which have been used in this present work for the construction of nomograms for the calculation of erythemal radiation were obtained by *Coblentz and Stair* (13, 15, 16) at the National Bureau of Standards in Washington U.S.A. The results are expressed in absolute units for radiation energy of wave-length shorter than 3,132 Å. At the same time that the measurements were made an investigation of the erythemal effect was undertaken (16). For this reason the results can be expressed in biological units. The unit which is employed is the threshold value of erythemal effect, MPE (Minimum perceptible erythema). The investigation established that the MPE $=$ $= 0.35$ Wh/m² for radiation of wave length less than and including 3,132 Å (in the original paper the MPE was given as about 1,250,000 erg/cm²).

Measurements of the sun's erythemal radiation were obtained in 1934 to 1942 (13, 15). Recordings of the global erythemal radiation were made in 1941 to 1943 (16). The photo-cells were of varying types and results were obtained with a variety of metals. Table 11 can be derived from the results of the recordings (16, Fig. 5). In addition the course of radiation during certain very clear days has been selected (16, Fig. 7) and shown in Table 12.

Table 12 shows that the global radiation maximum value at noon during June is 180 μW/cm² and that the maximum value at noon during December is 33 μW/cm². At these particular times the solar altitude is 73° and 28° respectively. It can also be established that the erythemal radiation is stronger in the afternoon than in the morning. These variations can be ascribed to the percentage of

Table 12. Global erythemal radiation on a horizontal plane with unobstructed horizon in Washington, according to Coblenz and Stair. Very clear sky. Zirconium photocell. Unit 1 $\mu W/cm^2$.

Time	12	11/13	10/14	9/15	8/16	7/17	6/18
4 June	180	169/168	132/135	84/92	42/48	14/18	2/2
11 April	114	102/106	74/79	40/48	15/20	4/6	
18 Sept	100	91/92	66/67	36/39	13/12	2/2	
21 Dec	33	29/29	16/17	6/5			

ozone in the atmosphere. The recordings also established, on some occasions, a weak erythemal radiation in the evening during the hour immediately after sunset. The intensity was naturally very weak. An erythemal radiation from the sky for low solar altitudes has also been established for the northern latitudes (13, 14). The turbidity of the atmosphere varies considerably from one day to another and this in turn causes considerable variations in the erythemal radiation, significantly greater than the corresponding variations in the illumination or the heat radiation.

The relationship between the radiation from the sky and the radiation from the sun on a horizontal plane for clear sky has been established a very great number of times (16). On the clearest days and for the highest solar altitudes (about 73°) the latter was only in exceptional cases greater than the former. The sky radiation was often two to five times stronger than the solar radiation, the former value at high solar altitudes, the latter at an altitude of about 30°. The mean value at a solar altitude of 57° (the highest in Sweden) was about 1.5 times.

Investigations of the erythemal radiation of the sun perpendicular to the direction of the radiation (15) show that the value during the clearest days at highest solar altitudes (about 73°) is 75 $\mu W/cm^2$. At noon during December, solar altitude about 28°, the radiation was 12 $\mu W/cm^2$.

A comparison with investigations of the erythemal radiation for higher latitudes (up to 78° N) has shown that no fundamental difference is forthcoming between radiation at different latitudes (13, 14).

Lunelund (60) has measured the ultra-violet radiation from the sun in Finland with a cadmium photo-cell but he has not expressed his measurement in absolute units, consequently his results cannot be used in this work.

Ronge (79) has made an approximate calculation of the erythemal radiation for different latitudes, and has found that the yearly radiation total on a horizontal plane for the 60° parallel is of the order of 45,000 $mWsec/cm^2 = 2{,}250$ MPE, according to his own conversion factor 1 MPE $= 20\ mWsec/cm^2$ at a wave-length of 2,970 Å.

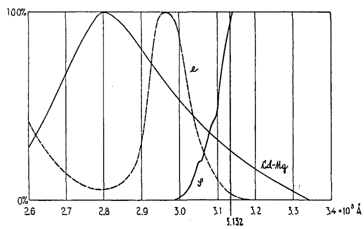


Fig. 8. Erythemal effect of radiation of different wave-lengths (e), spectral sensitivity of the cadmium-magnesium photocell (Cd-Mg) used in the recordings at Cleveland by Luckiesh, Taylor and Kerr (53), spectral distribution of radiation from the sun at 45° altitude (S) after Stair (83), and the upper limit (3,132 Å) of the measurements in Washington by Coblenz and Stair (13, 15, 16).

In Cleveland U.S.A. *Luckiesh, Taylor and Kerr* (50, 51, 54) have recorded the erythemal radiation during the years 1935 to 1939 and 1940 to 1941 (6 years). The measuring instrument was a Cadmium-magnesium photo-cell coupled to a recording apparatus (52). The results are given in a biological unit called "E-viton". 1 E-viton $= 10\ \mu W$ at a wave-length of 2,967 Å, where the erythemal effect is taken as $= 1$, or $10/e$ at some other wave-length with erythemal effect e. The erythemal effect of the radiation at different wave-lengths is shown in Fig. 8, which also shows the spectral sensitivity of the Cadmium photo-cell and the solar spectrum. The threshold value for the erythemal effect (MPE) is given as 40 E-viton-minutes per cm^2. The results of the recordings are shown in Table 13 where the radiation totals are expressed in MPE-units. These values have been used here for the control of the calculating methods.

In connection with the recordings in Cleveland the relationship has also been measured between the radiation from the sky and the radiation from the sun on a horizontal plane with free horizon and clear sky. At a solar altitude of 20° this relationship was equal to 10, at 70° altitude equal to 1. These values show a good agreement with those of *Coblentz and Stair* (16). See Fig. 7.

Table 13. Monthly and yearly totals of global erythemal radiation on a horizontal plane according to recordings in Cleveland 1935—41 by Luckiesh, Taylor and Kerr. Unit 1 MPE.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
eQ	77	108	273	420	645	714	714	579	416	215	83	45	4,289

Calculation of Heat Radiation

Meteorological Methods of Calculation

The methods for calculating radiation which are usually carried out in meteorology differ considerably from those which are employed in building technique in that they are almost always concerned with a horizontal plane without any screening object. Thence are calculated both the radiation on clear days and also the true radiation totals for the months of the year and the yearly total. By the aid of such calculations it has been shown that quite good agreement can be obtained between calculation and measurement.

Ångström (98, 99) has established an equation for the calculation of heat radiation which is as follows:

$$Q_z^{Gk} = Q_z^{GK} (0.235 + 0.765 \times s/S) \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 2$$

where Q_z^{Gk} is the monthly total of the global heat radiation on a horizontal plane with unobstructed horizon and with the prevailing nebulosity, Q_z^{GK} is the same radiation with completely clear sky, s is the duration of sunshine according to the autograph, and S is the duration of sunshine recorded by the autograph for completely clear sky.

Aurén (4,6) has put forward an equation for the calculation of the true radiation on a horizontal plane:

$$Q_z^{Gk} = R \times Q_z^{GK} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 3$$

where Q_z^{Gk} and Q_z^{GK} are the same as for *Ångström's* equation and R is the relative radiation. (See Page 21 and Fig. 6.)

Both these equations are founded on the global radiation with a clear sky combined with, in the first case, the autograph recordings, and in the second case, the nebulosity observations. As has already been indicated, calculations of radiation for purposes of building technique must be carried out for the sun radiation and the diffuse radiation separately, because screening objects can take away different percentage portions of the solar radiation and of the diffuse radiation. For example, a house facade orientated towards the north receives only a fractional part of the solar radiation received by a facade orientated towards the south, but the diffuse radiation will differ very little for both fa-

Table 14. Average values of the normal heat radiation (tE) from the sun on clear days as function of the altitude of the sun (h), according to recordings made in Helsinki 1927—33 by Lunelund. Unit 1 kcal/m²h.

h	2.5°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
tE	197	325	475	574	640	682	711	727	744	760	777

Table 15. Altitude of the sun about the 20th day of each month, read off from the solar chart for latitude 60° N. True solar time.

Time	12	11/13	10/14	9/15	8/16	7/17	6/18	5/19	4/20	3/21
VI	53.5°	52.0°	48.0°	42.0°	35.0°	27.5°	20.0°	13.0°	6.5°	1.0°
V VII	50.5°	49.5°	45.0°	39.0°	31.5°	24.5°	17.5°	10.0°	3.5°	
IV VIII	42.0°	40.5°	37.0°	31.0°	25.0°	17.0°	10.0°	2.5°		
III IX	30.0°	29.0°	26.0°	21.0°	14.5°	7.5°	0.0°			
II X	19.0°	18.0°	15.0°	10.0°	4.0°					
I XI	10.0°	9.5°	7.0°	2.5°						
XII	6.5°	5.5°	3.0°							

cades. For the purposes of building technology quite different methods of calculation of radiation must therefore be employed. The solar radiation with the prevailing nebulosity must be calculated for each part of the sun path and the values of radiation must then be added for those parts of the paths which are not screened by surrounding houses, trees, terrain, etc. To the total of the solar radiation obtained in this way must be added the diffuse radiation from the parts of the sky vault which are not screened. It is the purpose of this study to show how this should be done in the most simple way.

Heat Radiation from Sun with Clear Sky

From the results of his recordings of heat radiation in Helsinki during the years 1927—33 *Lunelund* calculated the average values for the perpendicular solar radiation on clear days as a function of the solar altitude (56, Table 73). He separated the months of the year so that it can be seen from the table that the radiation for the same solar altitude is stronger during the winter than during the summer. This derives partly from the humidity of the atmosphere which is less in winter than in summer, and partly because the distance of the earth from the sun is less in winter than in summer. He has also calculated the average value for the whole year, and this will be used during the course of the following calculations. See Table 14, and Fig. 14 Page 62.

From the solar chart for latitude 60° N (see Page 93), the solar altitude can be read off for each hour on the seven curves. These are summarized in Table 15.

Table 16. Perpendicular heat radiation (tE) from the sun, obtained from the sun chart for latitude 60° N and from Lunelund's average curve for clear sky. The values apply to the 20th day of each month. Unit 1 kcal/m²h. True solar time.

Time	12	13/11	14/10	15/9	16/8	17/7	18/6	19/5	20/4	21/3
VI	785	780	770	755	730	695	640	540	380	90
V VII	775	770	760	745	715	680	610	475	250	
IV VIII	755	750	740	715	680	605	475	200		
III IX	710	705	690	650	565	410	0			
II X	630	620	575	475	280					
I XI	475	465	395	200						
XII	380	345	225							

Table 17. Hourly totals and daily totals (tQ) of the perpendicular heat radiation from the sun alone with clear sky. The values apply to the 20th day of each month. Lunelund's average curve. Latitude 60° N. Unit 1 kcal/m². True solar time.

Time	11—12 12—13	10—11 13—14	9—10 14—15	8—9 15—16	7—8 16—17	6—7 17—18	5—6 18—19	4—5 19—20	3—4 20—21	2—3 21—22	daily totals
VI	783	778	767	743	715	670	592	472	263	13	11,592
V VII	773	768	755	733	700	645	547	375	80		10,752
IV VIII ..	755	747	730	698	647	547	360	72			9,112
III IX ...	708	698	673	613	493	247					6,864
II X	627	602	532	392	110						4,526
I XI	472	440	317	48							2,554
XII	375	305	92								1,544

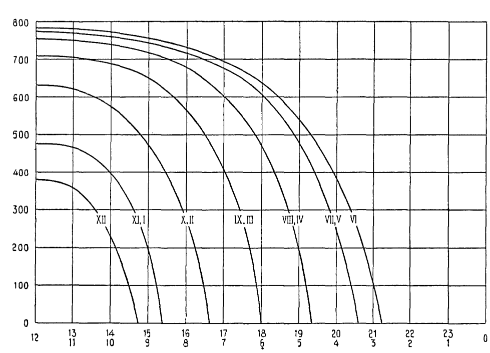


Fig. 9. Curves for 24-hour periods giving the perpendicular heat radiation from the sun alone, obtained from the solar chart for 60°N and from Lunelund's average curve for clear sky. The curves apply to the 20th day of each month (Roman figures). Vertical scale = kcal/m²h, horizontal scale = true solar time.

The perpendicular (normal) heat radiation for each of these solar altitudes can be read off from Fig. 14, see Table 16 and the diagram of Fig. 9. The curves have been integrated for each hour to give the hourly totals, which are added to give a 24-hour total for each curve, see Table 17. Since the sun paths on the solar

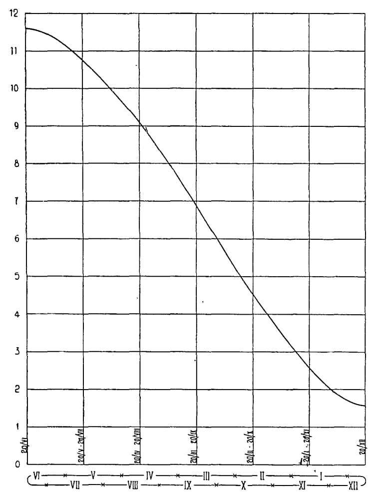


Fig. 10. Curve giving the perpendicular heat radiation totals per day from the sun alone for a year period, obtained from the solar chart for 60°N and from Lunelund's average curve for clear sky. The months are indicated by Roman figures. Vertical scale = Mcal/m²d, horizontal scale = time of the year.

Table 18. Mean daily totals for each month of the perpendicular heat radiation (tQ) from the sun alone with clear sky. Lunelund's average curve. Latitude 60° N. Unit 1 Mcal/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
tQ	2.20	4.18	6.47	8.73	10.50	11.48	10.95	9.38	7.27	4.90	2.88	1.68

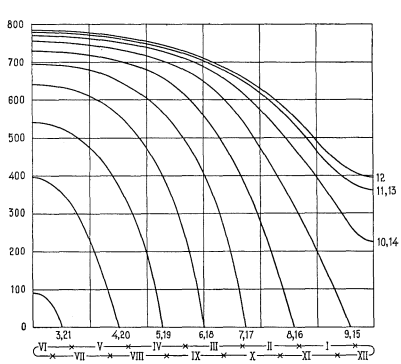


Fig. 11. Curves giving the perpendicular heat radiation for a year period, for every hour, from the sun alone, obtained from the solar chart for latitude 60°N and from Lunelund's average curve for clear sky. Hours are indicated by Arabic figures, months by Roman figures. Vertical scale = kcal/m²h, horizontal scale = time of the year.

chart apply to the 20th day (approximately) of each month, the values in the tables are also given for this date. In order to obtain the monthly totals the yearly curve is drawn over the 24-hour totals, see Fig. 10. This is integrated graphically for each month, to yield the average daily totals, see Table 18.

Table 19. Average monthly values for every hour of the perpendicular heat radiation from the sun alone with clear sky. Lunelund's average curve. Latitude 60° N. Unit 1 kcal/m²h. True solar time.

Time	12	11/13	10/14	9/15	8/16	7/17	6/18	5/19	4/20	3/21
I	470	440	358	142						
II	608	595	545	430	200	2				
III	698	688	672	625	522	325	47			
IV	748	743	732	705	663	585	420	120		
V	775	770	758	743	713	668	592	438	158	
VI	785	778	770	753	728	693	638	535	378	63
VII	780	770	765	748	720	682	617	488	268	7
VIII	760	753	742	720	687	618	500	245	8	
IX	718	710	697	662	585	443	153			
X	643	633	595	508	330	60				
XI	518	493	427	274	17					
XII	405	373	248	10						

For the comparison of the calculated with measured values of radiation, which will be carried out below, it is also essential to compare the strength of the radiation at different times of the day. With the assistance of the values given in Table 16, Fig. 11 has been drawn to show the variation in the normal radiation for each hour as a function of the time of year. The heat radiation is integrated from this diagram, for each curve and each month, to yield the values which are shown in Table 19.

Tables 18 and 19 apply to the clear sky. In order to derive the actual radiation from them, the values must be multiplied by the relative sunshine period, that is, the relation between the true sunshine period and the theoretical with a permanently clear sky.

Relative Duration of Sunshine

There are two ways of determining the relative duration of sunshine, the one derived from observations of nebulosity, the other from recordings of actual duration of sunshine recorders. The two methods give rather different results. The recorder is considered to yield the most truthful result since it is the sun itself which furnishes the information, whilst the other method is a by-product of the determination of nebulosity. The nebulosity is determined subjectively, which results in some uncertainty about individual values. The nebulosity is also an average determination for the whole sky, and not for the precise position where the sun is to be found. To achieve reliable and useful values of nebulosity, statistical means for many years are necessary. The nebulosity can be unequally distributed over the sky and it can change during the day, which results in difficulties in the employment of nebulosity data for radiation calculations. Sunshine recorders are, however, themselves not free of error. They over-estimate the duration of sunshine when the sun stands high in the sky, and under-estimate it when the sun is low. They also can sometimes be difficult to read. Nebulosity determinations are obtained, however, in a significantly greater number of places in Sweden than those that have sunshine recorders. It is therefore of considerable value to know how to employ nebulosity determinations for radiation calculations.

Whether nebulosity or autograph recordings are used as a basis for relative sunshine duration, good agreement is not always obtained between the calculated and the measured values. In the former case too great values are obtained and in the latter too small values. A detailed calculation will be performed below to shed light on this relationship, but first follows a statement on how both determinations of relative sunshine duration are obtained.

Observations of Nebulosity

Nebulosity is determined by subjective judgments, in which the observer estimates how great a part of the sky vault is covered with cloud. The judgments are expressed in terms of a 10-point scale, where 0 signifies a completely clear sky and 10 a fully overcast sky. The figures between these two express how many tenths of the sky are covered with cloud. The observations are made three times daily or, on the larger meteorological stations, every hour, at least during daytime. For some longer period, a month, a ten-day or a five-day period, an average value is calculated from the observations. This is often expressed as a percentage or by a decimal in the 10-point scale. The average values for the different periods are coordinated for a succession of years and from thence is derived an average value. In this way a fairly accurate value is gradually established for the nebulosity for different seasons. Thus the average for any one month during a ten year period is derived from about 900 different observations.

It is however actually the clarity of the sky which is of interest here and not the nebulosity. In the same way as the nebulosity, the clarity can be expressed on a 10-point scale or as a percentage. The values for the clarity can be derived from the average values for the nebulosity according to the equation

$$k = 100 - m \qquad \text{eqn 4}$$

where k is the clarity in percent and m is the nebulosity in percent.

It is however obvious that this subjective method of determining the clarity suffers from a certain inaccuracy associated with the individual values. A personal error can be proved for every observer, and a tendency to overvalue the nebulosity nearest to the horizon. It is therefore questionable as to whether such determinations have value other than as approximate indications. The investigations of *Hamberg* (27) have however suggested that the average value from such observations obtained during a 20-year series have an average error of about 1.5 %. This error is small in comparison with other variances. *Hamberg* has also investigated in what manner the average values of nebulosity determinations made three times and eight times per 24-hour period are inferior to observations made 24 times during the 24-hour period. The maximum deviation for determinations made during a 3-year period were 4 per cent for determinations made 3 times and 2 per cent for determinations made 8 times during the 24-hour period. The 3 determinations were made at 8.00 hours, 14.00 and 21.00 hours. It clan also be asserted with reason that determinations of nebulosity are a relatively accurate method if average values for a longer period of time are employed.

From the official average values of nebulosity there are however certain departures to be made if they are to be used for radiation calculations. The observations thrice daily in Helsinki, for example, were made at 7.00 hours, 15.00 hours, and 21.00 hours. During the greater part of the year those observations made at 21.00 hours were made in darkness. This also applies to the observation at 7.00 hours during the winter months. The observations which are made during darkness (after sunset or before sunrise) should naturally not be included in the calculation of the average values of nebulosity, in particular because the nebulosity during the day-time and during night-time can be fundamentally different. In this way, however, the number of different observations which go to establish the average value is reduced. Table 20 shows the average values of sky clarity both with (k_t) and without (k_d) the observations made during darkness.

It can be seen from the table that the difference between k_t and k_d can be fundamental. Thus during the winter half-year it is as much as 20 per cent on many occasions.

Table 20. Average values of the percentage clarity of the sky in Helsinki during the years 1928—35, including (k_t) and excluding (k_d) the observations taken during darkness, together with the relative duration of sunshine (r_a) according to autograph recordings in Ilmala, during the same period, + 16 % (addition for Helsinki).

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
k_t	17	30	35	33	39	44	40	34	34	24	17	15	30
k_d	13	26	30	31	39	44	40	33	28	19	14	12	28
r_a	12	29	40	44	57	61	59	50	37	24	12	10	43

Autograph Recordings (Sunshine Recorder)

The other method of determining the relative duration of sunshine was the recording of the actual duration of sunshine with a sunshine recorder. The most commonly employed recorder is that of Campbell-Stokes. This comprises a glass sphere, about 10 cm in diameter, which focuses the rays of the sun so that they burn a track in a strip of paper graduated in hours of the day. Such sunshine recorders are to be found operating in a large number of meteorological stations, for example twenty in Sweden.

The times during which the sun shines can subsequently be read off from the paper strip and the total radiation time can be found for every hour, day, or yearly period. These times are divided by the time that the sun is above the horizon (theoretical maximum) in order to obtain the relative duration of sunshine according to the autograph. This is indicated here by r_a and usually expressed as a percentage.

This would seem to be an ideal method, but the sunshine recorder, like all other instruments, has its weaknesses. The sensitivity is such that it draws a track when the intensity of the solar radiation is greater than 200 kcal/m²h. The intensity with high altitudes of the sun reaches as much as 700 to 800 kcal/m²h and therefore a very powerful track is burnt in the paper strip. With rapidly moving clouds which cover, for example, 25 per cent of the visible sky, a continuous track is burnt although not so strong as with a fully clear sky. Consequently on such occasions the sunshine recorder over-estimates the duration of sunshine. There is a possibility of correcting the information with the aid of observations of nebulosity. An investigation by *Lunelund* (56, Table 65) shows that the recorded duration of sunshine is very much dependent on the sensitivity of the recording apparatus.

When the solar altitude is low the solar radiation intensity is so small that it does not burn any track on the paper strip. Consequently no recording is made on the autograph paper half an hour to a whole hour before sunset or after sunrise. *Lindholm* (47) has recommended that this period should not be included in calculations but rather that the maximum duration of sunshine should be considered as that time during which the sunshine recorder traces a track with a fully clear sky during the day and not the time when the sun is above the horizon. In more southerly latitudes it is customary to neglect in radiation calculations the time when the sun stands lower than 10° above the horizon (23, Page 9). As far as radiation on a horizontal plane is concerned such an approximation can be accepted, for in such a case low solar altitudes have not much significance, but this cannot be done when considering the radiation on vertical surfaces.

Table 20 shows also the average monthly values of the relative duration of sunshine in Helsinki during the years 1928—35. No recordings are at present being made with the sunshine recorder in Helsinki but the information has been obtained by increasing, by a factor of 16 per cent, the values recorded on the sunshine recorder in Ilmala during the same period. *Lunelund* (59) has, indeed, from a calculation according to certain equations, found that the duration of sunshine in Helsinki should be only 2.5 per cent greater than in Ilmala. No great reliability can be attached to his figures, however, because the calculation was founded on a somewhat arbitrary equation (eqn 2, Page 37). If the sky clarity during the daytime in Helsinki and Ilmala are compared, taking into account only the observations at 7.00, 15.00 and 21.00 hours, it will be found that the clarity in Helsinki is 16 per cent greater than that in Ilmala. These figures are somewhat different for the different months with max 26 % for December and min. 9 % for March, and 16 per cent is a mean value for the whole year. These figures may appear perhaps to be rather great, since Helsinki and Ilmala are only some km apart, but taking into consideration the unequal distribution of cloud over Helsinki which will be studied in detail later, the difference is not impossible.

The relative duration of sunshine according to the sunshine recorder (r_a) is now compared with the percentage clarity of the sky k_d whence it can be seen that the differences are rather considerable. During the summer months r_a is significantly greater than k_d but the converse holds during the winter. The mean value for the year for r_a is 1.5 times greater than that for k_d. The question is, therefore, which of these two values is most suitable for the calculation of radiation from the sun?

Radiation with Prevailing Nebulosity

In order to investigate whether the values of clarity or recordings of the sunshine autograph are most suitable for radiation calculations the monthly totals for clear sky are calculated from the values in Table 18 and thence multiplied by k_d and r_a in Table 20. The values which are obtained in this way are compared with the perpendicular radiation totals which *Lunelund* (57) obtained with his recordings. See Table 21.

Table 21. Monthly totals of perpendicular heat radiation from the sun alone in Helsinki, partly calculated from Lunelund's average curve in combination with the percent clear sky ($k_d \times tQ$), partly the same curve in combination with the relative duration of sunshine according to the autograph recordings ($r_a \times tQ$), compared with the result obtained from the recordings in Helsinki 1928—35 (Reg), and also the percentage overestimate (+) or understimate (—) in relation to the recordings (diff). Unit 1 Mcal/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Reg	9.0	32.0	78.2	99.5	146.4	174.8	161.8	112.1	70.7	36.6	10.6	6.5	938.2
$k_d \times tQ$	9.4	30.4	60.2	81.2	126.9	151.6	135.7	96.0	60.6	28.9	12.1	6.3	800.5
diff	+4	—5	—23	—18	—13	—13	—16	—14	—14	—21	+14	—3	—15
$r_a \times tQ$	8.7	34.0	80.2	115.3	185.4	210.1	200.2	145.4	80.7	36.5	10.4	5.2	1,112.1
diff	—3	+6	+3	+16	+27	+20	+24	+30	+14	0	—2	—20	+19

It can be seen from this table that the summer values are too small if they are calculated by means of the factor k_d and too great if they are calculated using the factor r_a. The winter values are quite good for both k_d and r_a with the exception of the values for December for r_a. k_d gives a considerable under-estimate both for Spring and Summer. Neither k_d or r_a can be said to be satisfactory for radiation calculations. A more detailed study of the calculations can perhaps give the answer to the question why better agreement is not obtained. A calculation of the perpendicular radiation for each month and for each hour during the day has been performed. Each value in Table 19 is multiplied thus by the monthly values of k_d and r_a and then compared with the mean value which *Lunelund* obtained from his recordings. Tables 22 and 23 have been derived in this way.

The differences between the two methods of calculation can be seen more clearly now. If k_d is employed for the calculation a fairly good agreement is obtained for low solar altitudes. For high solar altitudes, however, the calculated values are lower than the measured values. No agreement can be expected with very low solar altitudes when the sun stands near to the horizon, because the refraction of the atmosphere together with other optical phenomena, then plays too great a part. No account has been taken of this influence of the atmosphere in the calculations. The anomalous figures for these solar altitudes are therefore put in brackets. Certain months, especially November, show individual anomalies which will be discussed later.

If r_a is employed for the calculations a considerable over-estimate is obtained with low solar altitudes during the summer months. During the winter months the agreement is better, which explains why a relatively good agreement is obtained in Table 21. For the high solar altitudes during the summer months the agreement is better than for low solar altitudes, but they show nevertheless a considerable over-estimate. It may be observed that in this case it is the *monthly average values* of the autograph recordings which have been used. If the average for each hourly period during the day is used instead, which is the more correct procedure, the apparent considerable over-estimate for the higher solar altitudes would increase and the over-estimate for the lower solar altitudes may be cancelled out or even converted into an under-estimate.

This comparison shows clearly that both clarity of sky and relative duration of sunshine according to autograph sunshine recorders cannot be employed directly for the calculation of radiation. As far as clarity is concerned, it is established by *Väisälä* (96) that the nebulosity is not equally distributed over the sky vault and also that certain variations in the nebulosity make their appearance in the middle of the day, especially in summer. On the other hand, as far as the sunshine recorder is concerned, certain anomalies result from the dependence of the recording on the intensity of the radiation. Both these variations will now be discussed in greater detail.

Table 22. Comparison between Lunelund's measured values for 1928—35 of the perpendicular heat radiation from the sun (A) and calculated values according to the average curve for clear sky × clarity (B). See Tables 14 and 20 (k_d). In column C are given the percentage over-estimate (+) or under-estimate (—) of B in relation to A. Unit 1 kcal/m²h.

Month	True solar time									
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	20 4	21 3
I: A	64	59	37	13						
: B	61	57	47	18						
: C	—5	—3	+27	+38						
II: A	176	167	149	110	48	2				
: B	158	155	142	112	52	1				
: C	—10	—7	—5	+2	+8	(—50)				
III: A	300	295	282	231	176	92	15			
: B	209	206	202	188	157	98	14			
: C	—30	—30	—28	—19	—11	+7	(—7)			
IV: A	316	303	297	266	243	198	127	38		
: B	232	230	227	219	206	181	130	37		
: C	—27	—24	—24	—18	—15	—9	+2	—3		
V: A	367	359	360	354	323	279	222	152	55	
: B	302	300	296	290	278	261	231	171	62	
: C	—18	—16	—18	—18	—14	—6	+4	+13	+13	
VI: A	422	420	408	399	388	347	309	238	150	45
: B	345	342	339	331	320	305	281	235	166	28
: C	—18	—19	—17	—17	—18	—12	—9	—1	+11	(—38)
VII: A	420	410	408	356	340	310	263	201	102	15
: B	312	308	306	299	288	273	247	195	107	2
: C	—26	—25	—25	—16	—15	—12	—6	—3	+5	(—87)
VIII: A	323	331	326	298	255	230	167	74	13	
: B	251	248	245	238	227	204	165	81	3	
: C	—22	—25	—25	—20	—11	—11	—1	+9	(—77)	
IX: A	269	245	230	218	176	126	47			
: B	201	199	195	185	164	124	43			
: C	—25	—19	—15	—15	—7	—2	(—9)			
X: A	172	157	141	115	75	21				
: B	122	120	113	97	63	11				
: C	—29	—24	—20	—16	—16	(—48)				
XI: A	62	61	52	32	2					
: B	73	69	60	38	2					
: C	+18	+13	+15	+19	(0)					
XII: A	50	44	31	1						
: B	49	45	30	1						
: C	—2	+2	—3	(0)						

Table 23. Comparison between Lunelund's measured values for 1928—35 of the perpendicular heat radiation from the sun (A) and calculated values according to the average curve for clear sky × relative duration of sunshine according to the autograph (B). See Tables 14 and 20 (r_a). In column C is given the percentage over-estimate (+) or under-estimate (—) of B in relation to A. Unit 1 kcal/m^2h.

Month	True solar time									
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	20 4	21 3
I: A	64	59	37	13						
: B	56	53	43	17						
: C	—12	—10	+16	+31						
II: A	176	167	149	110	48	2				
: B	176	173	158	125	58	1				
: C	0	+4	+6	+14	+21	(—50)				
III: A	300	295	282	231	176	92	15			
: B	279	275	269	250	209	130	19			
: C	—7	—7	—5	+8	+19	+41	+27			
IV: A	316	303	297	266	243	198	127	38		
: B	329	327	322	310	292	257	185	53		
: C	+4	+8	+8	+17	+20	+30	+46	+39		
V: A	367	359	360	354	323	279	222	152	55	
: B	442	439	432	424	406	381	337	250	90	
: C	+20	+22	+20	+20	+26	+37	+52	+64	+64	
VI: A	422	420	408	399	388	347	309	238	150	45
: B	479	475	470	459	444	423	389	326	231	38
: C	+14	+13	+15	+15	+14	+22	+26	+37	+54	(—26)
VII: A	420	410	408	356	340	310	263	201	102	15
: B	460	454	451	441	425	402	364	288	158	4
: C	+10	+11	+11	+24	+25	+30	+38	+43	+55	(—73)
VIII: A	323	331	326	298	255	230	167	74	13	
: B	380	377	371	360	344	309	250	123	4	
: C	+18	+14	+14	+21	+35	+34	+50	+66	(—69)	
IX: A	269	245	230	218	176	126	47			
: B	266	263	258	245	216	164	57			
: C	—1	+7	+12	+12	+23	+30	+21			
X: A	172	157	141	115	75	21				
: B	154	152	143	122	79	14				
: C	—10	—3	+1	+6	+5	(—33)				
XI: A	62	61	52	32	2					
: B	62	59	51	33	2					
: C	0	—3	—2	+3	(0)					
XII: A	50	44	31	1						
: B	41	37	25	1						
: C	—18	—16	—19	(0)						

Table 24. Average clarity of the sky in different zones of altitude and quadrants of the horizon at Ilmala according to Väisälä. Investigation during the period April—September 1922, from 9.00 hrs to 15.00 hrs. Percent excess (+) or deficiency (—) in relation to the average values for the whole sky (diff).

Zenith-angle	Quadrant					
	SE	SW	NV	NE	mean	diff %
0°—30°					29.7	+13
30°—60°	27.7	28.7	28.5	28.9	28.4	+ 8.4
60°—75°	28.1	27.6	25.8	27.8	27.3	+ 3.8
75°—90°	25.0	21.5	16.3	19.2	20.5	—22
0°—90°					26.3	
zenith					29.7	+13

Regional Variation of Nebulosity

Some careful investigations by *Väisälä* (96) show that the average values of nebulosity are different for different parts of the sky. His investigation took place in Ilmala during the period April—September 1922 and 1923. Only the summer half of the year is therefore represented. In addition his investigation was restricted to the hours 9.00 to 15.00, in certain cases 7.00 to 17.00. His investigations cannot therefore lead to very broad conclusions but nevertheless a certain amount of information on the variation of sky clarity can be obtained.

