SAND75-0565
Unlimited Release

IDN
TH
EXTH

Estimating the Direct Component of Solar Radiation

Eldon C. Boes

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Energy Research and Development Administration under Contract AT (29-1) 789

Printed November 1975

Sandia Laboratories
energy report

SF 2900-QQB(3-74)

Issued by Sandia Laboratories, operated for the United States Energy Research and Development Administration by Sandia Corporation.

NOTICE

SAND75-0565

ESTIMATING THE DIRECT COMPONENT OF SOLAR RADIATION

Eldon C. Boes, Sandia Laboratories
and New Mexico State University

ABSTRACT

The only readily available solar radiation data for the US consists of measurements of total radiation on a horizontal surface. A knowledge of the direct component is needed to estimate the solar energy available for focusing collectors or tilted flat-plate collectors. A review of some of the existing formulas for direct normal radiation is given. A study of the relationship between direct normal radiation and percent of possible was conducted using three special data samples. Finally, several more techniques for estimating direct normal radiation are presented.

Printed in the United States of America

Available from
National Technical Information Service
US Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy $4.50; Microfiche $2.25

I. INTRODUCTION

Quite a few schemes for utilizing solar energy will use focusing devices which are capable of collecting only direct beam radiation. Moreover, a method of separating total radiation into direct and diffuse components is needed in order to estimate the amount of solar energy which would be available to a flat-plate collector which is tilted upward and facing South. Unfortunately, the amount of direct solar radiation available at a given location is generally not known; regular measurements of direct normal radiation have only been made at a few of US locations. Since records of the total radiation on a horizontal surface exist for over 50 US locations, a technique for estimating direct radiation from total radiation and other parameters would be useful.

This paper reports the results of a search for such a technique. The search began with a study of the formulas for direct normal radiation which were found in the literature. Many of these are only applicable under clear sky conditions. A discussion of these formulas is given in the second section.

One of the conclusions in the second section is that the best type of formula which is independent of cloud conditions is the simple linear regression model suggested by Jordan and Liu [1] and used by Aerospace in their Mission Analysis [2]. In order that the validity of this type of formula could be more carefully established, a special data base was carefully prepared. This data base, which could readily be used for a variety of other studies including solar systems analysis, is described in the third section.

This data base was used to determine whether the Aerospace formula might be improved upon by introducing a little more complexity, such as using different regression lines for different times of day or different seasons or locations. These investigations are summarized in the fourth section.

The remaining sections of the paper are devoted to the presentation of several formulas for estimating direct normal radiation. Each section is devoted to a particular technique which is recommended for a particular type of situation.

Estimates of direct normal radiation availabilities based upon formulas such as those presented here can never replace the need for actual measurements. Use of these formulas can only be considered a temporary alternative until real data becomes available. In fact, even though the formulas presented are based upon some of the best data samples available, probably their most serious drawback is the limited amount of data from which they were derived. There is truly a critical need for more records of measurements of solar radiation, especially of direct normal radiation.

II. EXISTING FORMULAS

There are quite a few formulas for estimating the intensity of direct normal radiation. The listing here is intended to be representative rather than complete. Note that these are techniques for estimating intensities rather than integrals. Formulas which estimate daily totals or monthly averages of daily totals of direct radiation have been excluded, principally because the analysis of a system using a focusing collector usually requires some knowledge of the variability of direct beam radiation in addition to the integral for the day.

A fairly complete formula, frequently credited to Angstrom is the following, [3].

$$IDN = (Ro/R)^2 \int_o^\infty EXT_\lambda \; 10^{-(ma_A + m_r a_d + a_w)} d\lambda;$$

where

IDN = intensity of direct normal radiation

$(Ro/R)^2$ = earth-sun distance correction factor

λ = wavelength

EXT_λ = extraterrestrial intensity at wavelength λ

$m = pm_r/1000$ = air mass corrected to local altitude (pressure)

m_r = relative air mass, Bemporad tables

a_A = Rayleigh extinction coefficient for scattering by pure atmosphere

a_d = extinction coefficient for scattering by aerosols

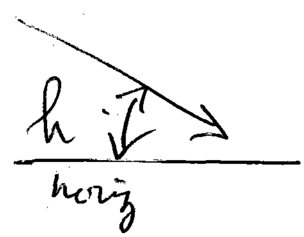
a_w = extinction coefficient for absorption, principally by water vapor

Of course, this formula is only valid under clear sky conditions. Note that application of the formula requires estimates for a_w and a_d which in turn require knowledge of atmospheric water vapor content and turbidity. Because these two parameters are quite variable and because frequent measurements are not available this formula generally cannot be applied in full detail. However, Robinson does give some fairly large charts for estimating IDN which are reasonably accurate in spite of the simplifying assumptions made.

Another set of curves which express IDN as a function of solar altitude, atmospheric water vapor, and dust under clear sky conditions are given by Rao and Seshadri [4]. Unfortunately, these suffer from the same lack of input as does the first formula.

