

INSOLATION DATA FOR SOLAR ENERGY CONVERSION  
DERIVED FROM SATELLITE MEASUREMENTS OF  
EARTH RADIANCE

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ABSTRACT

Detailed knowledge of the irradiance of the Sun at ground locations is essential for the design and evaluation of solar energy conversion systems. The primary source of such data is the global network of weather stations. Such stations are often too far apart and for most locations the data available are only daily total irradiance or monthly averages. Solar energy conversion programs require insolation data with considerably higher geographical and temporal resolution. Meteorological satellites gather routinely extensive data on the energy reflected and scattered into space by the Earth-atmosphere system. A program has been initiated to use such data for deriving ground insolation for energy conversion. Some of the preliminary results of this program will be discussed.

INTRODUCTION

Solar energy conversion systems require a knowledge of the energy available at the location where the systems are to be built. The primary source of such data is the global network of meteorological weather stations. The instrument most widely used at weather stations is the pyranometer which records the irradiance on a horizontal surface due to the Sun and the sky. This is referred to as the global irradiance as opposed to direct solar irradiance which is the irradiance due to the Sun alone received on a surface exposed normally to the Sun's rays. Daily totals and monthly averages of the global irradiance are available from many weather stations around the world. These measurements are coordinated through the World Meteorological Organization (WMO). From the point of view of solar energy conversion these data have certain drawbacks. The stations are too far apart. In continental United States there are about 90 stations, that is, on an average one station for about  $10^5$  km<sup>2</sup>. An excellent survey of irradiance over the whole Earth was made by Lof, Duffie and Smith [1,2]. They obtained pyranometer data from 668 stations and for 233 other stations where only data for sunshine hours were available, they used approximation methods to derive the global irradiance. This total of 901 stations provides on an average one station

for  $1.5 \times 10^5$  km<sup>2</sup>. This average is somewhat misleading as shown in Figure 1. There is a large concentration of stations in some areas like western Europe and Japan. In many parts of the world, for example, France, West Africa, East South America, India, only sunshine recorders are available.

There is a high degree of uncertainty in these data. The instruments are of many different types; calibration factors change with time; data logging techniques are also different. The insolation data of the U. S. weather stations provide an example of the degree of uncertainty. The National Climatic Center (NCC), of the National Weather Service of NOAA used to publish monthly and yearly records of the solar irradiance collected at the stations. However, in recent years, errors ranging from 5 to 30 percent were discovered in these data, so that in September '72, the NOAA requested the NCC to stop publishing the data. Currently insolation data are archived but not included in the routine publications of meteorological data of the NCC.

Another disadvantage of the WMO records is the lack of adequate time resolution. Most stations record only the daily totals. For the energy absorbed by a sloping surface as that of flat plate collector, the incident energy during the hours when the Sun's rays are nearly normal to the surface is considerably more important. Data are needed on the variation of irradiance with hours of the day.

#### AN ALTERNATE METHOD FROM SATELLITE DATA

In this paper we present an alternate method of deriving ground insolation data with considerably higher geographical and time resolution. Areas as small as one km<sup>2</sup> can be scanned and with time resolution of one half hour. The technique is to use the data on the radiation reflected and scattered back into space by the Earth-atmosphere system (the Earth albedo). Such data are routinely gathered by the synchronous meteorological satellite (SMS). Other satellites of the Nimbus or Tiros series also can be used. They have the advantage of having been launched several years earlier and hence the techniques of collecting their data and adapting them to specific needs have been better developed. But they have a smaller spatial resolution and view a given spot on the Earth far less frequently.

A program was initiated by NASA about a year ago to develop a method of obtaining ground insolation from satellite telemetry. There are three parallel approaches in this program. Our group at Goddard Space Flight Center has the responsibility of monitoring this program, and the three groups engaged in this are the department of Atmospheric Science, Colorado State U. (T. Vonder Haar), the Remote Sensing Laboratory, U. of Miami (H. W. Hiser) and the Applications Directorate, NASA/GSFC (M. P. Thekaekara).

