Determining daylight factor and insolation with radian diagrams

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1 Introduction daylight factor

The amount of daylight shed on a specific point in a room depends on many aspects:
- the sizes and the locations of the window openings;
- the extent to which these window openings are transparent for light (type of glass, pollution, etc.);
- any shielding off by buildings on the opposite side or by parts of the same building;
- external reflections, light reflected by other buildings, pavement, etc.;
- internal reflections, light that has come in and is reflected by inner walls, ceilings, etc.

All factors contributing together determine the lighting intensity inside according to the general lighting formula. However, it is obvious that the amount of incident light mainly depends on the amount of light available outdoors, the intensity of which may vary considerably.
At the same time, there is a distinction between direct light (focused sunlight) and diffuse light emitted by the dome of the sky with a specific luminance distribution.
Since the amount of light outdoors varies so much, the so-called daylight factor d is used for determining the extent of daylight lighting. This daylight factor indicates the proportion of the lighting intensity inside at a specific spot to the lighting intensity on the horizontal surface outdoors in the open field at the same point in time.

$$d = \frac{E_{inside}}{E_{outdoors,\ open\ field}}$$

In this formula direct sunlight is ignored; only light emitted diffusely by the dome of the sky is taken into account. It is known from measurements which lighting intensity is present in the open field. Referential values for the Netherlands are given in figure 1.

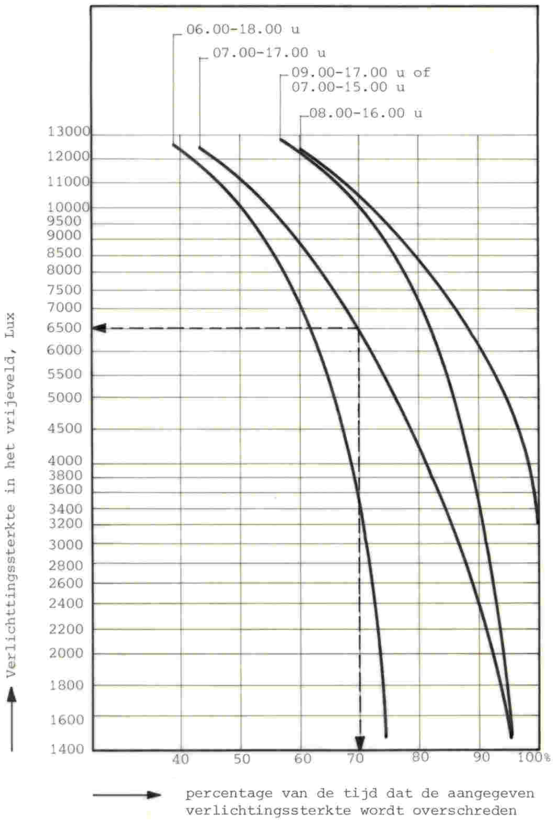


figure 1. referential values for lighting intensity in the open field in the Netherlands. Note: times are given in solar time

Suppose a lighting intensity of at least 400 lux is required in an office building on the working plane, and suppose the building had been designed in such a manner that the daylight factor d amounts to 6% for a workplace not too far from the window, this implies that when the lighting intensity outdoors decreases to a level lower than 400/0.06 = 6500 lux, the artificial lighting will have to be switched on. If the building's operating hours are 08:00-17:30 (clock time), the line in the diagram for 07:00-17:00 hrs fits best. This is because the lines in the diagram are given for specific solar times, so that the line chosen (in winter, at an average for the Netherlands) is valid for 07:40-17:40 hrs clock time.

It turns out that a value of 6500 lux for the lighting intensity outdoors is exceeded in 70% of the total time. In global terms, this means that during at least 30% of the time artificial lighting will have to be switched on. This corresponds to approximately 700 hours per year. In practice, however, the light will be on for a longer period of time, since people often forget to switch it off when they do not need it any longer. Facilities of modern control engineering may come in handy here.

2 Determining the daylight factor

The daylight factor is determined by the sum of:

- the direct contribution of the visible part of the dome of the sky: the sky component d_h;
- the contribution as a result of reflection of light against surfaces visible from the observation point, outside of the window (the light opening): the external reflection component d_e;

- the contribution as a result of reflections of light, which has come in through the light opening, against inner walls, ceiling, etc. in the room: the internal reflection component d_i.

Of importance here are the transparency for light of the material in the window opening (glass, sunblinds, etc.), its pollution, light-blocking parts of the building itself and of other buildings (porches and similar objects).
Any reduction in light caused by a polluted atmosphere is not taken into account in the calculation of the daylight factor, but it obviously has its influence on the light intensity outdoors in the open field. In areas which are seriously polluted the lighting intensity can be reduced to less than half of the intensity in a clean atmosphere.

