An Interactive Software for the Estimation of Solar Radiation in India

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ABSTRACT

An interactive software 'SOLRAD' has been developed in BASIC to estimate, for India: (i) Basic solar radiation parameters (solar time, declination angle, incidence angle, zenith angle, sunset hour angle and day length) for 50 locations; (ii) Monthly mean daily and hourly values of global, diffuse and direct radiation for 34 locations on both horizontal and tilted surfaces; and (iii) Daily global radiation for a month (using the Bendt et al. function) for 34 locations. The program is highly user friendly and has the advantage that new locations and application oriented calculations can be added and additional correlations can be included. Examples are shown and the function and versatality of the program explained.

INTRODUCTION

All solar energy processes (thermal and photovoltaic) require a knowledge of solar radiation availability at the location of interest. Though the solar radiation intensity outside the earth's atmosphere can be determined very accurately, its availability at the earth's surface is prone to a certain degree of uncertainty due to local climatic conditions.

The importance of the estimation of solar radiation cannot be overemphasized. An incorrect knowledge will either lead to oversizing of equipment or not obtaining the required output from solar conversion devices. Before installing any solar conversion device, it is important to know the radiation availability at the location of interest.

An interactive software 'SOLRAD' (for SOLar RADiation) for the estimation of solar radiation for Indian locations on both horizontal and tilted surfaces has been developed which will be useful for:

(i) Designers of solar thermal and solar photovoltaic devices;
(ii) Researchers, who need to estimate solar radiation values in the course of their work;
(iii) Architects, who need to estimate the solar heat gain in buildings;
(iv) Agricultural engineers who need to estimate the evaporation losses of water used for irrigation; and
(v) For teachers for demonstration purposes.

SOLRAD has been designed to:

(i) Calculate basic solar radiation parameters (solar time, declination angle, incidence angle, zenith angle, sunset hour angle and day length);

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(ii) Estimate the monthly mean daily and hourly values of global and diffuse radiation on a horizontal surface;
(iii) Estimate the monthly mean daily and hourly values of global and diffuse radiation on a tilted surface;
(iv) Statistically generate daily global radiation values for a month, by knowing the monthly mean daily global radiation.

PROGRAM DETAILS

The basic program details are given in Table 1.

The program can be divided into 5 major sections for describing its capabilities:

I. Calculation of basic solar radiation parameters
II. Calculation of monthly mean solar radiation on a horizontal surface
III. Calculation of monthly mean solar radiation on a tilted surface
IV. Calculation of daily global radiation for a month
V. Help

Figure 1 shows the complete block diagram of the SOLRAD computer program.

Table 1. Program details.

Name of the program	: SOLRAD
Software	: GWBASIC
Memory	: 70165 bytes
No. of lines	: 1143
No. of remark statements	: 63
Computer	: IBMPC XT, IBMPC AT compatibles

Calculation of Basic Solar Radiation Parameters

Solar Time

The solar time is calculated using the expression given by Duffie and Beckman (1980).

$$\text{Solar Time} = \text{Watch Time} - 4\ (L_{std} - L_{loc}) + E \quad [1]$$

The equation of time (E) is calculated using the expression given by Szokolay (1984) [quoting Page et al. (1978)].

$$E = 0.00037 + 0.43177 \cos x - 7.3464 \sin x - 3.165 \cos 2x - 9.3893 \sin 2x + 0.07272 \cos 3x - 0.2449 \sin 3x \quad [2]$$

where, x = [360 N/365].