In [5] Spencer presents a formula for estimating IDN under clear sky conditions at sea level which he derived by applying a curve fitting technique to the curves of Rao and Seshadri. His formula assumes an atmospheric dust content of 300 particles per cm^3; the formula is

$$IDN = 697 \begin{bmatrix} 1 & \log w & (\log w)^2 \end{bmatrix} \begin{bmatrix} B \end{bmatrix} \begin{bmatrix} \sin h \\ \sin^2 h \\ \sin^3 h \\ \sin^4 h \\ \sin^5 h \end{bmatrix}$$



where

$$IDN = \text{direct normal intensity in } Wm^{-2}$$

$$w = \text{precipitable water (mm)}$$

$$h = \text{solar altitude}$$

and the 3 x 5 matrix B can be found in [5].

Another clear sky formula for IDN which seemed quite accurate in a test with some Albuquerque data is given by Majumdar et al in [6]:

$$IDN = 1331\ (0.8644)^{(PM_r/1000)}\ (0.8507)^{(WM_r)^{0.25}}$$

$$p = \text{local pressure (millibars)}$$

$$M_r = \text{relative air mass}$$

$$W = \text{precipitable water vapor, (cm)}$$

and IDN is in Wm^{-2}. This formula assumes low turbidity.

All the formulas discussed thus far are only valid under clear sky conditions. A formula which is independent of cloud cover was desired. In [7] Klein gives both. For clear skies the formula is

$$IDN = a_z \cdot EXT$$

where

$$EXT = \text{intensity of extraterrestrial radiation}$$

a_z = a function of altitude and solar zenith angle derived by regression

Klein's formula for IDN under cloudy skies is

$$IDN = (1.05 - 0.98C) \cdot a_z \cdot EXT$$

where C = fraction of sky covered by clouds. Although this type of formula may be accurate in the long run, one would not expect accuracy on a short time basis because the parameter C records cloud amount without regard to the solar position.

In looking for a formula for predicting IDN over short time intervals such as 1 hour or less one soon realizes the need for an independent variable which in some way records the variable blocking of the sun's rays by clouds. The most promising variable is ITH, the intensity of the total (direct plus diffuse) radiation falling on a horizontal surface. Just how closely related the variables IDN and ITH are can be seen in Figure 2.1 which shows their graphs as a function of time for one day. The most obvious difference in the two graphs is that the graph of ITH includes a cosine effect which is due to the fact that this total intensity is measured on a horizontal rather than normal surface. This suggests that removal of the cosine effect from ITH might leave a linear relationship. This is an intuitive argument for the formula given by Jordan and Liu in [1]. After a slight modification, the formula is

$$IDN = 1917 \cdot PP - 516\ (W\ m^{-2}),$$

where

$$PP = \text{percent possible} = ITH/EXT_H$$

EXT_H = extraterrestrial radiation on a horizontal surface

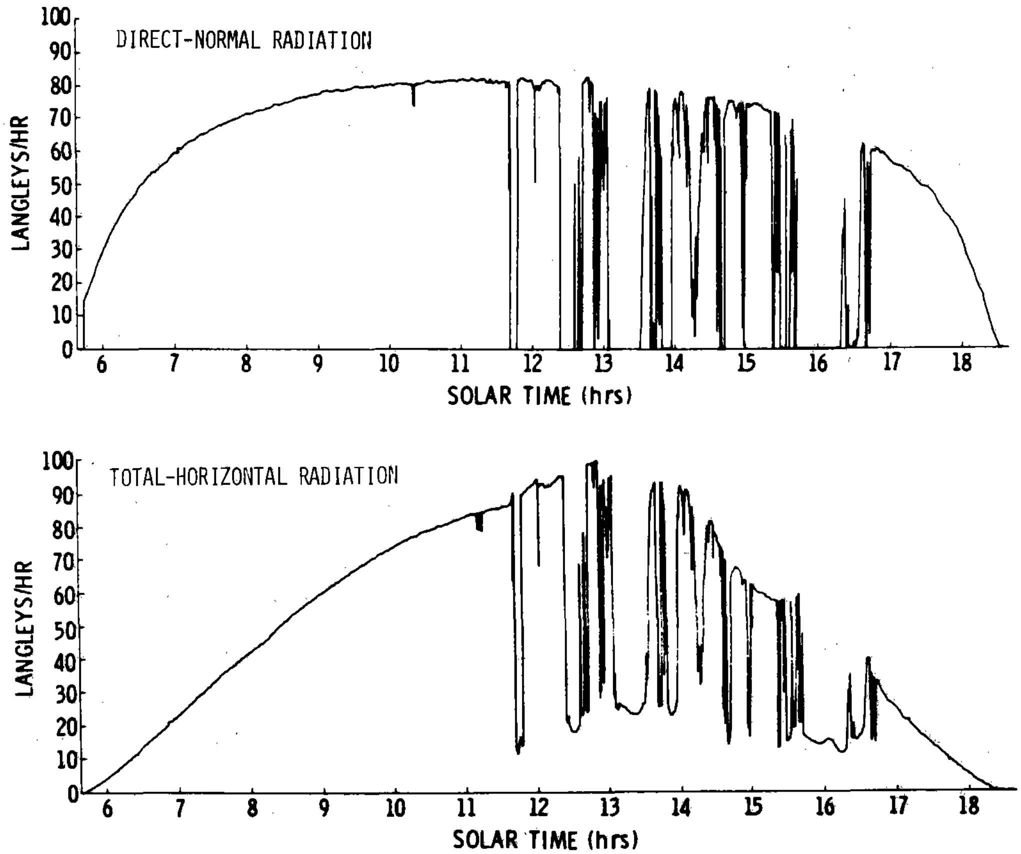


FIGURE 2.1 A COMPARISON OF THE GRAPHS OF DIRECT-NORMAL RADIATION AND TOTAL-HORIZONTAL RADIATION FOR ONE DAY (ALBUQUERQUE, APRIL 21, 1974)