2.1 The sky component, without glass losses, dh

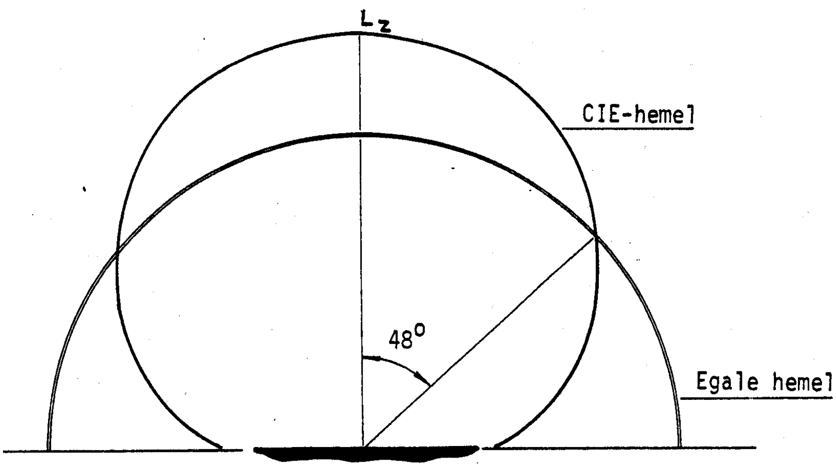
The direct contribution of the light emitted by the dome of the sky can be determined with the diagrams shown in module LI-3E; “Light – basic concepts (elaboration)” figures 8 and 9. As a rule, for the luminance of the dome of the sky one starts from a distribution as fixed by the C.I.E. (Commission Internationale de l’Eclairage) on the basis of research carried out by Moon and Spencer. This distribution is as given below:

$L(h) = L(90°) \cdot ((1+2 \cdot \cos \alpha) / 3)$ [$_{cd/m^2}$]

In this formula:

L(h)	the dome of the sky’s luminance at a specific height (angle h with the horizontal surface)
L(90°)	the luminance at the zenith

From measurements it appears that this distribution is also a good approach for most cloud conditions in the Netherlands. Only in case of very heavy, low-lying clouds the distribution matches a uniform sky better.
If, for a height of h = 42°, the luminance is equated for both distributions, they produce identical lighting intensities on the horizontal surface in the open field: E = π . L(42°) lux.



Both luminance are given in figure2 and table 1.

figure 2. luminance distributions for a uniform sky and for the sky according to C.I.E. Both distributions produce the same lighting intensity on a horizontal surface
(“CIE-hemel” = sky C.I.E.; “egale hemel” = uniform sky)

H	L(h)/L(42º)	H	L(h) /L(42º)
0º	0.43	45º	1.03
5º	0.50	50º	1.09
10º	0.58	55º	1.13
15º	0.65	60º	1.17
20º	0.72	65º	1.20
25º	0.79	70º	1.24
30º	0.86	75º	1.26
35º	0.92	80º	1.27
40º	0.98	85º	1.28
42º	1.00	90º	1.29

For an elevation (h) of 42º the luminance of the C.I.E. distribution equals the one for a uniform distribution, if both distributions produce identical lighting intensities on the horizontal surface.

table 1. values for the luminance distribution according tot C.I.E.

For determining the sky component light openings are plotted on the radian diagram.This produces a projection of that part of the dome of the sky that can be seen through the window. Also see the example in appendix A, figures A-1 up to and including A-4.
The Technical University Eindhoven has developed a diagram which can be used in combination with the radian diagram. This so-called daylight diagram is divided into a large number of squares, all of which equally (0.1%) contribute to the lighting intensity on the horizontal surface. The diagram comes in two versions: one for a uniform sky and one for a dome of the sky with a luminance distribution according to C.I.E.
In figure A-4 the number of squares can be counted (partial squares are to be counted as precisely as possible) in the diagram for a uniform sky. For the window approximately 48 squares are counted, for the dormer window approximately 62. This means a sky component (without glass losses) of d_h^* = 4.8% and d_h^* = 6.2% respectively.
If the diagram for the C.I.E. distribution is used, the results are d_h^* = 3.9% and d_h^* = 7.1% respectively. The sum of these values happens to be the same for both diagrams. However, for this luminance distribution the contribution of the dormer window is larger and that of the window in the façade smaller.

3 The external reflection component d_e^*

For determining the external reflection component, the luminance of, in principle, all surface areas capable of reflecting daylight into the direction of the light opening concerned should be determined. Next, the contribution of these reflections to the lighting intensity should be determined. This task is time-consuming and hard to be carried out in a precise way. That is why, and also because the contribution to the daylight factor often is rather small, we usually limit ourselves to the approximation described below.
The luminance of obstacles which may be visible through the light opening from the measuring point, is assumed to take up approximately 15% of the dome of the sky behind these obstacles. This implies that the external reflection component can be determined by calculating the sky component of the part of the dome of the sky that is hidden from view by the obstacles using the diagrams, and by multiplying the result by 0.15.

$d_e^* = 0.15 \cdot d_h^*$

Here, d_h* is the sky component of the part of the dome of the sky which is hidden from view by obstacles. If the surrounding buildings have very strong reflections (light colours), a value for the "reflection" slightly higher than 15% may be chosen. However, in this situation it is often worth while making a more precise calculation.
A very light floor cover can also substantially contribute to the lighting intensity indoors, through reflections against, for example, the room's ceiling. Usually, however, this contribution is negligible.

