6. SOLAR CALCULATIONS

It is mandatory to provide OPERA with values for the amount of solar radiation transferred through the windows of the building. The values, located in the input data file, see Figure 3, show how much heat, in kWh/m^2, that is transferred per month through one m^2 of a double-glazed window, and for each of four different directions. The orientation of the windows must not necessarily be north, east, south and west but for the sake of simplicity this is assumed. Thus 48 values have to be implemented in the file.

However, experience showed that these values were not very easy to calculate , at least not from information found in literature easily available in Sweden. One method for energy balance calculations, called the BKL-method [32], provides solar radiation values but there are no algorithms for actually calculating this amount. Therefore, it is necessary to implement values taken from a number of tables presented. If the orientation and the location of the building site do not coincide with the ones presented, one must interpolate between the values written in [32]. The values are specially calculated for the BKL-method, where only radiation for a few days a month actually is calculated. Further, they use a FORTRAN program implemented in a big computer, UNIVAC, which is not in common practice. BKL, however, has a greate advantage because it can calculate the influence of shading obstacles.

Also in another method, described in [33], a big computer was used, and only one day per month was actually calculated.

A third program, [34], is written in BASIC and calculates the energy balance for a building. There is, however, a solar radiation routine implemented, which calculates the radiation transferred through a window.

The programs above could of course be changed to be run in any computer, but the output is not suitable for direct implementation in OPERA. There was a need for a PC-program which could provide applicable solar radiation values. The program also had to be fast, easy to use and portable between different computers without reediting the source code. It was also important that no manual calculations were necsessary. The above mentioned facts necessiated a new program based on the earlier programs but specially elaborated for the input data file of OPERA.

6.1 The SORAD program and how to use it

The source code, written in C for portability and fastness, is presented in appendix D. It is based on facts and theories found in [33, 35, 36, 37, 38, 39 and 40]. Reference [40] is recommended to readers interesded in all the details in solar radiation calculations. The program is split in three parts, one called "main" and the other two, which work as functions to "main", called "direct" and "transm". The first part of the program opens the suitable input data file, called SUN.DAT, where all the necessary input data are stored, see Figure 17.

```
56. 90. 90.
3.1 3. 6.2 5.5 7.6 6.5 5.2 5.2 5.6 3.8 1.8 2.
19.2 16.4 13.4 11.6 8.1 8.4 8.8 9.6 9.1 14.4 18.8 21.1
```

Figure 17. Input data file SUN.DAT for solar calculations.

The first value shows the latitude, called "lat" in the program. The value must be expressed in degrees,(360 degrees in a full circle), and 56 degrees is the latitude of Malmö, Sweden. The second value presents the azimuth, "azyta" in the program, of the window, i.e. the angle between the normal of the window and the south. A window with its frames directed to the east and west has the azimuth 0 or 180 degrees. In this case the azimuth is set to 90 degrees.

The angle between the normal of the surface and the horizon is called "b" in the program, see appendix D, but β in the text in accordance with the references, and β is set to 90 degrees showing that the window is vertical, see Figure 18.