The clarity increases from the horizon up to the zenith. As can be seen on Table 24 this variation is quite considerable. It therefore follows that the clarity of the sky at the point where the sun is to be found will increase from sunrise to noon and thence will decrease from noon until sunset. The relative duration of sunshine will therefore also vary in the same way and this variation can be expressed as a function of the solar altitude $f_1(h)$ according to the equation

$$r_1 = f_1(h) \times k_d \quad \text{eqn 5}$$

where k_d is the mean value of the sky clarity for the whole sky and r_1 is the relative duration of sunshine calculated with k_d as a starting value. $f_1(h)$ is called here the *first distribution function* of the clarity.

This simple variation is complicated by a large number of other variations. As a result of the heating up of the earth's surface by solar radiation during clear days an ascending air stream is formed round about mid-day. This air stream gives rise to a cloud formation, cumulus cloud, which then disappears during the afternoon. From this it follows that the relative duration of sunshine is reduced when the sun stands high in the sky, an effect which counteracts the previous effect. This variation can also be expressed as a function of the solar altitude $f_2(h)$ and the equation can now be expressed as

$$r_{1+2} = f_1(h) \times f_2(h) \times k_d \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 6$$

where r_{1+2} is the relative duration of sunshine calculated with k_d as a starting value. $f_2(h)$ is called the *second distribution function* of the clarity.

The formation of cloud during the day has naturally a certain influence on the solar radiation on a horizontal plane. *Ångström* (98) has observed from his recordings a minimum radiation round about 14.00 hours, which he ascribes to the ascending air stream. At the same time he also mentions that on cloudy days the same air stream can break through the cloud cover and exercise an opposing effect, an increase of the relative duration of sunshine at noon. This effect is not clear from *Väisälä's* work but since it is associated with the preceding variation it may be difficult to discern it. Since this has the same cause as $f_2(h)$ it ought to be possible to include it in this function as far as average values are concerned.

A further variation arises for Helsinki which derives from the position of the town on the coast of south Finland. The nebulosity which ascends from the ground as a result of the sun's radiation having warmed up the earth's surface will not be formed over the sea. One can occasionally, during the summer, see how the low clouds suddenly cease just at the coast line and the sky over the sea is completely clear. See the photograph which forms the frontispiece of this book. As a result of the fact that the coast line lies approximately in an East-West direction the northern half of the sky will therefore be cloudy while the southern half, where the sun is to be found, is clear. The average nebulosity for the sky may therefore be greater than zero, but the sun radiates on the town uninterruptedly from the cloud-free southern hemisphere of the sky. The modifying influence of the noonday nebulosity on the radiation becomes considerably reduced, but at least half the value enters into the statistical value of nebulosity. A special investigation of cumulus cloud undertaken by *Väisälä* (96) in Ilmala shows that it is, to all practical purposes, non-existent in the Gulf of Finland, i. e. in the southern part of the sky. Since the coast line has an East-West direction the reduction will be approximately the same in the morning as in the afternoon and can therefore be expressed in the function $f_2(h)$. Equation 6 therefore requires no alteration.

Approximate values for some of these functions can be obtained from *Väisälä's* investigation. Table 24 shows clearly that the clarity of the sky as seen from the observation point varies considerably both in relation to the compass point and the altitude. These figures apply however to Ilmala, which lies some km north of Helsinki. The nebulosity will be altered markedly on the coastal area itself, with a lesser transference nearer or farther from the coast. The difference between the cloud formation over the land and over the sea derives evidently from the zone between the angles of altitude 75° to 90°, which in its southern part lies almost entirely over the sea but in its northern part lies over the mainland. A slight deviation from the East-West direction of the coast line can be read off the figures in Table 24. The south east quadrant is the most maritime and the north west quadrant the most continental, which agrees with the distribution of land and sea. The height of the sky, where the subjective estimate of clarity for the whole sky lies, is about 15° above the horizon.

Table 25. Sky clarity in Ilmala 1928—35 calculated from information in the Meteorologisches Jahrbuch für Finnland. Periods of darkness are indicated by heavy figures. Italicised figures are lower than the average values for daytime (k_d).

Month	East european time															k_d
	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
I	**15**	**12**	*9*	*10*	*10*	11	12	11	12	11	**12**	**13**	**13**	**14**	**13**	11
II	**22**	*19*	*19*	*19*	*21*	23	25	26	25	27	26	**27**	**29**	**32**	**33**	23
III	29	*28*	29	31	33	32	31	30	*27*	*27*	*27*	29	30	**35**	**39**	29
IV	30	29	27	*26*	*24*	*25*	*26*	*26*	*26*	27	29	29	30	**31**	**32**	27
V	34	35	36	35	*33*	34	*33*	*33*	*33*	*33*	34	34	34	*33*	35	34
VI	44	43	40	38	*36*	*34*	*33*	*33*	*34*	*36*	*36*	39	41	41	42	38
VII	35	34	*31*	*31*	*29*	*30*	*29*	*30*	*30*	*31*	33	33	33	35	37	32
VIII	29	28	28	27	*25*	*23*	*26*	*25*	*25*	27	28	28	29	29	**30**	27
IX	25	25	23	23	22	*21*	*18*	*19*	*19*	22	24	25	27	**33**	**37**	22
X	18	16	*15*	*14*	*15*	*15*	*15*	*15*	*15*	16	17	**18**	**24**	**26**	**27**	16
XI	**11**	*9*	*7*	*9*	*8*	*9*	10	11	12	12	**14**	**15**	**16**	**17**	**17**	10
XII	**12**	**10**	**10**	*9*	10	11	10	11	10	**9**	**12**	**13**	**11**	**11**	**13**	10

The variation of $f_2(h)$ can best be studied from the statistics of nebulosity. The daily course of the clarity has been calculated for Ilmala during the years 1928—35 and the monthly mean values are expressed in Table 25. The information was obtained from the Meteorologisches Jahrbuch für Finnland (39). According to this table the mean values of clarity are fairly similar for all times of the day with a minimum immediately after noon. This minimum, which derives from the above mentioned formation of cloud in the middle of the day, is approximately 10 per cent lower than the average value for the day. Because of the short time during which the observations were made, only 8 years, the values are somewhat irregular. The general tendency is however clear, lower clarity values for higher solar altitudes and higher values for lower solar altitudes.

It can be seen from the values during darkness that a serious error can be committed if, in the average values of clarity, the observations taken during this time are included.

Both the functions $f_1(h)$ and $f_2(h)$ vary very probably from place to place. The function $f_1(h)$ varies with the type of cloud. It is thereby above all the extent of the cloud in altitude which is critical. The function $f_2(h)$ varies with local conditions. The proximity to the sea or to large sheets of water, the conformation of the terrain, the direction of the wind etc, which influence the formation of cumulus cloud around mid-day, are fundamental to this variation.

At the Observatory Saint-Maur in Paris the nebulosity has been observed for 50 years and for every hour of the day. From the statistics of nebulosity (9) the second distribution function of clarity can readily be studied for Paris. The result cannot be applied to Helsinki, but it shows the same periodicity as the present investigation shows for the nebulosity in Ilmala.

Solar Time Function of Clarity

Some studies of the variation of nebulosity have been described above. These serve, however, to give no more than a general understanding of their characteristics. They link up generally and this concurrence can be expressed in the equation

$$\varkappa_k = f_1(h) \times f_2(h) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn 7}$$

$\varkappa_k$ is called here the *solar time function of the sky clarity*, and it can be defined as a relationship between the mean value of the sky clarity at the point where the sun is to be found (k_s) and the mean value of the average clarity of the whole sky (k_d)

$$k_s = \varkappa_k \times k_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn 8}$$

With the aid of the solar time function the relative duration of sunshine (r_k) which is based on the clarity of the sky, can be calculated for each point on the sky if the average clarity (k_d) is known. The relation between them can be expressed in the equation

$$r_k = k_s = \varkappa_k \times k_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn 9}$$

Solar Time Function of Clarity for Helsinki

It is not possible, with the aid of these studies of clarity, to obtain any serviceable values for this solar time function for Helsinki. The studies have, however, given a good understanding of the increases in, and the approximate order of, the variations in the clarity. In order to get values which are suitable for calculations, the nebulosity statistics must be carried out in much greater detail than is done at the moment and for a sufficiently long time so that an adequate statistical foundation is obtained. This may however be possible only at the big meteorological stations.

In this case, however, there is another method of calculating the solar time function of the sky clarity. The following equation applies to the average value of the strength of the radiation with a given solar altitude

$$E^{Sk} = E^{SK} \times \varkappa_k \times k_d \dots\dots\dots\dots\dots\dots \quad \text{eqn } 10$$

where E^{Sk} is the average value of the strength of the solar radiation which applies to the mean value of the sky clarity $= k_d$ and E^{SK} is the average value of the strength of the solar radiation for clear sky, $\varkappa_k$ is solar time function of the clarity. $\varkappa_k$ can be deduced from this equation if the statistical mean values of the solar radiation during a certain time are available, and also information on the solar radiation with clear sky and the nebulosity statistic during the corresponding time. Such data are available for Helsinki.

From his recordings of the perpendicular radiation in Helsinki during the years 1928—35, *Lunelund* (57) has calculated the average value of the strength of radiation for each hour and each decade (10-day period). These recordings were obtained with a Gorzynski Pyrheliograph set up on the roof of the University Institute of Physics. The values which *Lunelund* published have been recalculated in the units used in this report. The values for the forenoon and afternoon have also been grouped together symmetrically. There is found in the original values a preponderance in the afternoon but since in this work an average curve of the radiation as a function of solar altitude has been aimed at, this asymmetry has not been taken into consideration. The adapted values of radiation are shown on Table 26. Each value in this table is an average value from 160 recorded measurements (80 measurements only for 12.00 hours). The total number of recordings was over 35,000.

According to equation 10 these values, decade for decade (10-day period), should be divided by the average value of the sky clarity for the corresponding times. The mean value of clarity (k_d) can also be found in the same table. This has been calculated from the information in the Meteorologisches Jahrbuch für Finnland (39). As has already been explained, the observations of cloudiness in Helsinki occur three times daily, 7.00, 15.00, and 21.00 hours. The observations during darkness have been struck out. For the years 1928—35 therefore each value of clarity during 7 decades in the summer is the average of 240 observations, during 18 decades in spring and autumn an average value of 160 observations, and during 12 winter decades an average value of 80 observations comprising in all 5,000 observations.

From the division are obtained the values according to Table 27. These can be indicated as strengths of radiation with clear sky, modified for the solar time function of the clarity. They will now be inserted in a diagram and an average curve calculated.

Table 26. Perpendicular heat radiation from the sun in Helsinki. Average values for decades for every hour during the years 1928—35. Each value is a mean figure of 160 different measured values (means of 80 values for 12.00 noon). Morning and afternoon values are paired symmetrically. Unit 1 kcal/m² h. Sky clarity k_d in percent.

Month Decade	True solar time										k_d
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	20 4	21 3	
I: 1	46	45	25	1							11
: 2	48	41	29	7							14
: 3	95	88	57	30							14
II: 1	176	151	126	78	17						24
: 2	178	174	157	127	55	1					28
: 3	174	181	166	129	80	6					27
III: 1	274	269	248	209	147	46					35
: 2	298	256	212	294	182	101	3				26
: 3	326	320	308	251	197	127	39				30
IV: 1	279	250	226	234	207	175	99	4			29
: 2	304	303	325	263	241	186	119	31			32
: 3	365	358	341	307	282	233	164	79			34
V: 1	383	374	367	399	349	305	218	136	18		44
: 2	332	346	331	316	289	239	179	124	44		31
: 3	383	358	382	350	331	291	264	193	99	6	40
VI: 1	384	353	366	361	347	314	290	207	127	31	40
: 2	466	483	444	436	436	378	331	272	173	56	49
: 3	415	427	414	400	382	351	308	236	151	49	45
VII: 1	428	440	446	414	389	364	303	253	157	35	46
: 2	440	405	417	326	313	300	264	194	99	9	40
: 3	395	386	367	330	321	270	225	159	56	2	34
VIII: 1	291	322	319	284	247	251	199	112	23		34
: 2	342	354	334	330	276	230	163	81	2		33
: 3	335	322	323	284	243	213	142	34			32
IX: 1	283	260	253	270	210	167	87	10			30
: 2	292	262	259	237	207	133	45				31
: 3	232	212	179	198	111	78	8				23
X: 1	244	216	133	168	107	51					21
: 2	206	182	182	130	92	15					22
: 3	74	82	66	54	32						14
XI: 1	46	50	49	33	7						13
: 2	113	105	88	54	1						21
: 3	29	27	21	9							8
XII: 1	46	34	28	2							12
: 2	64	62	42	1							16
: 3	48	37	23								9

Table 27. Perpendicular radiation from the sun in Helsinki modified for the unequal distribution of nebulosity on the sky. Each value is a mean figure of 160 different measured values (except for noon, mean of 80 measurements). Morning and afternoon values have been grouped together symmetrically. Unit 1 kcal/m² h.

Month Decade	True solar time									
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	20 4	21 3
I: 1	418	405	228	9						
: 2	342	293	203	46						
: 3	678	629	403	214						
II: 1	733	629	523	323	68					
: 2	635	620	559	452	194	2				
: 3	644	669	613	478	295	21				
III: 1	783	768	708	597	420	130				
: 2	1,150	1,131	985	892	698	388	11			
: 3	1,086	1,065	1,026	836	657	421	130			
IV: 1	962	862	777	805	712	601	341	14		
: 2	950	945	1,015	820	752	581	372	95		
: 3	1,073	1,053	1,001	901	829	684	482	231		
V: 1	870	849	833	907	793	692	495	308	41	
: 2	1,071	1,117	1,076	1,018	931	771	578	400	142	
: 3	957	895	955	875	826	736	660	466	246	14
VI: 1	960	981	915	903	868	785	724	518	317	77
: 2	951	986	906	890	890	771	676	555	353	114
: 3	922	948	919	887	849	780	633	524	334	108
VII: 1	930	956	969	899	845	791	657	550	340	75
: 2	1,100	1,012	1,042	815	783	749	660	484	247	23
: 3	1,162	1,134	1,078	971	945	794	662	468	168	6
VIII: 1	856	946	938	834	725	739	584	330	68	
: 2	1,036	1,072	1,012	998	836	697	492	245	5	
: 3	1,046	1,007	1,010	888	760	664	444	105		
IX: 1	943	865	843	890	698	557	290	31		
: 2	941	845	834	764	666	432	145			
: 3	1,008	922	776	643	483	337	32			
X: 1	1,162	1,027	876	798	508	241				
: 2	936	827	828	589	416	69				
: 3	528	582	468	382	225					
XI: 1	353	381	372	250	50					
: 2	538	497	419	255	2					
: 3	363	338	257	107						
XII: 1	383	283	229	16						
: 2	400	384	262	6						
: 3	533	411	250							

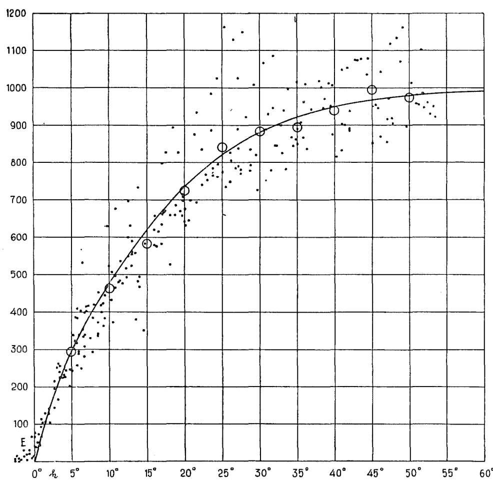


Fig. 12. Curve giving the perpendicular heat radiation from the sun modified for the solar time function of the sky clarity. The circles are average values for each solar altitude group. The points are the individual values from Table 27. Vertical scale = kcal/m²h, horizontal scale = solar altitude in degrees.

Now the solar altitude for each time of day and each decade can be calculated with the aid of the well known equation

$$\sin h = \sin d \times \sin \varphi + \cos d \times \cos t \times \cos \varphi \quad \ldots\ldots\ldots\ldots \text{ eqn 11}$$

where h is the solar altitude, d is the declination, φ is the degree of latitude and t is the hour angle. The solar heights have been calculated for the fifth, the fifteenth, and twenty-fifth of each month, as average values of the solar height for each decade. The calculated solar altitudes are shown on Table 28.

The values of radiation are drawn on the diagram in the form of points (Fig. 12). An average curve can now be calculated and thence the values are distributed in groups according to the solar altitude. Group 1 includes all the values between 2.5 degrees and 7.5 degrees solar altitude, group 2 all those between 7.5 degrees and 12.5 degrees, group 3 those between 12.5 degrees and 17.5 degrees and so on. The average value in each group corresponds to the average solar altitude of the group, that is to say for group 1 solar altitude 5°, for group 2 solar altitude 10°, for group 3 solar altitude 15°, and so on. The average values

Table 29. Perpendicular heat radiation from the sun alone, modified for the solar time function of clarity, as a function of the altitude of the sun. Average values calculated from Lunelund's recordings in Helsinki 1928—35. Unit 1 kcal/m²h.

Group	1	2	3	4	5	6	7	8	9	10
Limits	2.5°— —7.5°	7.5°— —12.5°	12.5°— —17.5°	17.5°— —22.5°	22.5°— —27.5°	27.5°— —32.5°	32.5°— —37.5°	37.5°— —42.5°	42.5°— —47.5°	47.5°— —52.5°
Mean altitude	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
Calculated	294	462	583	725	843	882	894	933	994	976
Curve	295	475	620	735	820	880	920	950	965	975

Table 28. Solar altitude in degrees for the 5th (1st decade), the 15th (2nd decade) and the 25th (3rd decade) in each month, for each hour. Latitude 60° N.

Month Decade	True solar time									
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	20 4	21 3
I: 1	7.2	6.3	3.6	—0.2						
: 2	8.6	7.7	4.8	0.8						
: 3	10.7	9.8	7.0	2.7						
II: 1	13.7	12.7	9.9	5.5	—0.2					
: 2	16.9	15.9	13.0	8.5	2.7	—2.6				
: 3	20.4	19.4	16.4	11.8	5.9	—1.0				
III: 1	23.8	22.8	19.7	15.0	8.9	2.0				
: 2	27.7	26.6	23.5	18.4	12.4	5.4	—2.0			
: 3	31.7	30.6	27.3	22.3	16.0	8.9	1.5			
IV: 1	36.0	34.8	31.4	26.2	19.8	12.6	5.2	—2.2		
: 2	39.7	38.5	34.9	29.6	23.1	15.9	8.4	1.1		
: 3	43.1	41.8	38.2	32.7	26.1	18.8	11.3	4.0	—2.7	
V: 1	46.2	44.9	41.1	35.5	28.8	21.5	14.0	6.7	0.1	
: 2	48.8	47.4	43.6	37.9	31.1	23.7	16.2	9.0	1.9	
: 3	50.9	49.5	45.5	39.7	32.9	25.5	18.0	10.8	4.3	—1.2
VI: 1	52.5	51.0	47.0	41.1	34.2	26.8	19.4	12.2	5.8	0.3
: 2	53.3	51.8	47.8	41.9	34.9	27.5	20.0	12.9	6.5	1.0
: 3	53.4	51.9	47.8	41.9	35.0	27.6	20.1	13.0	6.6	1.1
VII: 1	52.8	51.3	47.3	41.4	34.5	27.1	19.6	12.5	6.0	0.6
: 2	51.6	50.2	46.2	40.3	33.5	26.0	18.6	11.4	4.9	—0.6
: 3	49.1	48.3	44.4	38.7	31.8	24.4	17.0	9.8	3.3	—2.4
VIII: 1	47.1	45.7	42.0	36.3	29.6	22.2	14.8	7.5	0.9	
: 2	44.2	42.9	39.2	33.7	27.1	19.8	12.3	5.0	—1.7	
: 3	40.9	39.7	36.1	30.7	24.2	16.9	9.4	2.1		
IX: 1	36.9	35.7	32.3	27.1	20.6	13.4	6.0	—1.4		
: 2	33.2	32.0	28.7	23.7	17.3	10.2	2.8			
: 3	29.3	28.2	25.0	20.1	13.8	6.8	—0.6			
X: 1	25.4	24.3	21.2	17.0	10.4	3.4				
: 2	21.6	19.3	17.6	12.9	6.9	0.1				
: 3	18.0	17.0	14.1	9.5	3.7					
XI: 1	14.4	13.4	10.6	6.2	0.4					
: 2	11.6	10.7	7.9	3.6	—2.1					
: 3	9.3	8.4	5.7	1.4						
XII: 1	7.7	6.8	4.1	—0.1						
: 2	6.7	5.8	3.2	—1.0						
: 3	6.6	5.7	3.1	—1.1						

for each group are shown in Table 29. The values of radiation in the table are drawn in on Fig. 12 (circles) and a curve has been drawn through them which gives the radiation curve modified for the solar time function. This is also shown in the table.

Table 30. Monthly totals of the perpendicular heat radiation (sun alone) calculated from the modified radiation curve for clear sky combined with mean values of nebulosity for Helsinki (tQ), compared with Lunelund's recordings 1928—35 (Reg), and also the percentage over-estimate (+) or under-estimate (—) of the calculation in relation to the recording (diff). Unit 1 Mcal/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Reg	9.0	32.0	78.2	99.5	146.4	174.8	161.8	112.1	70.7	36.6	10.5	6.6
tQ	8.9	31.8	68.6	95.5	150.9	181.1	161.8	113.3	70.4	31.5	11.7	5.9
diff %	—1	—1	—12	—4	+3	+4	0	+1	0	—14	+10	—9

The curve can be tested by calculating the perpendicular radiation value during different months of the year with its aid and with the average values of clarity. This calculation has been obtained in the same manner as the corresponding calculation with *Lunelund's* average curve derived on Pages 38—48. The monthly totals so obtained are evident from Table 30 where *Lunelund's* recorded values are also shown for comparison. The average values of the perpendicular radiation strength for each hour and month have also been calculated and they are shown in Table 31. In both these tables the percentage departure from *Lunelund's* recorded values are given.

Both these tables can now be compared with Tables 21, 22 and 23. With regard to the calculated values based on the sky clarity (k_d), it can be seen that the considerable under-estimates for the summer months have now disappeared. The under-estimates for March and October have decreased but still remain. Table 22 shows that the under-estimates for the higher solar altitude have disappeared. The winter months show, however, some remaining irregularity. The following considerations apply to the under-estimates in March and October.

With regard to the calculation of clarity in November one observation only is used, that taken at 15.00 hours. According to Table 25 the clarity in Ilmala is then 12 % whereas the average value for daytime is 10 %. This does not, however, have a considerable influence on the modified average curve. The calculation of radiation is then carried out by multiplying the radiation from the clear sky (modified curve) by too high a value of clarity which gives an excess of 10 %. One can anticipate that the relationship is very much the same in Helsinki and Ilmala.

In March the clarity value taken for the calculation is an average between the observations at 7.00 hours and 15.00 hours, which gives a clarity of 28 % for Ilmala. The true average value lies at about 29 %. But this month shows the peculiarity that the clarity has a maximum at 11.00 hours, which is 33 %. This is completely the converse of the summer months where a minimum clarity is met with around mid-day. The month of April has approximately the

Table 31. Comparison between Lunelund's measured values 1928—35 of the perpendicular heat radiation from the sun (A) and calculated values according to the intensity curve, modified by the solar time function of the clarity × the clarity (B). Percentage over-estimate (+) or under-estimate (—) of B in relation to A is given in column C. Unit 1 kcal/m²h.

Month	True solar time									
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	20 4	21 3
I: A	64	59	37	13						
: B	58	56	43	16						
: C	—9	—5	+16	+23						
II: A	176	167	149	110	48	2				
: B	175	170	153	110	47	1				
: C	—1	+2	+3	0	—2	(—50)				
III: A	300	295	282	231	176	92	15			
: B	257	253	241	213	168	92	10			
: C	—14	—14	—15	—8	—5	0	(—33)			
IV: A	316	303	297	266	243	198	127	38		
: B	294	291	285	271	246	196	126	30		
: C	—7	—4	—4	+2	+1	—1	—1	—21		
V: A	367	359	360	354	323	279	222	152	55	2
: B	380	378	374	360	346	310	255	169	57	
: C	+4	+5	+4	+2	+7	+11	+15	+11	+4	
VI: A	422	420	408	399	388	347	309	238	150	45
: B	433	431	428	420	404	370	322	237	145	21
: C	+3	+3	+5	+5	+4	+7	+4	0	—3	(—53)
VII: A	420	410	408	356	340	310	263	201	102	15
: B	392	390	386	379	361	329	278	199	99	2
: C	—7	—5	—5	+6	+6	+6	+6	—1	—3	(—67)
VIII: A	323	331	326	298	255	230	167	74	13	
: B	317	314	310	298	277	232	154	72	2	
: C	—2	—5	—5	0	+9	+1	—8	—3	(—85)	
IX: A	269	245	230	218	176	126	47	3		
: B	251	247	239	218	183	124	36			
: C	—7	+1	+4	0	+4	—2	(—23)			
X: A	172	157	141	115	75	21				
: B	141	138	127	100	60	10				
: C	—18	—12	—10	—15	—20	(—53)				
XI: A	62	61	52	32	2					
: B	72	69	58	31	2					
: C	+16	+13	+12	—3	(0)					
XII: A	50	44	31	1						
: B	44	42	24	1						
: C	—12	—6	—23	(0)						

same average value of clarity as March, but shows a directly converse tendency. At 11.00 hours the clarity is 24 % as against 33 % in March. The minimum clarity in March is displaced towards the afternoon, around about 16.00 hours. It appears as if the solar radiation in March first brings about a reduced formation of cloud in the middle of the day and then an increased formation of cloud during the afternoon which then disappears in the evening.

In the calculation of the modified average curve, which is an average curve for the whole year, these peculiarities in the month of March have no considerable influence, nor do they make any impression on the average values of clarity. It follows therefore that there is a considerable under-estimate in the calculated values of radiation as compared with the recorded values. In the same connection it is interesting to see how the recorded values according to Table 27 group themselves around the average curve. For this reason Fig. 13, I—XII, has been prepared. The deviations of the values from the mean curve are in many cases considerable. Each month also shows an individual tendency. These deviations can partly be caused by the yearly variation in the atmospheric humidity. During the summer when the humidity is high the radiation value lies below the average curve, see the figures for the months April to September. During the winter months the values are more uneven and lie higher than during the summer. It is these values which raise the mean curve. In particular during March and October the values are higher for high solar altitudes. In November the values lie for the most part under the average curve.

It may be worth considering a summer-curve and a winter-curve which would perhaps give a better result than the year-curve. On the solar chart, see Page 93, however, the months of March and September are coupled together on one solar path. The curve for March is a typical winter-curve and September a typical summer-curve. One of them must be suffering as a result and so it is rather better to employ a common year-curve. Later a calculating chart of the same type as the solar chart will be constructed for the heat radiation from the sun and thence in order to avoid making the calculation too complicated a single curve ought to be used for the whole year. It is quite obvious that it is possible to reduce the percentage error by using an individual curve for each month. One of the purposes of this work is however to investigate how near to the true radiation one can arrive at with intensity curves founded on mean values for the whole year.

With respect to the solar time function one should not start from the mean value of clarity, but from the clarity with some given solar altitude, the same for all months. Sunrise would be a suitable starting point. On those meteorological stations where recordings of the solar radiation take place, the nebulosity observations ought to be obtained every hour so that the relation between the radiation and the nebulosity can be studied in greater detail than has been possible so far. At the same time sunshine recordings with the autograph should

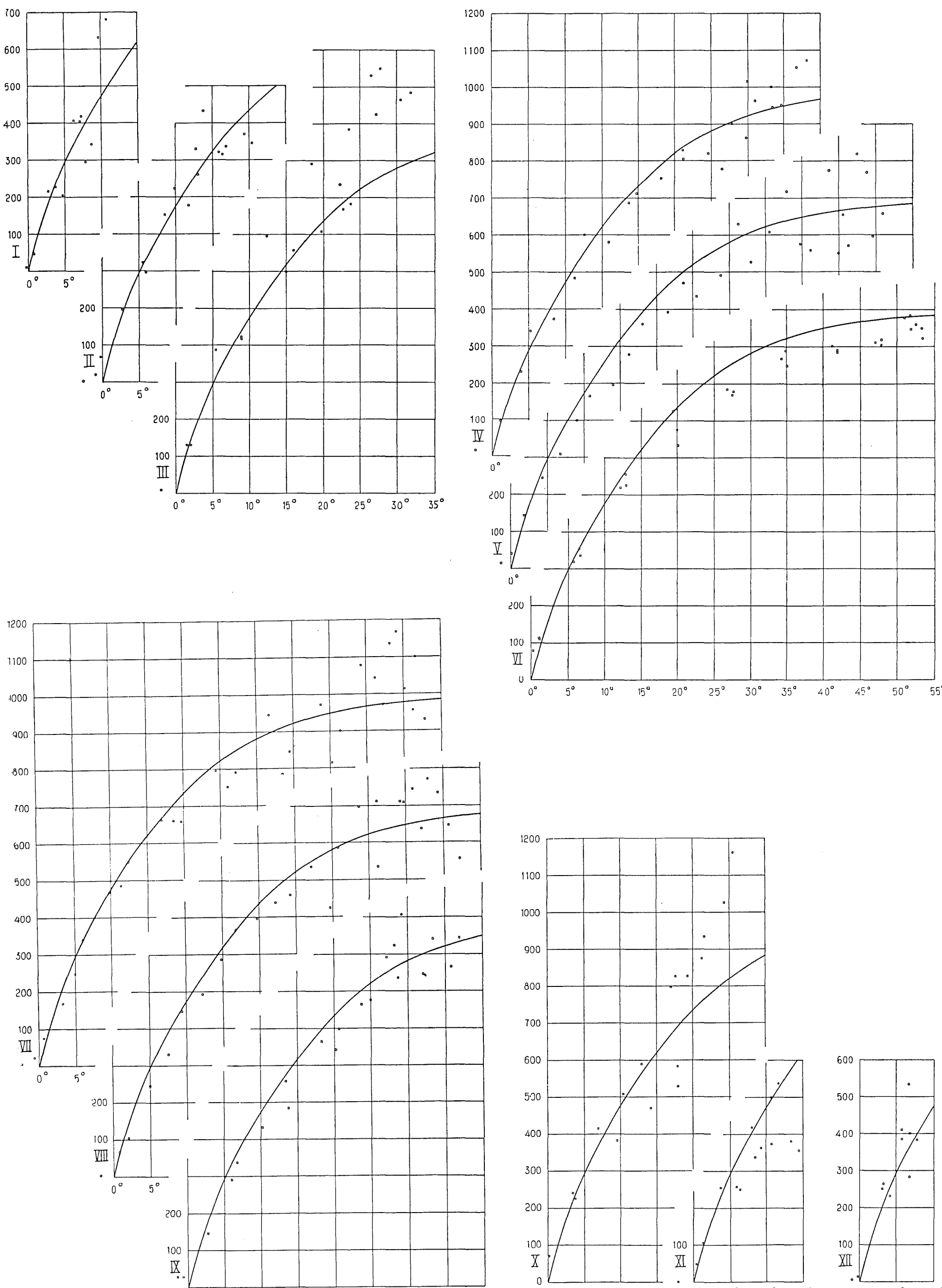


Fig. 13. Twelve figures which show how the individual values in Table 27 for each month (I—XII) are grouped around the curve according to Figure 12. Vertical scale = kcal/m²h, horizontal scale = solar altitude in degrees.

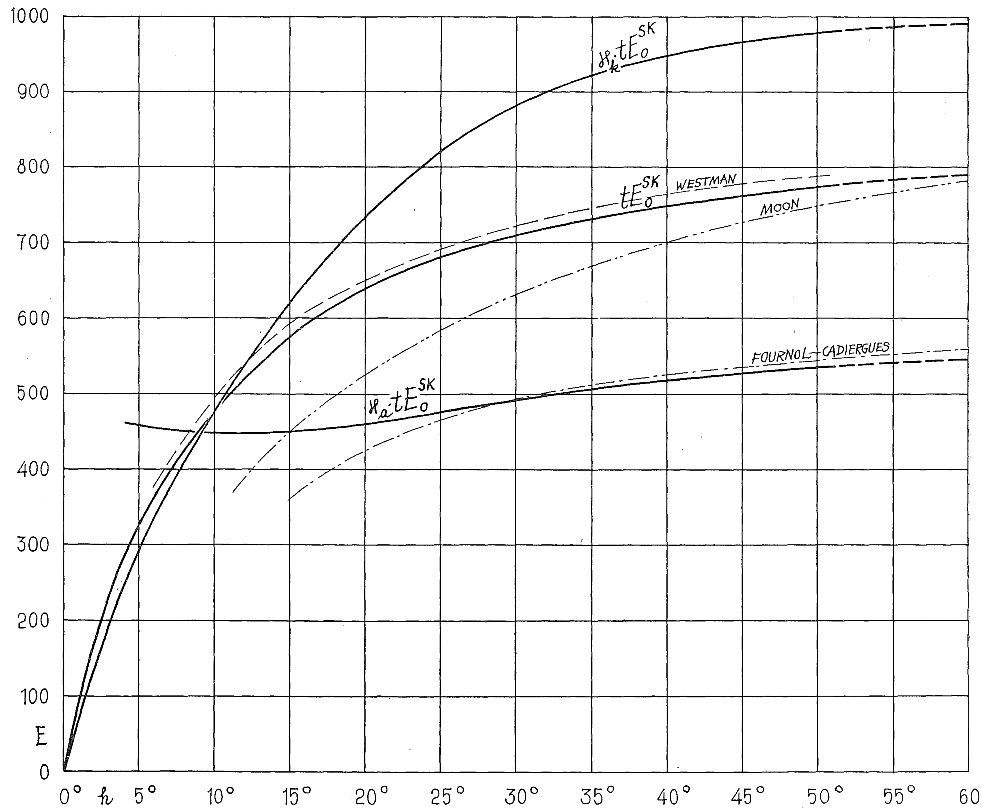


Fig. 14. The average curve for the perpendicular heat radiation from the sun with clear sky (tE_o^{SK}) according to Lunelund (56), the curve for intensity modified by the solar time function of the sky clarity ($\varkappa_k \times tE_o^{SK}$) and the curve for intensity modified by the solar time function of the sunshine autograph ($\varkappa_a \times tE_o^{SK}$) compared with the results of other investigations: Westman (88), Moon (65), and Fournol — Cadiergues (23). Vertical scale = kcal/m²h, horizontal scale = solar altitude in degrees.