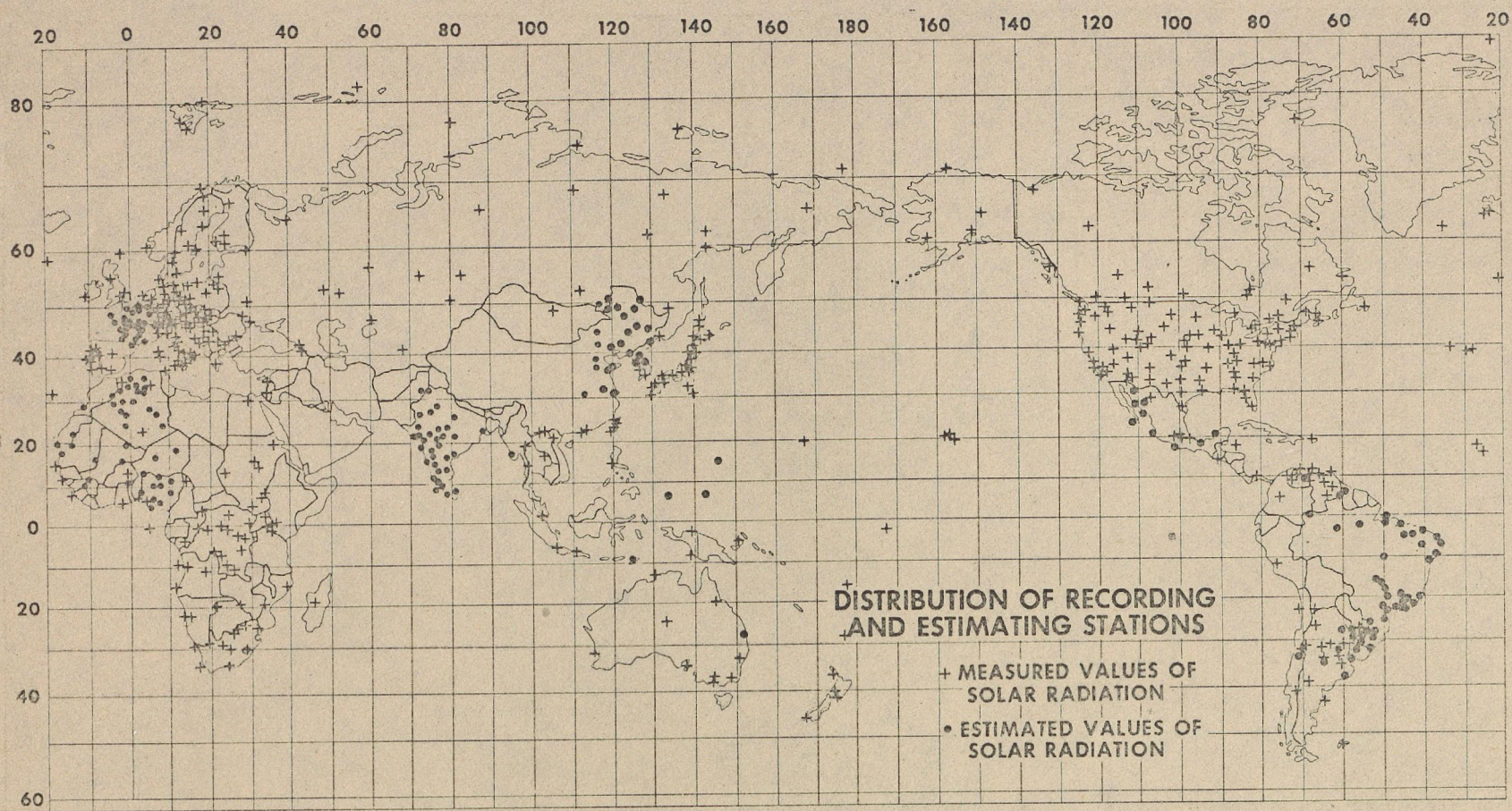


Figure 1. Global Distributions of Stations where Solar Irradiance Data are Collected.  
(Crosses indicate pyranometer stations and dots indicate sunshine recorder stations).

Key factors in using spacecraft data for insolation are that: (1) Cloud cover is a major factor in controlling the total insolation on an area. (2) Energy falling on the Earth's surface is the difference between the energy falling on top of the atmosphere and that absorbed or scattered back into space by the atmosphere. (3) Measurements made by a single detector, for example, that on a spacecraft have several advantages over those made by a large number of instruments at widely distant ground stations. (4) Considerably higher geographic resolution can be obtained with spacecraft, and places where ground stations are not feasible, for example, coastal waters, can be covered by a spacecraft. (5) Spacecraft data are routinely being gathered for other purposes such as meteorology, Earth-resources, etc.

#### CORRELATION BETWEEN CLOUD COVER AND INSOLATION

This method does not make observations from the ground obsolete or unnecessary. In fact ground measurements are essential at least at a few stations because remote sensing does not have the accuracy of ground measurements. The spacecraft is at a great distance away and what it measured is not the solar irradiance on the ground but the sum of what is reflected from the ground and what is scattered and reflected upwards by the atmosphere.