3.1 Losses in the light opening, factor c

Part of the incident light is reflected and absorbed by the glass (or other materials) in the light opening and by any sun-reflecting constructions. The factor Light Access Absolute (LTA; Du.: LichtToetredingsfactor Absoluut) shows which part of the incident light will manage to enter the room.
For single and double glazing LTA's are:
LTA 0.85 a 0.90 single glazing
LTA 0.70 a 0.80 double glazing

For bars of the window (rails and jambs) or for the influence of the window frame, a reduction factor c_k can be derived from the proportion of the net glass surface to the total surface including bars and/or frame, if these were initially left out of the calculation. If little is known of the window frame, we may assume as a preliminary value:

$c_{k=}$ 0.85

Due to pollution there may be a further reduction in light transparency of 0.9 to 0.5 times the value of a clean construction:

$c_{v=}$ 0.9 to 0,5

The preceding leads to a total of losses in the light opening of factor c:

C= LTA . c_k . c_v

3.2 The internal reflection component di

When light falls on a surface in a room, this surface will reflect part of the incident light depending on its own characteristics. In this way the surface, in its turn, will contribute to the lighting of other surfaces in the room, including the working plane. The calculation of this effect is very complicated; in principle the general lighting formulas as discussed in chapter LI-3E "Light – basic concepts (elaboration)" may be used for this. Fortunately, there are computer programs for determining the internal reflections, the resulting luminances of the various surfaces in the room and the lighting intensity on the working plane.
In order to get an impression of the size of the internal reflection component d_i without arithmetical work, Table 2 can be used. This table shows the component d_i in percentages for various reflection factors for walls, floor and ceiling (also see table 1, module LI-3E; "Light – basic concepts (elaboration)". In doing so the table takes into account an average situation for

losses in the light opening and any obstructions, taking single glazing as a starting point. When other glass types are used, possibly in combination with sun-reflecting constructions, the table value should be corrected for the actual LTA. The table now works with LTA = 0.9. Therefore, the correction factor for double glazing will be $LTAd_g/LTAe_g$ = 0.8/0.9 = approx 0.9. If it turns out from the calculation that the contribution of d_i is decisive for the total daylight factor, it is worth while making a precise calculation of the internal reflection component.

70% ceiling reflection

proportion glass surface to floor surface	**reflection factor floor**											
	10%				**20%**				**40%**			
	reflection factor inner walls											
	20%	**40%**	**60%**	**80%**	**20%**	**40%**	**60%**	**80%**	**20%**	**40%**	**60%**	**80%**
1 : 50	-	-	0.1	0.2	-	0.1	0.1	0.2	-	0.1	0.2	0.2
1 : 20	0.1	0.1	0.2	0.4	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6
1 : 14	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6	0.2	0.3	0.6	0.8
1 : 10	0.1	0.2	0.4	0.7	0.2	0.3	0.6	0.9	0.3	0.5	0.8	1.2
1 : 6.7	0.2	0.4	0.6	1.0	0.2	0.5	0.8	1.3	0.4	0.7	1.1	1.7
1 : 5	0.2	0.5	0.8	1.4	0.3	0.6	1.1	1.7	0.5	0.9	1.5	2.3
1 : 4	0.3	0.6	1.0	1.7	0.4	0.8	1.3	2.0	0.6	1.1	1.8	2.8
1 : 3.3	0.3	0.7	1.2	2.0	0.5	0.9	1.5	2.4	0.8	1.3	2.1	3.3
1 : 2.9	0.4	0.8	1.4	2.3	0.5	1.0	1.8	2.8	0.9	1.5	2.4	3.8
1 : 2.5	0.5	0.9	1.6	2.6	0.6	1.2	2.0	3.1	1.0	1.7	2.7	4.2
1 : 2.2	0.5	1.0	1.8	2.9	0.7	1.3	2.2	3.4	1.2	1.9	3.0	4.6
1 : 2	0.6	1.1	1.9	3.1	0.8	1.4	2.3	3.7	1.3	2.1	3.2	4.9

table 2. global values for the internal reflection component for single glazing (LTA = 0.9) and average circumstances for further losses in the daylight opening and external reflections

3.3 Determining daylight factor d – adding up the various components

The daylight factor can be seen in the sum of the components as calculated above.

$d = d_h + d_e + d_i$ or: $d = (d_h^* + d_e^*) . c + d_i^* . LTA/0.9$

In this formula:

d_h* sky component without glass losses
de* external reflection component without glass losses
c reduction factor for losses in the light opening ($c = LTA.c_k.c_v$)
di* internal reflection component from Table 4.2, including average losses
LTA light access factor of the window system (see e.g. figure 7.11 on page 125 in *Book Building Physics* (Du.: *Boek Bouwfysica*))

Using radian diagram and daylight diagram appendix A

Introduction

In this appendix the plotting of the projection of daylight openings on the radian diagram is discussed, and it is shown how the sky component (without glass losses) in the daylight factor can be determined with the aid of a daylight diagram.

The radian diagram

A point in space is established in a system of sphere co-ordinates by azimuth (α), elevation (ε) and the distance to the origin (r). The latter co-ordinate (r) is lost during projection in a flat (two-dimensional) surface. Therefore, in a radian diagram a point is only established by elevation and azimuth. Using some construction lines we can establish lines as well, along with points, in the diagram A-4. This is illustrated with an example (see figure A-1).