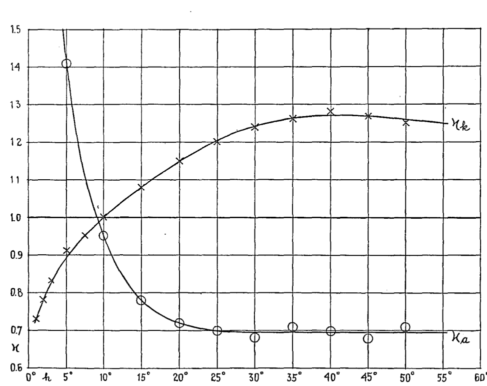


Fig. 15. The solar time function for the sky clarity ($\varkappa_k$) and for the sunshine autograph ($\varkappa_a$) in Helsinki, as function of the altitude of the sun (horizontal scale).

also take place for the same locality, for there is a close relation between the radiation and the number of hours of sunshine.

On the whole however it appears that the agreement between the calculated and the measured values is so good that radiation calculations can be founded on the modified average curve for the year. For the calculation of such a modified curve for other characters of radiation, for example illumination or erythemal radiation, the solar time function has to be established.

On Fig. 14 both *Lunelund's* average curves and the new modified curve are drawn in and the values for every fifth degree are found in Table 32. The modified values of radiation for each solar altitude will now be divided, according to equation 10, by *Lunelund's* average values. Thence are obtained the values for the solar time function of clarity according to the same table. The values are shown in Fig. 15 and a curve is drawn throught the points.

Table 32. Perpendicular heat radiation with clear sky, average values modified by the solar time function ($\varkappa_k \times tE$), Lunelund's average curve (tE) and solar time function of the clarity ($\varkappa_k$). Unit 1 kcal/m²h.

h	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
$\varkappa_k \times tE$	295	475	620	735	820	880	920	950	965	975
tE	325	475	574	640	682	711	727	744	760	777
k_d	0.91	1.00	1.08	1.15	1.20	1.24	1.27	1.28	1.27	1.25

The formation of cloud at mid-day emerges from the solar time function in the form of a little depression at the highest solar altitudes, but this depression is very small.

The "true" clarity for the position of the sun (k_s) has been calculated for every hour of true solar time employing the curve of the solar time function of clarity. By "true" clarity is implied the value which must be combined with the mean curve of solar radiation for clear sky in order to obtain the true values of radiation from the sun. See Table 33, next page.

Solar Time Function of the Sunshine Autograph

If the general trend of the relative duration of sunshine according to the autograph (r_a) is compared with the clarity (k_d) it is found that they are quite different. The clarity has in general its highest values in the morning and afternoon with a minimum in the middle of the day, whereas the relative duration of sunshine has on the contrary its lowest values in the morning and afternoon and a maximum at mid-day. This mid-day maximum can, during the summer, be twice as great as the simultaneous value of clarity.

Table 33. Calculation of the solar time function of the sunshine autograph ($\varkappa_a$).

A. Clarity of the sky for the position of the sun (k_s), calculated from the mean value (k_d) and the solar time function ($\varkappa_k$) respectively of the clarity. B. Relative duration of sunshine (r_a) calculated from the values for Ilmala × 1.16. C. Solar time function of the sunshine recorder ($\varkappa_a$ All values apply to Helsinki 1928—35.

Month	True solar time									
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	10 4	21 3
I: A	13	12	12	8						
: B	19	16	11	4						
: C	0.68	0.75	1.09	2.00						
II: A	29	29	27	25	22					
: B	40	39	36	29	9					
: C	0.73	0.74	0.75	0.86	2.44					
III: A	37	37	36	34	31	27				
: B	62	58	54	50	34	9				
: C	0.60	0.64	0.67	0.68	0.91	(3.00)				
IV: A	39	39	39	38	37	34	30	22		
: B	57	57	56	56	51	41	24	7		
: C	0.68	0.68	0.70	0.68	0.73	0.83	1.25	(3.14)		
V: A	50	50	50	50	49	46	43	39	30	
: B	70	70	71	70	68	63	58	41	13	
: C	0.71	0.71	0.70	0.71	0.72	0.73	0.74	0.95	2.31	
VI: A	55	55	56	56	55	54	51	46	41	31
: B	74	74	75	73	73	71	68	60	31	2
: C	0.74	0.74	0.75	0.77	0.75	0.76	0.75	0.77	1.32	15.5
VII: A	50	50	51	51	50	48	45	40	34	
: B	74	76	74	72	70	67	62	48	20	
: C	0.68	0.66	0.69	0.71	0.71	0.72	0.73	0.83	1.70	
VIII: A	42	42	42	42	40	38	34	30		
: B	66	64	65	60	58	52	41	18		
: C	0.64	0.66	0.65	0.70	0.69	0.73	0.95	1.67		
IX: A	35	35	34	33	31	28	23			
: B	51	52	52	48	40	20	3			
: C	0.69	0.67	0.65	0.69	0.78	1.40	(7.67)			
X: A	22	22	21	20	18					
: B	32	31	29	23	6					
: C	0.69	0.71	0.72	0.87	(3.00)					
XI: A	14	14	14	12						
: B	15	15	14	7						
: C	0.93	0.93	1.00	1.71						
XII: A	11	11	10							
: B	16	13	8							
: C	0.69	0.85	1.25							

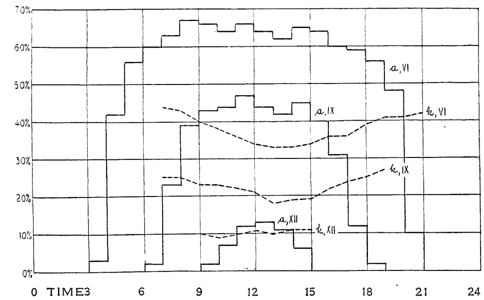


Fig. 16. Diurnal course of sky clarity (k) and relative duration of sunshine according to autograph recordings (a) in Ilmala near Helsinki. Average values for June (VI), September (IX), and December (XII) during the years 1928—35.

It is manifest that the recorded values of relative duration of sunshine cannot be employed directly in combination with the intensity curve for clear sky. A solar time function can, however, be calculated also for the sunshine autograph values. The following equation applies to this function:

$$\varkappa_a = k_s / r_a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 12$$

where $\varkappa_a$ is the solar time function of the autograph, r_a is the relative duration of sunshine according to the autograph, and k_s is the clarity of the sky for the sun's position.

It has been mentioned above that the duration of sunshine in Helsinki was not recorded during the years 1928—35. This was, however, done at the Observatory in Ilmala using a sunshine recorder of the Campbell-Stokes type. The results are published in the "Meteorologisches Jahrbuch für Finnland" (39) and from thence the duration of sunshine in Ilmala has been calculated for this period. Fig. 16 shows this relative duration of sunshine for several months. If the values of clarity in Ilmala and Helsinki are compared (see Tables 20 and 25) it is found that these are related in the ratio of 1.00 to 1.16. Since the duration of sunshine and the clarity vary tolerably in parallel, the duration of sunshine for Helsinki can be calculated with the aid of these figures.

The durations of sunshine in Ilmala for every hour of the day for every month are therefore multiplied by the factor 1.16 and the times obtained in this way are divided by the maximum duration of sunshine which is one hour × the number of days in the month. In this way the relative duration of sunshine is obtained for Helsinki such as would have been obtained by recordings of the sunshine autograph. See Table 33.

The solar time function of the autograph is calculated according to equation 12 for each hour. The values are arranged according to the mean solar altitude (the 15th of the month) and the mean values are calculated according to the same method as was employed earlier (Page 56). These are also shown in Table 33. A curve for this solar time function ($\varkappa_a$) is drawn in on Fig. 15.

The solar time function of the autograph is constant for all solar altitudes above 25 degrees. Below this value of solar altitude it changes very quickly and a very high value is found for the solar altitude of 5 degrees. The curve gives rise to several considerations concerning the sunshine autograph. With solar altitudes above 25 degrees the intensity of the radiation changes more or less insignificantly and the greater part of the glass sphere is operative as a refracting lens. However, the lower the sun sinks, the greater the part of the glass sphere which falls in the shadow of the holder for the recording paper. An exception to this is when the sun is in the neighbourhood of the meridian, that is to say about mid-day. The solar time function for the middle of the day for all seasons shows how the autograph should function if the glass sphere were not shaded. In this case it is seen that the solar time function is constant at a value of 0.70 right down to a solar altitude of 7 degrees to 8 degrees. The average value for the whole year for low solar altitudes is however dominated by the shading error of the autograph.

A modified intensity curve can also be calculated in this case. This is obtained by multiplying the curve of intensity for the clear sky by the solar time function of the autograph. Thence are obtained the modified intensity values according to Table 34, from which is drawn in a curve on Fig. 14. Good agreement is obtained for greater solar altitudes with the corresponding curve according to *Fournol and Cadiergues* (23) but for lower solar altitudes it differs fundamentally from this. The deviation depends probably on the shading error of the autograph. The result from Paris has presumably been obtained with an autograph whose glass sphere is not shaded at low solar altitudes (universal type).

Table 34. Mean values for perpendicular radiation from the sun with clear sky (tE), solar time function of the sunshine recorder ($\varkappa_a$) and modified values of the solar radiation calculated from both ($\varkappa_a \times tE$). h is solar altitude. Unit 1 kcal/m²h.

h	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°
tE	325	475	574	640	682	711	727	744	760	777
$\varkappa_a$	1.41	0.95	0.78	0.72	0.70	0.68	0.71	0.70	0.68	0.71
$\varkappa_a \times tE$	458	451	448	461	477	483	516	521	517	552

The sunshine autograph of Campbell-Stokes type does not seem to be, in its present form, an ideal instrument for recording of duration of sunshine if the result is to be used for a detailed calculation of radiation. At the same time as it over-values the duration of sunshine for high solar altitudes up to 40 per cent, the solar radiation is shadowed for small solar altitudes so that considerable under-valuation results. This under-valuation is different for different months. During the winter when the sun is found near the meridian the glass sphere is not shadowed and consequently no under-valuation is found. Round about autumn or spring equinoxes the two ends of the autograph cards protrude beyond the holder, which causes still more shadow so that the under-valuation for these periods becomes abnormal. The values of the solar time function for these times have been put in brackets and have not been included in the calculation for the average value. If the ends of the card are cut off when they are inserted and hence the same shadowing of the glass sphere is arranged for all seasons, the result will become serviceable for the calculations of radiation. The calculation of solar radiation could then be carried out with the modified intensity curve in the same way as with the curve which is based on the mean values of clarity.

It is not possible to base a calculation of radiation on the monthly average values of the relative duration of sunshine obtained by the autograph, because in that case the solar time function for a given solar altitude would be significantly different for different months and particularly for low solar altitudes. It would be necessary to work with a solar time function particular to each month.

From the detailed values of the solar time function according to Table 33 it can be seen that the clarity during November has altogether too high a value, for the function has the value of 0.93 at mid-day (12.00 hours). This deviates obviously from the corresponding value for the other months. In the same way it can be seen that the nebulosity in March is under-valued, for the value for mid-day (12.00 hours) is only 0.60. The mean value for the other months is 0.69. The causes of the error have already been discussed above (Page 58).

Diffuse Radiation from the Sky

Lunelund has recorded the diffuse radiation on a horizontal plane in Helsinki during the years 1928—35 (57). The apparatus was an *Ångström* pyranometer (see Page 23), which was provided with a ring to screen off direct solar radiation. This was set up on the roof of the Physics Institute of the University, about 40 metres above sea level, in the same position as that where recordings of the solar radiation took place. The results have been published in the form of average values for decades of strength of radiation on a horizontal plane for each hour of the day. These are shown on Table 35. Each value in the Table is an average value of 160 recorded values (for 12.00 hours only 80 values). In the same way as for the radiation from the sun the values for the morning and afternoon have been paired. The original values have also been re-calculated and expressed in the same units. Altogether more than 35,000 recorded values are concerned.

The points which are drawn in on the diagram, Fig. 17, are obtained from these radiation strengths plotted against the solar altitude. The solar altitudes are the same as those for the calculation of the solar radiation and they have been taken from Table 28. For the calculation of the average curve the values have been arranged in groups in the same way as for the solar radiation and the mean values calculated for each group. These are shown also in Fig. 17 (rings). With aid of these a curve has been drawn which is the average curve for the year of

Table 35. Diffuse heat radiation on a horizontal plane in Helsinki. Average values for decades and every hour during the years 1928—35. Each value is a mean figure of 160 different measured values (means of 80 values for 12.00 noon). Morning and afternoon values are paired symmetrically. Unit 1 kcal/m²h.

Month Decade	True solar time									
	12	13 11	14 10	15 9	16 8	17 7	18 6	19 5	20 4	21 3
I: 1	24	21	13	4						
: 2	30	27	18	6						
: 3	50	47	30	14						
II: 1	56	56	46	25	5					
: 2	84	82	62	42	15	1				
: 3	123	99	88	63	23	3				
III: 1	120	112	98	94	44	13				
: 2	127	124	113	86	55	24	2			
: 3	146	144	125	101	71	39	10			
IV: 1	155	148	130	108	77	47	18	1		
: 2	160	168	134	107	84	56	31	6		
: 3	175	167	146	132	106	78	44	17	1	
V: 1	153	155	135	107	98	69	49	24	5	
: 2	161	155	142	123	99	80	53	29	11	
: 3	161	155	131	133	112	80	59	35	16	1
VI: 1	168	168	154	133	115	95	66	43	20	5
: 2	145	152	140	128	97	83	54	40	22	7
: 3	172	167	133	140	97	85	63	39	23	7
VII: 1	157	155	128	120	110	84	62	41	21	7
: 2	157	155	151	136	128	87	63	41	17	4
: 3	166	175	145	130	121	88	61	38	14	1
VIII: 1	156	156	139	129	98	77	44	23	7	
: 2	156	160	149	105	95	67	48	18	4	
: 3	133	140	126	102	89	58	34	9		
IX: 1	139	121	105	99	72	45	20	2		
: 2	116	130	108	93	62	35	12			
: 3	122	109	97	81	46	21	4			
X: 1	77	79	74	77	40	11				
: 2	74	79	72	46	21	4				
: 3	44	48	36	27	11					
XI: 1	53	51	33	19	5					
: 2	40	34	26	11	2					
: 3	30	28	19	6						
XII: 1	23	21	13	4						
: 2	23	20	12	2						
: 3	23	21	11	2						

Fig. 17. Curve of the diffuse heat radiation on a horizontal plane. The circles are the mean values for each group of solar altitudes. The points are the individual values from Table 35. Vertical scale in kcal/m²h, horizontal scale gives altitudes of the sun in degrees.

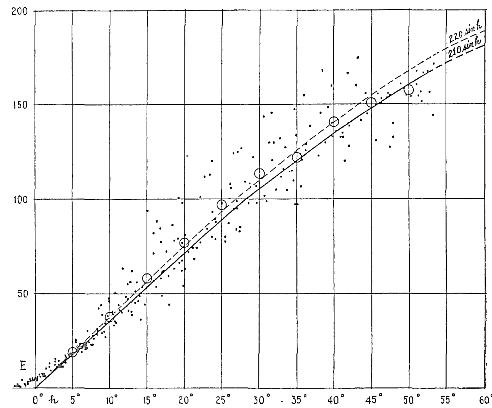
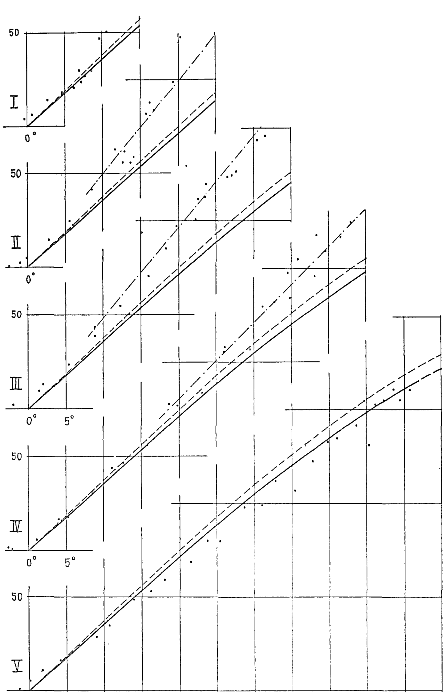
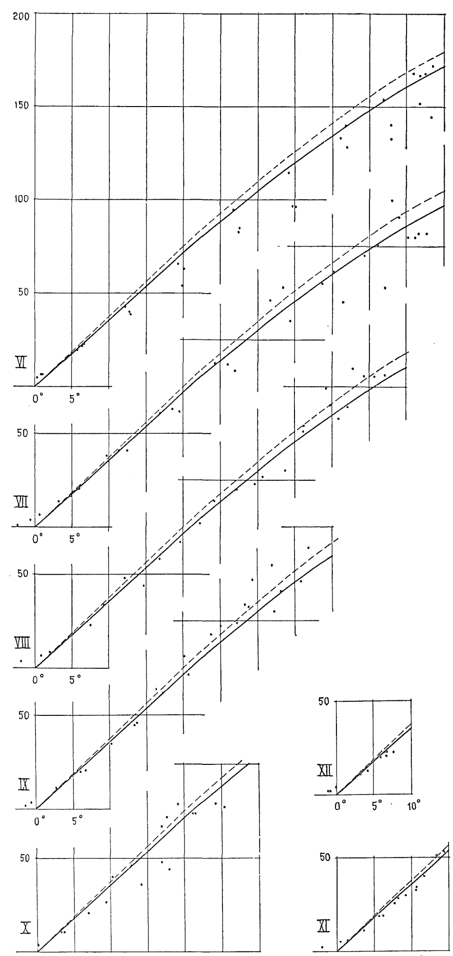


Fig. 18. Twelve figures which show how the individual values in Table 35 for each month (I—XII) are grouped around the curve $tE_{z}^{DK} = 210 \times \sin h$. Vertical scale in kcal/m²h, horizontal scale gives altitude of the sun in degrees.





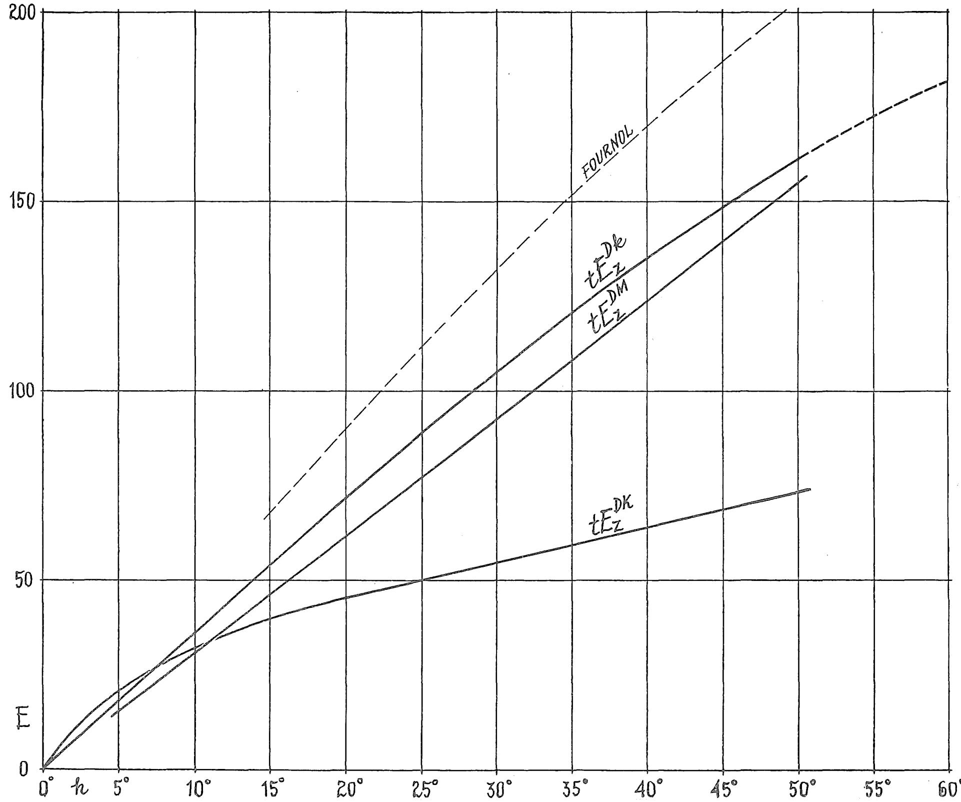


Fig. 19. Average curve for the diffuse heat radiation from the sky on horizontal plane (tE_z^{Dk}) according to equation 14, compared with Lunelund's curves for clear (tE_z^{DK}) and cloudy sky (tE_z^{DM}), see Table 5, and Fournol's curve (24).

the diffuse radiation of a horizontal plane. This curve follows fairly closely the equation:

$$tE_z^{Dk} = 220 \times \sin h \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn 13}$$

where the factor 220 is the diffuse heat radiation on a horizontal plane in kcal/m^{2}h when the sun is at the zenith, and h is the angle of altitude of the sun. If this equation is compared with the corresponding equation which *Fournol* (24) obtained from an investigation of the diffuse heat radiation in Paris, it is found that in his equation the factor 220 is replaced by a value of 264. *Fournol's* curve is drawn in on Fig. 19.

Fig. 18, I to XII, has been drawn up in order to study more closely how the values of radiation during different months are grouped around the average curve for the year. It can now be seen that the bending of the curve is due to the fact that the strengths of the radiation during February and March show greater values than the other months. January and April also show this effect to a certain degree. For each month the average curve is approximately a straight line. In February and March all the points lie above the average curve, in May to August almost all the points lie below the curve.

The cause of these yearly variations is to be sought partly in the variations of the nebulosity and partly in the influence of the snow covering during the winter. The atmospheric humidity will also have a certain influence.

The clear sky has weaker radiation than the cloudy sky, see Fig. 19. During the summer with its much clearer sky the diffuse radiation will therefore be, relatively, weaker than during autumn and spring. During the summer the atmospheric humidity is greater than during the other seasons, and this also contributes to the weakening of the radiation. During the winter lower, thicker, more absorbent types of cloud are experienced which reduce the radiation during this season.

The months in which snow is experienced in Helsinki are January, February and March. It is just these three months which show the highest values, relatively speaking, for the diffuse radiation. In February and March these values increase by as much as 40 per cent. See Fig. 18, II and III. According to the analysis by *Kalitin* (38) and *Ångström* (97) snow can influence the diffuse radiation to a considerable degree. When the sun shines from a sky with broken cloud on the snow-covered ground strong reflections result which are then reflected back by the clouds and the atmosphere, but the original radiation from the clouds can also be enhanced as a result of interreflections between the snow and the overcast sky. This is particularly the case for Helsinki when the Gulf of Finland is frozen over and the ice is covered with snow, for then up to 90 per cent reflection can be obtained from the snow-covered surface.

The reflections from the snow are however an increment which should not be in the curve that is to be used for the calculation of radiation from the sky. If the influence of the snow is eliminated the average curve follows instead the equation:

$$tE_z^{Dk} = 210 \times \sin h \quad \text{.................. eqn 14}$$

where the factor 210 is the diffuse radiation on a horizontal plane in kcal/m²h when the sun stands at the zenith, and h is the angle of altitude of the sun.

The diffuse heat radiation on a horizontal plane can be calculated with the aid of equation 14. The values of solar altitude are taken from Table 15. The result is shown in Table 36 where *Lunelund's* monthly totals are appended for comparison. It can be seen that the yearly variations pointed out above are reflected in the percentage error. This is positive during the summer and the early part of the winter, negative during the autumn and spring. The greatest deviation is met with during the snow months but no increment for the reflection of the snow has been added. No further discussion of the influence of the snow will be undertaken here.

From the points in Fig. 17 it can also be seen that at sunrise and sunset the radiation from the sky has a value of about 5 kcal/m²h. At a solar altitude of —3° the radiation is practically zero.

Global Radiation in Helsinki

The radiation which has the greatest significance from the point of view of climatic conditions is the global heat radiation on a horizontal plane from the unscreened vault of the sky. It is also this radiation which is usually recorded and this gives a good indication of which energy quantities apply to different places.

Table 36. Monthly and yearly totals of heat radiation on a horizontal plane in Helsinki during the years 1928—35 according to calculation (B), for the sun (S), for the sky (D), and global (G), compared with Lunelund's recordings (M). The percentage over-estimate (+) or under-estimate (—) are appended (diff). Latitude 60° N. Unit 1 Mcal/m².

Month		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
S	*B*	1.2	7.4	24.2	44.9	81.2	102.0	89.3	56.5	27.9	8.6	1.9	0.6	445.7
	M	1.2	7.0	27.5	45.4	76.3	97.0	88.8	56.8	30.0	10.6	1.6	0.7	445.8
	diff	0	+6	—12	—1	+6	+5	+1	—1	—7	—19	+19	—14	0
D	*B*	4.7	10.4	22.9	35.7	49.6	53.3	52.7	41.5	26.7	14.6	6.3	3.1	322.5
	M	4.8	13.0	28.9	40.4	46.3	50.8	51.1	42.1	28.1	14.5	5.3	2.5	324.2
	diff	—2	—20	—21	—12	+7	+5	+3	—1	—5	+1	+19	+24	—1
G	B	5.9	17.8	47.1	80.6	130.8	155.3	142.0	98.0	54.6	23.2	8.2	3.7	768.2
	M	6.0	20.0	56.4	85.8	122.6	147.8	139.9	98.9	58.1	25.1	6.9	3.2	770.0
	diff	—2	—11	—16	—6	+7	+5	+2	—1	—6	—8	+19	+16	0

In order to obtain the global heat radiation the method described on Pages 38—48 is employed to calculate the heat radiation from the sun on a horizontal plane with the aid of the modified curve in Fig. 14. Thence are obtained monthly totals, which are shown on Table 36. They are compared with *Lunelund's* recordings. The same percentage error will then be found which has already been discussed for the perpendicular radiation, see Page 58.

The radiation from the sun and the diffuse radiation from the sky are added. The total is the global radiation which also can be compared with *Lunelund's* recordings. It is seen that the solar radiation and the sky radiation will to a considerable extent correspond with each other during the course of the year. The exception is during the spring months when the snow results in a significant difference. If the yearly curves both for the solar radiation and the sky radiation are to be separated into two curves it would be most suitable to separate them into one curve for spring and autumn, and one curve for summer and winter. The agreement between the calculated and the measured radiation totals is, however, so good that the average curves can be accepted for the calculation of radiation.

Global Radiation in Stockholm

When this investigation was commenced into the radiation climate of Helsinki it was belived that the curves both for solar radiation and for diffuse radiation could also be applied generally to places in Sweden. This has however been found not to be the case.

If comparison is made between the recordings of heat radiation in Stockholm for the years 1935—42 and in Helsinki for the years 1928—35 it is found that the yearly totals are approximately the same for both towns, 774 and 770 $Mcal/m^2$ respectively. The clarity of the sky is however appreciably greater in Stockholm than in Helsinki, the average clarity during the year (daytime only) is 35 per cent and 28 per cent respectively. The difference between the relative duration of sunshine according to the autograph recordings is however not so great. The yearly average value is 42 per cent for Stockholm and 43 per cent (corrected value) for Helsinki during the same years as above. Consequently the solar radiation should be approximately the same for the two towns, and it also follows that this should apply to the diffuse radiation, for the diffuse radiation is rather independent of small variations in the nebulosity.

If one employs the clarity for the calculation of solar radiation it follows that the solar time function for the clarity for Helsinki cannot be used for Stockholm. This function is peculiar to Helsinki. The situation of the town on the boundary between land and water to the south gives it an unequally distributed nebulosity which influences the solar radiation to a considerable degree. The diffuse radiation may however be approximately the same in Sweden as in Finland. One can therefore without too great an approximation use equation 14 for Sweden.

If the heat radiation on a horizontal plane in Stockholm is calculated with the aid of the average curve for clear sky according to Fig. 14 and the information on nebulosity for daytime, and to this is added the diffuse radiation which was obtained for Helsinki, acceptable values can be obtained for the summer period, but an under-estimate during the winter in relationship to the recordings of radiation will be obtained, see Table 37.

If the months during which snow covers the ground are excepted, that is to say February and March, the agreement is fairly good between the calculated totals of radiation and the measured values obtained with *Aurén's* solarimeter (M2). Only October and December show a considerable deficit. The deviation from the recordings with *Ångström's* pyranometer (M1) is rather greater. There is a rather great difference between the recordings with both measuring instru-

Table 37. Monthly and yearly totals of the global radiation on a horizontal plane in Stockholm according to calculation (B) and compared with Ångström's pyranometer (M1) and with Aurén's solarimeter (M2), during the years 1935—42. The percentage over-estimate (+) or under-estimate (—) are appended (diff). No increment for the effect of snow covering has been added. Sky clarity (k) in percentage. Unit 1 Mcal/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
k_d	27	25	32	42	51	47	46	40	40	28	21	15	35
B	7.3	17.3	45.3	85.1	135.4	141.4	135.7	96.9	60.1	26.1	9.3	3.9	764.8
M1	8.3	20.3	56.4	90.3	127.3	138.0	128.0	98.8	65.2	30.2	10.0	5.3	778.1
diff	—12	—15	—20	—6	+6	+2	+6	—2	—8	—14	—7	—26	—2
M2	7.7	19.5	52.7	88.0	130.0	142.0	126.2	96.4	63.8	29.0	9.2	4.4	768.9
diff	—5	—11	—14	—3	+4	0	+8	+1	—6	—10	+1	—11	—1

ments, particularly during the winter months, where M2 shows values about 10 per cent lower than M1.

The under-estimate during the winter months for the calculated values is due partly to the fact that Stockholm lies in latitude 59° 21′ N, whereas the calculations apply to a latitude of 60° N. During the winter in these latitudes the sun stands low in the sky and small changes in the altitude result in great changes in the radiation. No greater precision during the winter time can therefore be expected.

The agreement is, however, so good that the method of calculation can be accepted. The fact that one can use *Lunelund's* average curve without any solar time function indicates that the clarity of the sky for the sun's position should be the same during the whole day. The reduction in the clarity during the midday period should be exactly compensated by the increase round about the sun at high solar altitudes. To the question as to whether or not this is a special case or has general validity, the radiation measurements which are at present being undertaken in Stockholm will gradually give an answer.

Directions for the Calculation of Radiation

Certain directions for the calculation of radiation arise from the investigations which have been carried out. Thus the statistics of nebulosity and not the autograph recordings should preferably be used for radiation calculations where there are obstructions. Illumination and erythemal radiation will therefore, in the following discussion, be calculated by means of the intensity curves for clear sky and the statistics of nebulosity.

In the case of places situated some distance from the sea or great lakes, the average intensity curve of solar radiation for clear sky can in general be used without correction. The influence of hilly terrain on the distribution of nebulosity in the sky has not been studied, but it would be advisable to expect special cloud conditions in mountainous tracts. The above therefore applies only to level country.

In the case of places lying close to the sea or great lakes, allowance can be made for the unequal distribution of nebulosity over the sky by mean of a special correction factor. The correction will be different for different orientations of the coastline: for a coast facing south the correction will be positive for the southern half of the sky, whereas for a coast facing the north it will probably be negative for the southern half of the sky. An east-facing coast will require a positive correction for the forenoon and a negative for the afternoon, while the reverse applies to a west-facing coast. Places nearer to the coast will require a correction numerically greater than places farther inland. Special studies of nebulosity must be undertaken for situations where it is suspected that inequalities in the distribution of nebulosity in the sky occur.

Calculation of Illumination

Illumination from the Sun

As has been explained above, *Lunelund* (56) has also recorded the illumination in Helsinki and *Aurén* (4, 6) has done the same in Stocksund near Stockholm. Neither of them has, however, separately recorded the sunlight and the skylight. Only on clear days have they measured the proportion of the sky illumination in the global illumination on a horizontal plane. *Lunelund* has obtained these measurements with a subjective photometer, therefore his results have been used in the analysis given below. *Aurén* made his measurements with a photocell which was provided with a blue filter. These measurements cannot therefore accord well with the spectral sensitivity of the eye and they are therefore not employed.