Although Jordan and Liu suggested this formula only for clear sky conditions it seems to be valid in some other situations. Essentially this same formula was used by the Aerospace Corporation in the insolation studies which was part of their Mission Analysis program [2]. Their formula is

$$IDN = \begin{cases} 1227 \cdot PP - 118 & \text{if } PP \geq 0.25 \\ 0 & \text{if } PP < 0.25 \end{cases}$$

Note that if PP is below 0.25 this formula assumes that the solar disc is completely obscured by clouds.

It is interesting to speculate on the significant difference in the regression coefficients in these last two formulas. There are several probable causes. The formula of Jordan and Liu was derived from a sample of clear sky data recorded at Hump Mountain, NC, over 55 years ago. On the other hand, the Aerospace data consisted of measurements of hourly integrals of total radiation along with interpolated values of direct normal radiation for Blue Hill and Albuquerque in 1962. Thus, differences are probably due to the different cloud conditions, the interpolation used in one sample, the different locations, and the different time periods involved.

Studies of the accuracy of these formulas were carried out using a sample of 64 clear sky data points recorded in Albuquerque in September of 1974. These studies showed that none of the formulas listed above is significantly more accurate than the simple linear regression equation between IDN and PP for these data.

Quite a few other formulas involving other parameters were also tested. Some examples are formulas of the form,

$$IDN = A \cdot PP + B \cdot m + C \cdot w + D$$

and

$$IDN = A \cdot e^{Bm + Cw}$$

where m is air mass and w is precipitable water vapor and the coefficients were selected by multiple regression techniques. These formulas also did not perform better than the simple linear regression.

Even for this carefully selected sample of points recorded when there were no clouds near the solar position during a single month interval, it was impossible to find a formula which could predict IDN with an average accuracy of better than 5 percent. The remaining variation is probably due to varying turbidity (measurements were not available), variation in atmospheric water vapor content (this was only measured twice daily), varying diffuse radiation from clouds away from the sun, and instrumental inaccuracies. At any rate, these studies led to the conclusions that the best way to estimate direct normal radiation under general atmospheric conditions is to use a formula which is basically similar to that of Aerospace, but which might be able to account for possible variation in the linear relationship between IDN and PP.

III. REPRESENTATIVE DATA SAMPLES

In order to more carefully study the relationship between IDN and PP some special data samples were prepared. These samples consist of simultaneous readings of ITH and IDN at 10-minute intervals; they were taken from the solar strip chart records for 1962 for three locations: Albuquerque, Blue Hill, and Omaha. These locations and this year were chosen because sufficiently complete records existed. Although direct radiation measurements are also made at Tucson, it was felt that conditions there would be fairly similar to those at Albuquerque. Direct radiation records for Madison are very incomplete and biased toward clear weather because the direct normal recorder is only operated continuously under such conditions.