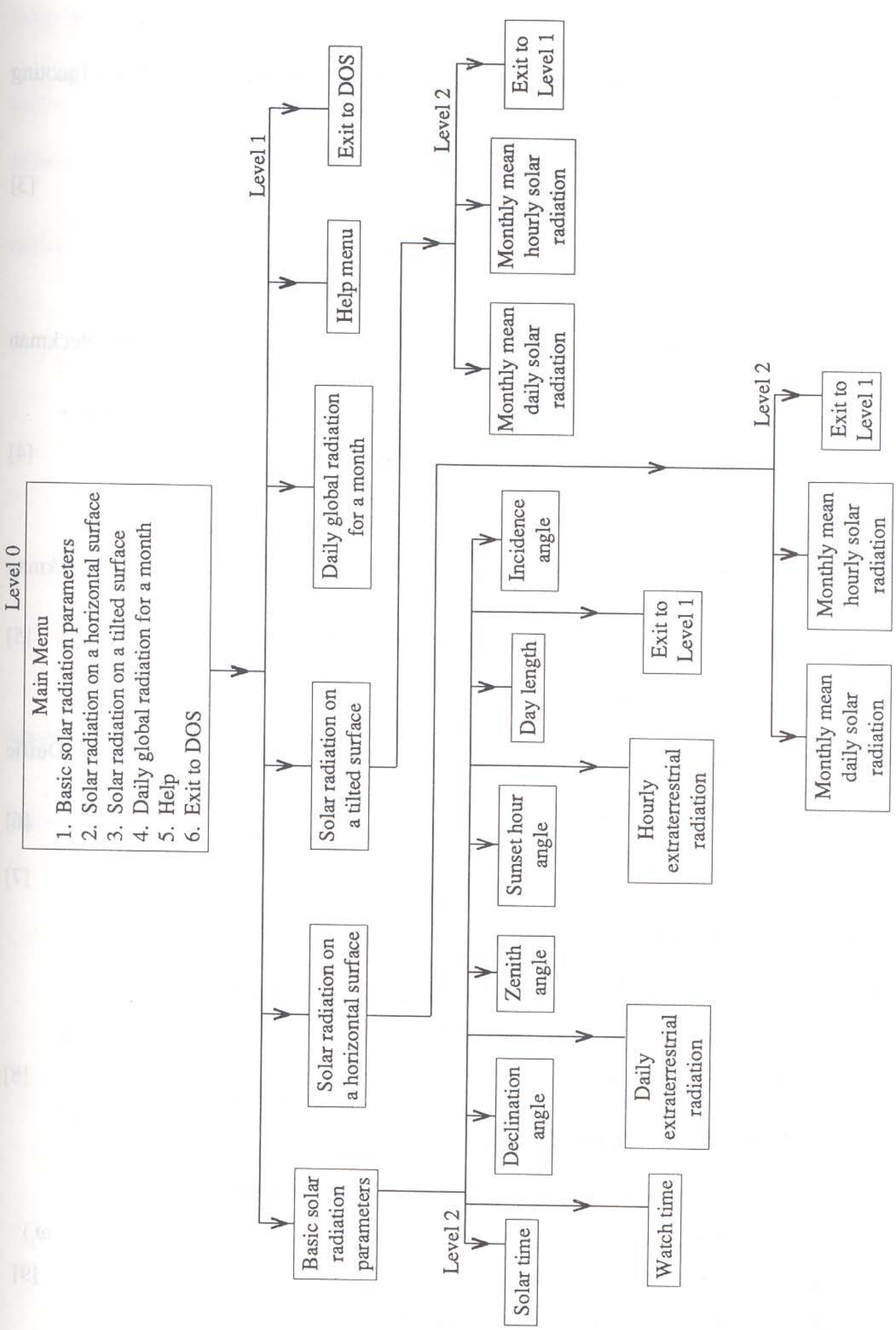

Fig. 1. Complete block diagram of the program.

Declination Angle

The declination angle (δ) is calculated using the equation given by Szokolay (1984) [quoting Page et al. (1978)].

$$\delta = 0.3328 - 22.984 \cos x + 3.7872 \sin x - 0.3499 \cos 2x + 0.0321 \sin 2x - 0.1398 \cos 3x + 0.0719 \sin 3x \quad [3]$$

where, $x = [360\,N/366]$.