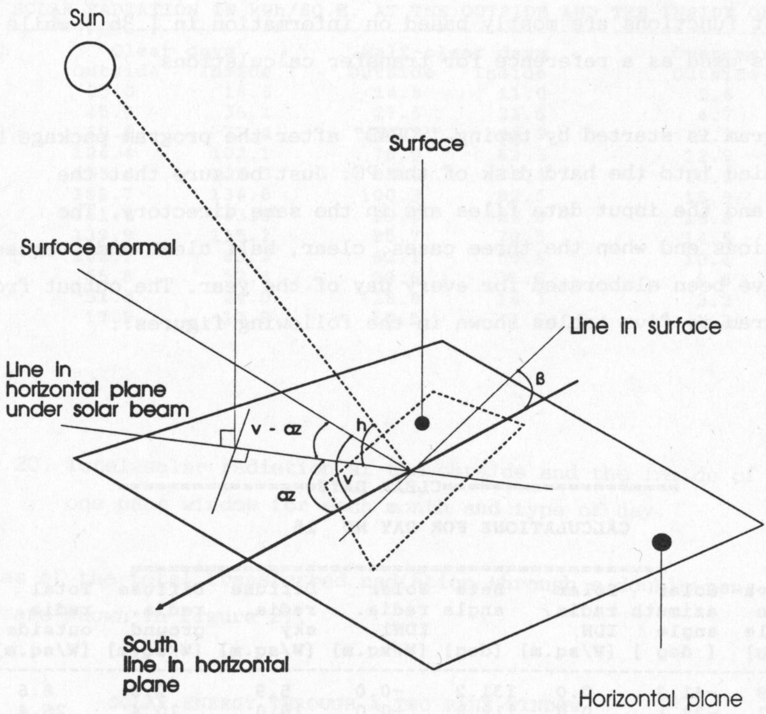

Figure 18. Names of the angles in solar calculations [37]

The next line in the input file shows the number of clear days for each month, while the third line presents the days overcast. The values are found in [33] and are applicable for Malmö in Sweden. Note that there is no "," between the values as is common in FORTRAN input data files, but instead a " " or a space. The values are stored in an array called "typer[2][12]", see appendix D.

The function called "direct" is used for the solar calculations while values for the total month are calculated in the main program. When the amount of radiation that hits the window surface has been calculated, a second function is called, calculating how much radiation is transferred through one window pane. The calculations in the first functions are mostly based on information in [36] while [35] is used as a reference for transfer calculations.

The program is started by typing "SORAD" after the program package has been copied into the hard disk of the PC. Just be sure that the program and the input data files are in the same directory. The calculations end when the three cases, clear, half clear and overcast days, have been elaborated for every day of the year. The output from the program is five tables shown in the following figures:.

===================CLEAR DAYS================

CALCULATIONS FOR DAY NO 15

True solar time [h]	Eleva-tion angle [deg]	Solar azimuth angle [deg]	Solar radia. IDN [W/sq.m]	Beta angle [deg]	Solar radia. IDN1 [W/sq.m]	Diffuse radia. sky [W/sq.m]	Diffuse radia. ground [W/sq.m]	Total radia. outside [W/sq.m]	Total radia. inside [W/sq.m
9	3.9	-41.3	0.0	131.2	-0.0	5.9	2.8	8.6	7.0
10	8.7	-28.1	0.0	117.8	-0.0	16.0	10.4	26.4	21.2
11	11.7	-14.3	0.0	104.0	-0.0	22.1	15.5	37.5	30.2
12	12.8	0.0	608.5	90.0	-0.0	27.9	17.2	45.1	36.3
13	11.7	14.3	586.8	76.0	141.6	31.0	15.5	188.1	116.7
14	8.7	28.1	502.5	62.2	234.2	27.8	10.4	272.4	214.2
15	3.9	41.3	240.8	48.8	158.7	12.0	2.8	173.4	146.7

The sum of the total outside radiation day no. 15 equals 751.5 Wh/sq.m.
The sum of the total inside radiation day no. 15 equals 572.2 Wh/sq.m.

Figure 19. Output from the solar radiation program SORAD.EXE day number 15, clear day.

The first one shows the solar radiation every hour for the chosen clear day, see Figure 19. The next two ones presents the same result but for half-clear and overcast days. The total radiation at the outside and inside of the window, for each month and for each of the day types, is presented in Figure 20.

SOLAR RADIATION IN kWh/SQ.M. AT THE OUTSIDE AND THE INSIDE OF THE WINDOW

Month	Clear days		Half-clear days		Overcast days	
nr	Outside	Inside	Outside	Inside	Outside	Inside
1	25.0	18.6	14.8	11.0	2.6	1.9
2	45.9	36.1	27.5	21.6	4.7	3.7
3	89.5	72.4	54.3	43.9	9.3	7.5
4	124.4	102.1	76.0	62.3	12.9	10.6
5	155.4	128.3	95.6	78.8	16.2	13.4
6	162.7	134.0	100.3	82.5	16.9	14.0
7	161.4	133.3	99.4	82.0	16.8	13.9
8	139.9	115.2	85.7	70.5	14.5	12.0
9	102.1	83.2	62.1	50.6	10.6	8.7
10	65.8	52.4	39.6	31.6	6.8	5.4
11	31.5	24.0	18.8	14.3	3.2	2.5
12	17.9	12.9	10.5	7.6	1.8	1.3

Figure 20. Total solar radiation at the outside and the inside of a one pane window for each month and type of day.