A first step in the development of the method is determine the degree of correlation between daily global insolation on a horizontal surface and the sunshine duration. As stated earlier, in many WMO stations, sunshine duration is the only type of solar data available. The widely used method of deriving insolation from such data assumes that a correlation does exist. Sunshine duration is measured by instruments like the Campbell-Stokes recorder on the sunshine switch. In the former sunlight is focussed to a point by a glass sphere and the point traces a line of partial burn on a paper strip. In the latter the duration of time when sunlight is clear enough to cast a shadow is recorded photoelectrically. The problems in these methods have long been recognized by meteorologists. The quality of the strip of paper is variable and the burnout is dependent on moisture, wind and other conditions. The sunshine switch is more dependable, but the threshold where the switch turns off and on has to be set empirically and varies with location and seasons of the year. We need to have a less arbitrary and more quantitative way of determining the duration of sunshine. The equation usually employed for the correlation is of the form

$$\frac{Q}{Q_0} = a + b \frac{S}{S_0} \quad (1)$$

where  $Q$  is the daily total energy received on a horizontal surface,  $Q_0$  is the same daily total if there were no atmosphere (or if the surface were outside the atmosphere and rotating with the Earth),  $S_0$  is the total time from sunrise to sunset,  $S$  is the duration of sunshine, and  $a$  and  $b$  are empirical constants.  $Q_0$  and  $S_0$  can be determined with a high degree of accuracy.  $Q_0$  is computed by finding the irradiance at any given time (it is a function of the solar constant, the Earth-Sun distance and solar zenith angle) and by integrating the expression for the whole day.  $Q$  and  $S$  have to be determined by actual measurement.  $Q$  was determined by a pyranometer mounted on top of a building at Goddard Space Flight Center. For a quantitative determination of  $S$  we adopted a 50% criterion to be used along with the half-hourly totals of the records of a normal incidence pyrheliometer (NIP) which was mounted close to the pyranometer and was made to track the Sun. If the NIP value was 50 percent or more of the maximum possible NIP value expected for that date and time, the half hour was assumed to be cloud free. The maximum NIP value was determined by examining cloudfree NIP data at other half-hours and extrapolating to the given half-hour, and also by computing the insolation from known values of extraterrestrial irradiance and air mass and assumed values of atmospheric transmission. The 50-percent criterion has some physical justification. Data collected by Millard and Arvesen [3] show that depending on solar zenith angle, cirrus clouds (the thinnest kind) transmit between 50 and 61 percent as much direct sunlight as does the cloudfree sky. Tables I and II summarize their data. Other clouds, such as altocumulus and stratus, are opaque and thus transmit much less direct solar radiation. It is therefore very important to determine if Equation (1) is also applicable to the method for computing  $S/S_0$ , the fractional amount of cloudiness per day, and the threshold that is most appropriate for recognizing a cloud as being in the direct beam.

After proving the applicability of the empirical equation, an attempt will be made to determine if satellite imagery data, such as those available from the SMS Geosynchronous Operational Environmental Satellite (GOES), can be used to provide the necessary cloud data from which the quantity  $S/S_0$  can be generated. This will require comparing the cloud statistics  $(S/S_0)_s$  generated from the data collected at the GSFC ground facility with the cloud statistics  $(S/S_0)_s$  generated from SMS images with a densitometer and those digital cloud statistics produced from data acquired by the Image Display and Manipulation System/Atmospheric Oceanic Interactive Processing System (IDAMS/AOIPS) facility at GSFC. The IDAMS/AOIPS facility can generate higher positional accuracy and more gray-level information than the densitometer, but its throughput is limited due to the numerous users and the complex computer analyses involved. Extensive cloud statistics data from SMS images are being generated by U. of Miami program.

After demonstrating the applicability of satellite imagery for generating cloud statistics for use in computing  $(S/S_0)$ , the method will be applied to other geographic regions where surface truth information are available. Atmospheric conditions at these locations must be available to enable calculation of new

Table I. Ground Solar Irradiance for Various Cloud Conditions  
(zenith angle 40°)

Sky Condition	Total Irradiance (MW/cm <sup>2</sup> )	Diffuse (MW/cm <sup>2</sup> )	Direct (MW/cm <sup>2</sup> )	Direct Ratio	(Cloud/clear)
Clear	85	15	70	1.0	—
Cirrus	70	35	35	<u>Cirrus</u> Clear	0.5
Alto cumulus	45	40	5	<u>Alto cumulus</u> Clear	0.07
Stratus	20	19	1	<u>Stratus</u> Clear	0.01

Table II. Variation of Ratio With Solar Zenith Angle

Solar Zenith Angle (Degrees)	Clear Sky Direct Irradiance (MW/cm <sup>2</sup> )	Cirrus Sky Direct Irradiance (MW/cm <sup>2</sup> )	Ratio Cirrus/Clear
0	90	55	0.61
20	87	50	0.57
40	70	35	0.5
60	40	20	0.5

regression coefficients. A likely source of ground truth locations is the National Oceanic and Atmospheric Administration (NOAA) network of solar radiation ground stations. Also, an intercomparison of results using this technique with those being developed at the University of Miami (by H. Hiser) and Colorado State University (by J. Ellis and T. Vonder Haar) will be conducted.