The monthly totals and the yearly totals which both investigators obtained from their recordings are in good agreement, see Tables 38 and 39. This would also be expected, since the heat radiations for Helsinki and Stockholm was much the same and approximately the same instrument was used for the recordings of the illumination. This gives an indication of the supposition that the solar time function for the clarity may be used also for the calculation of illumination for Helsinki but not for Stockholm.

The solar illumination is calculated here first. From Table 7 can be obtained the illumination on a horizontal plane from the sun alone, as a function of the altitude of the sun. The illumination perpendicular to the direction of the radiation can be obtained by division by sin h. These values are drawn in as a curve (vE_o^{SK}) on Fig. 20. The corresponding curve modified for the nebulosity in Helsinki ($\varkappa_k \times vE_o^{SK}$) has been obtained by multiplication with $\varkappa_k$. The former curve may be used for Stockholm and places with similar nebulosity and the latter curve for places with the same nebulosity-character as Helsinki.

Several other curves are also drawn in on the same figure for comparison. Thus the results from the measurements by *Kunerth and Miller* (44) are to be found, which were obtained in Ames (U.S.A.) and which for the greater solar altitudes lie lower than *Lunelund's* measurements, but for the lower solar altitudes lie higher. These measurements were made with a subjective photometer (Macbeth) which was provided with a filter to give a satisfactory colour match between

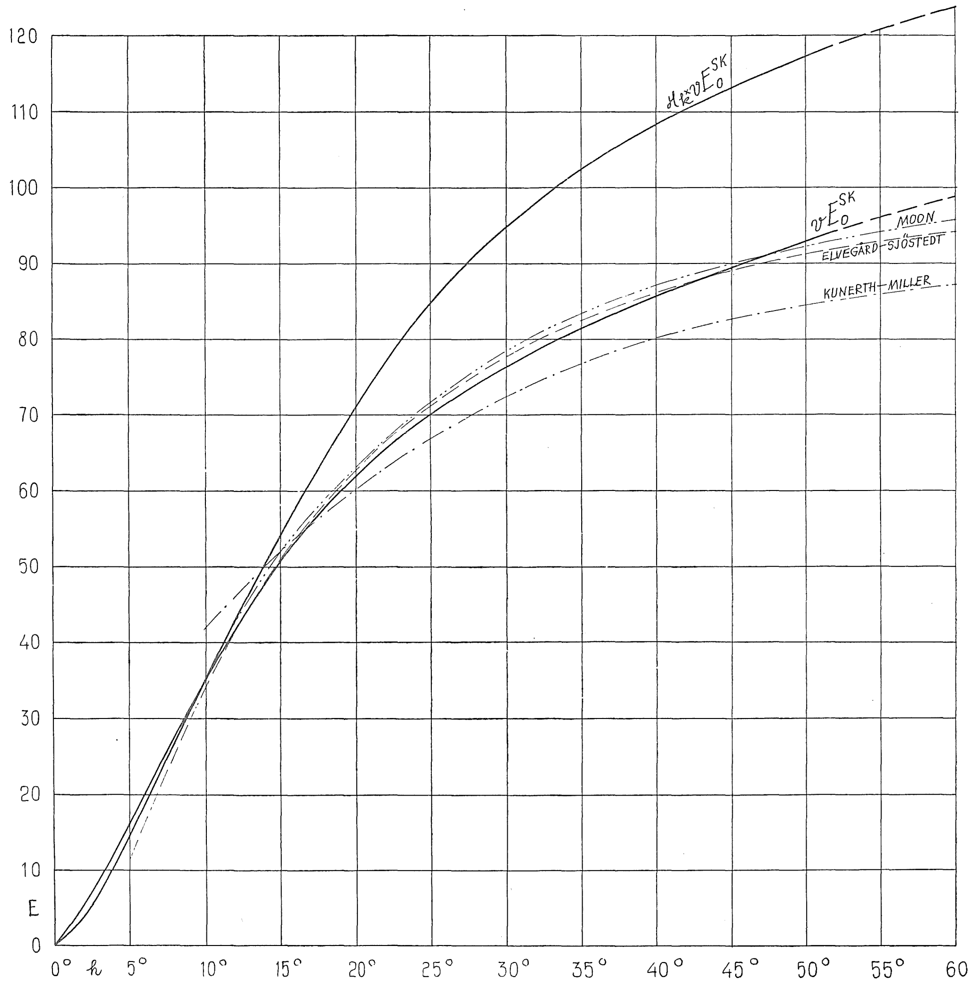


Fig. 20. Average curve for the perpendicular illumination from the sun (vE_o^{SK}) according to Lunelund (56) and the curve modified for the solar time function of clarity ($\varkappa_k \times tE_o^{SK}$), compared with the curves according to Elvegård and Sjöstedt (21), Kunerth and Miller (44), and Moon (65). Vertical scale = klx, horizontal scale = altitude in degrees.

daylight and the standard lamp, whereas *Lunelund's* measurements were obtained without the colour filter. Both these methods have their advantages and disadvantages which will explain the differences. The results are also considerably influenced by the colour vision of the observers and by the local radiation climate. *Moon* (65) and *Elvegård and Sjöstedt* (21) made calculations which agree well with *Lunelund's* measurements. The former of these are entirely independent but the latter are based on these measurements.

With the aid of both curves on Fig. 20 the illumination from the sun on a horizontal plane can now be calculated both for clear and cloudy skies in Helsinki and Stockholm. The solar altitude for latitude 60° N can be obtained from Table 15 and in the same way as described on Pages 38—48 the monthly totals and yearly totals of the illumination have been calculated. The percentage clear sky has been calculated for daytime during the months when the registrations were obtained in both towns. The results are shown on Tables 38 and 39.

Illumination from the Sky

As has been explained above there are no separate recordings of the illumination from the sky alone for northerly latitudes. *Kalitin* (38) has indeed obtained recordings in Slutsk (near Leningrad), but the results have not been worked out in a suitable form for these studies.

Pleijel (72) has performed, with the aid of *Lunelund's* recordings, the calculation of the diffuse illumination from the sky. The mean value of nebulosity for the whole 24-hour period was however used for this study, including time of darkness. This calculation showed, however, that the mean value of diffuse illumination is to a great extent almost independent of the nebulosity. If the nebulosity changes from 50 per cent to 80 per cent the illumination falls for high solar altitudes by 7 per cent and for low solar altitudes by 15 to 25 per cent. For the calculation a curve can be used to a reasonable degree of approximation which follows the equation:

$$vE_z^{Dk} = 575 \times h \quad \ldots\ldots\ldots\ldots \text{eqn 15}$$

where vE_z^{Dk} is the mean value of the diffuse illumination from the sky on an unobstructed horizontal plane with prevailing clarity k, expressed in lux, with solar altitude h.

Illumination recordings have been obtained in England by *McDermott and Gordon-Smith* (20) at the National Physical Laboratory at Teddington (near London). See also Page 29. The results are expressed in the form of mean values, for each month and each hour of the day, of the illumination on an unobstructed horizontal plane. The values are faired out in such a way that the irregularities in the recordings do not appear. An average curve has been constructed by the same method as was used for heat radiation from the sky (see Page 67). This appears to be a straight line according to the equation:

$$vE_z^{Dk} = 556 \times h \quad \ldots\ldots\ldots\ldots \text{eqn 16}$$

The notation is the same as for equation 15.

The nebulosity at Teddington (8) is certainly not the same as that in Helsinki or Stockholm. The average nebulosity is about 70 per cent during the year in all

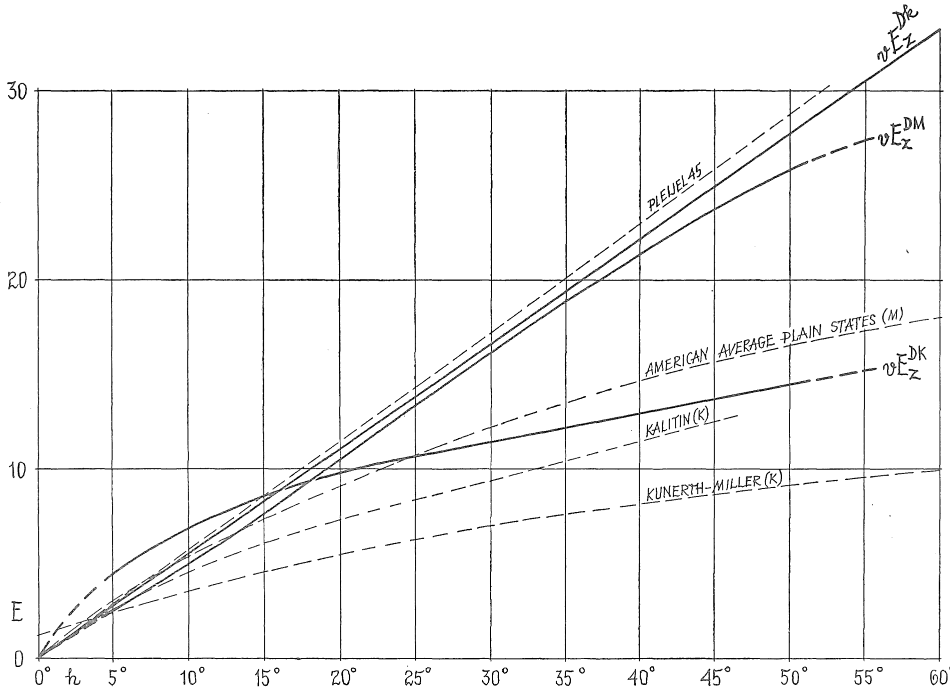


Fig. 21. Curves showing the diffuse illumination from the sky on a horizontal plane according to measurements obtained by McDermott and Gordon-Smith (20) (vE_z^{Dk}), compared with calculation by Pleijel (72), measurements by Lunelund (56) for clear sky (vE_z^{DK}) and for overcast sky (vE_z^{DM}), Kalitin for clear sky (38), Kunerth and Miller (44) for clear sky and American average curves for overcast sky for Plain States (34). Vertical scale = klx, horizontal scale = altitude in degrees.

three places but the distribution of nebulosity over the year is significantly different at Teddington. The extremely low solar altitudes and the high values of nebulosity which are characteristic of the North never come into the expression in equation 16.

Equations 15 and 16 show good agreement. They are both drawn in as curves on Fig. 21 where they can also be compared with the results of several other measurements. *Lunelund's* values (56) for the cloudy sky lie insignificantly below equation 16 while the curve for the clear sky lies above that for low solar altitudes (0 to 15 degrees) and below that for high solar altitudes (greater than 15 degrees). For solar altitudes of 50 degrees it is only half of equation 16. *Kalitin's* measurements (38) for cloudy sky are in good agreement with *Lunelund's* while the values for clear sky are somewhat lower. *Kunerth and Miller* (44) obtained much lower levels of illumination for the clear sky. See also Page 30. American average values (34) are also significantly lower than eqn 16, and below 45° solar altitude about the same for clear and cloudy sky.

Table 38. Monthly and yearly totals of the illumination on a horizontal plane in Helsinki during the years 1929—33 according to calculation (B), for the sun (S), for the sky (D), and global (G), compared with Lunelund's measurements of the global illumination (MG). The percentage over-estimate (+) or under-estimate (—) are appended (diff). Sky clarity (k) in percentage. Unit 1 Mlxh.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
k %	11	27	29	31	39	46	43	33	26	20	15	15	28
S	0.07	0.73	2.26	4.79	8.80	11.96	10.48	5.96	2.65	0.80	0.15	0.04	48.69
B *D*	0.71	1.54	3.53	5.76	8.12	8.97	8.65	6.51	4.31	2.23	0.93	0.43	51.69
G	0.78	2.27	5.79	10.55	16.92	20.93	19.13	12.47	6.96	3.03	1.08	0.47	100.38
MG	0.59	2.19	6.60	10.30	16.32	19.77	18.87	12.85	7.48	3.21	0.82	0.38	99.38
diff	+32	+4	—13	+2	+4	+6	+1	—3	—7	—6	+32	+24	+1

Table 39. Monthly and yearly totals of the illumination on a horizontal plane in Stockholm during the years 1928—37 according to calculation (B), for the sun (S), for the sky (D) and global (G), compared with Aurén's measurements of the global illumination (MG). The percentage over-estimate (+) or under-estimate (—) are appended (diff). Sky clarity (k) in percentage. Unit 1 Mlxh.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
k %	18	25	35	34	47	48	43	37	35	25	17	15	32
S	0.12	0.57	2.44	4.34	8.82	10.08	8.67	5.62	3.05	0.93	0.18	0.05	44.9
B *D*	0.71	1.54	3.53	5.76	8.12	8.97	8.65	6.51	4.31	2.23	0.93	0.43	51.7
G	0.83	2.11	5.97	10.10	16.94	19.05	17.32	12.13	7.36	3.16	1.11	0.48	96.6
MG	0.93	2.47	6.55	10.00	16.73	19.23	18.26	13.75	8.29	3.63	1.09	0.52	101.4
diff	—15	—14	—9	+1	+1	—1	—5	—12	—11	—13	+2	—8	—5

If equation 16 and equation 14 are combined the luminous efficiency of heat radiation is obtained, which varies between 150 lmh/kcal for low solar altitudes and 170 lmh/kcal for high solar altitudes. These values agree well with the luminous efficiency which is obtained for clear and cloudy sky, that is 180 and 150 lmh/kcal respectively, see Pages 30—33.

It seems perhaps peculiar that the yearly average illumination from the sky is stronger than that for both clear and overcast sky. This is explained by the reflected light which comes from the edges of the clouds. The reflection factor of cloud is fairly high, about 70 per cent, and the reflected sunlight contribution is therefore significant.

With the aid of equation 16 the mean monthly values of the illumination on a horizontal plane from the sky can be calculated. Since this illumination is almost independent of the clarity for the limits which are under consideration, a single curve can be used for all months. The relevant solar altitudes for the 60° N parallel of latitude can be obtained from Table 15 and the illumination levels for each hour can be read off from Fig. 21. The monthly totals and the yearly totals have been calculated for Helsinki and Stockholm. These will be the same, as no consideration is taken of the differences in nebulosity. The results are shown on Table 38 and 39.

Global Illumination in Helsinki and Stockholm

If the illumination from sun and sky are added the global illumination is obtained. This can be compared with *Lunelund's* own calculations of the monthly totals and a yearly total from the recordings at Helsinki. See Table 38. The agreement is good for all months except during winter. November, December and January show a considerable over-estimate. It is not so surprising that March shows an under-estimate of 13 per cent since no increment for snow conditions has been made.

Regarding the under-estimate during winter the following can be said. The recordings comprise only a five year period. It is very possible that during such a short period of time extreme circumstances will be met with which will upset the results. It is also likely that the nebulosity will influence also the mean value of the illumination. A nebulosity of 10 does not always mean the same thing as is obvious from *Kalitin's* investigation (38). Different types of cloud have a fundamentally different influence on the illumination. See Table 8.

The calculated illumination yearly total for Stockholm shows an under-estimate of 5 per cent, which is too great. If the different monthly values are inspected it is found that all the months except three show an under-estimate. It would appear therefore as if some systematic error is occurring. This can be sought for example in the type of unit (the E_s-unit) which both *Lunelund* and *Aurén* used for expressing their results. *Lunelund* has himself expressed his E_s-unit in lux but *Aurén* has not done this. In the determination of this unit a subjective factor enters, that the sky shall be fully clear. What is meant by a fully clear sky can be a subject for discussion. The turbidity of the atmosphere, which varies from day to day, plays a considerable part in the establishment of the unit. Other errors can also arise, for example, the influence which the nebulosity certainly has on the diffuse radiation from the sky. The difference between the apparatus used for the recordings can also have an influence. See Table 37, M1 and M2. A good agreement is obtained if the recorded monthly totals by *Aurén* are all reduced by 5 per cent.

The calculated values show, however, such a good agreement that the calculation method can be accepted. For Helsinki the curve for the illumination from the sun modified for the clarity of the sky should be used but for Stockholm *Lunelund's* curve for clear sky can be used directly. For the illumination from the sky the common curve according to equation 16 and Fig. 21 can be used.

Luminous Efficiency

By means of the calculations of heat radiation and illumination which have been performed above, the luminous efficiency of radiation for different months and for the year as a whole can be calculated. A computation has been made, therefore, of the illumination from the sun for the years 1928—35 using the values of clarity which are to be found in Table 20, Page 43. Table 40 has been derived by dividing the illumination totals by the totals of heat radiation.

Table 40. Luminous efficiency (v/t) of radiation from the sun (S), the prevailing sky (D), and the mean global radiation (G) on a horizontal plane. Helsinki 1928—35. Unit 1 lmh/kcal.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
S	67	89	100	107	111	112	113	105	106	91	74	50	108
D	151	148	154	161	164	168	164	157	161	153	148	139	160
G	134	124	126	131	131	131	132	127	133	130	130	124	130

It can be seen from this table that the luminous efficiency of global radiation can be taken to be effectively constant throughout the year, with an average value of 130 lmh/kcal, despite the fact that both the solar and sky radiation have a lower luminous efficiency during winter than during summer.

If a comparison is made between the luminous efficiency of global radiation according to the table, and *Lunelund's* own values according to Table 9, it will be found that there are differences in the winter values. This derives partly from the fact that there is a considerable overvaluation of the illumination which is obtained in winter according to Table 38 and which cannot be explained other than as due to random low values being recorded during the short recording period. It is, however, not due to any rule that the luminous efficiency of global radiation should be constant throughout the year, but rather a chance occurence for Helsinki. The greater the amount of direct solar radiation which is included in the global radiation, the lower will be the luminous efficiency, and the less the solar radiation, the higher the luminous efficiency. This is particularly the case in winter when the luminous efficiency of solar radiation is low, and less pronounced in summer, when it is relatively high.

Calculation of Erythemal Radiation

Radiation in Washington

For many years experiments have been made at the National Bureau of Standards in Washington to measure and record the erythemal radiation from sun and sky with several different types of photocell. See Pages 34—35. These investigations were undertaken by *Coblenz and Stair* (13, 15, 16). The results are expressed in absolute units (watts per area). A study has been made here with the aid of the published results to develop diagrams of the erythemal radiation from the sun and the sky separately, expressed as a function of the solar altitude, similar to those which were developed for the heat radiation and the illumination.

This radiation under consideration here is that in the region UV-B and has a wave-length of 3,132 Å as an upper boundary. One of the uses to mankind of this radiation is the erythemal effect (sunburn) on the human skin, another virtue is the formation of vitamins in the skin. See Pages 14—15. The energy quantities are extremely small. At a solar altitude of 45 degrees the erythemal radiation on a horizontal plane is about 0.5 watts per square metre while the total radiation (heat radiation) is about 500 watts per square metre, that is to say about a thousand times greater.

Table 12, Page 35, gives the information of the global erythemal radiation on a horizontal plane on fully clear days. These should however be considered as extreme maximum values. The corresponding solar altitudes have been obtained from a solar chart for latitude 40 degrees North (not shown here). On a diagram, see Fig. 22, the corresponding points have been drawn in for these levels of radiation and solar altitude. An approximate indication can be obtained therefore from which can be drawn an approximate curve relating the erythemal radiation as a function of the solar altitude.

Since the global radiation is only found in the form of monthly totals, a method of adjustment must be used, that is to say, by means of repeated calculations with curves giving the radiation strength which can be rectified bit by bit, one can obtain a calculated result in agreement with the recordings. Measurements are available of the perpendicular erythemal radiation from the sun alone, but

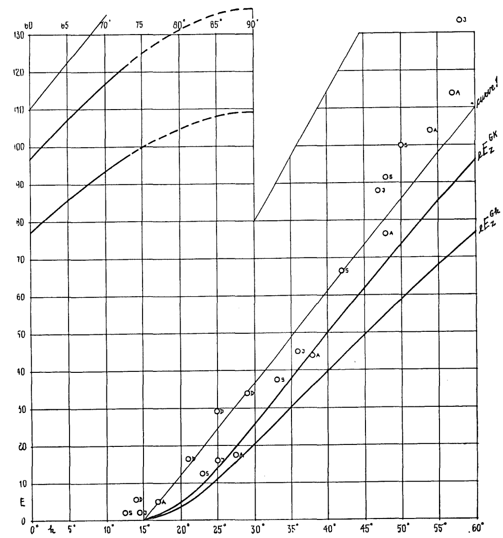
Table 41. Clarity of the sky (k_d) in Washington, average values for the years 1941—43, and corresponding relative erythemal radiation (eR), global erythemal radiation on a horizontal plane according to recordings (Reg), and according to calculation with the adjusted curve eE_z^{GK} (Ber), and ratio of the two latter (Reg/Ber). Unit 1 Wh/m² and percent.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
k_d %	45	51	45	40	46	44	44	54	56	48	53	42	47
eR %	78	82	78	75	79	78	78	84	85	80	83	76	80
Reg	20.5	39.3	76.8	123.1	171.7	192.1	178.7	165.8	122.7	63.6	30.1	14.2	1,198.6
Ber	27.0	52.4	113.2	168.0	221.7	237.0	233.1	191.3	129.6	74.4	33.6	18.0	1,499.3
Reg/Ber %	76	75	68	73	77	81	77	87	95	85	90	79	80

these also apply to particularly clear days and they can therefore only give an indication of how the mean curve for the solar radiation appears.

The nebulosity in Washington is fairly constant during the year and this assists in the adjustment. Table 41 shows the average values for the clarity of the sky ($k = 100 - m$) during the year in which the recordings were obtained. The information is taken from the United States Weather Bureau (64). The average value of the clarity during the year is 47 per cent. According to Fig. 6 the relative erythemal radiation is 0.80 at this clarity, that is to say, the global radiation on a horizontal plane is 80 per cent of the corresponding radiation for a completely clear sky. This means that the monthly totals according to Table 41 (Reg) should be 80 per cent of the corresponding totals for a clear sky. A curve will therefore first be sought which gives the monthly totals 25 per cent greater than those which are shown in Table 41 (Reg).

To begin with, a straight line was drawn from radiation 0 with 15 degrees solar altitude. This has been marked "curve 1" on Fig. 22. For 15 degrees solar altitude the erythemal radiation from sun and sky may as a rule be considered to be zero. The points in the diagram show a radiation also for some solar altitude less than 15 degrees but they should be considered as extreme values. The line was drawn in the direction of the points. With the aid of this curve the erythemal radiation on a horizontal plane has been calculated for a clear sky. For the greater part of the year the radiation totals were much too great. After this result the radiation curve was rectified and new calculations were carried out. The curve which is marked eE_z^{GK} was obtained after some calculations. When this curve is used for the calculation for Washington, a relative erythemal radiation $eR = 0.80$ is obtained. See Table 41. The different monthly values show relative radiations (Reg/Ber), which to a considerable degree agree with the values which were obtained from the mean values of the sky clarity (*eR*). The calculated radiation shows an over-estimate during spring and an under-estimate during



Fig, 22. Calculation of the global erythemal radiation on a horizontal plane according to recordings in Washington 1941—43. The points are the global radiation on a horizontal plane on some selected days when the sky was very clear, one day respectively during December (D), April (A), June (J) and September (S). Values for corresponding hours before and after noon have been paired together, see Table 12. Curve 1: rectlinear curve drawn from the point at solar altitude 15° where the radiation = 0 to pass through the points. Curve eE_z^{GK}: curve giving the average for the year of the global radiation on a horizontal plane with clear sky. Curve eE_z^{Gk}: curve giving the average for the year of the global radiation on a horizontal plane with the prevailing nebulosity in Washington 1941—43. Vertical scale in $\mu W/cm^2$, horizontal scale gives altitude of the sun.

autumn. This is in complete agreement with the observations in Washington and is connected with the ozone content of the atmosphere. See Page 17.

Curve eE_z^{GK} is reduced to 80 per cent, from whence a new curve is obtained marked eE_z^{Gk} in Fig. 22. This is a mean curve for the year for the global erythemal radiation on a horizontal plane for the prevailing clarity in Washington 1941—43. The part which originates from the sun will now be separated from the part which originates from the sky.

Radiation from the Sun

Luckiesh, Taylor and Kerr (54) have investigated the relationship between the radiation from the sun and the radiation from the sky with a clear sky. Their results agree to a considerable extent with similar investigations by *Coblenz and Stair* (16). Fig. 7 shows a curve giving that proportion of the global erythemal radiation on a horizontal plane with a clear sky for which the sky is responsible, derived from these investigations. These values for every fifth degree of solar altitude are shown in Table 42. In the same Table can be found also the global erythemal radiation on a horizontal plane with clear sky, according to curve eE_z^{GK} in Fig. 22. From these values the diffuse radiation with a clear sky is calculated, and by subtracting these values from the global radiation the solar radiation is obtained similarly as an average value for clear sky. The perpendicular radiation from the sun is obtained by dividing the horizontal value by sin h.

Table 42. Average values of the erythemal radiation on a horizontal plane with clear sky and different solar altitudes (h). GK = global radiation, DK = diffuse radiation from the sky, DK/GK = ratio of the two latter, SK = solar radiation. SK_o = = average value of the perpendicular erythemal radiation from the sun alone, with clear sky. Unit 1 $\mu W/cm^2$.

h	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°
GK	0.0	4.5	14.0	25.5	38.0	50.0	62.0	73.5	85.5	96.5	107.0	116.5	125.0
DK/GK		91	85	80	75	70	66	62	58	55	53	51	50
DK	0.0	4.1	11.9	20.4	28.5	35.0	40.9	45.6	49.6	53.1	56.7	59.4	62.5
SK	0.0	0.4	2.1	5.1	9.5	15.0	21.1	27.9	35.9	43.4	50.3	57.1	62.5
SK_o	0.0	1.2	5.0	10.2	16.6	23.3	29.8	36.4	43.8	50.1	55.5	60.7	64.7

Table 43. Yearly average values of the erythemal radiation on a horizontal plane with prevailing clarity at Washington 1941—43. Gk = global radiation, Sk = solar radiation, Dk = diffuse radiation from the sky. Unit 1 $\mu W/cm^2$.

h	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°
Gk	0.0	3.6	11.2	20.4	30.4	40.0	49.6	58.8	68.4	77.2	85.6	93.2	100.0
Sk	0.0	0.2	1.0	2.4	4.5	7.1	9.9	13.1	16.9	20.4	23.6	26.8	29.4
Dk	0.0	3.4	10.2	18.0	25.9	32.9	39.7	45.7	51.5	56.8	62.0	66.4	70.6

The curves for the erythemal radiation from the sun have been drawn in on Fig. 23. On the same figure can be found also several measurements obtained by *Coblenz and Stair* (13,15). These investigators have found that with a solar altitude of about 28 degrees the perpendicular erythemal radiation from the sun is 12 $\mu W/cm^2$ and at a solar altitude of 73 degrees it is 75 $\mu W/cm^2$. These solar altitudes are met with during clear days in Washington at noon round about the winter and summer solstices. These values are to be considered as mean maximum values and the curve for the perpendicular erythemal radiation should lie directly below them, which it also does. Two curves have also been drawn in giving the perpendicular erythemal radiation during clear days as obtained from the measurements during the years 1934 and 1935. The derived curve agrees very well with these and it lies directly below them. This therefore may be to a considerable degree correct.

Radiation from the Sky

The average values of the global erythemal radiation on a horizontal plane for the prevailing clarity is obtained by means of the curve for a clear sky multiplied by 0.80, which equals the relative radiation for the year. It is now assumed that

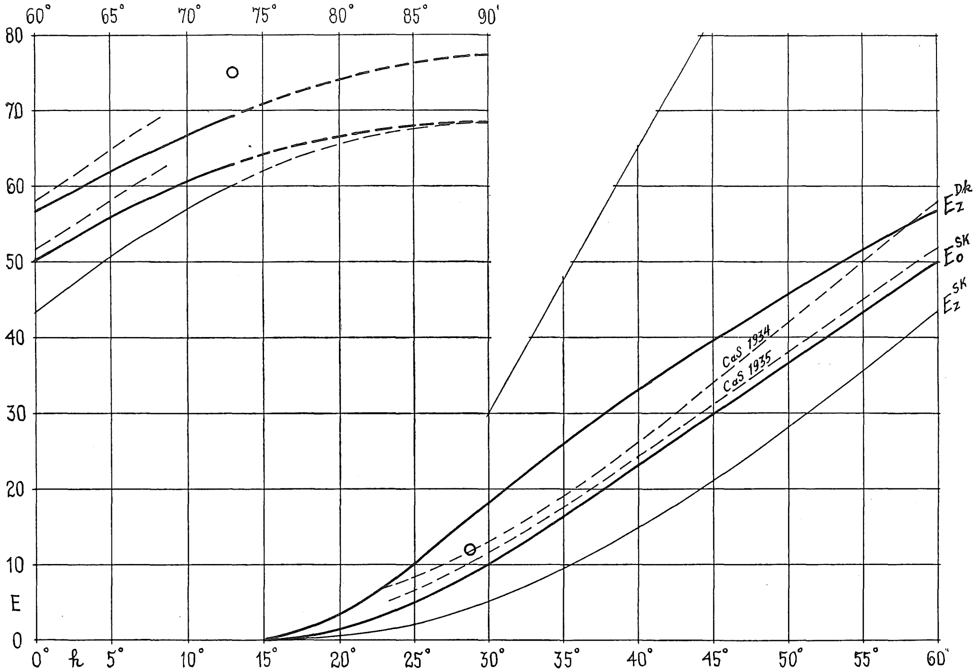


Fig. 23. Average curves for the year of the perpendicular (eE_{o}^{SK}) and the horizontal (eE_{z}^{SK}) erythemal radiation from the sun, with a clear sky, and also the diffuse erythemal radiation on a horizontal plane (eE_{z}^{Dk}). For comparison purpose two points and two curves are also drawn in, which show the perpendicular erythemal radiation from the sun during very clear days according to measurements in Washington by Coblenz and Stair (13,15). Vertical scale in $\mu W/cm^2$, horizontal scale gives the altitude of the sun in degrees.

the relative duration of sunshine, as a mean for every month, is uniformly distributed over the theoretical time of sunshine, which according to the calculations on Page 74 was probable for Stockholm and probably also applicable to Washington. This latter town lies sufficiently far from the coast for the influence of the sea not to make itself felt significantly, the terrain is to a considerable degree flat and the mountains in the west lie at such a distance that they cannot have any influence on the distribution of the nebulosity in the sky over the town. The erythemal radiation on a horizontal plane from the sun only, with clear sky, see Table 42, is therefore multiplied by the yearly mean value for the clarity = 0.47. Thence the yearly mean value of the erythemal radiation on a horizontal plane from the sun with prevailing clarity is obtained. These values are subtracted from the global radiation for the prevailing clarity, see Table 43, whence the average value for the year of the diffuse radiation on a horizontal plane for different solar altitudes is obtained. A curve for the diffuse radiation has been drawn on Fig. 23.

Table 44. Monthly and yearly totals of erythemal radiation on a horizontal plane with prevailing clarity in Washington 1941—43. B = calculated, Sk = solar radiation, Dk = diffuse radiation from the sky, Gk = global radiation, MG = global radiation according to the measurements, and diff = percentage over- (+) or underestimate (—) in calculation relative to the measurements. Unit 1 Wh/m².

Month		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
B	*Sk*	1.8	6.3	16.1	25.3	41.6	43.8	42.4	40.3	24.5	9.4	3.2	1.0	155.7
	Dk	19.5	37.0	75.3	106.8	137.3	144.9	143.2	120.6	84.6	51.2	24.3	13.6	958.3
	Gk	21.3	43.3	91.4	132.1	178.9	188.7	185.6	160.9	109.1	60.6	27.5	14.6	1,214.0
MG		20.5	39.3	76.8	123.1	171.7	192.1	178.7	165.8	122.7	63.6	30.1	14.2	1,198.6
diff		+4	+10	+19	+7	+4	—2	+4	—3	—11	—5	—9	+3	+1

Global Radiation and Check on the Curves

The curves on Fig. 23 of the erythemal radiation on a horizontal plane from the sun and from the sky can be checked by calculation of the sun radiation and the diffuse radiation separately. Thus the monthly totals for a clear sky of the radiation from the sun have been calculated, and multiplied by the monthly average values of the clarity. To these values have been added the monthly totals for the diffuse radiation. The monthly totals are added together to give a yearly total. See Table 44. This calculation has been made according to the method which has been described on Pages 38—48.

The global erythemal radiation on a horizontal plane calculated in this way is now compared with the recorded totals and they show certain differences. As would be expected the deviations are positive during spring, greatest in March (+19 per cent) and negative during the autumn, greatest in September (—11 per cent). The yearly variations are to be ascribed to the ozone content of the atmosphere, which, according to what has already been said, is greater during the spring than during the autumn.

The erythemal radiation in Cleveland has also been calculated in the same way as above but with the local clarity values. The clarity values are the mean figures for the same year as *Luckiesh, Taylor and Kerr* obtained their recordings, see Page 36. In order to be comparable, however, the calculations must be expressed in biological units.