The sums of the total transferred radiation through a double-pane window are shown in Figure 21.

SOLAR ENERGY THROUGH A TWO PANE WINDOW

The normal of the window directed 90.0 degrees clockwise from the south

Month no	Energy kWh/sq.m
1	5.51
2	11.43
3	30.50
4	44.66
5	66.45
6	67.01
7	64.15
8	53.89
9	39.57
10	19.78
11	6.72
12	3.28

The program has now come to its end

Figure 21. Solar radiation transferred through a double pane window for each month.

Put the values in Figure 21 into the data file of OPERA, as shown in Figure 3. Note that the values in Figure 3 and Figure 21 are not identical, due to recent changings in the SORAD programmming code.

6.2 The details of solar calculations

Above is shown how to use the SORAD program for calculating the solar values which have to be part of an OPERA session. However, nor is the information sufficient for full understanding of the solar program, and neither has it been described elsewhere. The chapters below are written for those of the readers who want to make enhancements in the code. A thorough description is therefore made.

6.2.1 The position of the sun

This part of the program is dealt with in the function "direct", see appendix D, and the first thing to do is to calculate the solar declination, i.e. the angle between a line through the sun and the earth, and a plane through the equator at noon for the true solar time. This means that the sun exactly is facing the south. In order to convert solar time to local time two corrections have to be made. First, the longitude of the site must be considered and then, the equation of time which shows the influence of perturbations in the earth's rate of rotation [40].

The expression for calculating the declination has been [36]:

$$\delta = \arcsin(- 0.3979 \cdot \sin C_1)$$

where:

$$C_1 = C_2 + 0.0334 \cdot \sin C_2 + 1.78128$$

$$C_2 = 0.017214 \cdot (DA - 2.8749)$$

DA = The number of the day during the year

The author to [36], however, refers to Heindel W. and Koch H.A. " Die Bereschung von Sonneneinstrahlungsintensitäten für Wärmetechnische Untersuchungen im Bauwesen", Gesundheits-Ingenier 97, 1976.

There are also other expressions that can be used and the authors to [32] and [41] seem to have used the same references viz. Spencer, J.W. "Fourier Series Representation of the Position of the Sun", Search, Vol. 2, No. 5, May 1971. Further information about different methods for finding the true solar position could be found in [42] where several methods are compared.

As is said above, day number 15 is shown explicitly when the program is run, and thus this day also is used as an example here. The values above will become:

$$C_2 = 0.2087, \quad C_1 = 1.9969 \quad \delta = -0.3707$$

Note that all the angles are calculated in radians.

The next thing to do is to elaborate the position of the sun due to the time of day. In [39] the following expressions occur:

$$\sin h = \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \cos t \quad (12)$$

$$\cos h = \cos \delta \cdot \sin t / \sin az \quad (13)$$

$$\cos h = (-\cos \varphi \cdot \sin \delta + \sin \varphi \cdot \cos \delta \cdot \cos t) / \cos az$$

where: h = the elevation angle, i.e. the solar height
az = the azimut angle, i.e. the horizontal angle
t = the hour angle of the sun
φ = the latitude angle on the earth surface

When the sun passes the horizon the angle "h" equals zero and if this is inserted in the first of the three expressions (12) above, the result will be:

$$\cos t = -((\sin \varphi \cdot \sin \delta)/(\cos \varphi \cdot \cos \delta))$$

It is thus possible to calculate the angle of time at sunrise or sunset. Inserting the values above for δ and φ, equalling - 0.3707 and 0.9773 which is 56 degrees in radians, results in a time angle of 0.9565 radians monitored from the true south direction. Each hour corresponds to 360/24 = 15 degrees = 0.2618 radians of the total circle and this means that the sun will rise 3.65 hours before, and set 3.65 hours after the true solar noon or at 8.35 and 15.65. Note that time is written in the decimal format.