Incidence Angle

The incidence angle (θ) is calculated using the equation given by Duffie and Beckman (1980).

$$\theta = \cos^{-1}[\sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\gamma + \cos\delta \cos\phi \cos\beta \cos\omega + \cos\delta \cos\omega \cos\gamma \sin\phi \sin\beta + \cos\delta \sin\beta \sin\gamma \sin\omega] \quad [4]$$

Zenith Angle

The Zenith angle (θ_z) is calculated using the expression given by Duffie and Beckman (1980).

$$\theta_z = \cos^{-1}[\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega] \quad [5]$$

Sunset Hour Angle and Day Length

The sunset hour angle (ω_s) and day length (*DL*) is calculated by the equation given by Duffie and Beckman (1980).

$$\omega_s = \cos^{-1}[-(\tan\phi \tan\delta)] \quad [6]$$

$$DL = (2/15) \cos \omega_s \quad [7]$$

Monthly Mean Daily Extraterrestrial Radiation

This is calculated by the expression given by Duffie and Beckman (1980).

$$\overline{H}_0 = [(24 * 3600 * sc)/\pi]\,(1 + 0.033 * \cos(360.N/365)).(\cos\phi \cos\delta \sin\omega_s + (2\pi\omega_s/360) \sin\phi \sin\delta) \quad [8]$$

Monthly Mean Hourly Extraterrestrial Radiation

This is found by the equation given by Duffie and Beckman (1980).

$$\overline{I}_0 = [(12 * 3600 * sc)/\pi]\,(1 + 0.033 * \cos(360.N/365)).(\cos\phi \cos\delta \sin(\omega_2 - \omega_1) + (2\pi(\omega_2 - \omega_1)/360) \sin\phi \sin\delta) \quad [9]$$

where ω_1 and ω_2 are hour angles which define an hour (ω_2 is the larger).

Solar Radiation on a Horizontal Surface

The calculation of monthly mean radiation on a horizontal surface has been divided into global, diffuse and direct radiation for both daily and hourly time scales.

Monthly Mean Daily Global Radiation

The monthly mean daily global radiation on a horizontal surface can be calculated by any one of the following five methods:

i) The expression given by Rietveld (1978)

$$\overline{H}_g = \overline{H}_0 \, [\, 0.18 + 0.62 \, (\overline{s}/\overline{S}) \,] \qquad [10]$$

ii) The expression given by Mani and Rangarajan (1983)

$$\overline{H}_g = \overline{H}_0 \, [\, 0.26 + 0.48 \, (\overline{s}/\overline{S}) \,] \qquad [11]$$

iii) The expression given by Modi and Sukhatme (1983)

$$\overline{H}_g = \overline{H}_0 \, [\, a + b \, (\overline{s}/\overline{S}) \,] \qquad [12]$$

They have given the regression parameters 'a' and 'b' for each month of the year.

iv) The expression given by Ogelman et al. (1984)

$$\overline{H}_g = \overline{H}_0 \, [\, 0.195 + 0.68 \, (\overline{s}/\overline{S}) \,] \qquad [13]$$

v) The expression given by Akinoglu and Ecevit (1990)

$$\overline{H}_g = \overline{H}_0 \, [\, 0.145 + 0.845 \, (\overline{s}/\overline{S}) - 0.28 \, (\overline{s}/\overline{S})^2 \,] \qquad [14]$$

Monthly Mean Daily Diffuse Radiation

The monthly mean daily diffuse radiation can be found by any one of the six methods given below.

i) The expression given by Gupta, Usha Rao and Reddy (1979)

$$\overline{H}_d = \overline{H}_g \, [\, 1.354 - 1.57 \, \overline{K} \,] \qquad [15]$$

ii) The expression given by Collares-Pereira and Rabl (1979)

$$\overline{H}_d = \overline{H}_g \, [\, 1.19 - 2.27 \, \overline{K} + 9.4 \, \overline{K}^2 - 21.87 \, \overline{K}^3 + 14.65 \, \overline{K}^4 \,] \qquad [16]$$

iii) The expression given by Erbs and Klein (1982)

$$\overline{H}_d = \overline{H}_g \, [\, 1.317 - 3.023 \, \overline{K} + 3.37 \, \overline{K}^2 - 1.77 \, \overline{K}^3 \,] \qquad [17]$$

iv) The expression given by Mani and Rangarajan (1983)

$$\overline{H}_d = \overline{H}_g \, [\, 1.108 - 1.351 \, \overline{K} \,] \qquad [18]$$

v) The expression given by Modi and Sukhatme (1983)

$$\overline{H}_d = \overline{H}_g \, [\, 1.412 - 1.696 \, \overline{K} \,] \qquad [19]$$

vi) The expression given by Muneer and Hawas (1984)

$$\overline{H}_d = \overline{H}_g \, [\, 1.35 - 1.61 \, \overline{K} \,] \qquad [20]$$