#### EQUATIONS OF CORRELATION

Solar radiation data for two periods (February 5 through April 24, 1975 (annual calendar days 36 through 114) and August 20 through October 23, 1975 (annual calendar days 232 through 295) were analyzed to determine the coefficients a and b of the linear regression equation relating the total amount of global radiation incident on a horizontal surface to the number of cloudfree hours. The degree of correlation, r, between  $Q/Q_0$  and  $S/S_0$  was also computed. Three

methods were used to determine  $(S/S_0)$  (and hence,  $a, b, r$ ) for the February through April data, and two methods for determining  $(S/S_0)$  were used in the analysis of the August through October data.

The objective is to find a relationship of the form  $Q/Q_0 = a + b(S/S_0)$ . The evaluation criterion is based on the method of least squares. For a linear equation of the form  $y = a + bx$ :

$$a = \frac{\sum y \sum x^2 - \sum x \sum xy}{N \sum x^2 - (\sum x)^2} \quad (2)$$

and

$$b = \frac{N \sum xy - \sum x \sum y}{N \sum x^2 - (\sum x)^2} \quad (3)$$

where  $x = S/S_0$  and  $y = Q/Q_0$  for a given day. To obtain a measure of the goodness of fit, a correlation coefficient,  $r$ , can be calculated. The formula for calculating  $r$  is as follows:

$$r = \frac{N \sum xy - \sum x \sum y}{\sqrt{N \sum x^2 - (\sum x)^2} \sqrt{N \sum y^2 - (\sum y)^2}} \quad (4)$$

where  $N$  is the number of measurements.

To solve these equations,  $Q/Q_0$  and  $S/S_0$  must be known for each day under consideration.  $Q$  is the measured irradiance for the day and requires no computation.  $Q_0$ , the total irradiance of the day on a horizontal surface outside the atmosphere, is given by the integral over the whole day (sunrise-sundown) of the instantaneous irradiance on a surface outside the atmosphere. The irradiance is  $E_0 \cos z / R^2$ , where  $E_0 = 1353$  watts per meter<sup>2</sup> (the normal irradiance at one astronomical unit;  $R =$  the Earth-Sun distance (astronomical units);  $z =$  the solar zenith angle given by  $\cos z = \sin \theta \sin \delta + \cos \theta \cos \delta \cos h(t)$ ;  $\theta =$  latitude;  $\delta =$  solar declination angle;  $h =$  hour angle.

Sundown,  $t_0$ , is the time when  $\cos z = 0$ . Thus

$$t_0 = 240 \cos^{-1} \left( \frac{-\sin \theta \sin \delta}{\cos \theta \cos \delta} \right) \quad (5)$$

where  $t_0$  is expressed in seconds since ephemeris transit. Similarly, sunrise is  $-t_0$ . Thus

$$Q_0 = \int_{-t_0}^{t_0} \frac{E_0}{R^2} \cos z \, dt \quad (6)$$

which can be reduced to the form

$$Q_0 = \frac{2E_0}{R^2} \left\{ t_0 \sin \theta \sin \delta + 240 \left[ \frac{180}{\pi} \left( \cos \theta \cos \delta \frac{\sin t_0}{240} \right) \right] \right\} \quad (7)$$

The factor  $180/\pi$  is necessary because the trigonometric functions used here are degree functions.

The quantity  $S/S_0$ , representing the fraction of the day which was sunny, can be determined in three different ways. The 50-percent criterion is always used, i.e., it is considered sunny at a given time if the measured normal irradiance is greater than 50 percent of some theoretical sunny day normal irradiance for the day. The three methods differ in the determination of theoretical normal irradiance and in the parts of the day that are considered for measurement.

For the first method, normal irradiance versus time graphs are used. The sunny parts of a number of these (as determined by inspection) are traced onto a single sheet giving a composite "typical" sunny day. To find  $S/S_0$ , the 50-percent criterion is used comparing the normal irradiance for the day every half hour with the "theoretical" possibility from the corresponding time on the composite graph. This is done from sunrise to sunset as determined from the graph. Two problems associated with this method are (1) that over a range of a few months the expected irradiance should differ significantly due to changes in  $\delta$ , the Sun's declination, so a single theoretical sunny day is insufficient; and (2) that cloudiness in early morning and late evening have little effect on total irradiance so these times should not need to be considered.