There is now an interval with possible sunshine on the earth and the program will calculate the solar radiation between 8.35 and 15.65 this day. However, at 8.35 the radiation is zero and thus the calculation starts at 9.00. At this hour the hour-angle equals - 0.7854 radians, i.e. 3 hours of 15 ° before the true solar noon. Using expression (12) once again for the new hour angle makes it possible to calculate the elevation angle at 9.00. Inserting this angle in expression (13) also yields the azimut angle. The angles become in radians:

$$h = 0.0682 \qquad az = -0.7216$$

6.2.2 The solar radiation flux

At the outer limit of atmosphere the irradiation from the sun is about 1400 W/m^2 [9 or 43]. In fact the extra terrestrial radiation differs between 1300 - 1400 W/m^2 due to the solar - earth distance [40]. However, because of the angle of incidence, atmospheric conditions etc. this value must be decreased before the radiation hits the earth surface. There are a number of different suggestions for calculating this decrease, see e.g. [34] or [40]. Here a method found in [36] is used, and the author in his turn refers to Rodhe B., " Calculated values on global radiation at clear days ", The Swedish Hydrological and Metrological Institute, 1977. The expression is:

$$I_{DN} = rd \cdot A \cdot e^{\left(-\frac{BB}{\sin h}\right)}$$

where: I_{DN} = The solar irradiation on the earth surface perpendicular to the solar orientation

rd = A coefficient that depends on the distance between the earth and the sun

A, BB = Constants showing the regression of measured irradiation, 991.64 and 0.09143 respectively

h = the hour angle of concern, in radians

The coefficient " rd " above has been calculated for each month over a year and they vary slightly around 1.0, see [36] or the variable rco[12] in the programming code, appendix D.

The result from the solar irradiation calculations day number 15 can be found in Figure 19.

6.2.3 Calculations for a tilted surface.

A window is not normally oriented in a way that the solar radiation hits the window at optimal conditions, i.e. the solar incidence and the normal of the surface do not coincide. The angle between the normal of the surface and the solar radiation must thus be calculated, and further it must be ascertained that the sun actually shines on the window front side, and not on the back where the building is.

In the case studied here, the surface azimute was set to 90 degrees which means that the normal of the window is oriented directely to the west. It is determined in the input data that the frame of the window is vertical as normal in an external wall. The azimut for the sun at 9.00 is - 0.7216 radians which equals - 41.34 degrees and thus the sun will shine on the back of the window, or on the other side of the building. Not until the solar azimut becomes greater than the surface azimut minus 90.0 degrees, the sun shine reaches the outside of the window. At 9.00 the radiation will thus become zero, see Figure 19. At noon the sun has moved so far that it reaches the window, and at 13.00 the azimut angle for the sun will equal 14.26 degrees. In the program, see appendix D, there is a routine for different cases of azimut angles for the surface and the sun, the difference between them and further if the sun is shining on the front of the window or not.

In [36] the incidence angle towards a tilted surface is presented as:

$$\cos i_{\beta} = \sin h \cdot \cos \beta + \cos h \cdot \sin \beta \cdot \cos \gamma$$

where: i_{β} = the incidence angle
β = the angle between the ground and the tilted surface
γ = the difference between the solar azimut and the surface azimut

Inserting the applicable values for day number 15 and 13.00, i.e. h, β and γ equalling 0.2044, 1.5708 and -1.3219 respectively will yield the angle, i_{β}, equalling 1.3272. All the values are in radians. The methods used in [34 and 41] are similar to the one used above.

The tilted surface will also weaken the solar radiation on the surface, and this must be noted according to the following expression:

$$I_{DN1} = C_1 \cdot I_{DN} \cdot \cos i_{\beta}$$

With the values above, and C_1 which is a coefficient for clouds described below equalling 1.0, I_{DN1} will become 154 W/m^2.