Monthly Mean Daily Beam Radiation

This is calculated by the following equation given by Duffie and Beckman (1980).

$$\bar{H}_b = \bar{H}_g - \bar{H}_d \quad [21]$$

Monthly Mean Hourly Global Radiation

The monthly mean hourly global radiation can be calculated by the equation given by Duffie and Beckman (1980).

$$\bar{I}_g = \bar{r}_t * \bar{H}_g \quad [22]$$

where,

$$\bar{r}_t = (\pi / 24) . (a + b \cos\omega) \, [(\cos\omega - \cos\omega_s) / (\sin\omega_s - (2\pi\omega_s / 360) . \cos\omega_s)] \quad [23]$$

Here 'a' and 'b' are calculated as follows:

$$a = 0.410 + 0.502 \sin(\omega_s - 60) \quad [24a]$$

$$b = 0.661 + 0.477 \sin(\omega_s - 60) \quad [24b]$$

Monthly Mean Hourly Diffuse Radiation

The expression given by Liu and Jordan (1960) is used to calculate monthly mean hourly diffuse radiation.

$$\bar{I}_d = \bar{r}_d * \bar{H}_d \quad [25]$$

where,

$$\bar{r}_d = (\pi / 24) \, [(\cos\omega - \cos\omega_s) / (\sin\omega_s - (2\pi\omega_s/360) \cos\omega_s)] \quad [26]$$

Monthly Mean Hourly Beam Radiation

The monthly mean hourly beam radiation is estimated by the equation given by Duffie and Beckman (1980).

$$\bar{I}_b = \bar{I}_g - \bar{I}_d \quad [27]$$

Solar Radiation on a Tilted Surface

The calculation of monthly mean radiation on a tilted surface has been divided into global, diffuse and direct radiation for both daily and hourly time scales.

Monthly Mean Daily Global Radiation

The monthly mean daily global radiation on a tilted surface can be calculated by the equation given by Duffie and Beckman (1980).

$$\bar{H}_{gt} = (\bar{H}_g - \bar{H}_d) \, \bar{R}_{bH} + \bar{H}_d \, [(1 + \cos\beta) / 2] + \bar{H}_g (0.2) \, [(1 - \cos\beta) / 2] \quad [28]$$

where,

$$\overline{R}_{bH} = [\cos(\phi - \beta)\cos\delta\sin\omega'_s] + [(\pi/180)\,\omega'_s\sin(\phi - \beta)\sin\delta]/ [\cos\phi\cos\delta\sin\omega_s + (\pi/180)\sin\phi\sin\delta] \quad [29]$$

and

$$\omega'_s = \min\left|\begin{array}{l}\cos^{-1} - (\tan\phi\tan\delta)\\ \cos^{-1} - (\tan(\phi - \beta)\tan\delta)\end{array}\right. \quad [30]$$

Monthly Mean Daily Diffuse Radiation

The expression given by Gopinathan (1990) [quoting Hay (1980)] is used to calculate the monthly mean daily diffuse radiation.

$$\overline{H}_{dt} = \overline{H}_d[(\overline{H}_g - \overline{H}_d)/\overline{H}_0]\,\overline{R}_b + ((1 - \cos\beta)/2)\,[(1 - (\overline{H}_g - \overline{H}_d))/\overline{H}_0] \quad [31]$$

Monthly Mean Daily Beam Radiation

The monthly mean daily beam radiation on a tilted surface is calculated by the equation given by Duffie and Beckman (1980).