For the second method, values for  $E$  (normal irradiance, watts per square meter) were obtained for a set of tables for differing values of water ( $H_2O$ ), ozone ( $O_3$ ), and atmospheric turbidity ( $\alpha$  and  $\beta$ ) for air masses 1, 1.5, 2, and 3. Then, for each group of values of  $H_2O$ ,  $O_3$ ,  $\beta$ , and  $\alpha$ , a quadratic fit of the form  $\ln E = A + Bm + Cm^2$  (where  $m$  is air mass) was found. Between air masses 1 and 3, the equation gives values for  $E$  which are within 0.1 percent of the tabulated values. For both periods for which data were collected, the average meteorological conditions were found to be  $H_2O = 2$  cm,  $O_3 = 0.34$  cm,  $\beta = 0.02$ , and  $\alpha = 1.3$ . The normal irradiance for these atmospheric conditions was given by:  $\ln E = 7.06935 - 0.22022 m + 0.01326 m^2$ .

Under typical conditions, if for a given day and time, the air mass is determined, it is possible to determine a theoretical irradiance using this formula. Because the formula is only accurate at low air masses, and early morning or late evening are not under consideration, times when  $m$  is less than 8 were chosen. Tables were made for various days giving theoretical irradiance as a function of time, and these are used for comparison with measured normal irradiance. The third method is the same, except that days in which  $S/S_0 = 0$  are not considered because there was considerable variation in  $Q/Q_0$  for these days. The choice of the preferred method still must be made.

Table III summarizes the values of  $a$ ,  $b$ ,  $r$ . Figures 2, 3, and 4 plot the regression lines for the two periods.

Table III. Regression and Correlation Coefficients

Period of Data Collection	Number of Days of Data		a	b	r
	Total	100 Percent Cloudy			
February 5 - April 24, 1975	58	18	0.264	0.554	0.912
	58	18	0.258	0.527	0.924
	58	18	0.396	0.348	0.937
August 10 - October 23, 1975	45	15	0.264	0.457	0.867
August 20 - October 23, 1975	45	15	0.332	0.368	0.864

The tables and figures show that a high correlation exists between the total amount of solar radiation ( $Q$ ) incident per day on a horizontal surface and the fractional amount of cloudiness per day ( $S/S_0$ ). The data points in Figures 2, 3 and 4 show that a higher order polynomial least-squares fit is not justified at this time because the primary objective is to relate the value of ( $S/S_0$ ) measured at the ground to that obtained from satellite imagery.

In assuming a regression equation of the form  $(Q/Q_0) = a + b (S/S_0)$  in the preliminary analysis, the tacit assumption was that the errors in  $Q/Q_0$  were greater than those in  $(S/S_0)$ . This is not the case.  $Q_0$ , the amount of sunlight on a horizontal surface per day outside the atmosphere, can be calculated to within the precision of knowledge of the solar constant ( $\pm 1.5$  percent).  $Q$ , the total irradiance on a horizontal surface per day, can easily be measured with a carefully calibrated pyranometer to within  $\pm 2$  to 5 percent. The actual normal irradiance, as measured by a normal incidence pyrheliometer (NIP)<sub>m</sub>, used in the calculation of  $S/S_0$ , can also be measured to within  $\pm 2$  to 5 percent with a carefully calibrated pyrheliometer. As much as  $\pm 10$  to 15 percent variability can

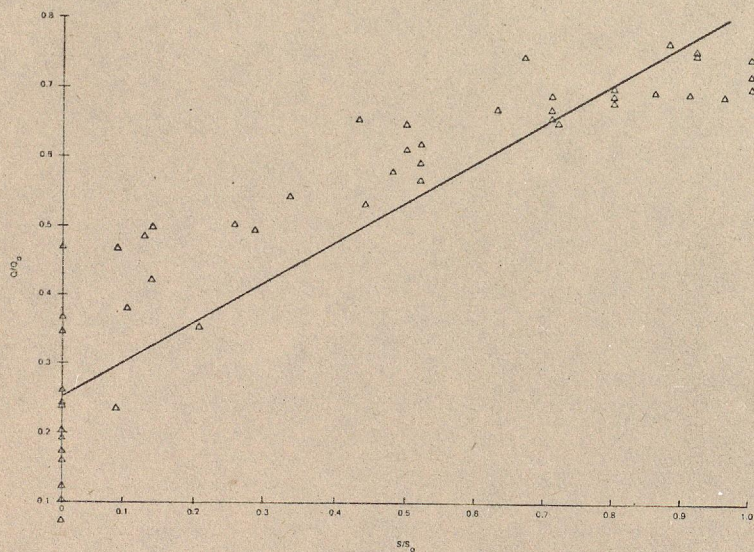


Figure 2. February 5 through April 24, 1975.  
Data - Method 1 Meteorological conditions:  
Average value derived from all 100 percent  
cloud free days. Method 2  $Q/Q_0 = 0.264 +$   
 $0.554 (S/S_0)$ ;  $r = 0.912$