6.2.4 Direct and diffuse solar radiation for different types of days

Up to now only the direct solar radiation has been taken into account. There is also a diffuse part, partly from the sky and partly from reflected direct radiation from the ground. In [36] the diffuse radiation is also considered to be influenced by the angle of direction. Very cloudy days this influence is minute but clearer days this has to be accounted for. The total solar radiation is thus calculated as:

$$I_{T\beta} = I_{DN1} + I_{d\beta} + I_{d\beta r}$$

where: $I_{d\beta}$ = the diffuse radiation from the sky

$I_{d\beta r}$ = the diffuse radiation reflected from the ground

In [36] it is also shown that use of so called Cloud Cover Factors makes it possible to model the irradiation also during cloudy and half clear days. The diffuse solar irradiation for one day, $I_{d\beta}$, is thus calculated as:

$$I_{d\beta} = I_{dH} \cdot (1 + C_1 \cdot (2 \cdot f - 1) \cdot \sin^2\beta) \cdot 0.5 \cdot (\cos ha + \cos \beta)$$

where: $I_{dH} = (C_3 + C_2 \cdot \sin h) \cdot I_{DN}$

ha = the horizontal shadowing angle, from other buildings etc

$f = 0.55 + 0.437 \cdot cv + 0.313 \cdot cv^2$

$cv = \cos h \cdot \cos \gamma$

C_1, C_2, C_3 = Cloud Cover coefficients

The value of "f" above is called the Threlkeld factor, which must exceed 0.45, and thus a limit is set in the program. I_{dH} is the diffuse solar radiation on a horizontal surface.

The coefficients C_1 to C_3 are presented as:

Table 5. Cloud Cover coefficients [31]

	C_1	C_2	C_3
Clear days:	0.9	0.2	0.04
Half clear days:	0.52	0.38	0.032
Overcast days:	0.1	0.35	0.016

The reflected solar radiation from the ground is assumed to be totally diffuse and in [36] the following expression is presented:

$$I_{d\beta r} = rm \cdot (2 - \cos ha - \cos \beta) \cdot I_{TH}$$

where: rm = the reflection factor of the ground

$I_{TH} = I_{DH} + I_{dH}$

$I_{DH} = C_1 \cdot I_{DN} \cdot \sin h$, i.e. the irradiation on a horizontal surface.

In Figure 19 are shown values on some of the above parameters, and for 13.00 and rm = 0.2, they are in W/m^2:

$I_{DN} = 586.8$ $I_{DN1} = 141.6$ $I_{d\beta} = 31.0$ $I_{d\beta r} = 15.5$

6.2.5 Transmittance of solar radiation through windows

When calculating the solar radiation transfer through the window panes, differences if direct, diffuse or reflected radiation are of concern. The calculations are elaborated in a special function called "transm()", see appendix D, and the arguments sent to the function are the incidence angle and the absorbation coefficient for the glass type of the window. This coefficient is set to 0.07 in the first lines of the function direct() described above. The procedures of calculation follow the ones found in [35].

The transmittance of direct solar radiation through a window depends mainly on the incidence angle of the sunlight. Some of the light is instantly reflected, some is absorbed in the window pane and some is transferred through the pane.

When the solar radiation hits the window surface the light is polarized in two components, one parallel to the incidence and reflection plane and one perpendicular to it. In [35] it is shown that the reflection factors for the two types of radiation can be explained as:

$$r_{=} = \left(\frac{nf^2 \cdot \cos i - (nf^2 - \sin^2 i)^{0.5}}{nf^2 \cdot \cos i + (nf^2 - \sin^2 i)^{0.5}} \right)^2$$

$$r_{\#} = \left(\frac{\cos i - (nf^2 - \sin^2 i)^{0.5}}{\cos i + (nf^2 - \sin^2 i)^{0.5}} \right)^2$$

where: $r_{=}$ = the parallel reflection coefficient

$r_{\#}$ = the perpendicular reflection coefficient

i_{β} = the angle between the incidence line and the normal of the window pane, see above

nf = refraction index, 1.52 for air to glass

The two coefficients are closely related and:

$$rt = \frac{r_{=} + r_{\#}}{2}$$

where rt = the total reflection factor defined as:

$$rt = \frac{I_r}{I}$$

I_r = The reflected part of the solar radiation and

I = The radiation to the window

In the program, see appendix D, the coefficients are calulated in the beginning of the function named transm(). The function is only called upon for those hours when the sun is actually shining on the window. Some values are shown below, for 13.00 day number 15. I_{β} will equal 76.0 degrees, see Figure 19, n equals 1.52 and thus:

$$r_{=} = \frac{-0.613}{1.727} = -0.355 \qquad r_{\#} = \frac{-0.928}{1.411} = -0.658$$