$$\overline{H}_{bt} = \overline{H}_{gt} - \overline{H}_{dt} \quad [32]$$

Monthly Mean Hourly Global Radiation

It can be calculated by the equation given by Duffie and Beckman (1980).

$$\overline{I}_{gt} = \overline{I}_b\,\overline{R}_{bI} + \overline{I}_d[(1 + \cos\beta)/2] + (\overline{I}_b + \overline{I}_d)\,(0.2)\,[(1 - \cos\beta)/2] \quad [33]$$

where,

$$\overline{R}_{bI} = [\cos(\phi - \beta)\cos\delta\cos\omega_s] + [\sin(\phi - \beta)\sin\delta]/ [\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta] \quad [34]$$

Monthly Mean Hourly Diffuse Radiation

Reindl et al. (1990) [quoting Hay and Davies (1978)] have proposed a model to predict the monthly mean hourly diffuse radiation on a tilted surface.

$$\overline{I}_{dt} = \overline{I}_d[(1 - A_I).((1 + \cos\beta)/2)] + A_I\,\overline{R}_{bI} \quad [35]$$

where,

$$A_I = (I_b/I_0)$$

Monthly Mean Hourly Beam Radiation

It can be calculated using the expression given by Duffie and Beckman (1980).

$$\overline{I}_{bt} = \overline{I}_{gt} - \overline{I}_{dt} \quad [36]$$

Daily Global Radiation for a Month

Bendt et al. (1981) have given the cumulative distribution function for the daily global radiation on a horizontal surface as,

$$F(K) = [\exp(\gamma K_{min}) - \exp(\gamma K)] / [\exp(\gamma K_{min}) - \exp(\gamma K_{max})] \quad [37]$$

where F(K) is the fractional time during which the daily clearness index is $\leq K$,

$$K_{min} = 0.05 \quad [38]$$

For India, Joshi (1984) has given the following expression to calculate K_{max} as,

$$K_{max} = 0.362 + 0.597\,\overline{K} \quad [39]$$

The value of γ is found by solving the transcendental equation,

$$\gamma = [((\gamma K_{min} - 1)\exp(\gamma K_{min}) - (\gamma K_{max} - 1)\exp(\gamma K_{max}))] / [\exp(\gamma K_{min}) - (\exp(\gamma K_{max})] \quad [40]$$

Knowing K_{min}, K_{max} and for a given fractional time F(K), the value of K is found from equation [37]. Since,

$$H_g = (K / \overline{K}) . \overline{H}_g \quad [41]$$

The daily global radiation (Hg) is then calculated (Reddy et al., 1987).

If the values are needed for a month, the fractional time is divided into the number of days in a month and the above calculation is done as many times as there are days in that month. The values of K (and therefore H_g) will be in ascending order increasing from K_{min} to K_{max}. By doing random sampling (without replacing), the global radiation for a month for a given location can be estimated.

The inputs required for each calculation and the program output are given in Tables 2, 3 and 4.

Help

A help menu has been included in the program to assist the user in running the software. The inputs given to each calculation are clearly explained.

A data file has been created which contains latitude, longitude and altitude (the height above the sea level) for 50 locations. However, the monthly mean clearness index (K), the sunshine duration (SD) and the ambient temperature (T_{amb}) values for all the 12 months in a year are available for only 34 cities.

The complete details of the calculation procedure is given by Jeyakumaran (1991).

RESULTS AND DISCUSSION

The results obtained by running the program have been verified with data for known locations (both India and elsewhere) using examples in standard textbooks, namely, Duffie and Beckman (1980), Kreith and Kreider (1981) and Reddy (1987), and also with available data for Indian locations contained in Mani and Rangarajan (1983).

Though most of the data have been taken from Mani and Rangarajan (1983), the software has an added advantage that many recent calculations have been included. This program is extremely flexible in that:

(1) The data file can be expanded to include more locations (both Indian or elsewhere);
(2) New correlations can be added as and when more accurate methods are developed;
(3) Additional calculations for thermal and photovoltaic applications can be included; and
(4) It is highly user friendly.

The following examples demonstrate the program's applicability.