According to measurements of the sensitivity of the skin to ultra-violet radiation with wave-lengths less than 3,132 Å carried out by *Coblenz and Stair* (16), MPE = 0.35 Wh/m², see Page 34. The monthly totals can be converted according to this factor from Wh/m² to MPE and then compared directly with the recordings. See Table 45. The calculated values show a considerable underestimate for all months except February. The yearly total is 19 per cent lower than

Table 45. Monthly and yearly totals of the global erythemal radiation on a horizontal plane with prevailing clarity in Cleveland during the years 1935—38 and 1940—41. k = clarity of the sky, B = calculation, M = measurement, diff = percentage over- (+) or under-estimate (—) in the calculated values in relation to the measurements. Unit MPE.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
k %	16	22	32	38	48	44	57	50	47	40	27	15	
B	59	115	252	380	495	547	575	458	305	171	75	41	3,473
M	77	108	273	420	645	714	714	579	416	215	83	45	4,289
diff %	—23	+6	—8	—10	—23	—23	—19	—21	—27	—20	—10	—9	—19

the measurements. The distribution of the deficit suggests a fundamental error. The most obvious source of error is that introduced by the conversion from Wh/m^2 to MPE. It is difficult to establish the biological factor, for it is a characteristic of the individual and can vary very considerably with the state of health. Furthermore the conversion factor can be only guessed between two neighbouring values, the greater with the observed erythemal effect and the lesser without the observed effect. *Coblenz and Stair* give their results in the form of such limits, which often show a difference of about 40 to 50 per cent. In order to obtain a conversion figure an average value must be calculated and it is clear that this is liable to a considerable uncertainty. No greater number of determinations of the MPE have been published.

It is also risky to calculate the conversion factor according to the erythemal curve for the spectral distribution of the radiation is not known in detail. For such calculations see *Ronge* (79).

Local factors can be considered to have an influence, for example, the nebulosity and the dust content in the atmosphere. The photo-cells which were used in the two series of recordings were different and for the recordings in Cleveland ultra-violet radiation with longer wave-length than 3,132 Å was also included. The sensitivity curve showed an upper limit around about 3,340 Å see Fig. 8. The answer to the questions about the error can only be given through a detailed study of the recordings in Cleveland.

Radiation in Stockholm and Helsinki

If it is assumed that the curves in Fig. 23 apply also to the atmospheric conditions of the North, the erythemal radiation can be calculated for Stockholm and Helsinki. It was established from the results of an Artic expedition up to latitude 78 degrees North that the erythemal radiation for northern latitudes is approximately the same as in Washington with a comparable solar altitude. The results are described in detail by *Coblenz, Gracely and Stair* (14).

Table 46. Monthly and yearly totals of the erythemal radiation on a horizontal plane with prevailing clarity in Stockholm during the years 1928—37. k = clarity of the sky, Sk = solar radiation, Dk = diffuse radiation, Gk = global radiation, Dk/Gk = = percentage diffuse radiation of the global radiation. Unit 1 Wh/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
k %	18	25	35	34	47	48	43	37	35	25	17	15	
Sk	—	0.1	1.8	7.7	22.7	29.5	23.9	11.7	3.3	0.2	—	—	100.9
Dk	—	2.0	21.7	60.9	100.4	116.4	110.1	76.6	33.3	5.3	—	—	526.7
Gk	—	2.1	23.5	68.6	123.1	145.9	134.0	88.3	36.6	5.5	—	—	627.6
Dk/Gk %	—	95	92	89	82	80	82	87	91	96	—	—	84

Values for Helsinki during the years 1928—35 gave *Sk* = 12 %, *Dk* unaltered, and *Gk* = 2 % greater values.

The calculation of the erythemal radiation in Stockholm is obtained according to the method described on Pages 38—48. The solar altitude is obtained from Table 15 and the radiation values from Fig. 23. The result is shown in Table 46. It can be seen from this Table that during 3 (—5) months (October to February) practically no erythemal radiation is received at latitude 60° N. The yearly total is about half that of the radiation for latitude 40° N. During the summer the former is up to 75 per cent of the radiation for the latter latitude.

In the case of Helsinki it is not necessary to employ or construct any modified curve as was done for heat and light radiation. A multiplication factor can be employed with a good result. This is established from the solar time function of the clarity according to Fig. 15 for the regions where erythemal radiation is received. For a solar altitude below 15 degrees practically no radiation is received and between 15 degrees and 25 degrees it is very weak, see Fig. 23. Above 25 degrees solar altitude it varies markedly and from this solar altitude up to 53.5 degrees the solar time function must be employed. The mean value between these two solar altitudes is 1.25. The calculation requires therefore that the radiation with clear sky should be multiplied by 1.25, that is to say an increment of 25 per cent should be applied because of the unequal distribution of cloud in the sky.

It can also be observed that on the average 84 per cent of the erythemal radiation comes from the sky and only 16 per cent directly from the sun. This shows that from the point of view of erythemal radiation it is of no consequence whether the facades of houses are orientated towards the north or the south. Calculations for a vertical surface with or without screening may indicate if this is indeed the case. Such calculations are not carried out here.

For Helsinki the erythemal radiation is obtained by means of a 25 per cent increment to the solar radiation with a clear sky. Because of lesser clarity in the sky in Helsinki this causes only 12 per cent increase in relation to Stockholm. The erythemal radiation from the sky will be the same and the yearly total will be 2 per cent greater than for Stockholm, a relatively little difference. The yearly total of the erythemal radiation on a horizontal plane in Stockholm is, according to the table, 627.6 Wh/m^2, which according to the conversion factor 1 MPE = = 0.35 Wh/m^2 gives a yearly total of 1,792 MPE. *Ronge* (79) obtained a yearly total of 2,250 MPE from his calculations. The agreement is therefore good in view of the fact that *Ronge* used the maximum values in his calculations and made only an approximate estimate of the influence of the nebulosity.

Calculation of Duration of Solar Radiation

It is, as a matter of fact, out of the question to establish numerically the duration of solar radiation in a town, for the screening objects, houses, trees, terrain etc. have often a very complicated form, particularly in the centre of a town and in parks. The terrain formation in mountainous areas is also very irregular. A graphical method such as that which is described below is therefore to be preferred.

Solar Chart

The solar chart shows graphically the path of the sun over the sky. See Fig. 24. The solar paths, one for the winter solstice, one for the summer solstice and five for the different spring and autumn months paired together, are graduated on a scale of hours so that for every hour of the day it is possible to read off the exact position of the sun in the sky vault.

Such nomograms of the sun's path in the sky are available in many varieties and they have been in use for a long time for the calculation of solar radiation duration. Only a few of the different types have been given in the bibliography here (22, 48, 63, 71, 72, 87, 95). The older forms of nomogram have, however, been more and more supplanted by more practical types. The stereographic projection is today considered to be the best method of presenting the path of the sun in the sky. According to this method of projection the solar chart is radial, which facilitates the employment for the investigation of orientation. The relative accuracy of the diagram is approximately the same for reading off the lowest solar altitudes and the highest. They are graphic in the same way as star maps of a familiar type.

It is of advantage to use a graphical method to derive these solar charts. The stereographic projection, known and employed by astronomers from antiquity, permits the solar paths to be laid out on a plane surface with the aid of a compass and a ruler. It is, however, unnecessary to go into the geometry of this projection method. The following discussion will deal only with what is necessary for a clear understanding of the derivation. The solar charts are fundamental in all calculations of radiation in towns and houses and therefore it has been con-

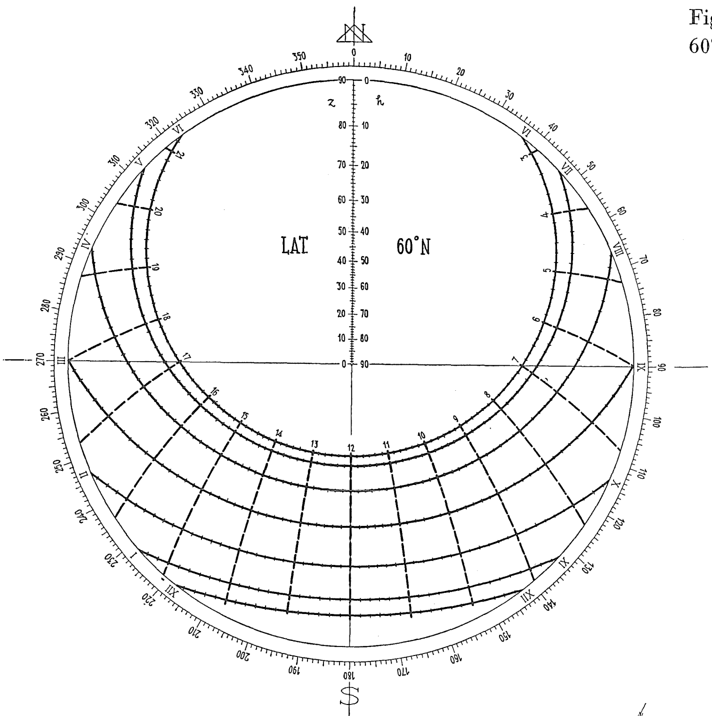
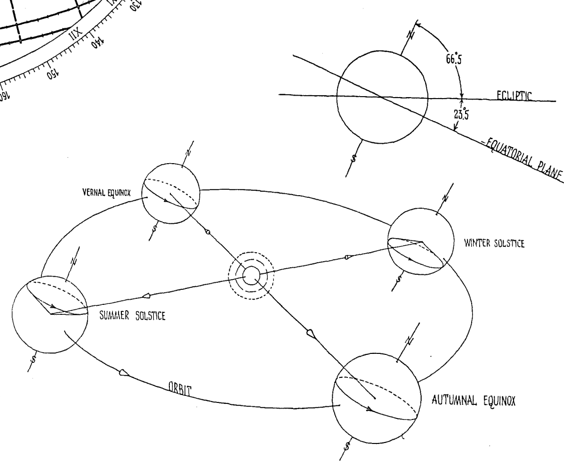


Fig. 24. Solar chart for latitude 60°N.

Fig. 25. The earth revolves once every year round the sun, and rotates on its axis once every twenty-four hours.



sidered necessary to give a short description of the astronomical relations of the sun and the earth.

The earth revolves once yearly around the sun. The orbit is slightly elliptical but for the derivation of the solar charts it is assumed that the orbit is circular. Notice of the eccentricity can be taken in the form of a correction which will be described below. The earth's orbit lies in a plane through the sun which is called the ecliptic. The axis of the earth is inclined at a constant angle of 66.5 degrees with the ecliptic and it is always directed towards the same point of the sky, i.e. the Pole Star. The axis of the earth therefore performs a parallel movement as the earth revolves. See Fig. 25.

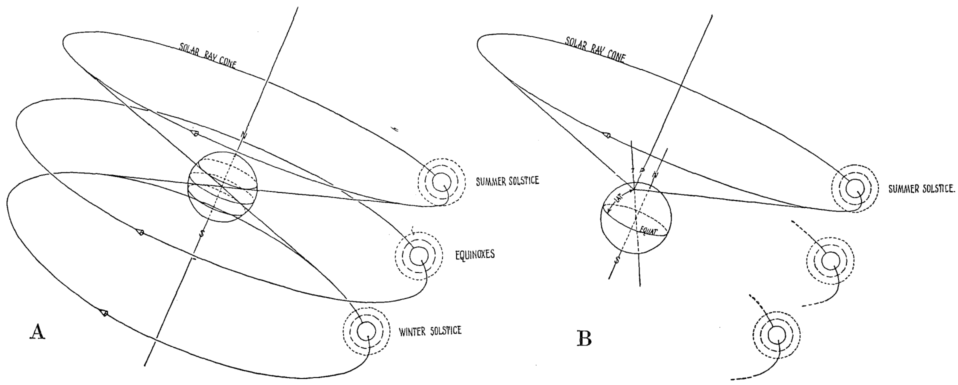


Fig. 26. A. Solar ray cones for the solstices and the equinoxes. B. The solar ray cones are similar for every point on the earth.

The plane through the equator is called the equatorial plane. The angle between this plane and the ecliptic is always 23.5 degrees. The angle which the direction of the solar rays at the earth makes with the equatorial plane is called the sun's declination. As the earth revolves the equatorial plane makes a parallel movement and the declination varies. For the northern hemisphere the maximum declination is +23.5 degrees at the summer solstice on the 21st June, 0 degrees at the autumnal equinox the 23rd September. It has its minimum —23.5 degrees at the winter solstice on the 22nd December, and then increases and achieves 0 degrees at the vernal equinox on the 20th March and is again +23.5 degrees at the summer solstice. The declination is independent of the calendar number of the year and can be established for every date. Minor deviations from the data given above arise from the methods of graduating the calendar year. Because of the elliptical form of the earth's orbit the winter half-year is nine days shorter than the summer half-year. During the winter the sun is somewhat nearer to the earth than during the summer and the radiation therefore is somewhat greater. The difference winter-summer is of the order of 6.5 per cent.

The earth rotates during every twenty-four hour period once on its axis. In order to see more clearly how this movement appears for an observer on the earth the movement can be described in another way. The sun revolves during a twenty-four hour period once around the earth. A ray path from the sun to the centre of the earth will, during the course of a twenty-four hour period, generate the envelope of a cone which has the earth's axis as its own axis. This cone is here called the *solar ray cone*. See Fig. 26 A. This depends, however, on the assumption that the declination is not altered during the day, which is approximately correct since the alteration is small. The apex angle of the solar ray cone is determined by the declination so that if the declination is d the apex angle of the cone will

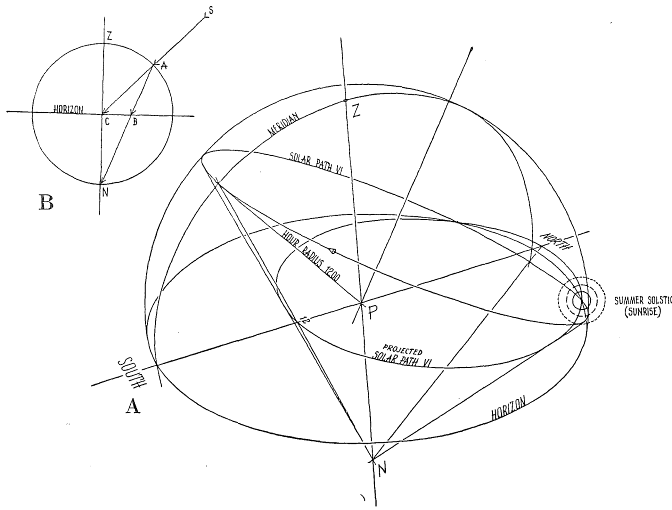


Fig. 27. A. The point under investigation has the projection sphere described around it, and the intersections are taken between this sphere and the solar ray. The intersections are called "solar paths". They are projected stereographically on the horizontal plane, where a solar chart is obtained.
B. Stereographic projection. A ray from the sun to the point C cuts the projection sphere in A. The point A is projected through N (nadir) down to the horizontal plane, which it intersects in B. The distance C—B = tan z/2 where z is the angle between the ray S and the zenith. The circles of intersection between the solar cone and the sphere are projected down to the horizontal plane, where they again are circles.

be = 180 degrees minus $2d$. The envelope of the cone is divided radially in twenty-four equal parts, each of which comprises one hour. Each dividing radius represents therefore an hour-stroke and is here called an hour-radius. The hour-radius for 12.00 hours points towards the south.

According as the declination varies so also will the appearance of the solar ray cone and the apex angle vary. The distance of the sun from the earth is so great that all rays from the sun which meet the earth can be assumed to be parallel. A sunbeam which meets any point on the earth's surface will therefore generate exactly the same cones as described above with the same divisions of the time and with a common axis parallel to the axis of the earth. See Fig. 26 B.

Seen from a point on the earth's surface the sun appears to move in an arc over the sky. This arc is longer and higher during the summer and shorter and lower during the winter. In order to establish the altitude of the sun in relation to the point P on the earth's surface the intersections are taken of the solar ray cones with apex in P and a sphere with P as a centre. The intersection lines will be circular on the surface of the sphere, parallel and with the centre point on the axis of the cone. These are called here the solar paths. The intersection is taken also between the sphere and a horizontal plane through P. The angle between the axis of the cone and the horizontal plane is the same as for the latitude for which the solar chart has been constructed.

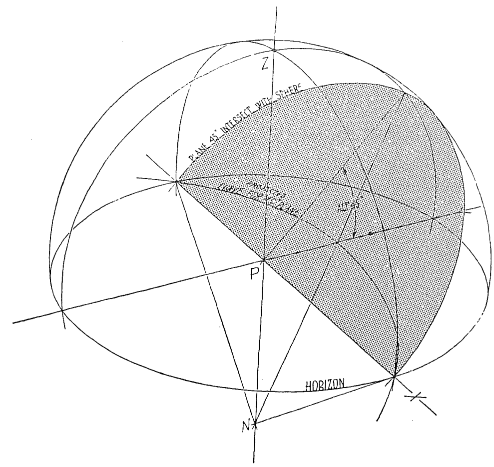
The hour-radii for the same time (true solar time) of day on all cones lie in a plane, the hour-plane, through the axis of the cones. The hour-plane for 12.00 hours (and 24.00 hours) true solar time lies in a strictly north-south direction. The intersection is taken between the hour-planes and the sphere. The lines of intersection are great circles on the surface of the sphere going through the intersection points on the axis of the cones with the sphere, each of the two points representing the poles of the sky. The intersection lines are called hour-lines and are marked for the respective hour.

The circles on the surface of the sphere (solar paths) are now projected with the nadir (N) as centre down on to the horizontal plane where a *solar chart* is set up. See Fig. 24 and 27. This type of projection is called the stereographic projection. The horizon of the solar chart is the intersection of the sphere with the horizontal plane, and inside this lie all parts of the solar paths which are located above the horizon. The zenith lies in the middle of the diagram. Around the horizon is set off a scale of azimuth with the zero point in the north and divided into 360 degrees in clockwise fashion. A scale of solar altitude is laid out from the zenith to the horizon in the north. The distance on this scale, measured from the zenith, will be proportional to $\tan \frac{z}{2}$, where z is the zenith angle. Small altitude angles are represented better than greater, which favours the winter sun. The screening influence of objects near the horizon, such as are most commonly met with, can be read off with greater accuracy than screening in the central parts of the diagram. This is an obvious advantage.

In order to simplify the solar chart the spring months and the autumn months have been linked together so that a single solar path applies to a month during the spring and the corresponding month during the autumn. Starting from the winter- and the summer-solstice and the spring and the autumn equinoxes one day in each of the different months has been selected so that, in the most convenient manner, they lie at similar distances from each other and besides so that the declination of the sun is the same for the days in the months which have been paired together. The data for the relevant paths of the sun (for the year 1954) can be obtained from the table below which gives the relevant declinations.

22 Dec.	—23.5°
22 Nov., 21 Jan.	—20.0°
24 Oct., 19 Feb.	—11.5°
23 Sept., 21 March	± 0.0°
23 Aug., 20 April	+11.5°
24 July, 21 May	+20.0°
21 June	+23.5°

Fig. 28. The intersections are taken between the projection sphere and planes with different inclinations through the x-axis and y-axis. The lines of intersection are projected stereographically to get the screen card.



The solar charts are drawn up for true solar time. The times which are read off from the chart must be corrected for the equation of time and the longitude in order to obtain local time. With regard to this see reference (72).

Screen Card

With the aid of the same method of projection it is possible to draw up a design of obstructing objects which surround the point under investigation. The design is called the screen-figure and is prepared on the same scale as the solar chart (that is to say the circle of the horizon is made to have the same diameter). The screen-figure is laid on the solar chart and thence can be read off directly the radiation duration for the point under investigation. A special screen card has been constructed in order to facilitate the drawing of such screen-figures. This is described below.

Through the centre of the projection sphere two axes are drawn in the horizontal plane, perpendicular to one another, the x-axis and the y-axis. See Fig. 28. Through these axes are then drawn planes with angles of different inclination to the horizontal plane. The angles of inclination are counted from the positive part of the axes, from 0 degrees to 180 degrees with 10 degrees intervals. The intersection between these planes and the sphere will be great circles through the points of intersection of the axes with the sphere. These are then projected from the sphere with the nadir (N) as centre down on to the horizontal plane. Since they are circles on the surface of the sphere they will again be circles on the horizontal plane going through the intersection points of the axis with the horizon. The construction is therefore very simple. The appearance of the screen card is shown on Fig. 29.

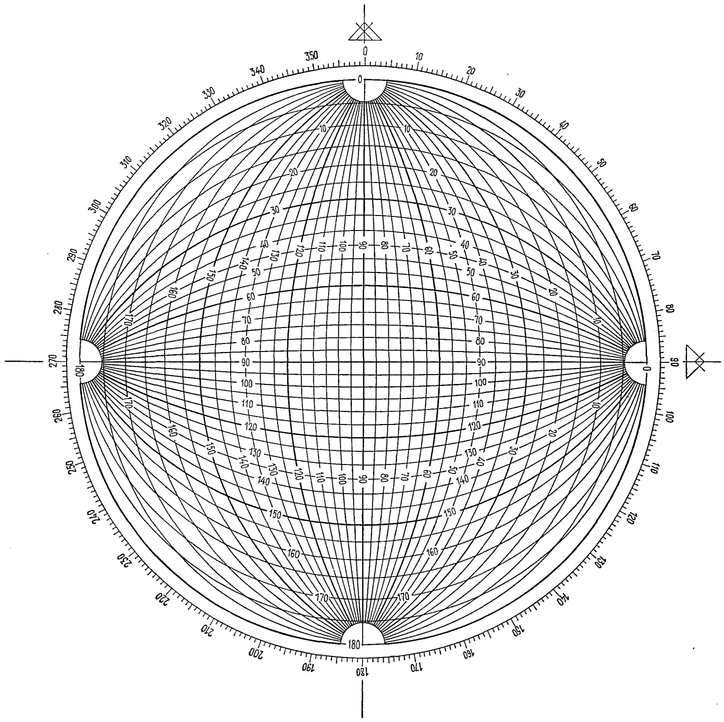


Fig. 29. Screen card.

In the practical application, these lines represent horizontal and inclined edges of roofs. Vertical corners of houses become radial lines from the zenith to the horizon and they can be drawn in directly if the screen card is laid on the map of the town. See an example on Pages 130—131.

The Globoscope

The most labour- and time-consuming process in such theoretical computations of radiation is the drawing up of the screen figure. A new screen figure has to be drawn for every point under investigation. In old and irregularly built-up areas, this process can be significantly more complicated than in the example given on Pages 130—131. Consequently quite a small investigation can take a considerable time. When new buildings are under consideration, which are only in the design stage on paper, there is no alternative but that one screen figure after the other must be drawn, but when the investigation is concerned with areas already built up, the work can be simplified considerably with the aid of the photographic method described below.

Fig. 30 shows how a stereographic projection of the surroundings of a point can be obtained by means of a paraboloidal mirror. An apparatus has been constructed on this principle, called the *Globoscope*.

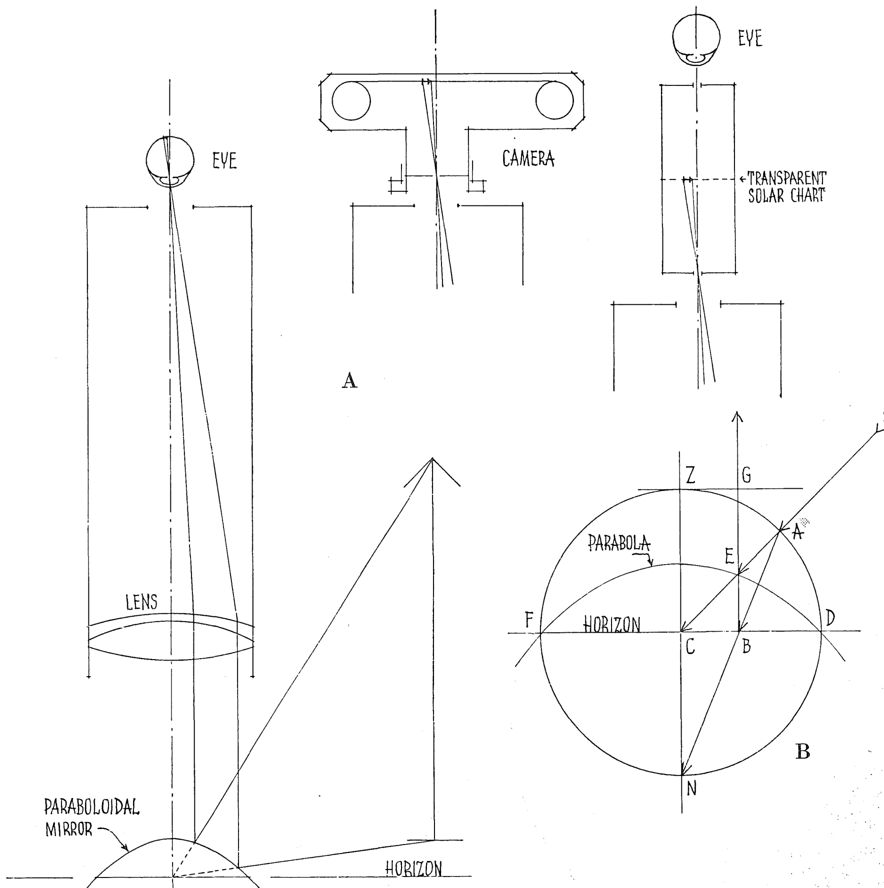


Figure 30. A. Section through the Globoscope with camera and a small accessory apparatus for direct combination of the screen figure with a transparency of a solar chart or other nomograms. B. The stereographic projection and the paraboloidal reflector. A ray of light from S towards C meets the circle ZFND in A. From A is drawn a line to N. This meets the horizontal plane at B. The point B is then the stereographic representative of A, and thence for S (the sun) as seen from C (the observation point). From B is drawn a line parallel to the vertical NCZ. This line intersects AC at E. Inspection: The point E lies on a parabola with ZCN as axis directrix and C as focus. Proof: Since BEG is parallel to ZCN, the triangles ABE and ANC are congruent. However AC = CN = BG (ZG is parallel to FCD). Then AE = BE and CE = EG. Thence FED is a parabola.

The Globoscope consists of a paraboloidal mirror with the equation:

$$x^2+y^2 = 8z^2 \quad \text{eqn 17}$$

where 8 is the diameter in centimetres of the circle of intersection of the paraboloid in the xy-plane. It is arranged that the z-axis is vertical. If the mirror is observed from above, a distorted image of the surroundings is seen in the mirror. Between the eye and the mirror is placed an achromatic lens whose focus is at the eye. See Fig. 30.

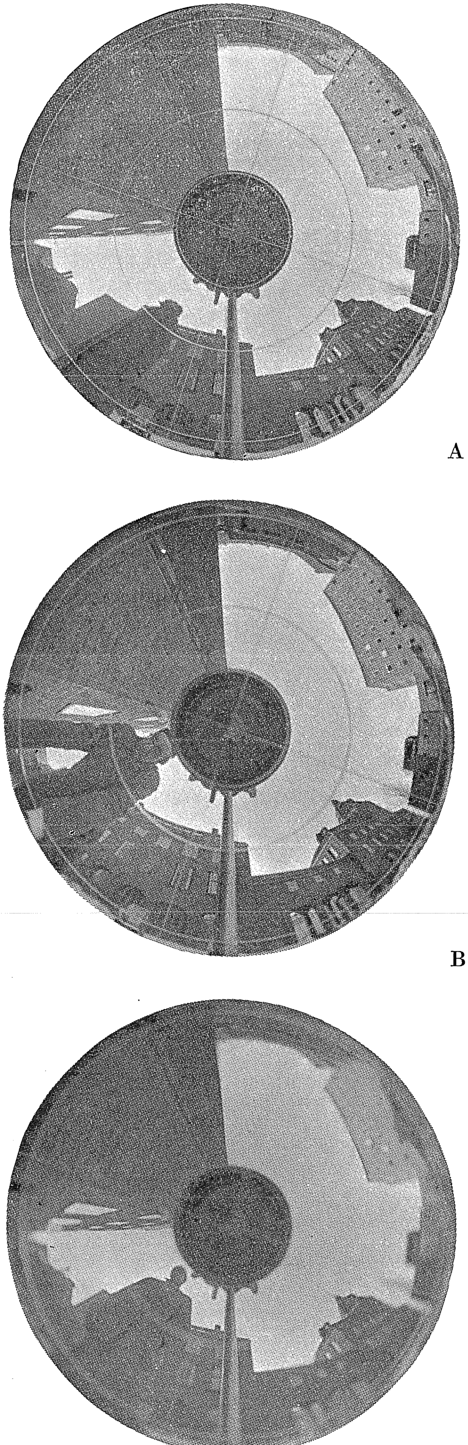


Fig. 31. Globoscope photographs taken with apertures of f 22 (A), f 8 (B), and f 2.8 (C).

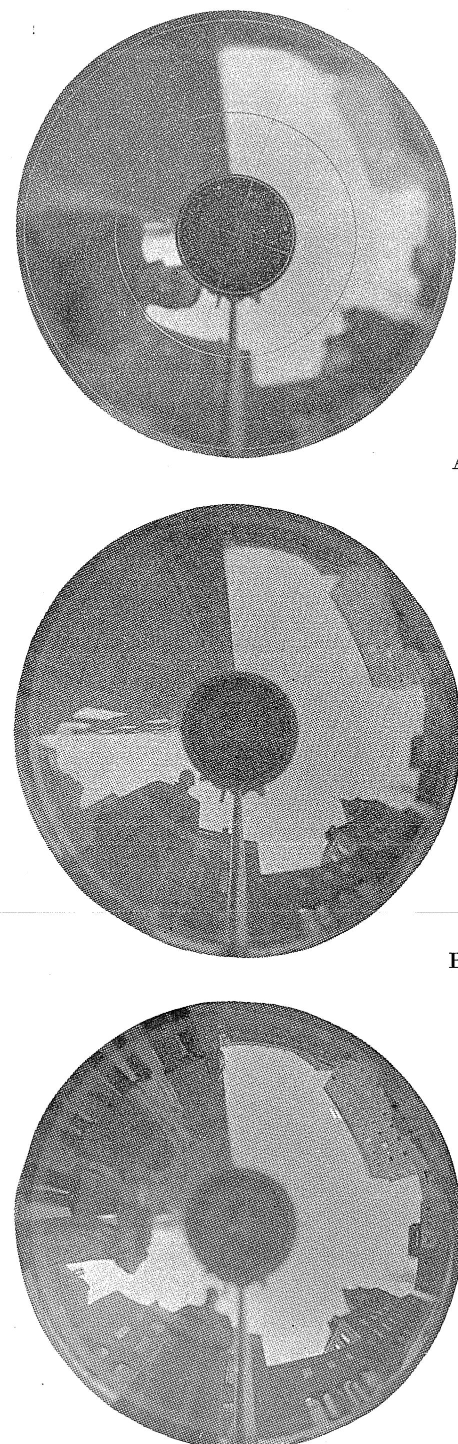


Fig. 32. Globoscope photographs taken with f 2.8 and distance settings 37 cm (A), 44 cm (B), and 50 cm (C).

The image in the mirror comprises the whole sky vault, except for the part around the zenith. The horizon appears as a periphery round the entire image. Some areas below the horizon are depicted. Since the image is a stereographic projection of the surroundings it can be combined with the solar chart and the radiation nomograms, from which can be read off the times of solar radiation and the radiation components. This combination can be achieved by engraving the solar paths on the mirror, or better by introducing a solar chart in the form of a transparency, by means of the small accessory apparatus shown in Fig. 30. The globoscope image and the solar chart are thus seen simultaneously through the upper lens. The diapositive should be interchangeable so that different nomograms can be put in position.

The image in the globoscope can be made permanent if a camera, placed in the eye position, is used to photograph the image. This can be an ordinary miniature camera with a standard lens system. When the pictures are printed a transparency of the nomogram can be laid over the photographic paper so that the nomogram appears in its correct position on the resultant photograph, appearing as a negative. The orientation of the image must first be obtained with great care, and the horizon which is engraved on the mirror must be made to coincide with the horizon of the transparency of the nomogram. By means of the globoscope picture, the radiation at the point under investigation can be computed, whether this is a matter of the heat, light, or ultra-violet radiation. See the example on Pages 136—138.

Several technical studies have been made of the properties of the Globoscope. It has been shown to be necessary to provide the camera with a supplementary lens of 2 dioptres ("Proxar" or "portrait attachment" of focal length = 50 cm). Fig. 31, A—C, shows three photographs taken with lens apertures of f. 22 (A), f. 8 (B), and f. 2.8 (C). They show that the whole depth of focus of which the camera is capable must be used if all parts of the image are to be sharp. At an aperture of f. 22 the exposure is 1/25 second when fast film (hypersensitive panchromatic type) is used. This enables exposures to be made with the apparatus held in the hand.

Fig. 32, A—C, shows three photographs taken with different distance settings of the camera. Photograph A, which is taken with the camera focussed for a distance of 37 cm (including the supplementary lens), gives a sharp image of the mirror graduations only. Photograph B, focussed for 44 cm shows a sharp image of those parts of the picture at an altitude of 40°. Finally photograph C, with the lens system focussed for 50 cm gives a sharp image at an angle of altitude of 10°. The virtual image has therefore a considerable extension, demonstrating that an aperture of f. 22 must be employed if a sharp rendering of the whole image is to be achieved.

Considered as an idea, the Globoscope is not new. Photographs of the same kind as the globoscope images are often to be seen as comic pictures suitable for illu-

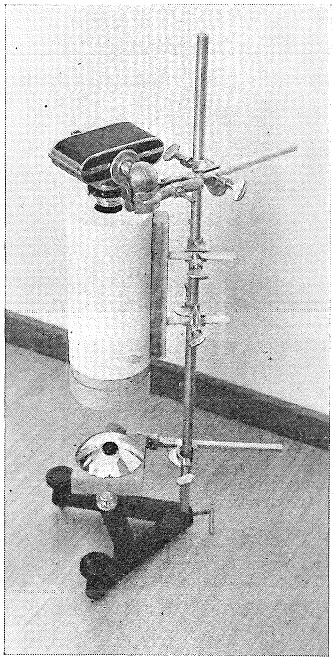


Fig. 33. The Globoscope in its present form (mock-up). It is an apparatus for taking photographs of screen-figures (obstruction diagram). It can be used for the calculating of irradiation from sun and sky in complicated built-up areas, where the photographic method simplifies the work considerably.

strations in the weekly press. The technical use of such pictures has however been overlooked.