When the solar radiation hits the window surface one part is reflected and one is transmitted. Some of the radiation is then absorbed in the glass and the window pane will thus get warmer. The absorbed part of the radiation is calculated as:

$$\alpha = (1 - rt) \cdot (1 - e^{\aleph})$$

where: $$\aleph = \left(af \cdot s \cdot \frac{nf}{(nf^2 - \sin^2 i)^{0.5}} \right)$$

af = the absorbed fraction of transferred radiation

s = the thickness of the glass pane in m

The coefficient α has different values for the two directions of polarization, and thus it is possible to calculate:

$\alpha_{=} = 0.076$ $\alpha_{\#} = 0.049$ when: $af \cdot s = 0.07$

When the solar radiation hits the other surface of the window pane the radiation is reflected again and partly absorbed and so on. These reflections are decreasing as a geometrical series and the resulting coefficient will be:

$$R_r = r + \frac{r \cdot (1 - r)^2 \cdot (1 - \alpha)^2}{1 - r^2 \cdot (1 - \alpha)^2}$$

In the same way coefficients for the absorbation and for the transmission are developed:

$$A_{\alpha} = \frac{\alpha \cdot (1 - r) \cdot (1 + r \cdot (1 - \alpha))}{1 - r^2 \cdot (1 - \alpha)^2}$$

$$T = \frac{(1 - r)^2 \cdot (1 - \alpha)}{1 - (r^2 \cdot (1 - \alpha)^2}$$

The calculations are to be utilized for the two cases of polarization and the mean value must then be calculated. The following values are calculated by the program:

$$R_{=} = 0.209 \qquad A_{=} = 0.075 \qquad T_{=} = 0.716$$
$$R_{\#} = 0.585 \qquad A_{\#} = 0.047 \qquad T_{\#} = 0.368$$
$$R_{m} = 0.397 \qquad A_{m} = 0.061 \qquad T_{m} = 0.542$$

where the indices "m" stands for mean value. Note that all the sums R+A+T equal 1.00, a fact that is examined in the program.

The diffuse radiation is dealt with in almost the same way but the angle of incidence is calculated somewhat differently. In [33] the following expressions are presented:

$$i_{es} = 59.68 - 0.1388 \cdot \beta + 0.001497 \cdot \beta^2$$

$$i_{eg} = 90 - 0.5788 \cdot \beta + 0.002693 \cdot \beta^2$$

where i_{es} and i_{eg} are the incidence angle from the sky and from the ground respectively and β the angle between the ground and the tilted surface. When β equals 90 degrees the two values above will become 59.31 and 59.72 degrees respectively.

The total amount of heat, finally transferred through the window, is then calculated as: [33]

$$W = I_{D\beta} \cdot (T_D + nm \cdot A_D) + I_{d\beta} \cdot (T_{d\beta} + nm \cdot A_{d\beta}) + I_{d\beta r} \cdot (T_{d\beta r} + nm \cdot A_{d\beta r})$$

where: $nm = m_o / (m_o + m_i)$

m_o and m_i are the convection heat transfer coefficients on the outside and the inside respectively. Values from the example above are:

$$W = 141.6 \cdot (0.541 + 0.3 \cdot 0.061) + 31.0 \cdot (0.78 + 0.3 \cdot 0.07) +$$

$$+ 15.5 \cdot (0.78 + 0.3 \cdot 0.07) = 116.7 \text{ W/m}^2$$

6.2.6 Half-clear and overcast days

Under an earlier heading the solar radiation heat flux during half-clear and overcast days was discussed. The calculations above are thus repeated but now for these other types of days. In Figure 20 the resulting values are presented for a one pane window, and now only the number of different type days for each month during the year must be decided. In Table 6 some values are presented and the solar transfer for January is thus calculated as:

$$W_{Jan} = (18.6 \cdot 3.1 + 11.0 \cdot 8.7 + 1.9 \cdot 19.2) / 31.0 = 6.12 \ W/m^2$$

The values in Figure 20 are valid for a one pane window and they must be reduced in order to show the solar radiation transfer for a two-pane ditto. In [33] it is shown that this can be done by a so called shading coefficient and it is found that about 10 % more of the solar radiation is reflected and absorbed for two-pane windows than for the first type. The value 6.12 above shall thus be multiplied by 0.9 and the resulting solar heat transfer during January will be 5.51 W/m^2, see Figure 21.