Example – 1

To calculate the declination angle on March 7 and display the location of Bangalore.

Result

Name of the city	: Bangolore
Month	: March
Date	: 7
Latitude (degrees)	: 12.95
Longitude (degrees)	: 77.12
The declination angle is	: –5.60 degree

Example – 2

To calculate the monthly mean daily global solar radiation on a horizontal surface at Delhi for March, using:

(1) Mani and Rangarajan method.
(2) Akinoglu and Ecevit method.
(3) Rietveld method.

Results

Name of the city	: New Delhi
Month	: March
Latitude (degrees)	: 28.58
Longitude (degrees)	: 77.02

Method	Monthly Mean Daily Global Radiation (MJ/m^2)
Mani & Rangarajan	19.23
Akinoklu & Ecevit	19.38
Rietveld	19.34

Table 2. Program input and output for the calculation of basic solar radiation parameters.

Calculation	User Input	Program Output	Units
Solar time	CC, MN, DT, WT	Solar time	Hours & minutes
Declination angle	CC, MN, DT	Declination angle	Degrees
Incidence angle	CC, MN, DT, WT	Incidence angle	Degrees
Zenith angle	CC, MN, DT, WT	Zenith angle	Degrees
Sunset hour angle	CC, MN, DT	Sunset hour angle	Degrees
Day length	CC, MN, DT	Day length	Hours
Watch time	CC, MN, DT, ST	Watch time	Hours & minutes
Monthly mean daily extraterrestrial radiation	CC, MN	Monthly mean daily extraterrestrial radiation	MJ/m^2
Monthly mean hourly extraterrestrial radiation	CC, MN, WT	Monthly mean hourly extraterrestrial radiation	MJ/m^2

CC – City Code MN – Month Number DT – Date
WT – Watch Time ST – Solar Time

Example – 3

To calculate the monthly mean hourly diffuse solar radiation on a tilted surface (tilt angle = 5°) for Madras (for the hour 10:10 to 11:10 AM watch time) in July.

Result

Name of the city : Madras
Month : July
Latitude (Degrees) : 13.12
Longitude (Degrees) : 80.28
For the hour : 10 hour 10 minutes – 11 hour 10 minutes.
Tilt angle of the surface : 5 degrees
The monthly mean hourly diffuse radiation : 0.057 MJ/m^2

Example – 4

To calculate the daily global radiation on a horizontal surface for Kodaikanal for all days in February.

Daily global radiation for a month

Name of the city	: Kodaikanal
Month	: February
Latitude (Degrees)	: 10.23
Longitude (Degrees)	: 77.47
Monthly mean daily global radiation	: 21.88MJ/m^2
Monthly mean clearness index	: 0.7090

Day	Daily Global Radiation (MJ/m^2)	
	DRA*	DRR**
1	1.54	24.23
2	16.53	23.41
3	18.15	16.53
4	19.10	23.28
5	19.77	20.29
6	20.29	22.13
7	20.72	21.08
8	21.08	23.53
9	21.39	22.70
10	21.66	23.01
11	21.91	24.14
12	22.13	18.15
13	22.34	19.77
14	22.52	23.15
15	22.70	23.96
16	22.86	22.86
17	23.01	23.75
18	23.15	23.64
19	23.28	22.52
20	23.41	21.91
21	23.53	1.54
22	23.64	20.72
23	23.75	21.39
24	23.86	19.10
25	23.96	23.86
26	24.05	21.66
27	24.14	24.05
28	24.23	22.34

DRA* – Daily global Radiation value in Ascending order. It does not pertain to the day number.

DRR** – Daily global Radiation value in Random order.

Table 3. Program input and output for the estimation of monthly mean solar radiation on a horizontal surface.