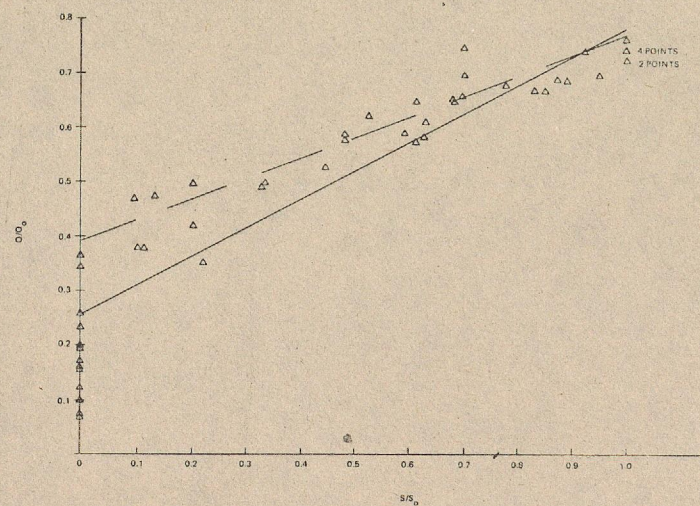


Figure 3. February 5 through April 24, 1975,  
Data - Methods 2 and 3 Average meteorological  
conditions; water vapor = 2 cm; ozone = 0.34  
cm; coefficients;  $\alpha = 1.3$ ,  $\beta = 0.2$ . Solid Line  
is Method 2:  $Q/Q_0 = 0.258 + 0.527 (S/S_0)$ ;  $r =$   
 $0.924$ ; Dashed Line is Method 3:  $Q/Q_0 = 0.396$   
 $+ 0.348 (S/S_0)$ ;  $r = 0.937$

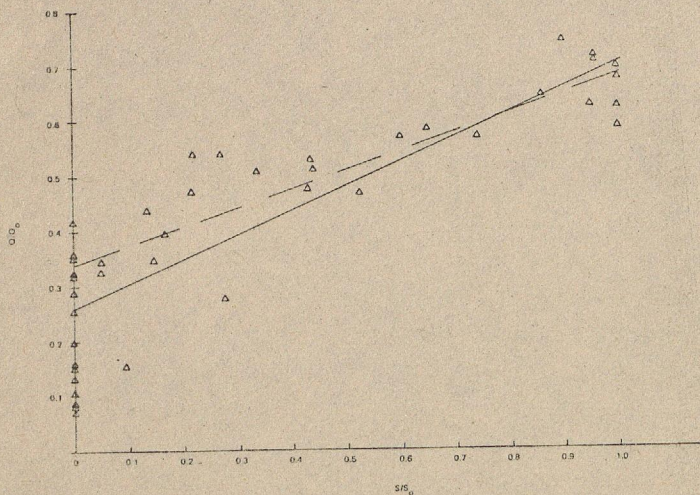


Figure 4. August 20 through October 23, 1975, Data Average meteorological conditions; Water vapor = 2 cm; ozone = 0.34 cm; turbidity coefficients:  $a = 1.3$ ,  $\beta = 0.02$ . Solid Line is Method 2:  $Q/Q_0 = 0.264 + 0.457 (S/S_0)$ ;  $r = 0.867$ . Dashed Line is Method 3:  $Q/Q_0 = 0.368 (S/S_0)$ ;  $r = 0.864$

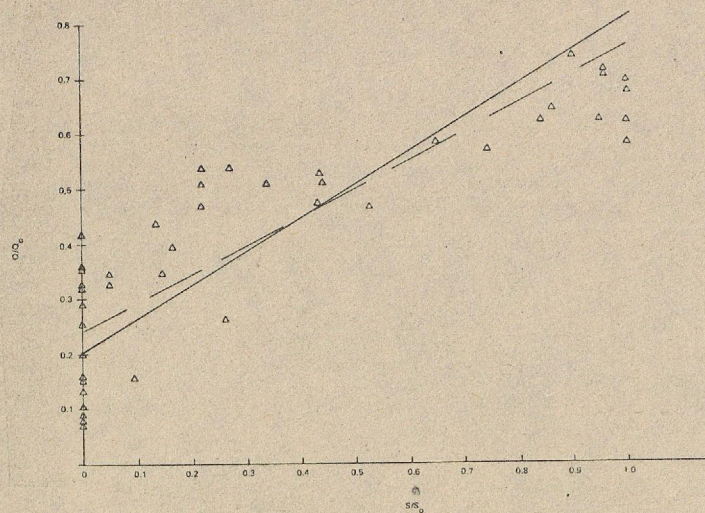


Figure 5. August 20 through October 23 Data Average meteorological conditions: Water vapor = 2 cm; ozone = 0.34 cm; turbidity coefficients:  $a = 1.3$ ,  $\beta = 0.02$ . Solid Line is Method 2:  $W/S_0 = -0.350 + 1.647 (Q/Q_0)$ ;  $r = 0.867$ . Dashed Line is Method 3:  $S/S_0 = -0.542 + 2.03 (Q/Q_0)$ ;  $r = 0.864$