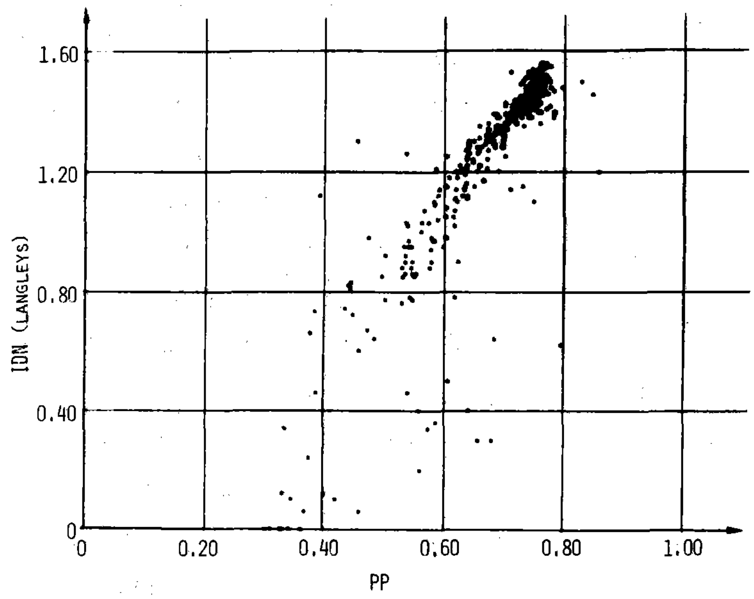


FIGURE 4.1 PLOT OF IDN VS. PP FOR THE ONE-WEEK WINTER SAMPLE FOR ALBUQUERQUE

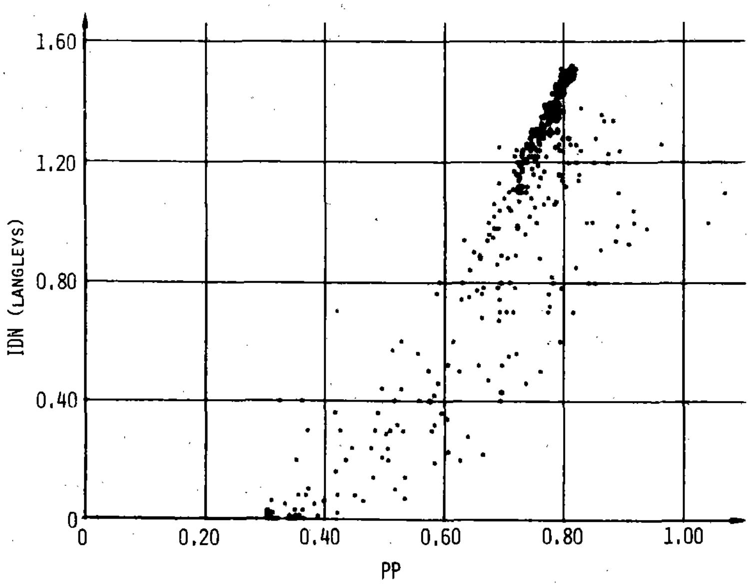


FIGURE 4.2 PLOT OF IDN VS. PP FOR THE ONE-WEEK SPRING SAMPLE FOR ALBUQUERQUE

The data samples for Albuquerque consist of four 1-week samples which are representative of the four seasons in the following sense. The total radiation in each sample week is equal to the long-term average of weekly totals for that season in Albuquerque. The data sample for Blue Hill is of precisely the same type. Of course, the sample weeks for Blue Hill do not coincide with those of Albuquerque.

Because of the incompleteness of records for Omaha, it was impossible to select four sample weeks of data for that location. Instead, in each season a set of 7 disjoint days was selected whose total radiation was equal to Omaha's long term average of weekly total radiation for that season.

Although these data samples were prepared in order to study the relationship between IDN and PP, the general lack of direct normal radiation data probably makes them valuable for other purposes such as solar system analyses. The data will be generally available in the very near future.

A difficulty which always arises in connection with using US pyranometer data is the question of whether to apply any adjustment factors to the data. Even though calibration records and instrument histories are reasonably complete, it seems impossible to trace and correct all errors. The decision made was to use those adjustment factors suggested by Hanson et al [8] along with linear interpolation to adjust for response drift if such a drift was indicated by a terminal calibration. These factors and arguments for them will be available with the data.

IV. THE RELATIONSHIP BETWEEN IDN AND PP

There is definitely not a fixed, absolute linear relationship between direct normal radiation and percent of possible. This is clearly evident in Figures 4.1 and 4.2 which shows plots of the Winter and Spring representative samples for Albuquerque. (Sample points with $PP \leq 0.30$ are not shown). Note that for the regions having the heaviest concentrations of points, the simple linear regression line for the Spring sample would have a larger slope and would be below the regression line for Winter.

Another interesting point evident in Figure 4.1 is that if we restrict our attention to the strip $0.60 \leq PP \leq 0.80$, the data strongly suggest a linear relationship. The same is true for the range $0.65 \leq PP \leq 0.85$ in Figure 4.2.

However, the type of relationship between PP and IDN for those points with PP values below these intervals is not at all evident. Although for values of PP between 0.30 and 0.40 the points cluster along the axis IDN = 0, in the range $0.40 \leq PP \leq 0.60$ the points are very scattered. These PP values occur under a variety of atmospheric conditions: the sun dimmed by clouds, the sun shining through a hole in a sky nearly covered by dark cumulous clouds, the sun partially blocked by the edge of a cloud, or completely blocked by very bright clouds, etc. Each of these situations could produce a PP value of 0.50 and yet give substantially different direct normal intensities. No parameter or group of parameters which might specify the situation has been recorded; the extreme variability of these conditions would render such a task almost impossible.

In Figure 4.2 even in the interval $0.65 \le PP \le 0.85$ where the relationship seems so clearly linear there are quite a few points scattered below the cluster. Of course, a few of these are probably due to data reduction errors - the ITH and IDN readings were not quite simultaneous. But many of them are also due to various cloud conditions. For instance, it is not uncommon to have one cloud block half the sun and reduce IDN while other nearby bright clouds are concentrating radiation onto the pyranometer and thus producing a high ITH reading.

The observations thus far suggest that the Aerospace formula can perhaps be made more accurate by systematically adjusting for the variation in the linear relationship between PP and IDN, and by using some model other than a linear one in that middle range of PP values where the data is quite scattered. The first stage in trying to devise such a model was to determine what data source changes produced significant changes in the relationship between IDN and PP.

The particular source factors tested for influences on this relationship were time of day, season, and location. It is reasonable to expect that the dependence of IDN on PP might also vary from year to year in a given season; this was the motivation behind the decision to select data samples which were representative of season and location.

The actual determinations of what factors affect the dependence of IDN on PP were made using an extensive battery of statistical t-tests. Before the results are summarized, an example will be given to illustrate the technique used. This example examines the functional dependence of IDN on PP at Omaha in the summer as opposed to this same functional dependence at Omaha in the fall. The two data sets are separated into 10 categories each, corresponding to PP values between 0.3 and 0.35, 0.35 and 0.4, and so on up to 0.75 and 0.8. In each category, the two samples of data corresponding to the two seasons are used to perform an unrelated means t-test. Actually, tests were only performed on alternate categories because this seemed more than adequate for establishing whether or not the distributions were different. The results of this example are summarized in Table 4.1. Note that in each category except the first the value of the test statistic is significant at the 95-percent level.