Burchard (10) describes an apparatus consisting of a spherical mirror, which should be observed through an aperture in a plate, centrally placed above the mirror on a tripod. The image that is seen in the mirror comprises the whole sky vault, but the projection is different from that of the Globoscope. In particular it is not a uniform central projection, for the projection centre is different for different parts of the image. The apparatus cannot therefore be used in combination with models, which is, however, possible with the Globoscope.

Curved mirrors have been employed in meteorology, for example in the "Heliopanorama Camera" of *Pers* (69). This also had a spherical mirror, and the purpose was to determine how much of the path of the sun was obstructed by mountains, buildings, or trees. This is of great significance in mountainous terrain, where in many cases, e.g. Norway, only a small part of the solar radiation penetrates down into the valleys.

Extremely wide-angle objectives have also been used for the purpose of taking in the whole sky vault in one picture. The cloud camera of *Hill* (30) was thus constructed primarily for a meteorological purpose, but it could also be used for the solution of the present problem.

Tonne (86) has made a study of a mechanical-optical method of drawing the screen figure. His Horizontograph ("Besonnungsschreiber") is a simple and cheap instrument but demands rather more time than does the Globoscope for an extensive analysis. He has later made an instrument called "Horizontoscope" of a construction similar to the Globoscope.

The Globoscope in its present form is shown on Fig. 33. It should be observed that it is in a mock-up form at the moment and does not meet any special claims to precision. There is, however, a considerable possibility that the apparatus will be finalised in a form handy and easy to work with. This might be as an accessory apparatus to an ordinary miniature camera.

Under the heading "Example II" on Pages 136—138 a Globoscope picture is shown combined with a solar chart and some radiation nomograms, of the type described below. It will be evident from these illustrations that, by means of the Globoscope, there is a considerable possibility of performing analyses of radiation in cases where the screen figures are troublesome to construct.

Tables and Nomograms for Solar Radiation

With the aid of the solar chart and the screen card or a globoscope photo the duration of solar radiation can be calculated in a relatively simple fashion. Investigations of radiation are however not in general limited only to the figure for the duration of sunshine but also one often requires to know how strong the radiation is. It is thereby very convenient, for an investigation of the strength of radiation, to employ three previously calculated and tabulated, mutually perpendicular components. Nomograms can also be calculated from these tables, one for each component, which facilitates considerably the calculation of the radiation totals. The component method for the calculation of radiation is the basis of these tables and nomograms.

The Component Method

The radiation from the sun at a point can be regarded as a vector, that is to say, it has both magnitude and direction. See Fig. 34. This vector is divided into three components in a suitably convenient perpendicular co-ordinate system with axes, x, y and z. The following equations apply to these components:

$$E_x^S = E_o^S \times \cos h^S \times \cos a^S \quad \text{eqn 18 } x$$
$$E_y^S = E_o^S \times \cos h^S \times \sin a^S \quad \text{eqn 18 } y$$
$$E_z^S = E_o^S \times \sin h^S \quad \text{eqn 18 } z$$

where E_o^S is the intensity of the radiation perpendicular to the direction of the radiation, E_x^S, E_y^S and E_z^S are the components of the radiation, h^S and a^S are respectively the angle of altitude and the azimuth of the sun. The azimuth is measured from the positive x axis and has a positive direction clockwise.

With the aid of these components the radiation can next be calculated with reference to a surface with any given orientation and inclination, by projection of the components on to the normal to the surface. See Fig. 35. The following equation applies to this calculation:

$$E_A^S = E_x^S \times \cos h_A \times \cos a_A + E_y^S \times \cos h_A \times \sin a_A + E_z^S \times \sin h_A \ldots \quad \text{eqn 19}$$

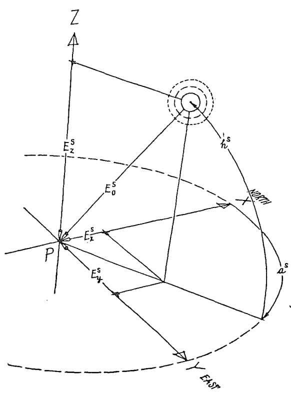


Fig. 34. The radiation from the sun is divided into three components.

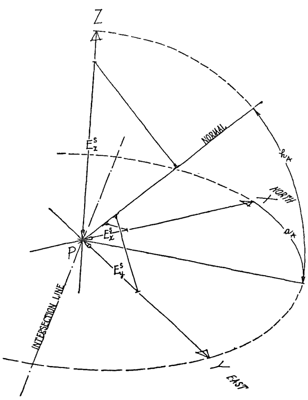


Fig. 35. The components are projected on to the normal of the surface under investigation.

where E_A^S is the intensity of the radiation on the surface A, E_x^S, E_y^S and E_z^S are components of the radiation, and h_A and a_A are the altitude and azimuth of the normal, the latter being calculated in the same way as a^S.

By means of this equation the intensity of the radiation on a given occasion can be calculated. The components can be tabulated for each degree of latitude, thus facilitating the calculation. See below.

Often it is not the intensity of the radiation for any particular occasion which is required, but rather the total radiation between two points in time, daily totals, monthly totals or yearly totals. The points in time between which it is necessary to know the radiation are often established by the surrounding objects, which screen certain parts of the solar path. The calculation can then be undertaken in the manner which has been applied to the perpendicular radiation on Pages 38—48. This, however, often becomes very time-consuming. The calculation is facilitated considerably if there are available previously calculated successive integrals of the three components, starting from a given point of time. From a diagram with such successively accumulated radiation totals it is possible to read off the totals between the two points in time and the difference between these will be the required radiation totals. The following equation applies:

$$Q_{xyz}^S = \int_{t0}^{t2} E_{xyz}^S \times dt - \int_{t0}^{t1} E_{xyz}^S \times dt \quad \ldots\ldots\ldots\ldots \text{ eqn } 20$$

where Q_{xyz}^S is the component of the radiation totals between the time points $t1$ and $t2$, $t2$ later than $t1$, and $t0$ is the starting point for the integration.

These Q-components can then be dealt with exactly as the E-components for the calculation of radiation totals for a surface with any given orientation and inclination. Equation 19 can thus be applied if one exchanges the letter E for letter Q.

A diagram is drawn up for the Q-components, one for each component, from which it is possible to read off directly the respective radiation totals between the two points in time ($t1$ and $t2$). The points $t1$ and $t2$ are established most suitably with the aid of a screen figure which is laid on the solar chart. The points in time for the emergence ($t1$) and the disappearance ($t2$) of the sun can then be read off. The relevant totals for these points of time are found on the component diagram, Q_{t1} subtracted from Q_{t2}, and thence are obtained the components.

The component tables and diagrams are derived for the solar radiation from a clear sky. With these and with the equations (19 and 20) are then obtained the radiation without a reduction for nebulosity. If the radiation for the prevailing nebulosity is required, this can be obtained directly for a given place by multiplying the radiation by the statistical average value of the clarity of the sky (k_d). This can therefore be obtained for a given place in the way that has been described previously on Pages 45—49, and probably applies for most places at some distance from the sea or great lakes which influence the distribution of nebulosity in the sky, and with a surrounding country which is not too mountainous. For places which do not fall into this category, for example, Helsinki, modified intensity curves must be employed, and the component tables and the radiation diagrams must be drawn up in such a way that the unequal distribution of nebulosity is incorporated. Many different tables and diagrams are thus obtained for different parts of the world on the same latitude. It is worth investigating whether one can, without great error, take into account the unequal distribution of cloud merely by means of a correction coefficient. This is certainly possible for erythemal radiation, see Page 90.

Radiation Cards

The work of calculation can be facilitated considerably if a nomogram is drawn up of the same type as the solar chart for the successive accumulated radiation totals. The solar paths can be divided into energy units instead of into time units. Three radiation nomograms are obtained, one for each component, which can be combined directly with the screen-figure and from which can be read off directly Q_x^S, Q_y^S and Q_z^S. These are then added in the usual way according to equation 19. The same applies to these radiation cards as for the radiation diagrams, that is, that being drawn up for clear skies, they apply only to certain conditions, see above. Different cards must be drawn up for places with uncommon distributions of nebulosity in the sky.

The component tables and radiation cards have been calculated here for clear sky in general and for the nebulosity distribution which is representative of the conditions prevalent at Helsinki. They have been obtained for heat radiation, for illumination and erythemal radiation. In order to show the progress of the calculation, the arrangement of the heat cards for Helsinki has been described in greater detail, whereas the other conditions are presented only in the summarized form of component tables and radiation cards.

The following directions have been selected for the three axes, x, y and z: the z-axis is vertical, the x-axis lies in the North-South direction, with North as positive and South as negative, the y-axis lies along the East-West direction with East as the positive direction and West as negative. Thence the radiations E_x and E_y, Q_x and Q_y are read off directly to give values for facades with North, South, East, or West orientations, and E_z and Q_z can be read off directly to give the radiation on a horizontal plane.

The first is to calculate the angles which the sun's radiation makes with the three axes. These angles are calculated from the positive parts of the axes, and can therefore take values between 0° and 180°. The values of radiation will therefore be negative for westerly and southerly directions, which is in complete agreement with the vectorial concept. The intensity for every hour is obtained from the diagram of the solar heat radiation as a function of solar altitude, see Fig. 14, Page 62. The intensity is multiplied by the cosine of the angle of incidence = the above determined angles with the axes of coordinates. Of these, the angles with the z-axis are also called zenith-angles and they are complementary angles to solar altitude angles ($z = 90—h$). Thence are obtained the intensities of the radiation components, which are shown in Table 47. Figures 36, 37 and 38 are diagrams drawn to show these components. From these are calculated the hourly totals, which are next successively added from 12.00 noon, true solar time. New diagrams are drawn up for these totals, see Figures 39, 40 and 41. These diagrams can be used in combination with the solar chart and screen figures for the calculation of the heat components. An example of such a calculation is shown in Fig. 39. With the aid of the diagrams the solar paths on three heat radiation cards are graduated to give the successive accumulated totals of heat radiation from 12.00 noon. See Fig. 42 x, y, z.

Component tables and radiation cards for the heat radiation from the sun with clear sky have also been calculated, and also tables and charts for the illumination and the erythemal radiation. See Tables 48—51 and Figures 43—46. Examples of the employment of the charts will also be found on Page 130—138.

Fig. 36. Diagram of the x-component of the heat radiation from the sun, as a function of true solar time. The intensity of the radiation is modified for the distribution of nebulosity in Helsinki. Vertical scale = kcal/m²h, horizontal scale = true solar time.

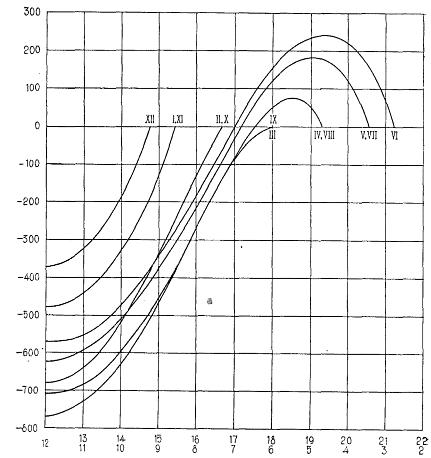
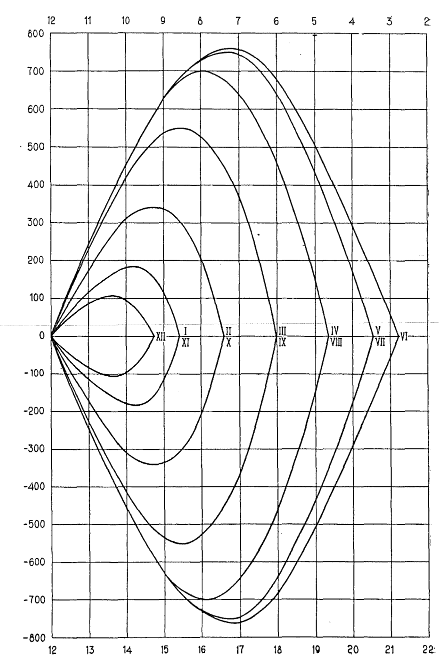


Fig. 37. Diagram of the y-component of the heat radiation from the sun, as a function of true solar time. The intensity of the radiation is modified for the distribution of nebulosity in Helsinki. Vertical scale = kcal/m²h, horizontal scale = true solar time.



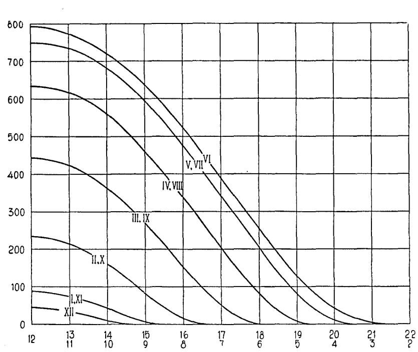


Fig. 38. Diagram of the z-component of the heat radiation from the sun, as a function of true solar time. The intensity of the radiation is modified for the distribution of nebulosity in Helsinki. Vertical scale = kcal/m²h, horizontal scale = true solar time.

Fig. 39. Diagram of the successive totals of the x-component of the heat radiation, as a function of true solar time. The radiation is modified for the distribution of nebulosity in Helsinki. Vertical scale = Mcal/m²d, horizontal scale = true solar time.

Example: Find the x-component for June 20th between the times t1 = 10.15 and t2 = 19.15.
$Q_{t1} = 0.95$, $Q_{t2} = -1.46$. $Q_{(t1 \rightarrow t2)} = Q_{t2} - Q_{t1} =$
$= 0.95 + 1.46 = 2.41$.

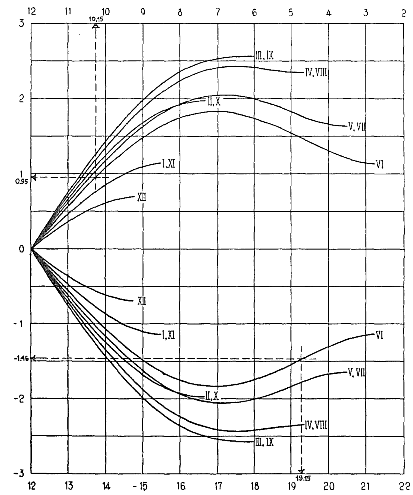
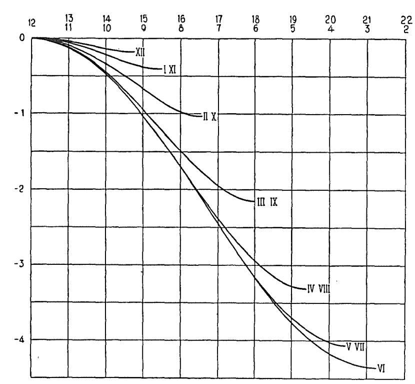


Fig. 40. Diagram of the successive totals of the y-component of the heat radiation, as a function of true solar time. The radiation is modified for the distribution of nebulosity in Helsinki. Vertical scale = Mcal/m²d, horizontal scale = true solar time.



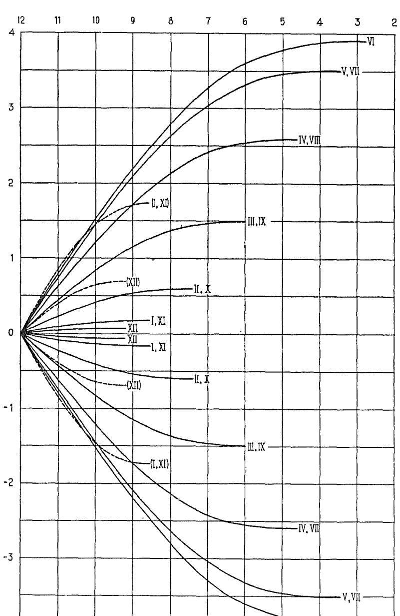


Fig. 41. Diagram of the successive totals of the z-component of the heat radiation, as a function of true solar time. The radiation is modified for the distribution of nebulosity in Helsinki. Vertical scale = Mcal/m²d, horizontal scale = true solar time.

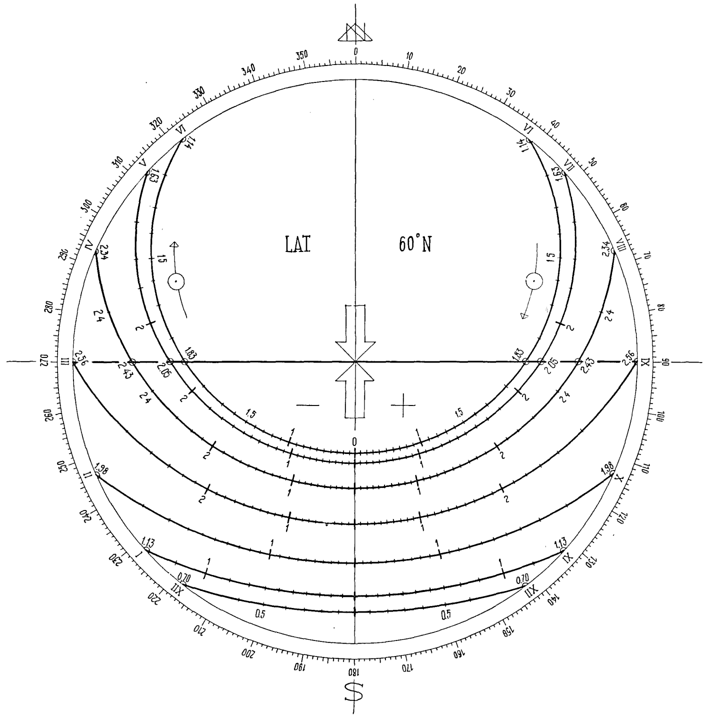


Fig. 42x. Heat card for the x-component valid for the nebulosity in Helsinki. Unit 1 Mcal/m²d.

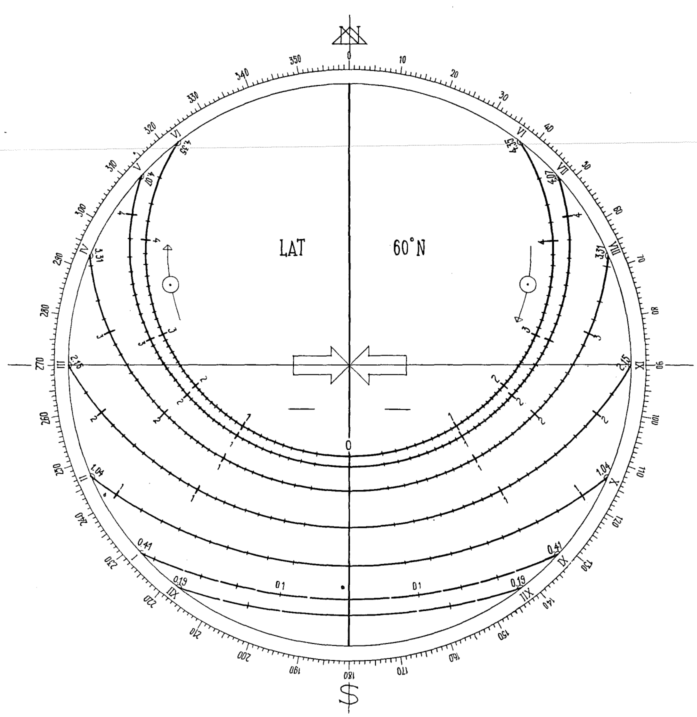


Fig. 42y. Heat card for the y-component valid for the nebulosity in Helsinki. Unit 1 Mcal/m²d.

Time		12	13/11	14/10	15/9	16/8	17/7	18/6	19/5	20/4	21/3
VI	x	—571	—556	—472	—335	—168	±0	+155	+236	+221	+73
	y	±0	±237	±450	±628	±732	±760	±683	±506	±293	±62
	z	+792	+773	+724	+640	+529	+389	+255	+128	+40	+2
V VII	x	—622	—594	—512	—377	—217	— 29	+124	+183	+123	
	y	±0	±244	±461	±632	±729	±746	± 642	±435	± 176	
	z	+756	+737	+683	+595	+468	+340	+ 205	+83	+13	
IV VIII	x	—710	—685	—596	—454	—269	—83	+49	+53		
	y	±0	±246	±460	±627	±700	±643	±463	±154		
	z	+639	+618	+ 563	+460	+349	+198	+82	+7		
III IX	x	—768	—730	—627	—468	—268	—87	±0			
	y	±0	±226	±419	±537	±530	±373	±0			
	z	+444	+424	+367	+272	+153	+51	±0			
II X	x	—681	—639	—519	—339	—132					
	y	±0	±175	±311	±337	±212					
	z	+234	+215	+161	+84	+17					
I XI	x	—479	—446	—330	—133						
	y	±0	±117	±179	±119						
	z	+89	+77	+46	+8						
XII	x	—372	—326	—186							
	y	±0	±82	±97							
	z	+40	+32	+11							

Table 47. Components of heat radiation from the sun, valid for the distribution of nebulosity in Helsinki. Latitude 60° N. Unit 1 kcal/m²h. True solar time. y-component forenoon positive, afternoon negative.

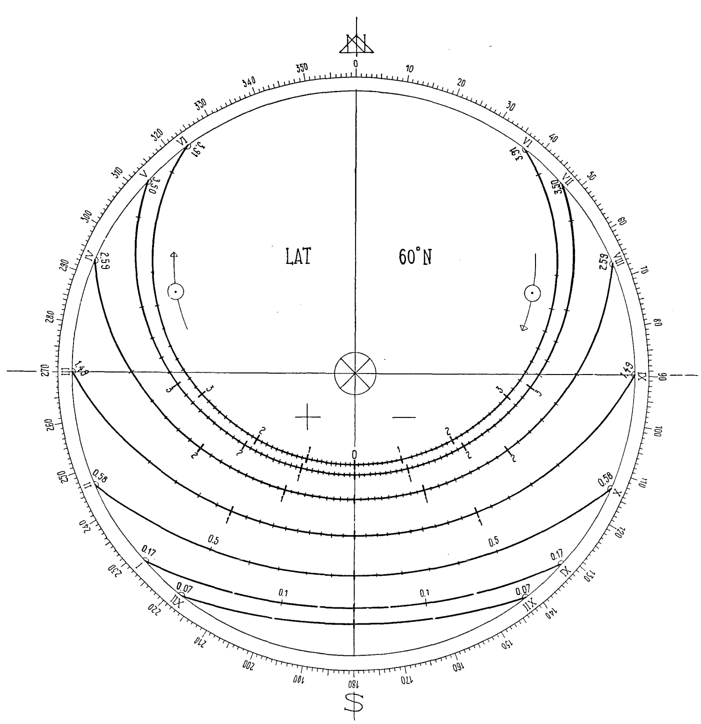


Fig. 42z. Heat card for the z-component valid for the nebulosity in Helsinki. Unit 1 Mcal/m²d.

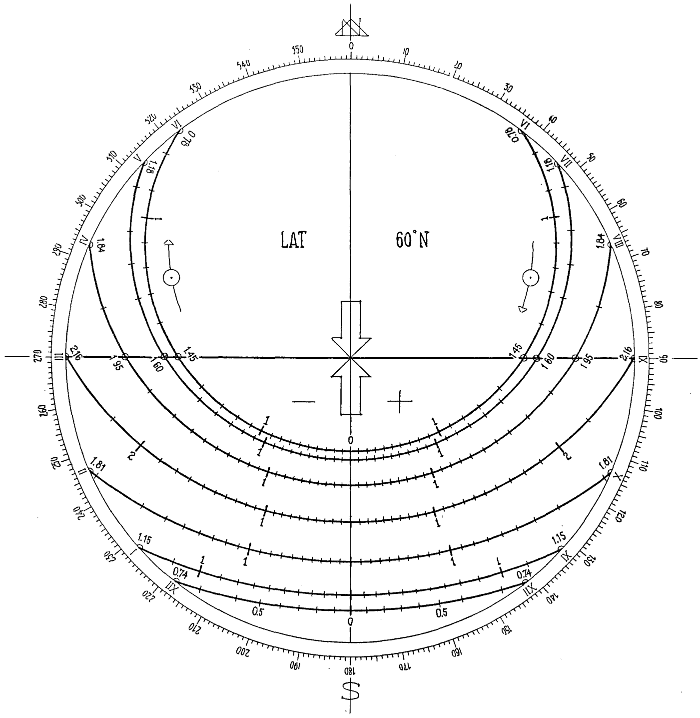


Fig. 43x. Heat card for the x-component, valid for clear sky. Unit 1 Mcal/m²d.

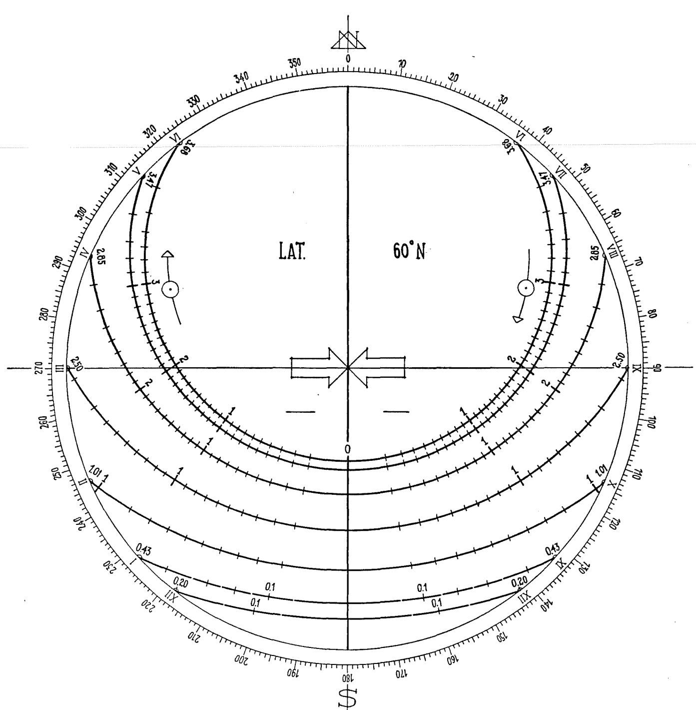


Fig. 43y. Heat card for the y-component, valid for clear sky. Unit 1 Mcal/m²d.

Time		12	13/11	14/10	15/9	16/8	17/7	18/6	19/5	20/4	21/3
VI	x	—467	—442	—373	—252	—133	±0	+133	+228	+229	+69
	y	±0	±189	±356	±495	±579	±616	±587	±479	±303	±59
	z	+631	+615	+572	+505	+419	+321	+219	+122	+43	+2
V VII	x	—493	—469	—403	—297	—173	—24	+111	+182	+143	
	y	±0	±193	±363	±498	±582	±619	±575	±432	±205	
	z	+598	+581	+537	+465	+374	+282	+183	+82	+15	
IV VIII	x	—561	—539	—471	—363	—227	—74	+50	+65		
	y	±0	±194	±364	±501	±577	±574	±465	±190		
	z	+505	+487	+445	+368	+287	+177	+82	+9		
III IX	x	—615	—588	—516	—400	—248	—92	±0			
	y	±0	±182	±345	±460	±489	±396	±0			
	z	+355	+342	+302	+233	+137	+54	±0			
II X	x	—596	—569	—479	—333	—148					
	y	±0	±160	±288	±330	±237					
	z	+205	+192	+149	+82	+20					
I XI	x	—467	—445	—347	—150						
	y	±0	±112	±188	±134						
	z	+87	+77	+48	+9						
XII	x	—378	—348	—200							
	y	±0	±87	±104							
	z	+43	+38	+12							

Table 48. Components of heat radiation from the sun, valid for clear sky. Latitude 60° N. Unit 1 kcal/m²h. True solar time. y-component forenoon positive, afternoon negative.

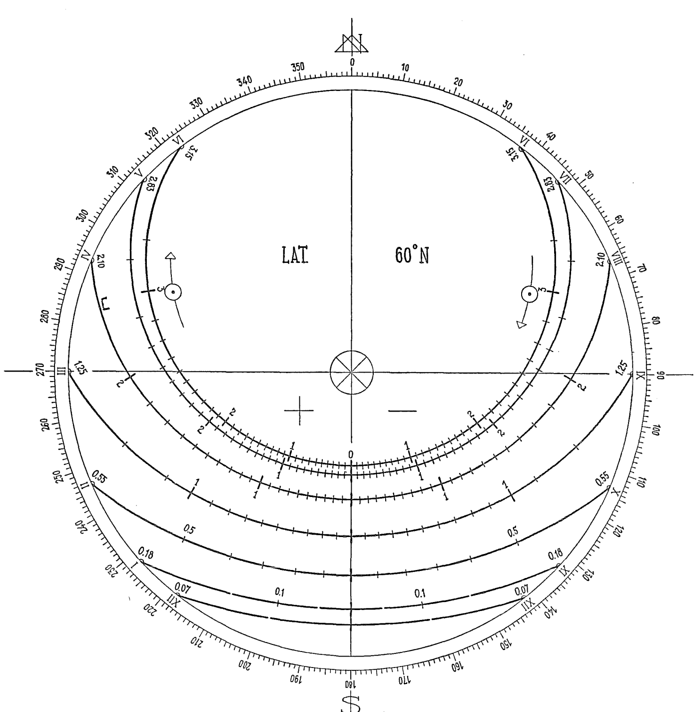


Fig. 43z. Heat card for the z-component, valid for clear sky. Unit 1 Mcal/m²d.

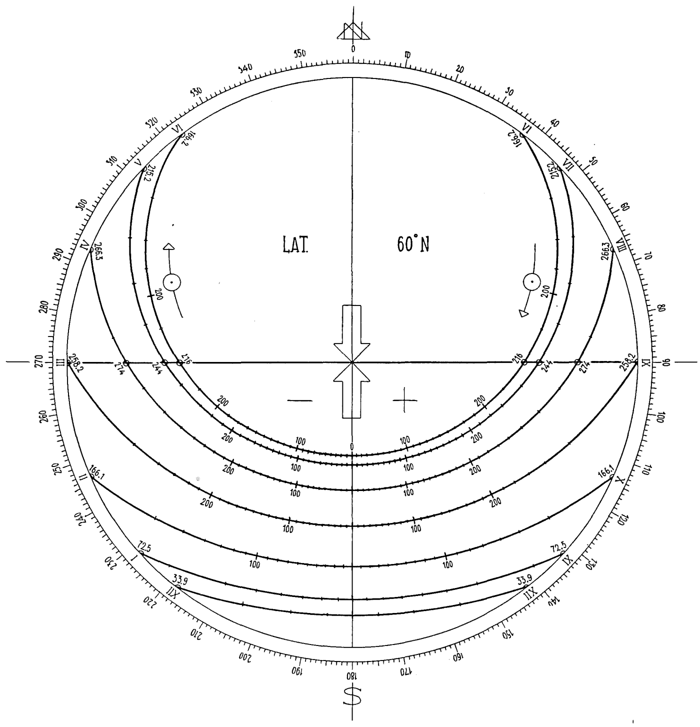


Fig. 44x. Illumination card for the x-component, valid for the nebulosity in Helsinki. Unit 1 klxh/d.

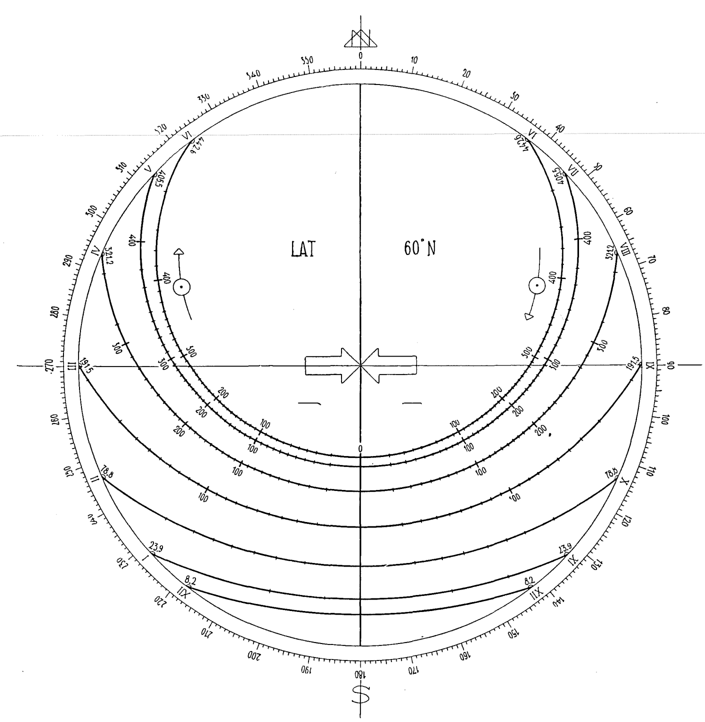


Fig. 44y. Illumination card for the y-component, valid for the nebulosity in Helsinki. Unit 1 klxh/d.