In a room there are a window and a dormer window. In order to be able to determine elevation and azimuth of the boundaries of the window and the dormer, a construction surface N is put in, in such a manner that the boundaries of window and dormer are parallel or perpendicular to this surface
The values of α (azimuth) and ε_1 (lines ⊥ N) and ε_2 (lines // N) can be measured or calculated in a simple way from the floor plan and the section of the room (see figures A-2 and A-3). If the angles are known, the matter can be plotted into the radian diagram (see figure A-4).
Finally, a transparent daylight diagram can be put on the plotted projection, so that the sky component can be determined by counting the squares.

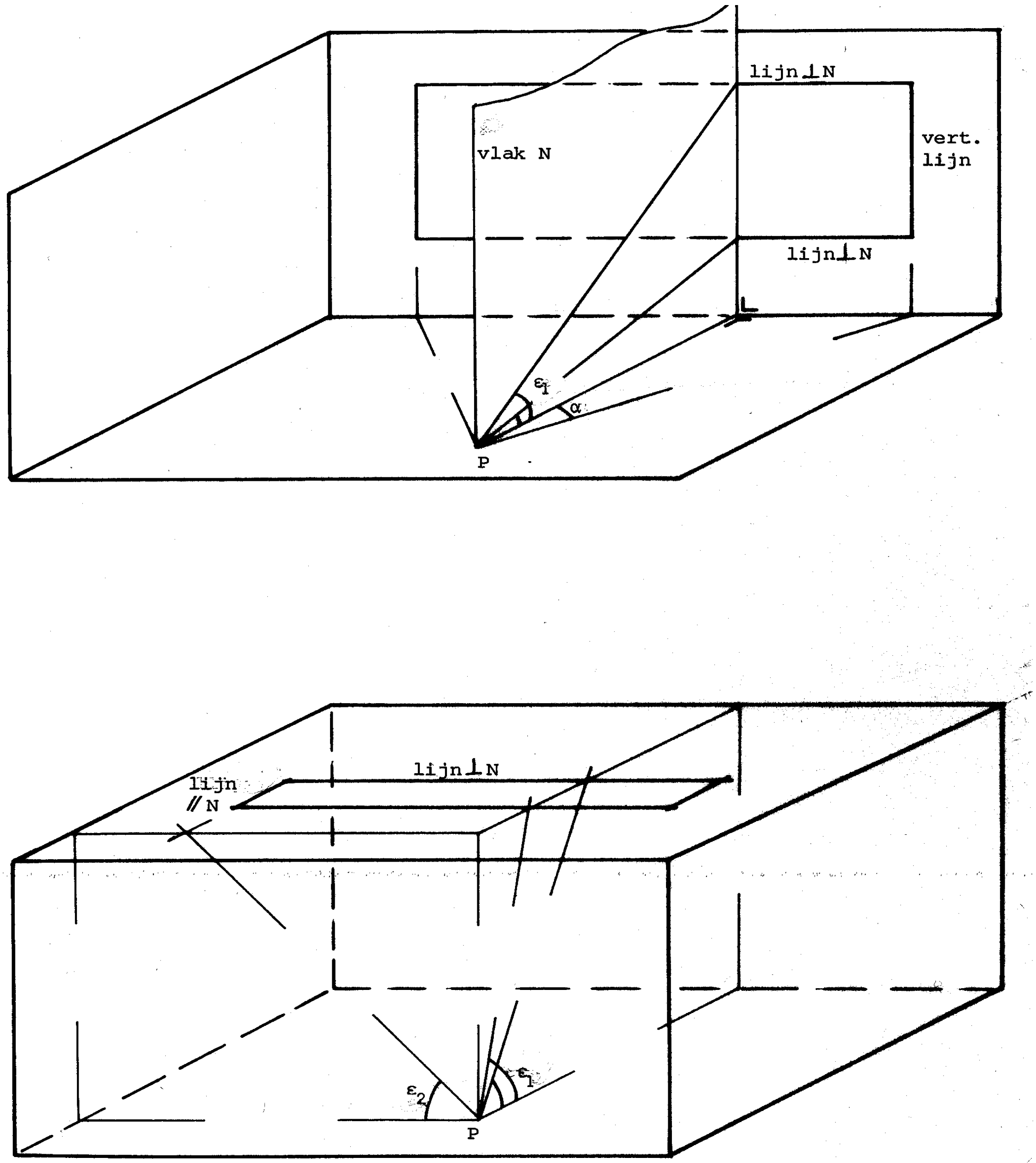


figure A-1. establishing azimuth (α) and elevation (ε) of the boundaries of surfaces for projection into a radian diagram
("lijn" – line ⌊ N; construction surface N; "vert.lijn" = vertical line)