$0.35 \leq PP < 0.40$	n = 35		n = 11
	mean = 0.16		mean = 0.12
	variance = 0.042		variance = 0.028
		t = 0.56	
$0.45 \leq PP < 0.50$	n = 14		n = 23
	mean = 0.45		mean = 0.18
	variance = 0.068		variance = 0.034
		t = 3.64	
$0.55 \leq PP < 0.60$	n = 21		n = 26
	mean = 0.62		mean = 0.35
	variance = 0.080		variance = 0.097
		t = 3.15	
$0.65 \leq PP < 0.70$	n = 52		n = 27
	mean = 0.90		mean = 0.53
	variance = 0.060		variance = 0.157
		t = 5.05	
$0.75 \leq PP < 0.80$	n = 55		n = 99
	mean = 0.97		mean = 1.21
	variance = 0.136		variance = 0.022
		t = 5.82	

Table 4.1 Example: Statistical comparison of the relationships of IDN and PP in the summer and fall at Omaha.

Because of the limited amount of data available for analysis, the results of all these tests can only be taken as indications of the variation of IDN as a function of PP. The conclusions must not be considered absolute.

The tests indicated that the relationship between IDN and PP does vary from season to season. As Table 4.2 shows, this is especially true at Albuquerque.

PP Interval	Sp-Su	Sp-Fa	Sp-Wi	Su-Fa	Su-Wi	Fa-Wi
			Albuquerque			
0.35, 0.40			S	S		
0.45, 0.50			S	S	S	S
0.55, 0.60	S		S	S	S	S
0.65, 0.70	S	S	S	S	S	S
0.75, 0.80	S	S	S	S	S	S
			Omaha			
0.35, 0.40						
0.45, 0.50				S		S
0.55, 0.60	S		S	S		S
0.65, 0.70	S		S	S		S
0.75, 0.80		S	S	S	S	S
			Blue Hill			
0.35, 0.40	S	S			S	S
0.45, 0.50						
0.55, 0.60	S	S		S		
0.65, 0.70	S	S	S	S		S
0.75, 0.80	S		S		S	S

Table 4.2 Seasonal comparisons of the dependence of IDN on PP. An S indicates a significant difference at the 95% level.

A change in location also seems to produce a change in the relationship between IDN and PP. As Table 4.3 shows, this is especially true for higher PP values. That the relationship depends to some extent on location is unfortunate because the direct and total radiation data necessary to derive a regression model is only available for a few US locations. On the other hand, for a given PP interval, the differences in IDN values for different locations were generally less than 25 percent.

PP Interval	Sp	Su	Fa	Wi
	Albuquerque vs Blue Hill			
0.35, 0.40			S	S
0.45, 0.50			S	S
0.55, 0.60	S		S	
0.65, 0.70		S	S	S
0.75, 0.80	S	S	S	S
	Albuquerque vs Omaha			
0.35, 0.40				S
0.45, 0.50				
0.55, 0.60	S	S	S	S
0.65, 0.70	S	S	S	S
0.75, 0.80	S	S	S	S
	Blue Hill vs Omaha			
0.35, 0.40		S	S	
0.45, 0.50			S	
0.55, 0.60	S	S	S	
0.65, 0.70	S	S	S	
0.75, 0.80	S			S

Table 4.3 Results of the effect of different location on the functional relationship between IDN and PP.

Tests to determine whether the relationship between IDN and PP varies with time of day were also performed. For this, the day was broken into three periods; early a.m., midday, and late p.m. The time divisions actually were based upon whether the sun's zenith angle was less than a certain cutoff angle of about 67°. This corresponds to an air mass value of about 2.6 at sea level. One would hope that at least there is not much change in the relationship of IDN and PP between early morning and late evening. The tests generally substantiated this. The next question was whether there was a difference between midday and the ends of the day. The results of these tests were rather surprising; they indicate that time of day is a factor in Albuquerque, but not in Blue Hill or Omaha. The results are given in Table 4.4. Note that in this table an S appearing in a cell has a slightly different meaning; it means that in that cell, the midday data differed significantly from the early morning data and from the late evening data, taken separately.

PP Interval	Sp	Su	Fa	Wi
	Albuquerque			
0.35, 0.40				S
0.45, 0.50				
0.55, 0.60				S
0.65, 0.70	S	S	S	S
0.75, 0.80	S	S		S
	Blue Hill			
0.35, 0.40				
0.45, 0.50		S		
0.55, 0.60				
0.65, 0.70			S	
0.75, 0.80				S
	Omaha			
0.35, 0.40				
0.45, 0.50				
0.55, 0.60				
0.65, 0.70				
0.75, 0.80				

Table 4.4 An S indicates that IDN is a different function of PP during midday than in the early or late sunlight hours.

The results of these tests give an indication of how much complexity one should introduce in using sample data to derive formulas for IDN as a function of PP. Until further information becomes available, the conclusions seem to be that one should use different formulas for different seasons and for different locations. For a high altitude location with a fairly sunny climate one should consider using a different formula for different times of day.