exist in atmospheric moisture and turbidity. This can introduce the same error in the calculation of  $S/S_0$  because the theoretical irradiance for a particular day used in the calculation of  $S/S_0$  may deviate by 10 to 15 percent from the true value. Table I shows that an error on the order  $\pm 10$  percent can exist in the assumption that the sky is clear, if the ratio of the measured and theoretical  $(NIP)_t$  normal incidence irradiance,  $(NIP)_m / (NIP)_t \geq 0.5$ . A better regression equation to use may be of the form

$$\frac{(S)}{(S_0)} = a' + b' \frac{(Q)}{(Q_0)} \quad (8)$$

This regression equation was obtained by using methods 2 and 3 with the data acquired from August 20 through October 23, 1975. Figure 5 presents a plot of the regression lines obtained therefrom and the values of  $a'$ ,  $b'$ ,  $r$ . In accordance with statistical theory, the correlation coefficient does not change. Furthermore, the slope of the line is steeper for this case (Figure 5) than for the corresponding case (Figure 4) using Equation (1). The proper form of the regression equation to use warrants further studies. Nevertheless, it can be concluded that a linear relationship exists, with high correlation, between the total irradiance on a horizontal surface per day ( $Q$ ) and the fractional number of clear hours per day ( $S/S_0$ ) as determined from direct measurement and theoretical prediction of the direct solar irradiance.

Having demonstrated the applicability of the new technique of determining  $S/S_0$  with a pyrheliometer and theoretical calculations, the major emphasis of future research should be to determine if the quantity  $S/S_0$  can be determined from high resolution satellite imagery (SMS, etc.). If the value of  $(S/S_0)$  as measured from a satellite,  $(S/S_0)_s$ , can be correlated with those measured at the surface  $(S/S_0)_g$ , satellite data can be used as input into Equation (1). Whether or not a correlation exists between satellite- and ground-based determinations of  $S/S_0$  can be ascertained by using 2 weeks of (hourly) SMS imagery data obtained from NOAA. These 184 images have been Earth located and digitized by H. Hiser in such a way that the distribution of clouds, and, perhaps, the type also can be studied. This digitized data for SMS-1 will be analyzed to determine if there exist any clouds along a line connecting the pyrheliometer at a given location and the Sun. Fourteen values of  $(S/S_0)_s$  will be computed from these 184 data points. Also, the 184 satellite data points will be correlated against 184 ground measurements to determine if both the satellite and ground instrumentation agree that there is a cloud along the line of sight. Finally, the AOIPS/IDAMS facility at GSFC will be used to evaluate the quality of the digitized data prepared from the SMS photographs. IDAMS or AOIPS, its-soon-to-be-activated successor, offers greater location precision and more gray-level information, at the expense, however, of more computer and operator time. Whenever possible, those days and times for which IDAMS tapes have already been prepared will be used in the validation.

## ATMOSPHERIC ENERGY BUDGET

The method we have discussed above is almost entirely empirical. A more theoretical approach is to consider the well-known energy equations of the dynamics of the atmosphere. This approach has been developed under the NASA program by T. Von der Haar.

A schematic representation of the terms in the energy equation is shown in Figure 6.  $Q_0$  is the energy incident on top of the atmosphere. At the average Sun-Earth distance the value is according to the NASA/ASTM standard  $1353 \text{ Wm}^{-2}$ . A part of this energy,  $Q_m$ , is absorbed in the atmosphere by ozone, water vapor particulate matter (aerosols) and other molecules and another part is scattered upwards. The part scattered upwards has three components,  $Q_R$  due to Rayleigh scattering,  $Q_H$  due to haze (also referred to as aerosols, turbidity, pollution) and  $Q_C$  due to clouds. The balance of input energy and absorbed/scattered energy is  $Q_S$ , the insolation which reaches the ground. In this simple approach we are considering a single ray of light. Actually  $Q_S$  is from all directions and over  $2\pi$  steradian. Expressions which involve integrals over all angles and multiple scattering at different layers of the atmosphere will be needed for a more complete treatment of the problem. The Earth's surface absorbs a part of the energy  $Q_S$ , and the rest  $RQ_S$  (where  $R$  is the reflectance of the Earth's surface) is reflected upwards.  $Q_a$  is the Earth albedo, the sum of the energy terms reflected and scattered upwards. The quantity  $Q_a$  is what is measured by a satellite.