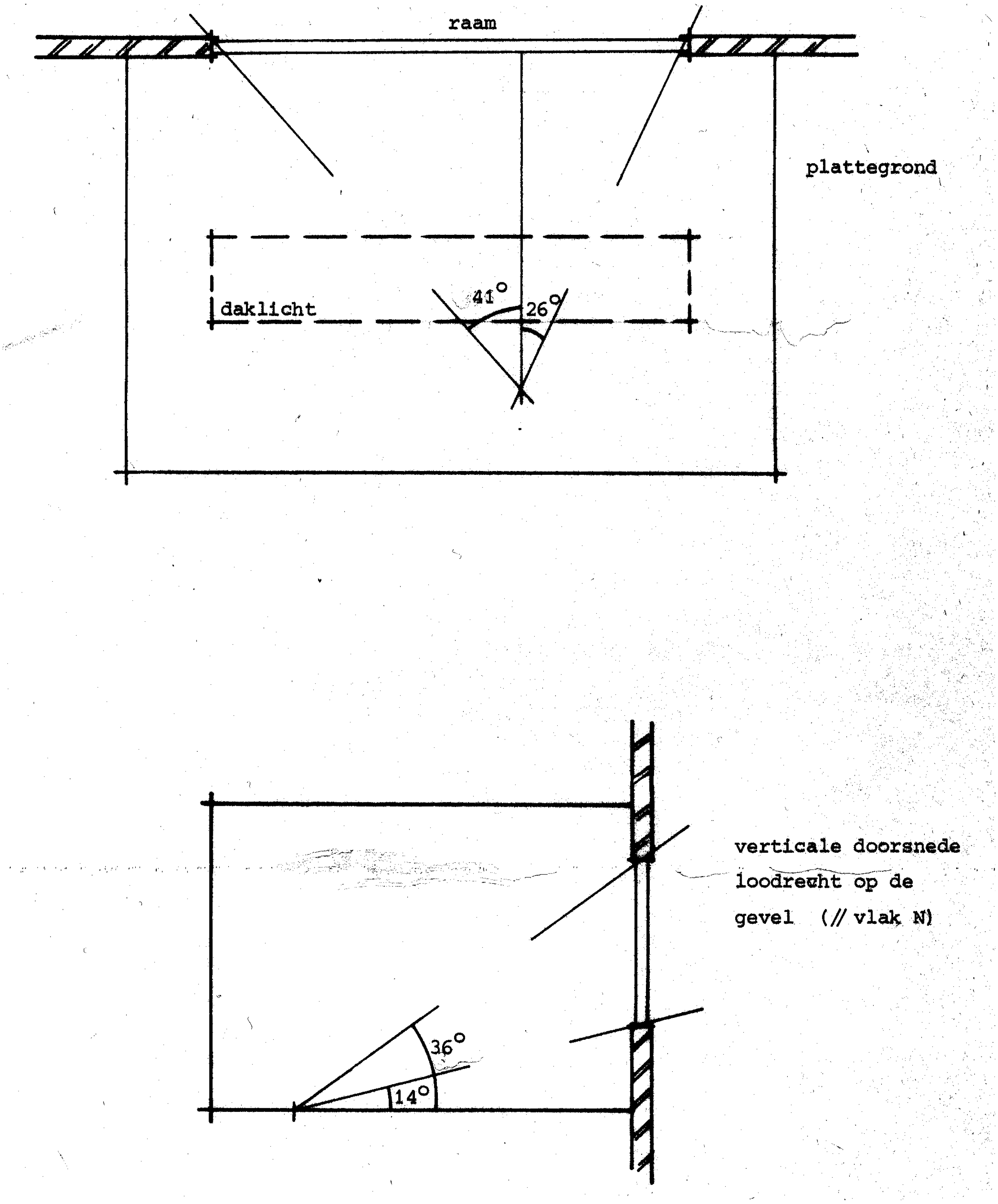
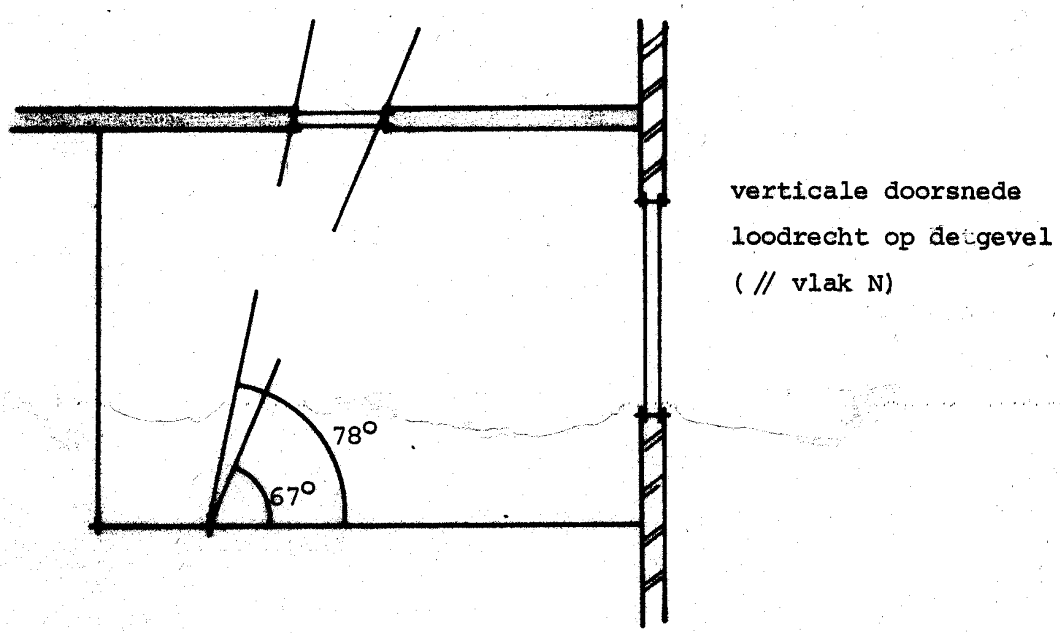