Radiation	Method	User Input	Program Output
Daily Global	Mani & Rangarajan	CC, MN	Monthly Mean Daily Global Radiation
	Modi & Sukhatme	CC, MN	Monthly Mean Daily Global Radiation
	Akinoglu & Ecewit	CC, MN	Monthly Mean Daily Global Radiation
	Ogelman	CC, MN	Monthly Mean Daily Global Radiation
	Rietveld	CC, MN	Monthly Mean Daily Global Radiation
Daily Diffuse	Mani & Rangarajan	CC, MN	Monthly Mean Daily Diffuse Radiation
	Modi & Sukhatme	CC, MN	Monthly Mean Daily Diffuse Radiation
	Gupta, Usha Rao & Reddy	CC, MN	Monthly Mean Daily Diffuse Radiation
	Muneer & Hawas	CC, MN	Monthly Mean Daily Diffuse Radiation
	Erbs & Klein	CC, MN	Monthly Mean Daily Diffuse Radiation
	Collares-Pereira & Rabl	CC, MN	Monthly Mean Daily Diffuse Radiation
Daily Beam		CC, MN	Monthly Mean Daily Beam Radiation
Hourly Global		CC, MN, WT	Monthly Mean Hourly Global Radiation
Hourly Diffuse		CC, MN, WT	Monthly Mean Hourly Diffuse Radiation
Hourly Beam		CC, MN, WT	Monthly Mean Hourly Beam Radiation

CC – City Code MN – Month Number DT – Date
WT – Watch Time ST – Solar Time

Table 4. Program input and output for the estimation of monthly mean solar radiation on a tilted surface.

Radiation	User Input	Program Output
Daily Global	CC, MN, TA	Monthly Mean Daily Global Radiation
Daily Diffuse	CC, MN, TA	Monthly Mean Daily Diffuse Radiation
Daily Beam	CC, MN, TA	Monthly Mean Daily Beam Radiation
Hourly Global	CC, MN, WT, TA	Monthly Mean Hourly Global Radiation
Hourly Diffuse	CC, MN, WT, TA	Monthly Mean Hourly Diffuse Radiation
Hourly Beam	CC, MN, WT, TA	Monthly Mean Hourly Beam Radiation

CC – City Code MN – Month Number DT – Date
WT – Watch Time ST – Solar Time TA – Tilt Angle of the Surface

CONCLUSION

A micro computer software has been developed to calculate the monthly mean daily and hourly global, diffuse and beam radiation on horizontal and tilted surfaces. In addition, the daily global radiation for a month, solar time, declination angle, incidence angle, zenith angle, sunset hour angle and day length can also be computed. All these parameters can be estimated for fifty locations in India. This application software will be useful for researchers, students and designers of solar equipments who need data on solar radiation in India. The program has the added advantages that more locations can be added and that it is user friendly. Interested users can obtain information and copies of the SOLRAD software from the authors.

NOMENCLATURE

A_I	Anisotropic index
DL	Day length (hours and minutes)
E	Equation of time (minutes)
h	Relative humidity
H	Daily radiation (MJ/m^2)
I	Hourly radiation (MJ/m^2)
k	Hourly clearness index
K	Daily clearness index
L	Longitude (degrees)

n	Number of days in a month
N	Day number of the year (from 1 to 365)
r	Ratio of the monthly mean hourly diffuse fraction to that of the daily fraction
R	Ratio of the monthly mean daily global radiation on a tilted surface to that on a horizontal surface
s	Actual sunshine duration (hours and minutes)
S	Maximum possible sunshine duration (hours and minutes)
sc	Solar constant (1353 W/m^2)
ST	Solar time (hours and minutes)
T	Temperature (^0C)

Greek

α	Solar altitude angle (degrees)
δ	Declination angle (degrees)
β	Tilt angle or slope (degrees)
θ	Incidence angle (degrees)
ρ	Ground reflectance
ϕ	Latitude (degrees)
θ_z	Zenith angle (degrees)
ω	Hour angle (degrees)
γ	Azimuthal angle (degrees) constant, defined by equation 40

Subscripts

b	Beam
d	Diffuse
g	Global
H	Daily
I	Hourly
0	Extraterrestrial
t	Tilted surface
amb.	Ambient temperature
s	Sunset hour angle
std	Standard (for Indian L_{std} = 82.5°E)
loc	Local
—	Monthly mean values, e.g., $\overline{H}_0$

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