Another point which is independent of these tests is that one should consider using something other than a linear regression model in those situations where the percent of possible is between roughly 0.30 and 0.60. This is especially true if one wants to reproduce values of IDN which are as variable as actual IDN measurements tend to be.

The particular type of formula one selects for estimating IDN values depends on the input data available and the desired result. For instance, if one wishes to use hourly totals of total radiation for a month to compute the daily average of direct normal radiation for that month in order to compare these averages at several locations, one can simply compute hourly PP values and then use a single linear regression equation to generate estimates of hourly direct readings. Relative comparisons based upon the averages of daily totals of these direct readings would probably be valid. At the other extreme, if one wishes to use total radiation readings at 10-minute intervals to generate direct radiation readings for solar systems analysis, one should use a more complicated model which depends on the location and varies with season and which reproduces the variability which is characteristic of direct normal radiation under varying cloud conditions. At the present time total radiation data at 10-minute intervals only exists on strip chart records, except for a few isolated samples, so this situation is not too important. However, current plans of the National Weather Service call for digital recording at 1-minute intervals of total radiation intensities to begin at all stations in their solar network sometime in 1976. Less than half of the stations will record direct or diffuse radiation.

V. A FORMULA FOR SHORT TIME INTERVALS

This section describes how a reasonably accurate formula for generating values of direct radiation at short time intervals can be devised from a four-week representative sample of data like those discussed earlier. This particular type of technique has been tested for Albuquerque; some results are given below.

The first step is to separate the data for each season into two categories; data from the middle of the day, and data recorded within about 2 hours of sunrise and sunset. (If tests have shown that these two data sets are not significantly different, this is unnecessary.) Next, examine a plot of IDN vs PP for each data set to identify that portion of the data which seems to obey a linear relationship. For these points the simple linear regression line is derived. Finally, all the points for midday are used to build a midday frequency table. This is simply the tabulation of the two dimensional frequency distribution of the midday data sample; the PP intervals run from 0.0 to 1.0 and have width 0.05. In langleys, the IDN intervals run from 0.0 to 2.0 and have width 0.1. A frequency table for the early and late readings is built in the same way.

Such a frequency table can be used to build a probabilistic model which will generate IDN values having the same distribution as the sample data. The technique is simple; for PP in a given interval one uses the distribution of the sample IDN values for that interval along with a random number to select an IDN value. The formula given below uses this technique only under certain conditions; the intriguing possibility of using such a probabilistic model entirely has not been pursued.

The description of a formula for each season can now be given; actually there are two formulas for each season, one to be used near sunrise and sunset, and the other to be used during the remaining bulk of the day. One of these is shown in Fig. 5.1; in this model it is assumed that the interval in which the relationship seems linear starts at PP = 0.55.

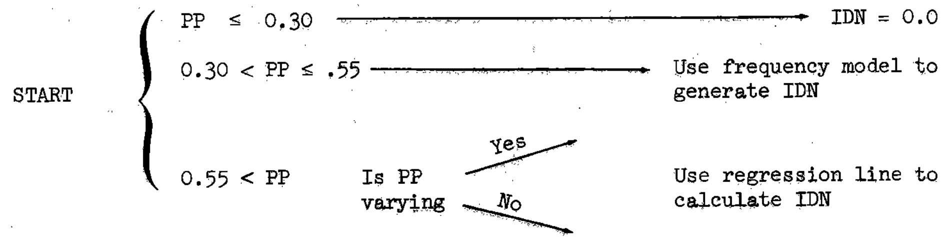


Figure 5.1 General model for estimating IDN at short time intervals.

This formula uses the frequency model even when PP > 0.55 if the PP values are varying because such variation would suggest a partly cloudy condition. The criterion used is whether the preceding, current, and succeeding values have a maximum variation exceeding 0.06.

The formula needs two small refinements. Occasionally an unreasonably high PP value will occur due to concentration by bright clouds near the solar position. So that these will not produce unrealistic IDN values, the regression line should be truncated at the upper end. Secondly, an unreasonably high PP value near sunrise can be caused by the fact that PP is the ratio ITH/EXT of two very small numbers at that time. Such a PP value should be replaced by something like two-thirds of the succeeding value before IDN is computed. An analogous correction is used for such exceptional values near sunset.

Values of IDN for dates between seasons can be estimated by linear interpolation between the values given by the seasonal formulas.

Ideally, such a formula should be constructed using sample data from the location in question. However, since such data samples are at present generally unavailable, a reasonable alternative is to use some combination of the data samples described earlier.

All of the total radiation and direct normal radiation strip charts for 1962 for Albuquerque have been digitized at 10-minute intervals. (This solar data was merged with relevant weather parameters on computer tape; it will be available through the Argonne Data Center in the near future.) Some of this data has been used to test the type of 10-minute formula given above. Figure 5.2 gives two illustrations of the results obtained. That this technique does tend to duplicate highly variable direct normal radiation conditions is especially evident in the first illustration in this figure. In all, the formula was tested on four different periods of 10 to 20 days each. For each period, the integral of the estimated IDN values was compared with the integral of the actual values. The percent errors were + 4.0, - 0.7, + 9.3, and + 0.5.