figure A-2. establishing azimuth (α) and elevation (ε) for the window in the room used as an example
("raam" = window; "plattegrond" = floor plan; "daklicht" = dormer window)
("verticale doorsnede loodrecht op de gevel" = vertical section perpendicular to the façade) (// surface N)



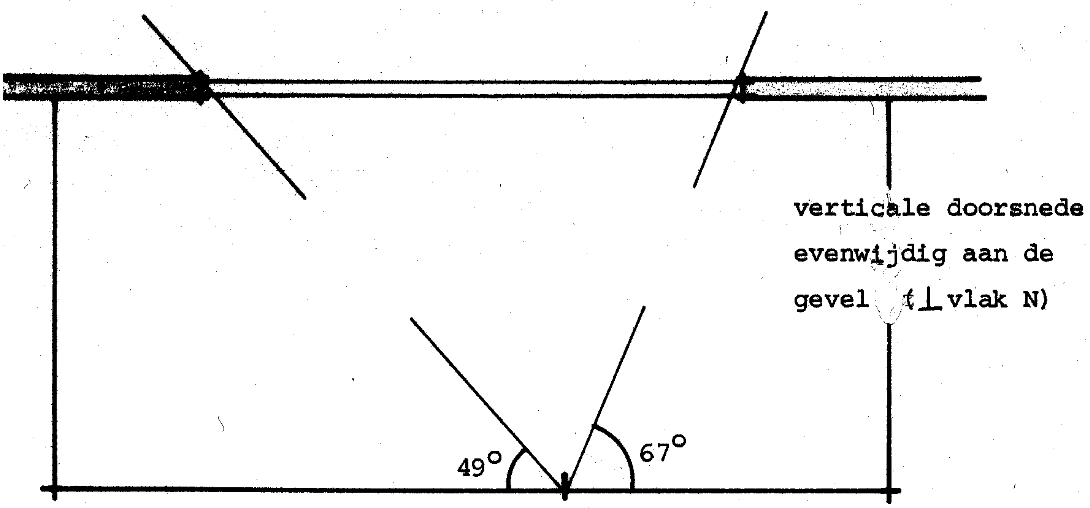


figure A-3. establishing azimuth and elevation for the dormer window in the room used as an example ("verticale doorsnede loodrecht op de gevel" = vertical section perpendicular to the façade (// surface N; "verticale doorsnede evenwijdig aan de gevel" = vertical section parallel to the façade (⊥ surface N)