Table 6. Number of clear and overcast days in Malmö, Sweden

Month	Clear	Overcast	Month	Clear	Overcast
January	3.1	19.2	July	5.9	8.8
February	3.0	16.4	August	5.2	9.6
March	4.3	13.4	September	5.6	9.1
April	5.6	11.6	October	3.8	14.4
May	7.6	8.1	November	1.8	18.8
June	6.5	8.4	December	2.0	21.1

6.3 Simplified flow chart of the SORAD program

In Figure 22 a simplified flow chart is shown over the SORAD program.

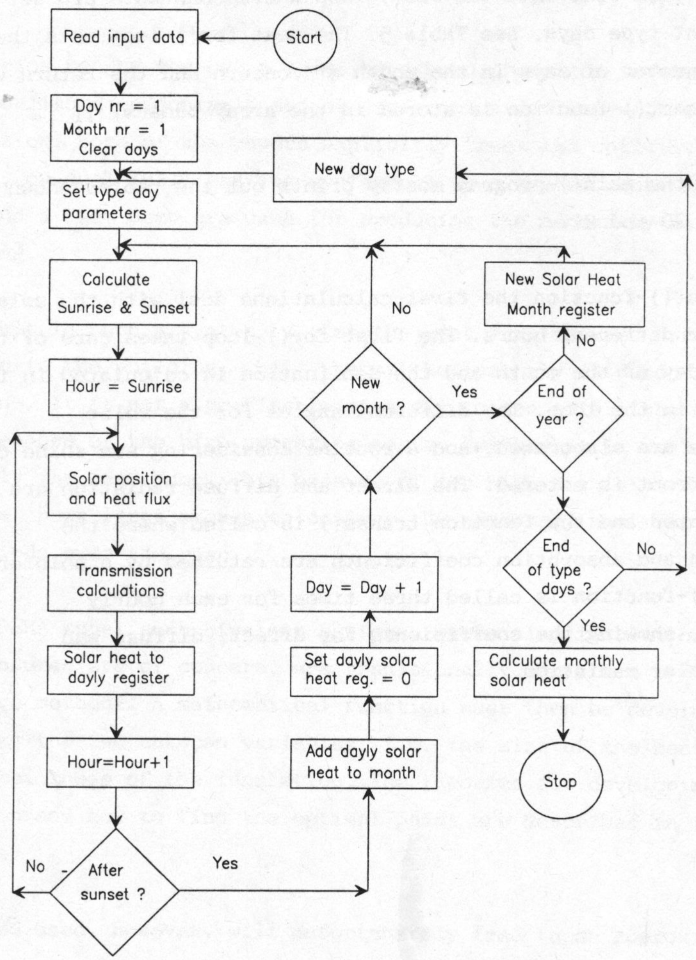

Figure 22. Simplified flow chart of the solar radiation program

The calculations start in the main() program. After setting proper type definitions at the variables, the file SUN.DAT is opened. Values are read until the end of file, EOF, mark is encountered. The horizontal shadowing angle," ha ", is set to 0.0 degrees and the reflection factor, "rm", is set to 0.2.

The program then runs into the for()-loop where constants are set for the different type days, see Table 5. The next for()-loop sets the applicable number of days in the month of concern and the return value from the direct()-function is stored in the array mansum[ ][ ].

The rest of the main()-program mostly prints out the tables shown in Figures 19, 20 and 21.

In the direct()-function the first calculations deal with the solar position for different hours. The first for()-loop takes care of the applicable day of the month and the declination is calculated in the first lines in the loop. The different angles for the solar calculations are elaborated, and a routine considering sun shine on the window front is entered. The direct and diffuse radiation are then calculated and the function transm() is called where the transmission and absorbtion coefficients are returned by a pointer. The transm()-function is called three times for each hourly calculation, showing the coefficients for direct, diffuse and reflected solar radiation.