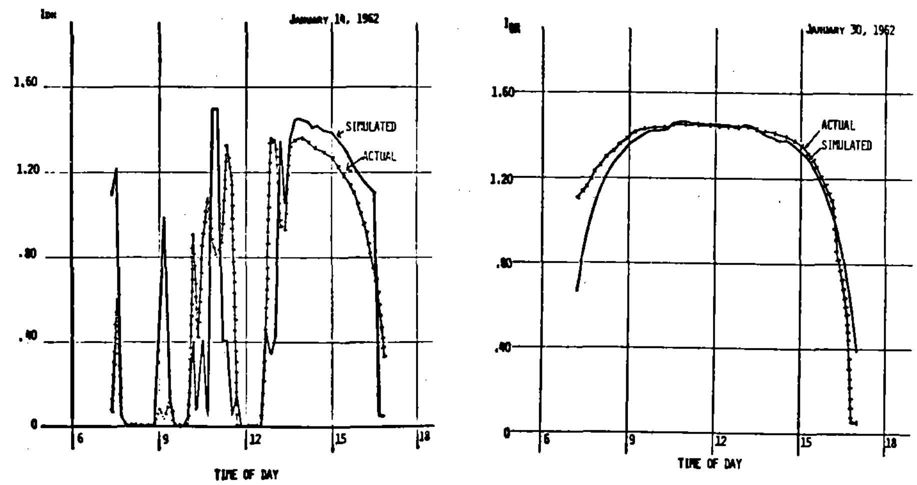


FIGURE 5.2 ONE-DAY COMPARISONS OF ACTUAL AND SIMULATED VALUES OF IDN

VI. A FORMULA FOR HOURLY DATA

At the present time the most accessible type of data available from the National Climatic Center at Asheville, NC, consists of hourly integrals of total radiation. Such data is available on computer tape for about 50 stations. The hourly integrations are performed by hand by the station observers; the standard practice is to estimate the integral for every 20 minutes and sum the three for each hour.

This integration technique smooths out the variation in ITH values which would occur under partly cloudy conditions. Because such variation is difficult to reproduce accurately, there is not much justification for using a complex probabilistic model with this hourly input data. Consequently, the hourly models which are given here consist of a collection of linear regression models for different seasons, times, and locations. The input variable is an hourly percent of possible; it is the ratio of the hourly total radiation divided by the hourly extraterrestrial. Except near sunrise or sunset, the hourly extraterrestrial can be calculated with sufficient accuracy by simply multiplying the intensity at mid-hour by 60 minutes.

The general form of the hourly models is

$$IDN = \begin{cases} 0.0 & PP \le 0.30 \\ A \cdot PP + B & 0.30 < PP \le C \\ M & PP > C \end{cases}$$

The graph is given in Figure 6.1. The number M is a maximum IDN value,

PP = Total H / EXT H

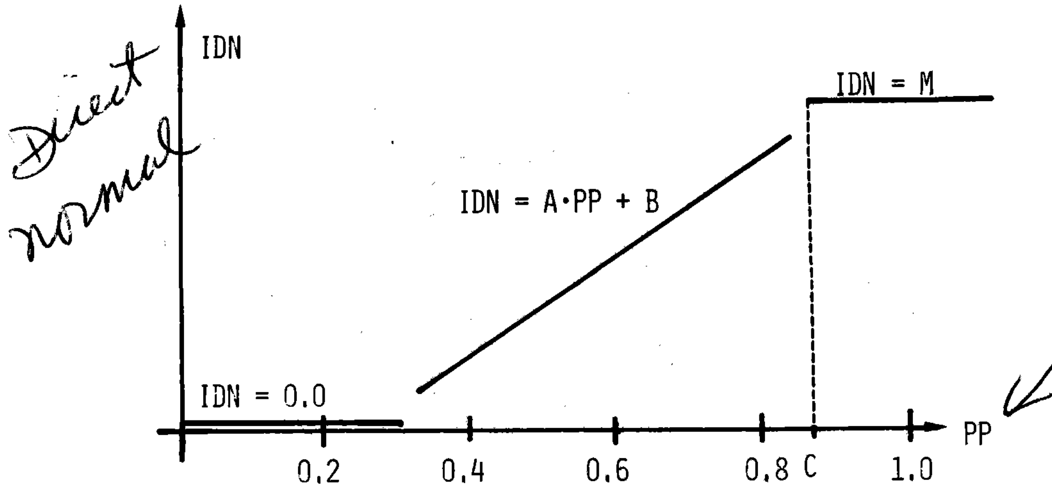


FIGURE 6.1 THE GENERAL FORM OF THE VARIOUS HOURLY FORMULAS FOR IDN

and the number C represents the maximum value for PP under normal conditions. Both M and C vary with season, location and time, as do the regression coefficients A and B. Note that in Figure 6.1 the ends of the regression line do not exactly meet the two horizontal portions of the graph. This reflects the fact that the regression line is the best least-squares fit for the actual data sample while the ends of the graph are somewhat idealized.

The different values for the parameters A, B, C, and M which were derived from the representative data samples mentioned earlier are given in Table 6.1. These coefficients will give IDN estimates in $kW \cdot hr \cdot m^{-2}$.