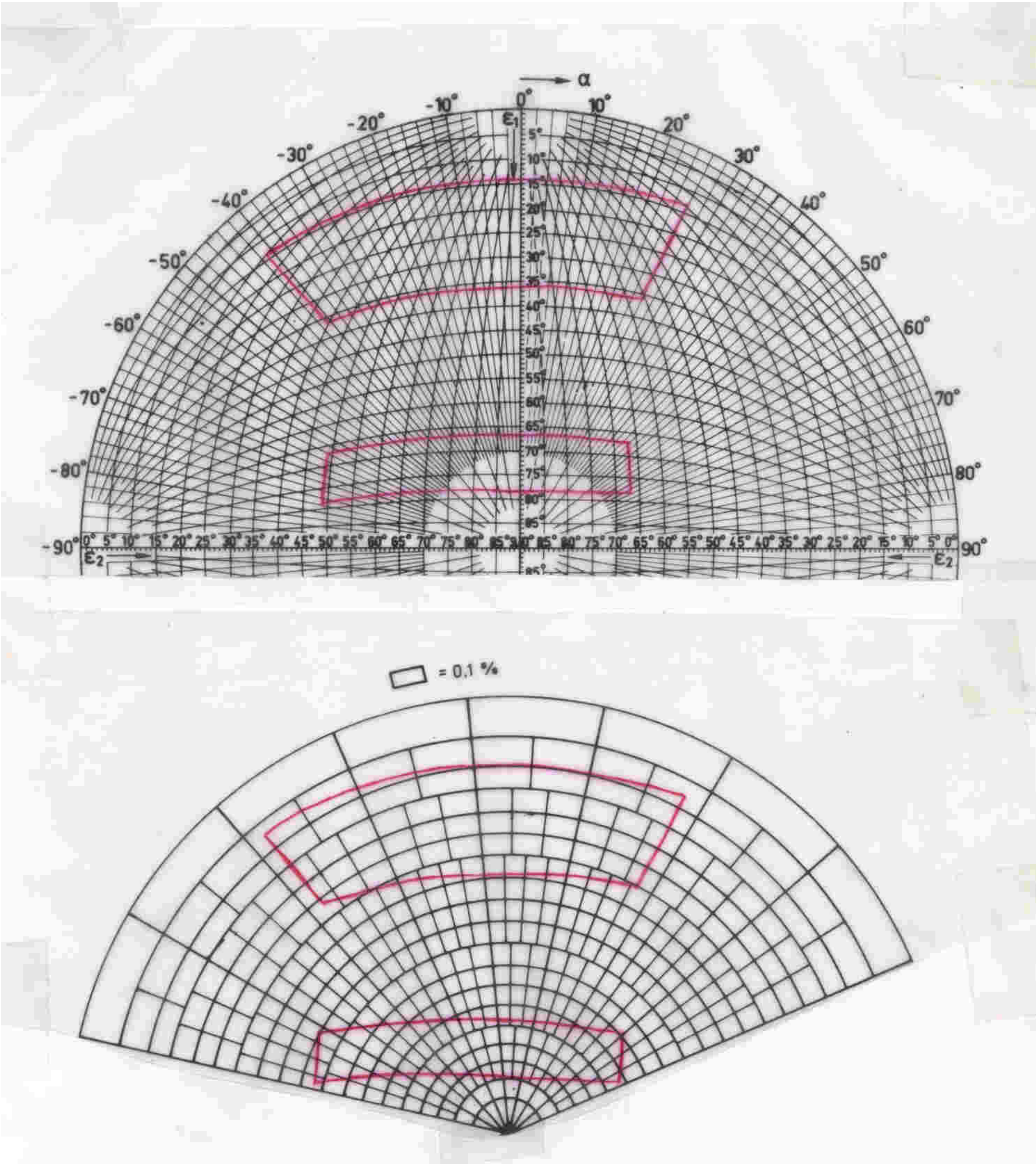


figure A-4. window and dormer window plotted into a radian diagram and a diagram for the determination of the sky component for an even distribution of the luminance (uniform sky) ("raam: 48 vakjes" = window: 48 squares; "daklicht: 62 vakjes"= dormer window: 62 squares

Using radian diagram and sun trajectory diagram appendix B

Introduction

In the Lecture notes Introduction to Building physics (ct3071) a sun trajectory diagram is discussed. This diagram can also be used in combination with the radian diagram for the evauation of sun access through a window. This is explained using the following example. The insolation of point P is investigated, at a distance of 1 metre from the façade in the middle of a window, in this example directed to the southeast.

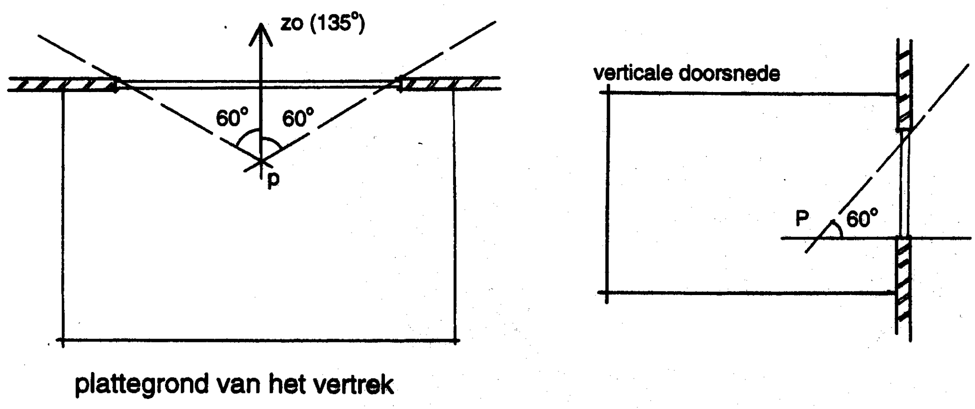


figure B-1. determining the angles needed for plotting the projection of the window into the radian diagram ("plattegrond van het vertrek" = floor plan of the room; "verticale doorsnede" = vertical section)

Plotting the window into the radian diagram is done in the way described above (in Appendix A).