Time		12	13/11	14/10	15/9	16/8	17/7	18/6	19/5	20/4	21/3
VI	x	—71.8	—67.4	—56.0	—36.9	—18.7	±0	+14.9	+19.7	+12.3	+1.1
	y	±0	±28.8	±53.3	±72.5	±81.3	±78.9	±65.6	±41.2	±16.4	±9.8
	z	+96.5	+93.8	+85.8	+73.9	+58.8	+41.1	+24.5	+10.5	+2.3	+0.3
V VII	x	—74.7	—71.2	—59.9	—42.9	—23.5	—2.9	+11.5	+13.4	+4.9	
	y	±0	±29.2	±53.9	±70.9	±79.0	±76.0	±59.4	±31.9	±7.0	
	z	+90.7	+87.9	+79.9	+67.6	+50.7	+34.6	+18.9	+6.1	+0.5	
IV VIII	x	—82.1	—78.4	—66.8	—49.0	—28.2	—7.5	+3.7	+1.8		
	y	±0	±28.2	±51.7	±67.6	±71.7	±58.3	±34.3	±5.2		
	z	+73.9	+70.8	+63.2	+49.7	+35.7	+18.0	+6.1	+0.2		
III IX	x	—81.8	—77.6	—65.2	—45.6	—23.0	—5.6	±0			
	y	±0	±24.1	±43,5	±52.3	±45.5	±24.1	±0			
	z	+47.3	+45.1	+38.1	+26.5	+12.7	+3.3	±0			
II X	x	—64.2	—59.6	—45.0	—24.5	—5.6					
	y	±0	±16.8	±27.0	±24.3	±8.9					
	z	+22.1	+20.1	+14.0	+6.1	+0.7					
I XI	x	—34.4	—31.6	—19.8	—4.5						
	y	±0	±8.3	±10.7	±4.0						
	z	+6.4	+5.4	+2.7	+0.3						
XII	x	—20.4	—17.9	—6.2							
	y	±0	±4.5	±3.2							
	z	+2.3	+1.9	+0.4							

Table 49. Components of illumination from the sun, valid for the distribution of nebulosity in Helsinki. Latitude 60° N. Unit 1 klx. True solar time. y-component forenoon positive, afternoon negative.

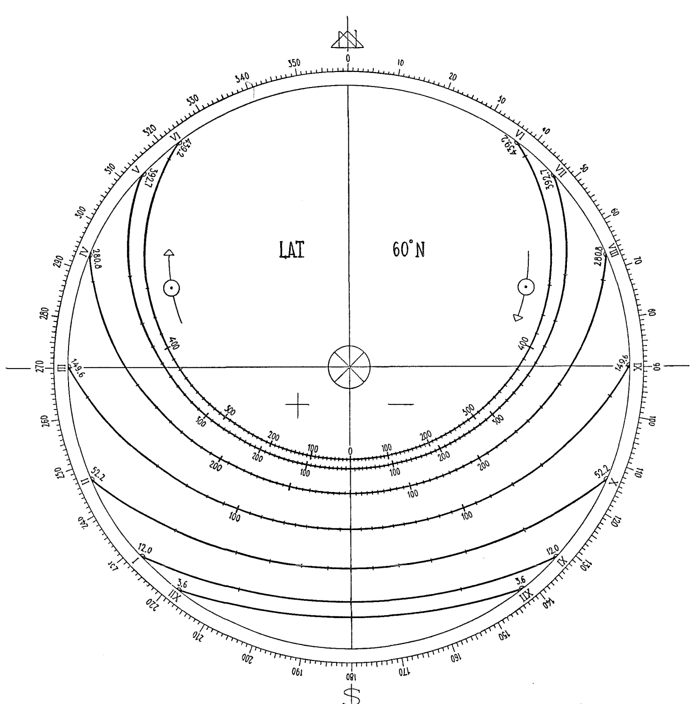


Fig. 44z. Illumination card for the z-component, valid for the nebulosity in Helsinki. Unit 1 klxh/d.

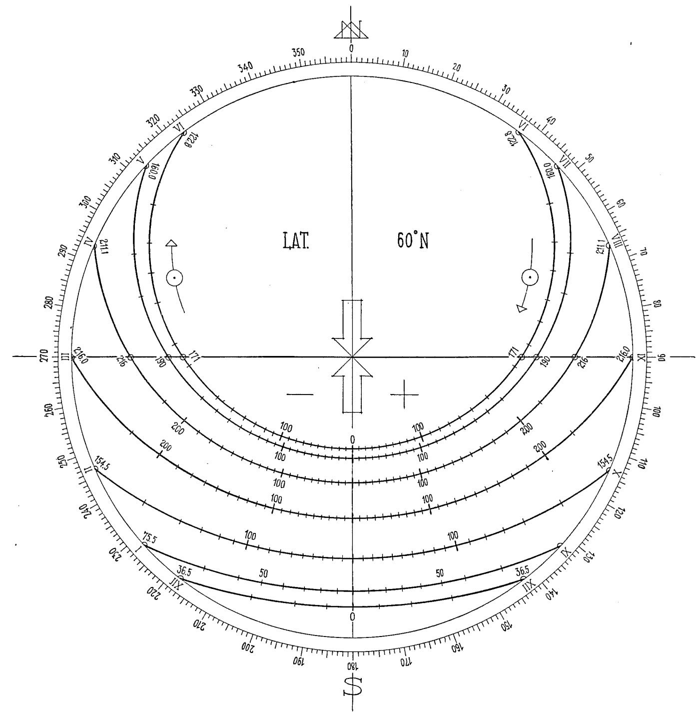


Fig. 45x. Illumination card for the x-component valid for clear sky. Unit 1 klxh/d.

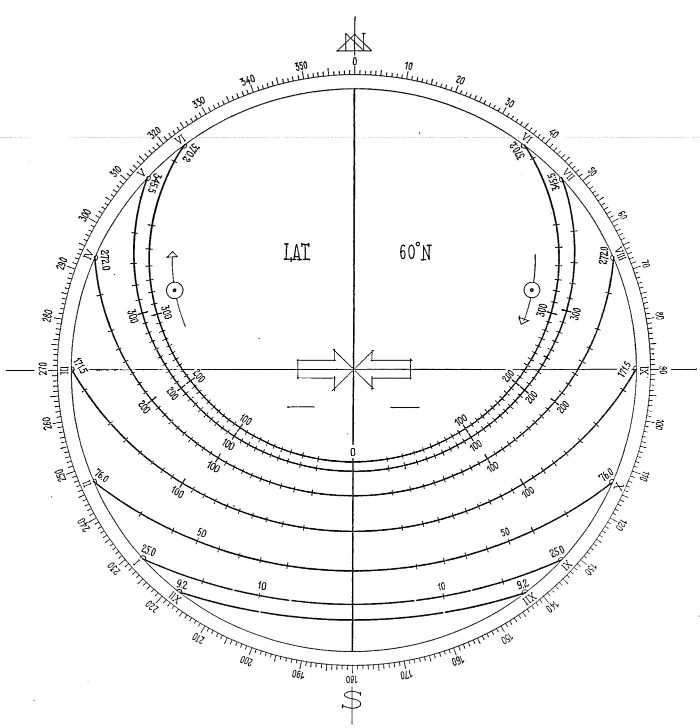


Fig. 45y. Illumination card for the y-component valid for clear sky. Unit 1 klxh/d.

Time		12	13/11	14/10	15/9	16/8	17/7	18/6	19/5	20/4	21/3
VI	x	—56.8	—53.5	—44.4	—29.0	—14.8	±0	+12.9	+19.0	+13.2	+1.9
	y	±0	±22.9	±42.2	±57.1	±64.7	±65.2	±56.9	±39.9	±17.6	±1.6
	z	+76.8	+74.5	+68.0	+58.2	+46.8	+33.9	+21.2	+10.1	+2.5	+0.1
V VII	x	—59.5	—56.3	—47.4	—33.9	—18.9	—2.4	+10.3	+13.4	+6.0	
	y	±0	±23.2	±42.7	±56.9	±63.5	±63.2	±53.3	±31.9	±8.6	
	z	+72.1	+69.8	+63.3	+53.0	+40.8	+28.8	+17.0	+6.1	+0.6	
IV VIII	x	—64.6	—61.9	—52.8	—39.3	—23.4	—6.8	+3.7	+2.3		
	y	±0	±22.3	±40.9	±54.3	±59.4	±52.6	±34.3	±6.6		
	z	+58.2	+55.9	+49.9	+39.9	+29.6	+16.2	+ 6.1	+0.3		
III IX	x	—66.2	—62.5	—53.6	—39.4	—21.5	—5.9	±0			
	y	±0	±19.4	±35.8	±45.3	±42.4	±25.1	±0			
	z	+38.3	+36.4	+31.4	+22.9	+11.9	+3.4	±0			
II X	x	—56.7	—53.2	—42.1	—24.5	—6.6					
	y	±0	±15.0	±25.3	±24.3	±10.6					
	z	+19.5	+17.9	+13.1	+6.1	+0.9					
I XI	x	—36.4	—32.0	—21.1	—5.2						
	y	±0	±8.4	±11.5	±4.7						
	z	+6.7	+5.5	+2.9	+0.3						
XII	x	—21.9	—17.4	—8.0							
	y	±0	±4.4	±4.2							
	z	+2.5	+1.9	+0.5							

Table 50. Components of illumination from the sun, valid for clear sky. Latitude 60° N. Unit 1 klx. True solar time. y-component forenoon positive, afternoon negative.

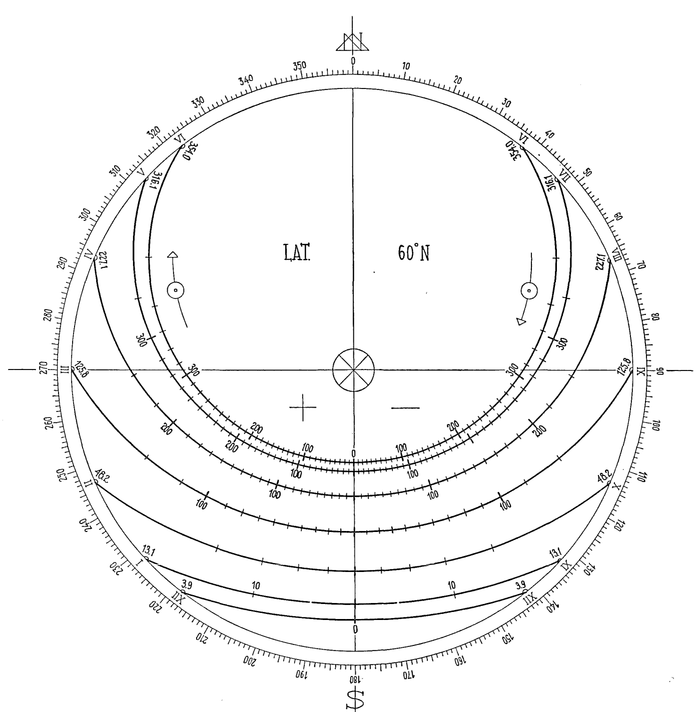


Fig. 45z. Illumination card for the z-component valid for clear sky. Unit 1 klxh/d.

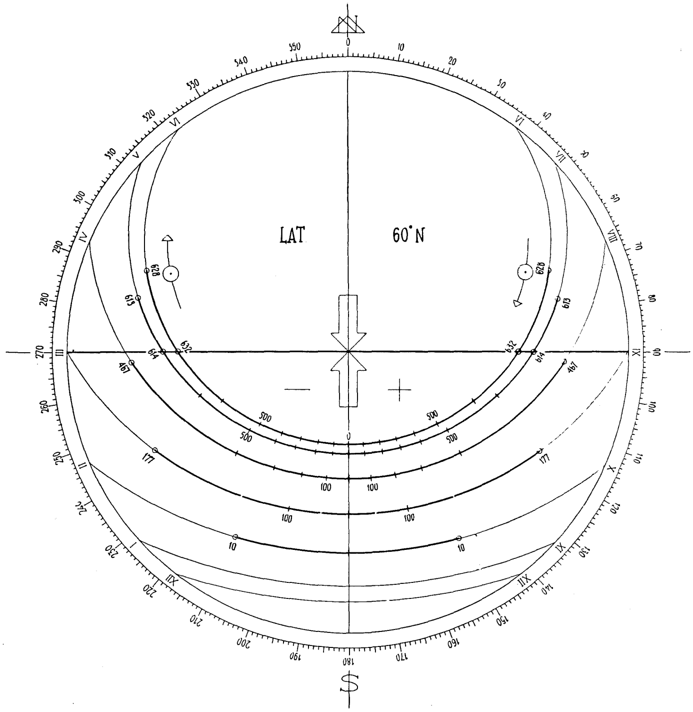
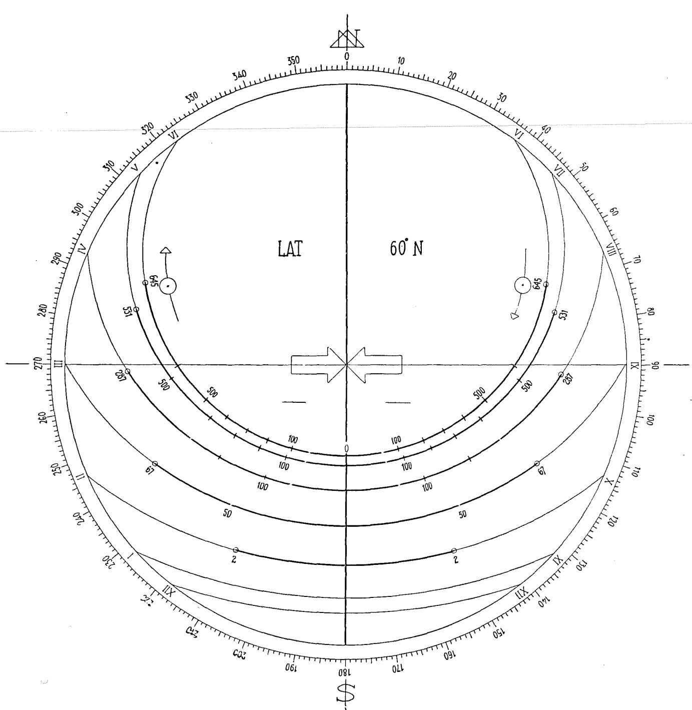


Fig. 46x. Erythemal card for the x-component valid for clear sky. Unit 1 Wh/m²d.



Fig, 46y. Erythemal card for the y-component valid for clear sky. Unit 1 Wh/m²d.

Time		12	13/11	14/10	15/9	16/8	17/7	18/6	19/5	20/4	21/3
VI	*x*	—247	—224	—165	—87	—30	±0	+3	—	—	—
	y	±0	±96	±157	±171	±131	±67	±14	—	—	—
	z	+334	+311	+253	+174	+95	+35	+5	—	—	—
V VII	*x*	—239	—219	—159	—88	—29	—2	+1	—	—	
	y	±0	±90	±143	±147	±98	±41	±5	—	—	
	z	+289	+274	+212	+137	+63	+19	+2	—	—	
IV VIII	*x*	—193	—173	—121	—58	—17	—0	—	—		
	y	±0	±62	±94	±81	±42	±2	—	—		
	z	+174	+156	+114	+59	+21	+1	—	—		
III IX	*x*	—91	—75	—45	—12	—	—				
	y	±0	±23	±30	±14	—	—				
	z	+53	+44	+26	+7	—	—				
II X	*x*	—9	—5	—	—	—					
	y	±0	±1	—	—	—					
	z	+3	+2	—	—	—					
I XI	*x*	—	—	—	—						
	y	—	—	—	—						
	z	—	—	—	—						
XII	*x*	—	—	—							
	y	—	—	—							
	z	—	—	—							

Table 51. Components of erythemal radiation from the sun, valid for clear sky. Latitude 60° N. Unit 1 mW/m². True solar time. y-component forenoon positive, afternoon negative.

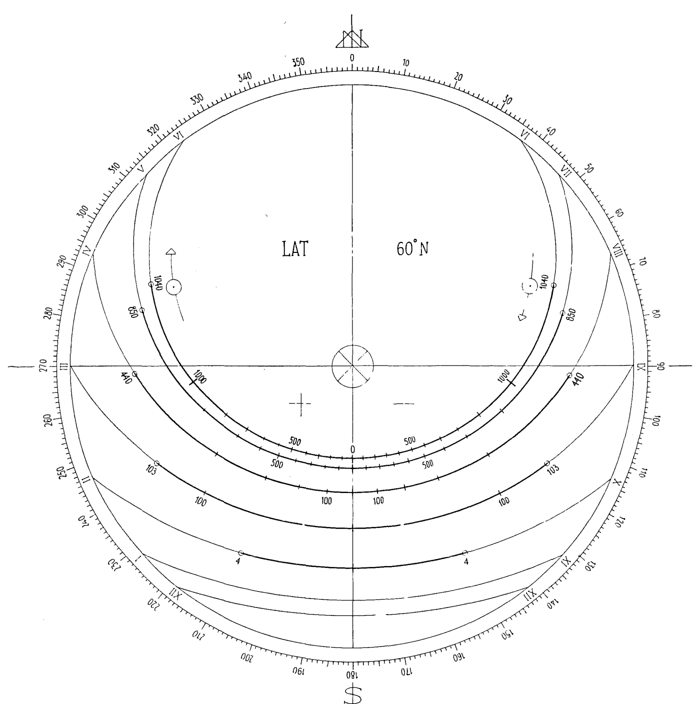


Fig. 46z. Erythemal card for the z-component valid for clear sky. Unit 1 Wh/m²d.

Tables and Nomograms for Radiation from the Sky

The Component Method

The same procedure can be used for the radiation from the sky as was used for the radiation from the sun. The sky, or those parts of it which are not obstructed by surrounding objects, are projected on to a cupola with radius = 1 (sphere of unit radius). Let it be assumed initially that the luminance of the sky is the same over its whole surface, which will also apply to the unit sphere. The non-uniformity of the sky luminance will be discussed later.

From a surface element ΔH on the sphere with radiation density B, a radiation reaches the point P under investigation. See Fig. 47. This radiation is divided into three components along the axes, which are the same as for the solar radiation: x, y and z. The following equations then apply:

$$E_x^{\;H} = B \times \Delta H \times \cos h \times \cos a \quad \ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 21x$$
$$E_y^{\Delta H} = B \times \Delta H \times \cos h \times \sin a \quad \ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 21y$$
$$E_z^{\;H} = B \times \Delta H \times \sin a \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 21z$$

where E_x, E_y and E_z are components of the radiation, h and a are the angle of altitude and the azimuth of the surface element. The azimuth is calculated from the positive x-axis and has positive direction clockwise.

Assume that the part of the sphere which irradiates the point P is H. To calculate the components the equations are integrated over this surface. Thence are obtained:

$$E_x^H = B \times \int^H \cos h \times \cos a \times dH \quad \ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 22x$$

$$E_y^H = B \times \int^H \cos h \times \sin a \times dH \quad \ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 22x$$

$$E_z^H = B \times \int^H \sin h \times dH \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 22z$$

It is convenient to express the diffuse radiation in the form of a ratio, the radiation factor, which is defined by the equation:

$$D^H = E^H / E_z^{H0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 23$$

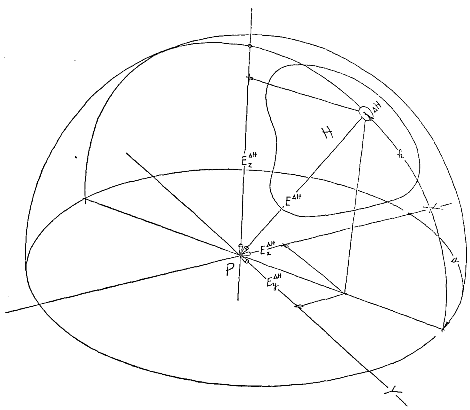


Fig. 47. The radiation from Δ H is divided into three components.

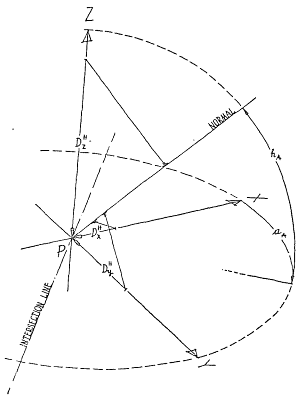


Fig. 48. The components are projected on to the normal of the surface under investigation.

where E^H is the intensity of radiation from the surface H on the sphere, E_z^{H0} is the intensity of radiation from a hemisphere (the whole vault) on a horizontal plane (the xy-plane), D^H is the *radiation factor* for the surface H.

The value of E_z^{H0} can be calculated according to the photometric law, which gives the equation:

$$E_z^{H0} = 2\pi B \int_o^{\pi/2} \cos h \times \sin h \times dh = \pi B \qquad \text{thus } D^H = E^H/\pi B \ \ldots \ \text{eqn 24}$$

Substituting in equations 22xyz, we have:

$$D_x^H = \frac{1}{\pi} \int^H \cos h \times \cos a \times dH \ \ldots\ldots\ldots\ldots\ldots\ldots \ \text{eqn 25}x$$

$$D_y^H = \frac{1}{\pi} \int^H \cos h \times \sin a \times dH \ \ldots\ldots\ldots\ldots\ldots\ldots \ \text{eqn 25}y$$

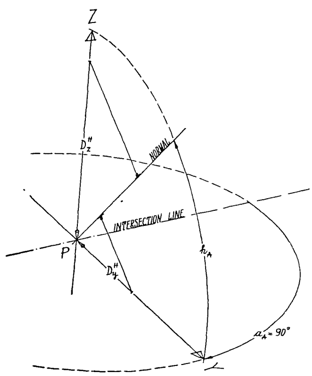
$$D_z^H = \frac{1}{\pi} \int^H \sin h \times dH \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ \text{eqn 25}z$$

The integrations in these equations are solved graphically by projecting the surface H orthogonally on the xy-, the yz-, and the xz-planes. If these areas are divided by π, which is the area of the hemisphere projected orthogonally on to the xy-plane, the components of the radiation factor are obtained according to equations 25xyz. These are added according to the equation:

$$D_A^H = D_x^H \times \cos h_A \times \cos a_A + D_y^H \times \cos h_A \times \sin a_A + D_z^H \times \sin h_A \ldots \ \text{eqn 26}$$

where D_A^H is the radiation factor for the part of the sky H on the surface A at the point P, D_x, D_y, and D_z are the components of the radiation factor, h_A and a_A are respectively the angle of altitude and the azimuth of the normal to the surface A. See Fig. 48.

Fig. 49. The coordinate system is turned so that the horizontal projection of the normal coincides with the positive y-axis.



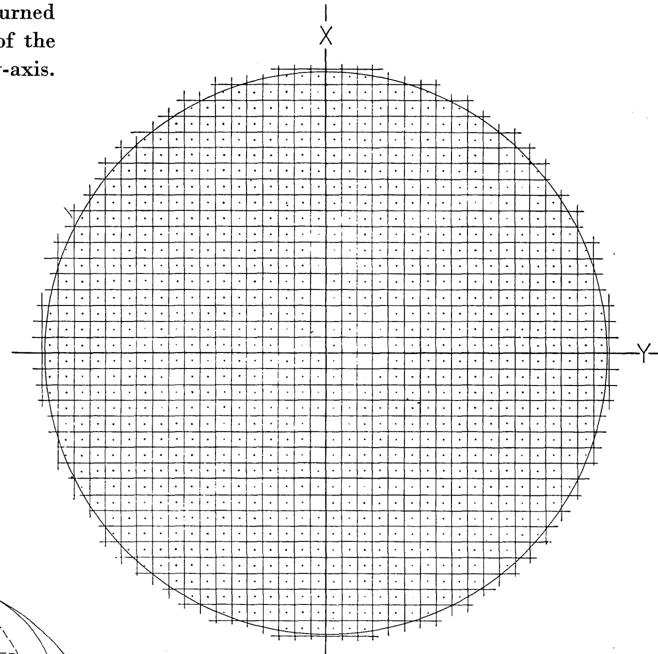


Fig. 50. The area of the circle is divided into a network of squares whose centres (and centroids) are marked by points. Each point represents 1/1004th part of the area of the circle.

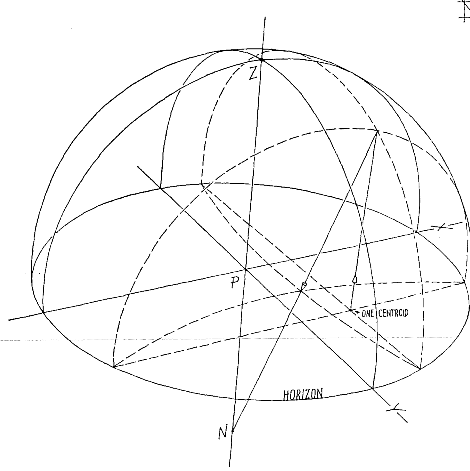


Fig. 51. The projection of the centroids from the horizontal plane up on to the surface of the sphere, and back again on to the horizontal plane with the nadir (N) as projection centre.

This calculation can be simplified by means of a coordinate system turned about the vertical z-axis so that the horizontal projection of the normal to the surface A coincides with the positive y-axis. It then follows that $\sin a_A = 1$ and $\cos a_A = 0$. The equation is simplified to:

$$D_A^H = D_y^H \times \cos h_A + D_z^H \times \sin h_A \ldots\ldots\ldots\ldots \quad \text{eqn 27}$$

Thus the intersection line of the surface A and the horizontal plane coincides with the x-axis. Only the y- and the z-components need to be calculated. See Fig. 49.

Radiation Cards

In many cases it is a considerable labour to project the screen figure on to the xy- and the xz-planes. The stereographic projection was employed for the cal-

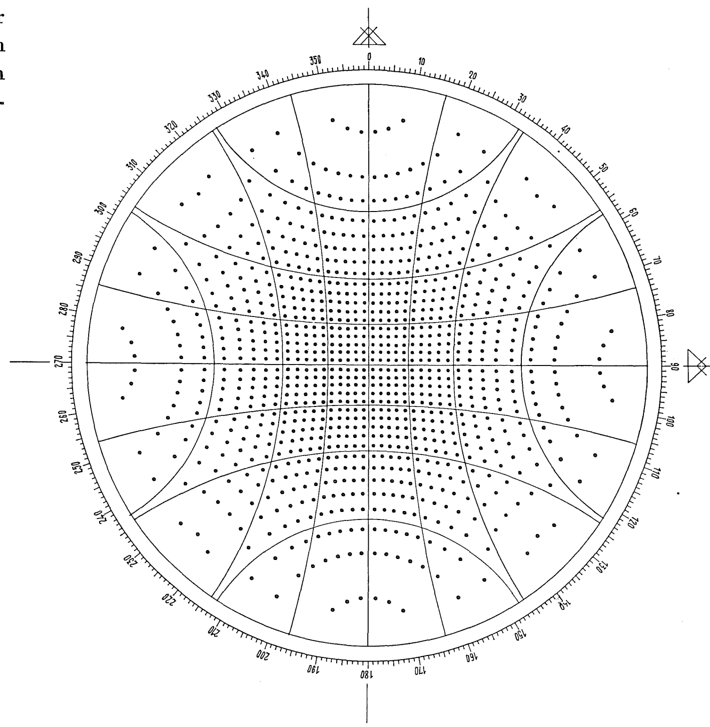


Fig. 52. Sky-card for the z-component from an overcast sky with uniform density of radiation.

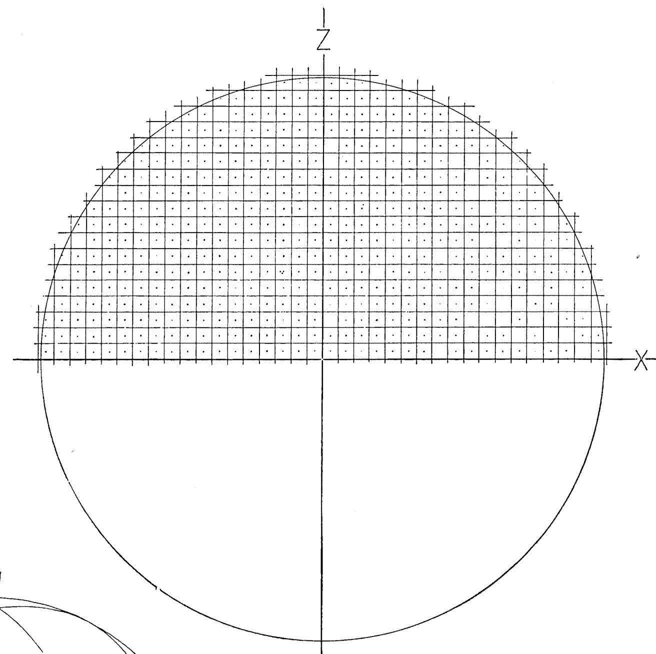
culation of solar radiation and for the duration of such radiation, and the screen figures can also be represented in the same way. It would therefore facilitate the calculation of radiation considerably if the same projection method could be employed for the diffuse radiation instead of the orthogonal projection. The same screen figure could then be used for all the calculations. This is possible and nomograms have been constructed according to the methods below.

The card for the D_z-component is set out in the following way:

The circular area obtained by projecting the unit sphere on to the xy-plane is divided into squares by means of a network, with an area of every square of 1/1000th part of that of the circle. See Fig. 50. Each square is represented by its geometrical midpoint, which also is the centroid of the radiation.

These points lie therefore on the intersection points between two groups of lines with the interval equals the side of the squares. The groups of lines are laid parallel to the x-axis and the y-axis. They are then projected perpendicularly from the xy-plane up on to the surface of the unit sphere. They are then projected again on to the xy-plane with the nadir (N) as centre (stereographic projection). See Fig. 51. The midpoints of the squares now lie on the intersection points of the projected line systems. The appearance of the nomogram is shown on Fig. 52.

Fig. 53. The area of the semicircle is divided into a network of squares similar to Figure 50. Each centre point (and centroid) thus represents 1/1,004th of the horizontal circular area in Figure 50.



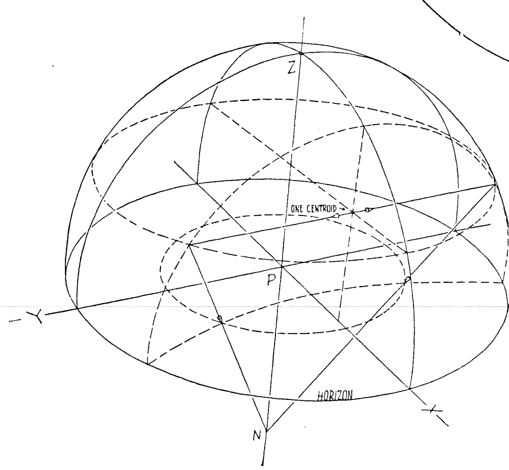
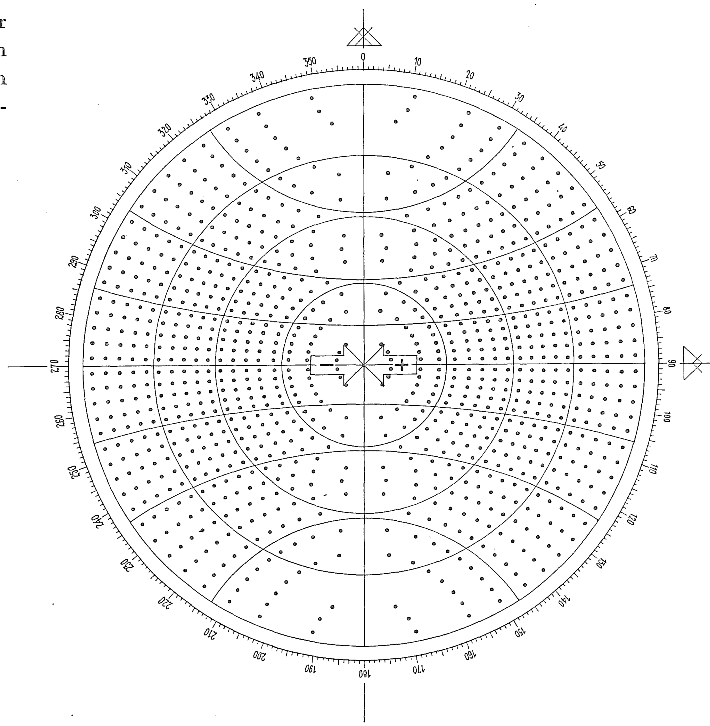


Fig. 54. The projection of the centroids from the vertical plane, first on to the surface of the sphere, then on to the horizontal plane, with the nadir (N) as projection centre.

The construction is fairly simple, since the projections of the groups of lines on the sphere become circles with their centres on the x-axis and y-axis. Circles are again obtained with the re-projection on to the xy-plane. Two points on these circles are known, the intersection of the circles with the horizon (the periphery of the base surface) and only a third point needs to be constructed, conveniently the intersection of the group of lines with the x-axis and the y-axis. Thence three points on each circle of the nomogram are known, and it is consequently simple to construct them.

It is not possible to get exactly 1,000 points with this method of dividing the circular area. The number of points in the base circle will be either 996 or 1,004 because of the symmetry of the figure. The number of points on Fig. 50 and 52 is therefore 1,004. These points are equivalent, they represent 1/1,004th part of the

Fig. 55. Sky-card for the y-component from an overcast sky with uniform density of radiation.



radiation factor of the whole sky vault, $D_z^{H0} = 1$. In use, a screen figure is laid on the nomogram and the number of points are counted which fall on the sky of the screen figure. This figure is divided by 1,004, from whence the z-component of the radiation factor is obtained. To facilitate the calculation the points have been collected together into groups of 25 (not at the horizon).