For Omaha and Blue Hill, the 10-minute data was summed to give hourly data before the regression coefficients were derived. For Albuquerque this process would have produced too small a sample for early and late periods; consequently, the regression coefficients for Albuquerque were derived directly from the 10-minute data. A comparison of the hourly regression equations with the 10-minute regression equations for Blue Hill indicated that they are essentially equivalent, just as one would expect.

Interpolation of adjacent seasonal estimates can be used between seasons. When selecting a formula or a combination of formulas from Table 6.1 to apply at some other location, one should bear in mind that altitude plays an important role in determining the clear sky values for IDN. One indication of this can be seen in the values for M given in Table 6.1; those for Albuquerque are consistently higher than the corresponding values for Blue Hill or Omaha. Of course, if a reliable local data sample is available, the values for A, B, C, and M should be derived from it.

	Spring		Summer		Fall		Winter	
				Albuquerque				
	Mid	E-L	Mid	E-L	Mid	E-L	Mid	E-L
A	1.64	1.13	1.65	1.07	1.56	1.15	2.42	1.68
B	-0.43	-0.19	-0.35	-0.17	-0.47	-0.21	-0.78	-0.25
C	0.85	0.85	0.80	0.80	0.85	0.85	0.80	0.80
M	1.07	1.07	0.95	0.95	0.97	0.97	1.09	1.09
				Blue Hill				
A	1.60		1.86		1.93		2.10	
B	-0.52		-0.56		-0.58		-0.71	
C	0.80		0.70		0.75		0.80	
M	0.89		0.81		0.87		1.03	
				Omaha				
A	1.69		1.62		1.88		1.67	
B	-0.62		-0.50		-0.68		-0.48	
C	0.85		0.80		0.85		0.85	
M	0.89		0.87		0.96		0.98	

Table 6.1 The linear regression coefficients and the maximum PP and IDN values for the hourly formulas.

VII. A GENERAL FORMULA

In cases where one is concerned with averages over a long time interval or with making relative comparisons of different locations, accurate estimates on a short term basis are not necessary. In these situations a single general formula will suffice. Such a formula, derived from the combination of the representative samples from all three locations, is the following:

$$\text{IDN} = \begin{cases} 0.0 & \text{PP} \le .30 \\ 1.79\ \text{PP} - 0.55 & 0.30 < \text{PP} \le 0.85 \\ 1.00 & \text{PP} > 0.85 \end{cases}$$

Just as in the preceeding section, PP is an hourly percent of possible and IDN is an hourly total of direct normal radiation in $\text{kW}\cdot\text{hr}\cdot\text{m}^{-2}$. (One can also treat IDN as an average intensity during the hour, in $\text{kW}\cdot\text{m}^{-2}$).

REFERENCES

1. R. Jordan and B. Liu, "The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation," Solar Energy, IV, p. 1, 1960.
2. Aerospace Corporation, "Solar Thermal Conversion Mission Analysis; Vol. III, Southwestern US Insolation Climatology," Report No. ATR-74 (7417-16)-2, Prepared for NSF/RANN, November 1974.
3. N. Robinson, Solar Radiation, Chs. 3 and 4, Elsevier, 1966.
4. K. Rao and T. Seshadri, "Solar Insolation Curves," Ind. J. of Met. & Geophys., 12 (2), April 1972.
5. J. Spencer, "Computer Estimation of Direct Solar Radiation on Clear Days," Solar Energy 13, p. 437, 1972.
6. N. Majumdar et al, "Prediction of Direct Solar Radiation for Low Atmospheric Turbidity," Solar Energy 13, p. 383, 1972.
7. W. Klein, "Calculation of Solar Radiation and the Solar Heat Load on Man," J. of Meteor., 5, p. 119, 1948.
8. K. Hanson, et al, "A Report on the Pyranometer Calibration Program of the US Weather Bureau, ESSA, and NOAA; 1954-1972." To be published as an ERL/NOAA Technical Report.

Distribution:

Charles Randall
Aerospace Corporation
El Segundo Blvd.
El Segundo, CA 90009

James Benson
Energy Research and Development
Administration
1800 G St., NW
Washington, DC 20545

William C. Dickinson
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, CA 94550

Floyd Blake
Martin Marietta Corporation
P. O. Box 179, Mail No. 1610
Denver, CO 80201

Michael Riches, Solar Specialist
National Weather Service, NOAA
8060 13th St.
Silver Spring, MD 20910

Robert San Martin
Department of Mechanical Engineering
New Mexico State University
Box 3449
Las Cruces, NM 88003

Department of Mechanical Engineering
University of Minnesota
Minneapolis, MN 55455
Professor Richard C. Jordan
Professor Benjamin Liu

1223 R. R. Prairie
5000 A. Narath
5700 J. H. Scott
5710 G. E. Brandvold
5711 R. P. Stromberg
5711 E. C. Boes (50)
5712 J. A. Leonard
5715 R. H. Braasch
8180 C. S. Selvage
6011 G. C. Newlin
3141 L. S. Ostrander (5)
8266 E. A. Aas (2)
3151 W. L. Garner (3)
for ERDA/TIC (unlimited release)
3171-1 R. P. Campbell (25)

Org.	Bldg.	Name	Rec'd by*	Org.	Bldg.	Name	Rec'd by*

*Recipient must initial on classified documents.