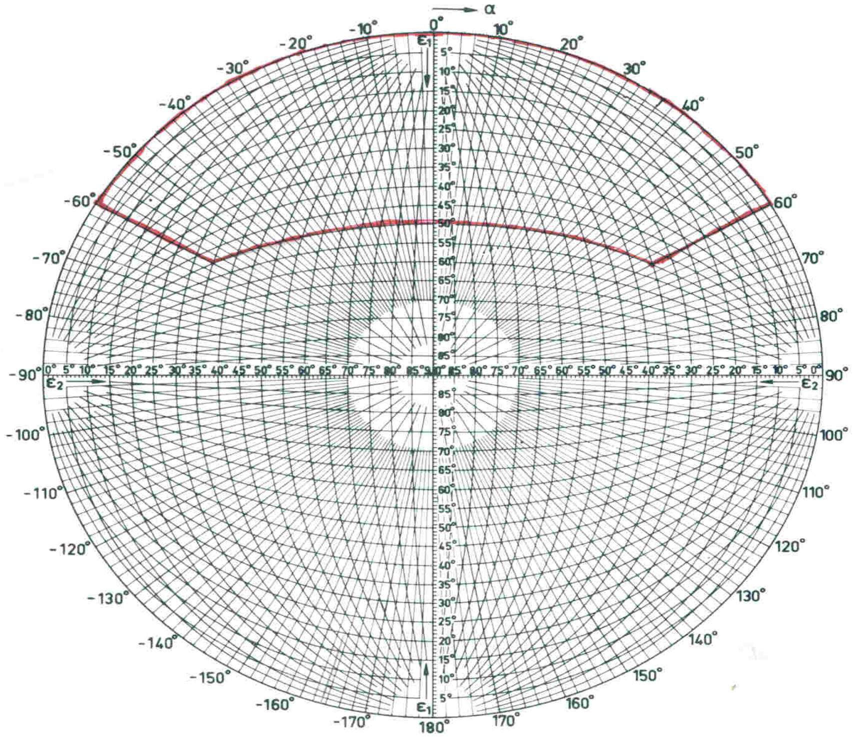


figure B-2. the window of figure B-1 plotted into the radian diagram

Now a transparent version of the sun trajectory diagram is put on the radian diagram into the correct direction. The top of the radian diagram (azimuth α = 0º for plotting) has an azimuth of 135º in relation to the arrow indicating the north, since the window faces the southeast. This is shown in Figure 4B-3. It is to be seen from this Figure that the point P is lit from 09:00 until 13:45 hrs on 22 December, from 06:35 until 12:55 on 21 March and 23 September, and from 06:40 until 10:05 on 22 June MEMT.

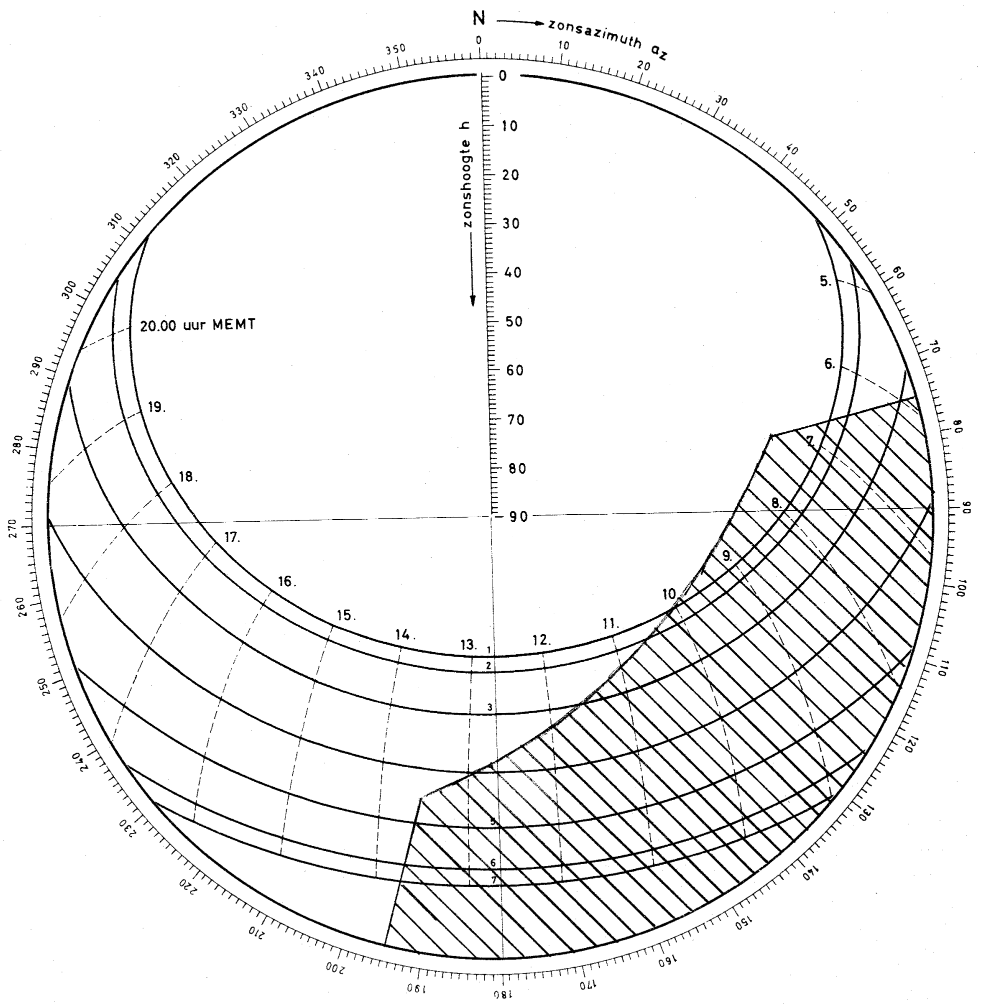


figure B-3. projection of the window from the example of Figure 4B-1 on the sun trajectory diagram with the aid of the radian diagram
("zonnebaandiagram" = Sun trajectory diagram for 52° north latitude; "zonazimut" = sun azimuth; "zonshoogte" = height of the sun h)

1. 22 June
2. 23 July and 21 May
3. 23 August and 20 April
4. 23 September and 21 March
5. 23 October and 19 February
6. 22 November and 20 January
7. 22 December