The card for the D_y-component (and eventually the D_x-component also) is set out in the following way:

The unit sphere intersects the vertical xy-plane also in a circle. The upper half of this is divided with a similar square network as was used for the xz-plane.

The groups of lines through the midpoint of the squares are laid parallel with the x-axis and the z-axis. See Fig. 53.

The groups of lines are then projected perpendicular from the xz-plane on to the surface of the sphere. From thence it is projected down on to the xy-plane with the nadir (N) as centre (stereographic projection). See Fig. 54. The midpoints of the squares now lie on the intersection points of both groups of lines. The appearance of the nomogram is shown on Fig. 55.

The construction is fairly simple in this case also. The projections of the linear systems on the sphere are circles with centres on the x-axis and the z-axis. The projections on to the xy-plane will then be circles again. For the group of lines

Table 52. Diffuse heat radiation on a horizontal plane. Latitude 60° N.

Hourly and daily totals in kcal/m².

Time	11—12 12—13	10—11 13—14	9—10 14—15	8—9 15—16	7—8 16—17	6—7 17—18	5—6 18—19	4—5 19—20	3—4 20—21	2—3 21—22	daily totals
VI	168	161	149	131	109	85	60	37	15	1	1,832
V VII	161	155	141	122	99	74	49	25	4		1,660
IV VIII ..	139	132	118	99	75	48	22	2			1,270
III IX ...	104	98	84	65	41	14					812
II X	67	60	47	27	5						412
I XI	37	31	18	2							176
XII	23	16	4								86

Monthly and yearly totals in Mcal/m².

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
tQ	4.7	10.4	22.9	35.7	49.6	54.3	52.7	41.5	26.7	14.6	6.3	3.1	322.5

Table 53. Diffuse illumination on a horizontal plane. Latitude 60° N.

Hourly and daily totals in klxh.

Time	11—12 12—13	10—11 13—14	9—10 14—15	8—9 15—16	7—8 16—17	6—7 17—18	5—6 18—19	4—5 19—20	3—4 20—21	2—3 21—22	daily totals
VI	29.5	27.9	25.1	21.5	17.4	13.2	9.1	5.4	2.0	0.1	302.4
V VII	27.8	26.3	23.4	19.7	15.6	11.5	7.5	3.7	0.5		272.0
IV VIII ..	23.1	21.7	19.1	15.6	11.6	7.6	3.4	0.2			204.6
III IX ...	16.4	15.3	13.1	10.0	6.1	2.1					126.0
II X	10.4	9.3	7.0	3.9	0.7						62.6
I XI	5.5	4.7	2.7	0.3							26.4
XII	3.5	2.5	0.7								13.4

Monthly and yearly totals in Mlxh.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
vQ	0.71	1.54	3.53	5.76	8.12	8.97	8.65	6.51	4.31	2.23	0.93	0.43	51.7

parallel with the z-axis, the circles are identical with those which previously were obtained for the lines parallel with the y-axis. For the linear system parallel with the x-axis, the circles on the sphere are parallel with the xy-plane and they

Table 54. Diffuse erythemal radiation on a horizontal plane. Latitude 60° N.

Hourly and daily totals in mW/m².

Time	11—12 12—13	10—11 13—14	9—10 14—15	8—9 15—16	7—8 16—17	6 —7 17—18	5—6 18—19	4—5 19—20	3—4 20—21	2—3 21—22	daily totals
VI	495	460	400	310	200	85	10	—	—	—	3,920
V VII	465	425	360	265	150	50	1	—	—		3,432
IV VIII ..	355	320	250	150	55	3	—	—			2,266
III IX ...	180	150	85	20	—	—	—				870
II X	25	10	—	—	—						70
I XI	—	—	—	—							—
XII	—	—	—								—

Monthly and yearly totals in W/m².

Month	I	II	III	IV	V	VI	VII	XIII	IX	X	XI	XII	Year
eQ	—	2.0	21.7	60.9	100.4	116.4	110.1	76.6	33.3	5.3	—	—	526.7

have the z-axis as centre. They therefore offer no difficulty in the projection down on to the xy-plane, where they have the origin as centre.

In this case also the nomogram comprises 1,004 points of which 502 are positive and 502 are negative. In use, the screen figure is laid on the nomogram with the horizontal projection of the normal to the surface A coinciding with the y-axis. The positive and the negative points are counted. The latter are subtracted from the former and the result divided by 1,004, whence is obtained the y-component of the radiation factor.

Radiation Tables

In order to be able to calculate the true radiation and not only the radiation factor, tables must be calculated of the radiation on a horizontal plane with free horizon, E_z^{H0} and Q_z^{H0}. This calculation is achieved by means of equation 14 for heat radiation, equation 16 for illumination, and the curve of Fig. 23 for erythemal radiation, which are combined with information on the solar altitude according to tables or solar charts. Such calculations have been undertaken here for latitude 60° N. The result is shown on Tables 52, 53 and 54, which apply to the three types of radiation under investigation here. They comprise hourly and daily totals for the 20th day of each month, as well as monthly and yearly totals.

The Radiation Density of the Sky

In the foregoing computations it has been assumed that the sky has equal density of radiation at all points. This is a simplifying assumption, which agrees only approximately with the truth. According to measurements by *Kimball and Hand* (41) in the U.S.A., *Kähler* (45) in Kiel, *Hopkinson* (32) in Stockholm, et alia, the overcast sky has a luminance (light density) which decreases from the zenith to the horizon. According to *Moon and Spencer* (66) this should have a significant influence on the indoor daylight. Certain investigations by *Vezey* (94) show that this influence is not, however, of very great significance. This does not imply any contradiction, however, for *Moon* calculated only the light directly from the sky, whereas *Vezey* employed model measurements and thus took reflected light into account. *Vezey*, moreover, expresses the daylight indoors as a fraction of the daylight on the (vertical) window, and therefore the difference between the uniform and the non-uniform sky does not appear. An inequality in the luminance of the sky has in most cases only a small influence on the illumination indoors. This effect cannot, however, be considered to be completely investigated.

Since, however, it has been unanimously established that the radiation density of the overcast sky has a particular distribution, the calculation methods should be adjusted accordingly. *Moon and Spencer* (66) have proposed an equation for the luminance:

$$B_z = B_o(1-2 \cos z)/3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{eqn } 28$$

where B_z is the luminance at a zenith angle z, and B_o is the luminance at the zenith. It can be supposed that the distribution of radiation density is similar for heat radiation and for erythemal radiation, certainly at least for the former. Further studies are required, however, to establish that this is the case.

It is not difficult to adjust the nomograms according to equation 28. The density of the points can be altered so that they become more sparse near the horizon, and closer together near the zenith, the number of points on the nomogram remaining unaltered. This can, however, be deferred until this distribution of luminance has been recommended by the Commission Internationale de l'Eclairage, whose next conference takes place at Zürich in 1955.

Lunelund (58) has established that on clear days the half of the sky where the sun is to be found has a greater light radiation than the other half. The difference can be considerable. At a solar altitude of 45°, 70 % of the diffuse radiation on a horizontal plane comes from the sun's half on the sky, whereas the other half contributes only 30 %. The difference is not so great for lower solar altitudes; when the sun's altitude is 5° the figures are respectively 58 % and 42 %. Since this inequality in the luminance of the sky forms a ring round the sun and follows the sun round during the course of the day, it should by rights be included in the calculation of solar radiation. According to *Pokrowski* (77) the luminance distribution of the clear sky is composed of two parts, one which varies with the altitude and the other which varies with the angular distance from the sun. The latter part should be to some extent related to the sun, but the former will be the luminance of the clear sky. A similar procedure should also be applied to the sky with broken cloud. It is, however, quite a small addition to the radiation from the sun, only about 5 %. No consideration has been taken of these inequalities in this work.

Example I

Screen Figure combined with Solar Chart and Radiation Cards

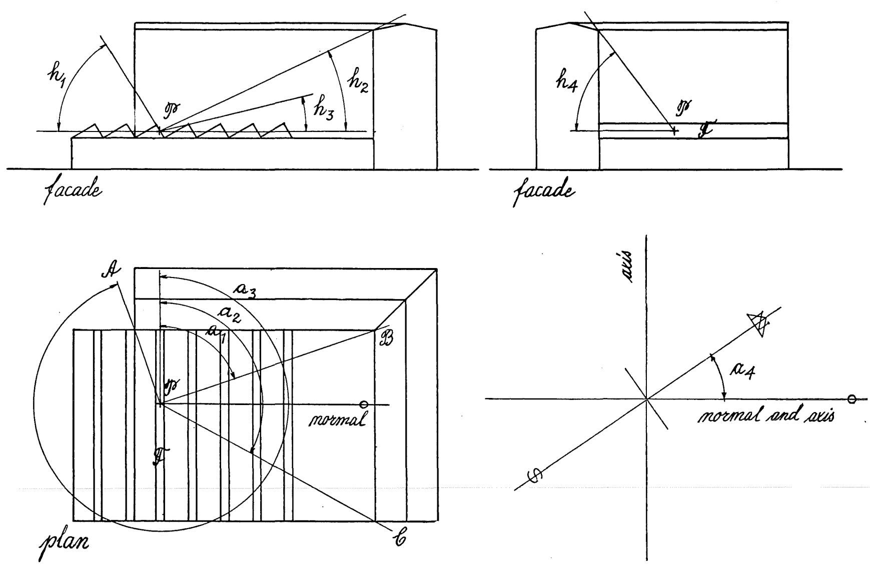


Fig. 56. Plan and facades of a factory building. The heat radiation on the roof-light F in the point P is required.

The calculation of radiation with the solar charts, screen card, and radiation cards proceeds as follows:

The drawing Fig. 56 shows a factory building in Helsinki whose lower section is lighted by saw-tooth roof lights. It is required to determine the heat radiation from the sun and sky at a point *P* on one of these roof-lights *F*.

Stage 1. The azimuths a_1, a_2, a_3 and a_4 and the angles of altitude h_1, h_2, h_3 and h_4 from the point *P* to the obstructing parts of the building are determined, and are drawn on a piece of tracing paper placed over the screen card. Fig. 57:1.

Stage 2. The appearance of the screen figure will now be as shown, and it must now be combined with the solar chart and the radiation cards. Fig. 57:2.

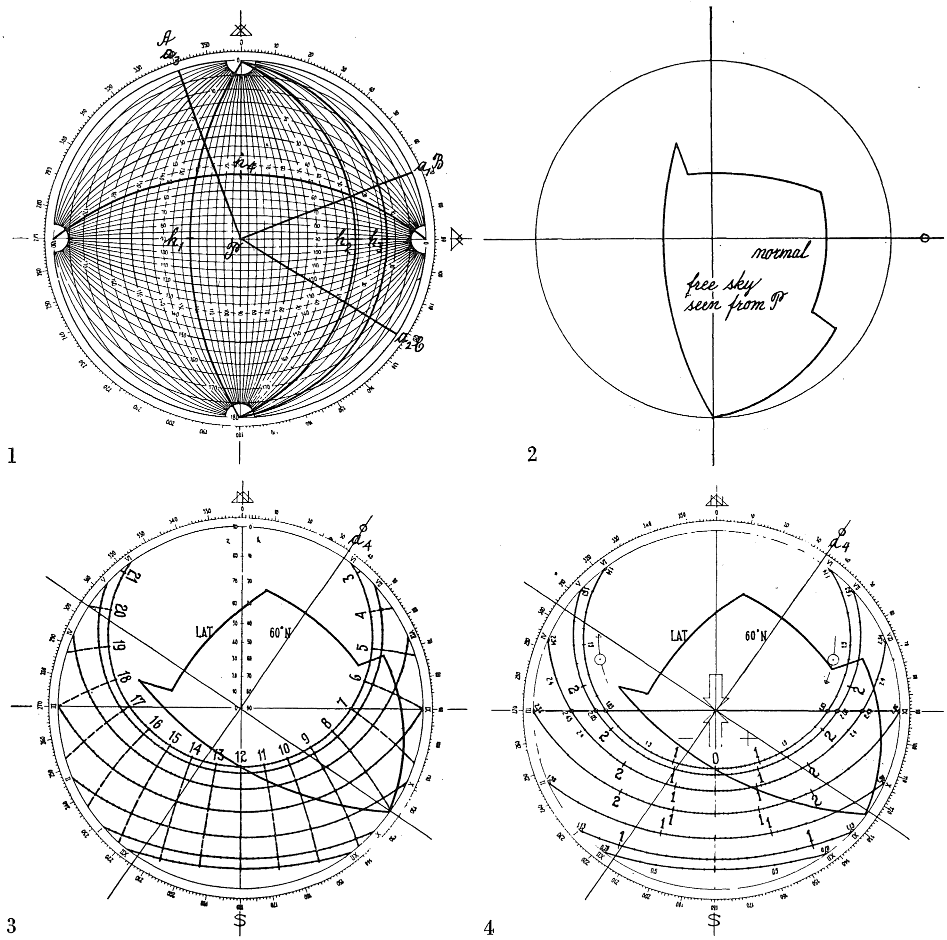


Fig. 57. Stage 1: The screen figure is determined with aid of the screen card. Stage 2: The screen figure. Stage 3: The screen figure combined with the solar chart. Stage 4: The screen figure combined with the heat card for the x-component, Fig. 42x.

Stage 3. The screen figure is placed on the solar chart and orientated correctly with respect to the north-south line. Fig. 57:3. The following insolation times for the point P are read off the chart. There is no sun during November, December and January.

VI	V, VII	IV, VIII	III, IX	II, X
05.20—12.00	05.10—11.30	05.50—10.40	06.40—09.40	07.40—08.30

Stage 4. The screen figure is then placed on the heat card for the x-component, see Fig. 57:4. The heat totals for the time of the sun's emergence $t1$ and disappearance $t2$ are read off the sun paths. The x-component is obtained by substituting in the equation $Q_{(t1\rightarrow t2)} = Q_{t2} — Q_{t1}$ (see eqn 20).

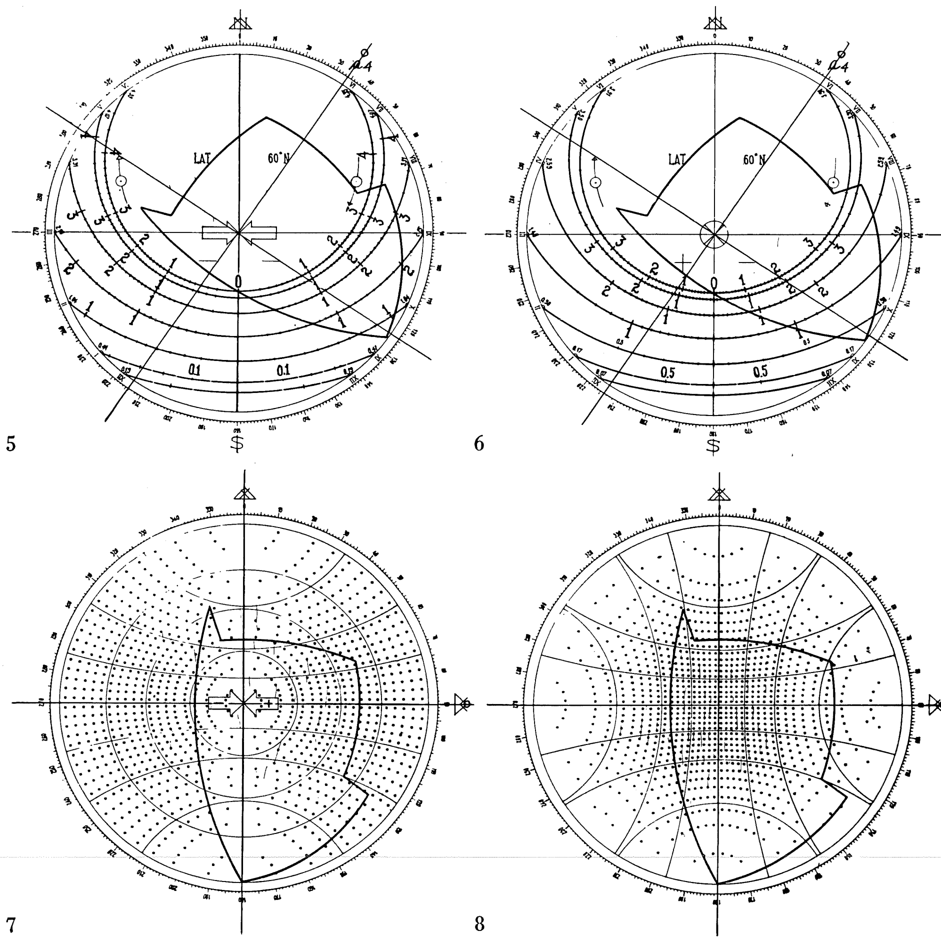


Fig. 57. Stage 5: The screen figure combined with the heat card for the y-component, Fig. 42y. Stage 6: The screen figure combined with the heat card for the z-component, Fig. 42z. Stage 7: The screen figure combined with the sky card for the y-component, Fig. 55. Stage 8: The screen figure combined with the sky card for the z-component, Fig. 52.

Note that the values for times before noon are positive and for after noon are negative. The totals Q_x for a 24-hour period for the 20th of the different months are as follows (Mcal/m²).

VI	V, VII	IV, VIII	III, IX	II, X
0.00—1.63	0.25—1.88	0.90— 2.41	1.60—2.53	1.80—1.95
—1.63	—1.63	—1.51	—0.93	—0.15

Stage 5. The screen figure is placed on the heat card for the *y*-component, see Fig. 57 : 5. The calculation is carried out as for Stage 4. Note that the values

are negative, both for forenoon and afternoon. The totals Q_y for a 24-hour period for the 20th of the different months are as follows (Mcal/m²).

VI	V, VII	IV, VIII	III, IX	II, X
0.00+3.50	—0.05+3.55	—0.20+3.00	—0.60+2.00	—0.80+1.01
+3.50	+3.50	+2.80	+1.40	+0.21

Stage 6. The screen figure is placed on the heat card for the z-component, see Fig. 57: 6. The calculation proceeds as for Stage 4. Note that the values for times before noon are negative and for times after noon are positive. The totals Q_z for a 24-hour period for the 20th of the different months are as follows (Mcal/m²):

VI	V, VII	IV, VIII	III, IX	II, X
0.00+3.72	—0.30+3.41	—0.75+2.47	—0.93+1.47	—0.53+0.58
+3.72	+3.11	+1.72	+0.54	+0.05

Stage 7. The screen figure is then placed on the sky card for the y-component, see Fig. 58: 7. It should be orientated to make the normal at P coincide with the positive y-axis. The unobstructed part of the sky includes 222 positive points and 52 negative points. The component D_y is therefore (222—52)/1,004 = 0.619.

Stage 8. The screen figure is placed on the D_z-card, seeFig. 57: 8. The orientation in this case is unimportant. The unobstructed part of the sky includes 605 points, all positive. The component D_z is therefore 605/1,004 = 0.603.

Stage 9. The calculation of the radiation reaching the window F at the point P now proceeds by the addition of the Q_{xyz}- and D_{yz}-components according to the equations:

$$Q_P = Q_x \times \cos a \times \cos h + Q_y \times \sin a \times \cos h + Q_z \times \sin h$$
$$D_P = D_y \times \cos h + D_z \times \sin h$$

where a = azimuth of the normal to F in P, h = angle of altitude for the same normal.

Solar Radiation

The calculation will be performed here in detail for the month of June (VI) only. The components Q_{xyz} according to Stage 4, 5, and 6 are substituted in the equation for solar radiation. The normal to F in P has the azimuth value a = 34° and the angle of altitude h = 30°. Cos 34° = 0.829; sin 34° = 0.559; cos 30° = = 0.866; sin 30° = 0.500.

Table 55. Monthly and yearly totals of heat radiation for point P on roof-light F, see Fig 56, calculated with the heat radiation tables and cards for Helsinki. $S\varkappa$ = sun radiation by clear sky, modified for the solar time function of clarity for Helsinki, k = per cent clear sky in Helsinki 1928—35, Sk = actual radiation from the sun, Dk = actual radiation from the sky, and Gk = actual global radiation. Unit 1 $Mcal/m^2$ and percent.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
$S\varkappa$	—	0.6	8.4	30.0	58.9	69.6	65.7	40.3	13.5	2.2	—	—	—
k	13	26	30	31	39	44	40	33	28	19	14	12	—
Sk	—	0.2	2.5	9.3	23.0	30.6	26.3	13.3	3.8	0.4	—	—	109.4
Dk	2.1	4.7	10.3	16.0	22.2	24.3	23.6	18.6	12.0	6.5	2.8	1.4	144.5
Gk	2.1	4.9	12.8	25.3	45.2	54.9	49.9	31.9	15.8	6.9	2.8	1.4	253.9

The heat radiation Q_P from the sun for the 20th June is thus:
$Q_P = -1.63 \times 0.829 \times 0.866 + 3.50 \times 0.559 \times 0.866 + 3.72 \times 0.500 = -1.17 + 1.70 + 1.86 = 2.39$ $Mcal/m^2$.

The radiation values for the 20th of the different months are in $Mcal/m^2$:

VI	V, VII	IV, VIII	III, IX	II, X	I, XI	XII
2.39	2.09	1.14	0.28	0.02	0	0

These values are used to enable a year-curve to be drawn, see Fig. 58, which is integrated for all the months, and multiplied by the percentage clear sky, see Table 20, whence the monthly totals in Table 55 are obtained for the prevailing nebulosity, expressed in $Mcal/m^2$.

Diffuse Radiation

The heat radiation factor for diffuse sky radiation is:
$D_P = 0.169 \times 0.866 + 0{,}603 \times 0.500 = 0.146 + 0.302 = 0.448$.

The actual radiation totals, see Table 55 (Dk), for the different months are obtained by multiplying the monthly values for heat radiation on an unobstructed horizontal plane (see Table 52) by the factor D_P.

Global Radiation

The corresponding radiations from sun *S* and sky *D*, according to Table 55, are added and thus the global radiation *G* is obtained.

The heat radiation on an unobstructed horizontal plane for Helsinki is:
Sun $S = 446$ $Mcal/m^2$, Diffuse $D = 323$ $Mcal/m^2$, Global $G = 768$ $Mcal/m^2$. See Table 36.

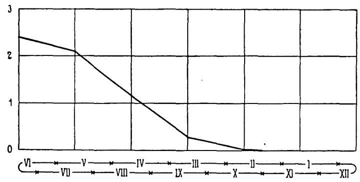


Fig. 58. Curve giving the heat radiation in the point P of the roof-light F, see Fig. 56, for a year period. Vertical scale = Mcal/m²d, horizontal scale = time of year.

The required heat radiations are the following percentages of these values:

Sun	S	$109.4/446 = 0.25$	or 25 %
Diffuse	D	$144.5/323 = 0.45$	or 45 %
Global	G	$253.9/768 = 0.33$	or 33 %

Compared with the figures for a horizontal light opening the percentage diffuse radiation is therefore very much greater than the percentage solar radiation; this is an advantage, because the diffuse radiation has a higher luminous efficiency than solar radiation. Consequently good lighting will be obtained without too great a degree of heat penetration.

For a complete analysis of the lower section of this factory building, several points evenly distributed about the roof-lights should be investigated, at least three and preferably five points for every row of windows. Experience with the method will indicate how many points should be taken, and will also lead to many simplifications in the procedure. For example, calculations made for a few selected significant points will enable approximate curves to be drawn from which values for all other required points can be obtained by interpolation. Similarly, buildings and obstructions with symmetrical layouts lend themselves to simplifications in the calculations. Such an analysis will not be carried out here.

Example II

Globoscope Picture combined with Solar Chart and Radiation Cards

The calculation of radiation by means of the globoscope pictures proceeds as follows:

The globoscope picture is first orientated correctly with respect to the points of the compass. This can be done with the aid of the town planning map to a scale of 1 : 4000 or 1 : 1000. Using an ordinary miniature slide projector the globoscope picture can then be projected on to the appropriate nomogram for the radiation calculations and the radiation components can be read off. If copies of the globoscope picture are required, a nomogram can be placed above the sensitised paper and printed at the same time as the picture. If the prints are made on dimensionally-stable sensitised material the nomogram can subsequently be laid on top of the print and the components can be read off exactly as with a theoretical screen figure. It is important to ensure that the horizon of the photograph and the pointer coincide with the corresponding lines in all these combinations of nomogram and globoscope picture.

Some examples are given below of combinations of nomograms and globoscope pictures which were made in a photographic enlarger. The horizon circle has a diameter of 15 cm on the originals.

Fig. 59 shows the globoscope picture of Fig. 31 A combined with the solar chart for latitude 60° N and the radiation card of Fig. 42 z and Fig. 52 which refer to the heat radiation from sun and sky on a horizontal plane (Helsinki).

From Fig. 59 A are read off the time points for the emergence and disappearance of the sun, and the following radiation times are obtained for the 20th of the months:

VI	V, VII	IV, VIII	III, IX	II, X
+16.20—6.05	+18.30—6.35	+14.00— 6.45 +18.20—17.00 +18.50—18.40	+9.30— 6.45 +12.35—10.00	+9.00— 8.20 +11.45—11.10
12 h. 15 m.	12 h. 5 m.	8 h. 45 m.	5 h. 10 m.	1 h. 15 m.

There is no sun visible during November, December, and January.

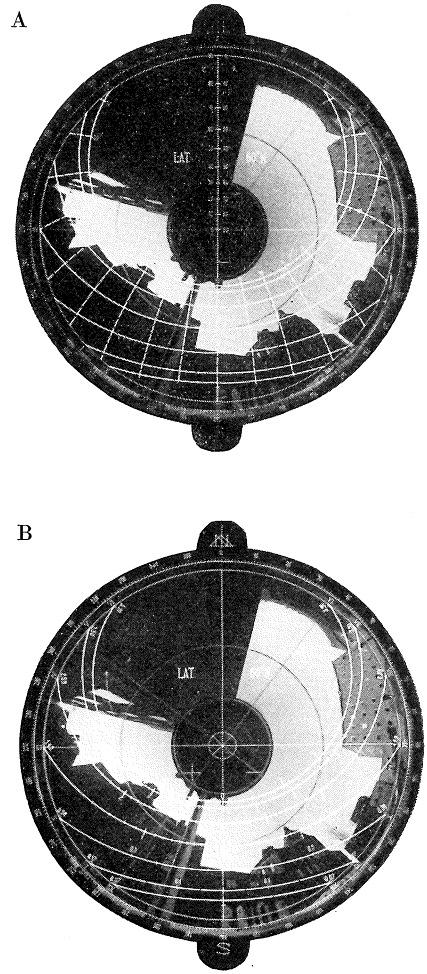


Fig. 59. A: The globoscope picture Fig. 31 A combined with the solar chart for latitude 60° N. B: The same globoscope picture combined with the heat card for the z-component, Fig. 42z.

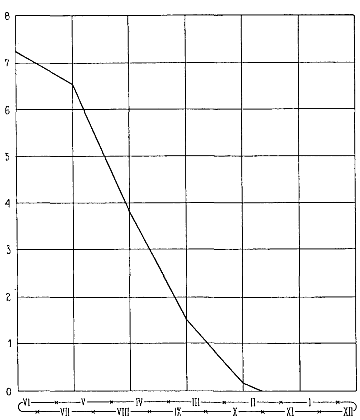


Fig. 60. Curve giving the heat radiation on the horizontal plane in the point where the globoscope picture has been taken. Vertical scale = Mcal/m²d, horizontal scale = time of the year.

From Fig. 59 B are read off the accumulated totals for the sun's emergence ($t1$) and disappearance ($t2$) and these are substituted in the equation $Q_{(t1\rightarrow t2)} = Q_{t2} - Q_{t1}$. The following totals in Mcal/m²d are obtained:

VI	V, VII	IV, VIII	III, IX	II, X
+3.66+3.57	+3.39+3.15	+1.30+2.45 +2.54—2.41	—1.00+1.45 +0.26+0.82	—0.52+0.55 —0.05+0.20
7.23	6.54	3.88	1.53	0.18

During November, December, and January there is no direct radiation from the sun. A diagram is drawn up with the aid of these figures, see Fig. 60, from which the totals are found as shown in Table 56.

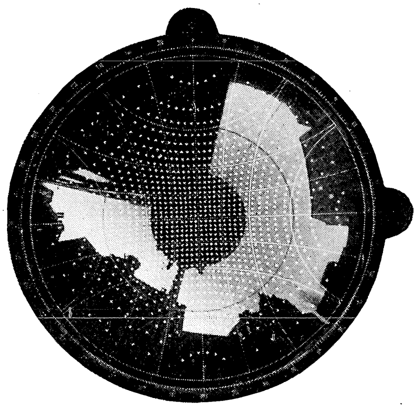


Fig. 59 C: The same globoscope picture combined with the sky card for the z-component, Fig. 52.

Fig. 59 C gives the number of points which can be counted on the unobstructed part of the surface of the sky. This number is 634. This figure is divided by the total number of points = 1,004, whence the radiation factor D_z is 634/1,004 = =0.63. The monthly totals according to Table 52 are multiplied by this factor to give the actual monthly radiation totals, see Table 56.

Table 56. Monthly and yearly totals of heat radiation for the point on the horizontal surface where the globoscope picture, according to Fig. 31 A, has been taken. $S\varkappa$ = sun radiation by clear sky, modified for the solar time function of clarity for Helsinki, k = percent clear sky in Helsinki 1928—35, Sk = actual radiation from the sun, Dk = actual radiation from the sky, and Gk = actual global radiation. Unit 1 $Mcal/m^2$ and percent.

Month	1	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
$S\varkappa$	—	4.8	41.9	104.4	185.4	210.9	203.1	133.9	59.1	14.0	—	—	—
k	13	26	30	31	39	44	40	33	28	19	14	12	—
Sk	—	1.2	12.6	32.4	72.3	92.8	81.2	44.2	16.6	2.7	—	—	356.0
Dk	3.0	6.6	14.4	20.4	31.2	33.6	33.2	26.1	16.8	9.2	4.0	2.0	200.5
Gk	3.0	7.8	27.0	52.8	103.5	126.4	114.4	70.3	33.4	11.9	4.0	2.0	556.5

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FÖRTECKNING ÖVER BYGGNADSLITTERATUR

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Statens Byggeforskningsinstitut

The Danish National Institute of Building Research
Borgergade 20, Köpenhamn K

Rapporter (Reports)

1. *Becher, Poul.* Økonomisk varmeisolering (Economical Heat-Insulation, with an English summary). 1949. 2. udgave 1950. 61 p. Dkr. 7: —.
2. *Becher, Poul.* Gymnastiksales akustik (Acoustics of Gymnasia, with a brief English summary). 1950. 2 p. (Udsolgt—out of print.)
3. *Andersen, Johs., Nerenst, Poul* and *Plum, Niels M.* The Non-Destructive Testing of Concrete with Special Reference to the Wave Velocity Method (engelsk tekst). 1950. 80 p. (Udsolgt—out of print.)
4. *Andersen, Johs., Bredsdorff, Per, Krarup, Niels H., Malmstedt-Andersen, K., Nerenst, Poul* and *Plum, Niels M.* Testing of 11 Danish Concrete Mixers (engelsk tekst). 1951. 236 p. Dkr. 25: —.
5. *Krarup, Niels H.* Sammenlignende undersøgelse af træ- og stålstilladser til husbygning (Wooden and Steel Scaffolding for Building Construction, with an English summary). 1951. 44 p. (Udsolgt—out of print.)
6. *Plum, Niels M.* Vinterbyggeri, forsøg afholdt af Statens Byggeforskningsinstitut i årene 1947—50 (Winter Construction, Experiments made by the Danish National Institute of Building Research in 1947—50, with an English summary). 1951. 108 p. (Udsolgt—out of print.)
7. *Plum, Niels M.* Dæk og huse. 1. del: Tekst, 178 p. 2. del: Figurer, 46 p. (Floor Constructions and Houses. Part 1: Text, Part 2: Figures, with an English summary.) 1952. Dkr. 20: —.
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The Computation of Natural Radiation in Architecture and Town Planning

UDC 551.521:711:72

Existing methods for the computation of radiation from sun and sky are unsuitable for use in architecture and town planning. They are too slow and are greatly in error, especially in coastal regions. A new method is presented, which is more speedy and yields a result in good agreement with the measurements which have been obtained in various stations in the North. The method, which is a combination of graphical and numerical procedures, is devised for the computation of three manifestations of radiation: heat, light and ultra-violet. Nomograms for the calculation of these qualities are presented together with examples of their use. A photographic instrument, the Globoscope, which has been constructed in order to facilitate the calculations in certain situations, is described also with examples.

Beräkning av naturlig strålning inom arkitektur och stadsplanekonst

UDK 551.521:711:72

De beräkningsmetoder för strålningen från sol och himmel som finnas äro olämpliga att använda inom arkitekturen och stadsplanekonsten. De äro för långsamma och ge stora fel, i all synnerhet i kusttrakter. En ny metod presenteras, som är snabbare och ger ett resultat i god överensstämmelse med de mätningar som utförts på skilda håll i Norden. Metoden, som är en kombination av grafiskt och numeriskt förfarande, genomföres för tre strålningskvaliteter: värme, ljus och ultraviolett. Beräkningsnomogram för dessa presenteras jämte exempel på användningen. Ett fotografiskt instrument, globoskopet, konstruerat för att i vissa situationer underlätta beräkningen, beskrives också jämte exempel.

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