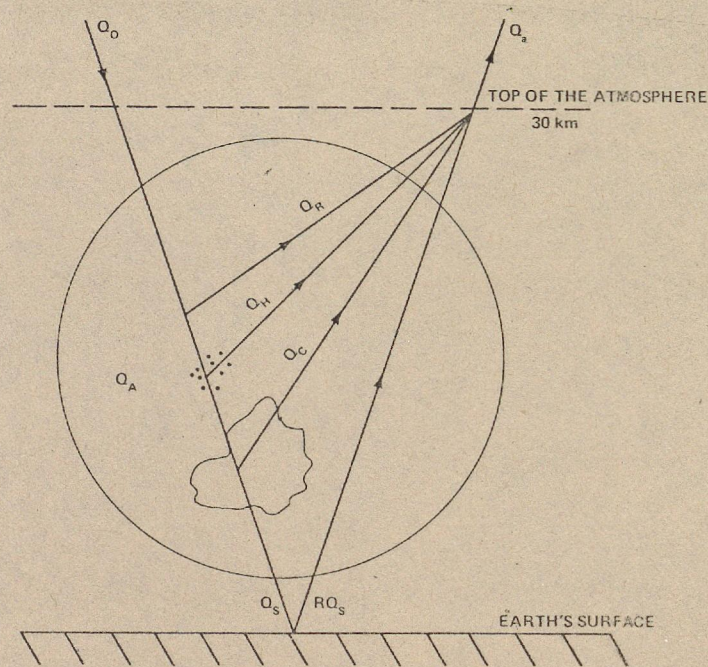


Figure 6. Schematic representation of the terms in the Energy Budget Equation

For purposes of deriving insolation,  $Q_S$ , from albedo,  $Q_a$ , we introduce two more terms,  $A_S$  the fractional area free of clouds, and  $Q_{a,\min}$  the minimum value of albedo for a given location. The minimum value occurs when the atmosphere is free of haze or clouds, that is when the two terms  $Q_H$  and  $Q_C$  tend to zero. Regrouping terms [4] it can be shown that

$$Q_S = Q_0 - (Q_a - A_S Q_{a,\min} + Q_A + A_S Q_R) \quad (9)$$

All terms on the right hand side of eqn. (9) are known or can be determined.  $Q_0$  is the solar constant with due correction for the Sun-Earth distance.  $Q_a$  and  $Q_{a,\min}$  are the albedo measured by the spacecraft. The fractional area  $A_S$  free of clouds can be determined by electronic optical planimetry of satellite data.  $Q_A$ , the energy absorbed in the atmosphere, varies with location and seasons of the year, but is a smoothly varying function. It can be determined both from ground observations and from satellite data. Representative values are between 12 and 20 percent for continental United States. The values are significantly higher for the tropics, between 15 and 28 percent. The final term  $Q_R$ , that due to Rayleigh scattering, is one which can be computed with a high degree of accuracy.

There are several approximations involved in deriving eqn. (9) and some of the terms cannot be determined with sufficient accuracy. Hence it will be necessary to check the insolation data derived from satellites against ground observations.

#### PRELIMINARY RESULTS

In the application of Equation (9) the main effort hitherto has been to study the mesoclimate over selected areas using the data of spacecraft launched in earlier years. The bulk of the data analyzed were from the Sun-synchronous satellites. They measure the albedo at one local time in the visible part or the near infrared part of the solar spectrum. Cloudiness is the primary factor causing variability of radiances on a day-to-day basis. Hence an instantaneous once-per-day measurement of radiance is not truly representative of the mean daily condition. However models have been developed which show how the cloudiness varies with the hour of the day at different locations and for different seasons of the year. Such models permit determination of the correction factors to be applied to the albedo data of Sun-synchronous satellites. The satellites used in this study are Nimbus 3 launched in 1969 and the NOAA 2, 3, and 4 satellites launched between 1973 and 1975. All four have Sun-synchronous polar orbits with equatorial crossing time 11.30 am for Nimbus 3 and 9.00 am for the other three. The space resolution is 200 km for Nimbus 3, and 11 km for the other three. Auxiliary data available for verifying the spacecraft data are provided by 20 pyranometer stations, 4 pyrliometer stations, 20 stations with surface observed cloudcover, the RAOB network for atmospheric water content and SMS imagery for diurnal cloud cover models.

Some preliminary results based on the work of Vonder Haar and Ellis for four stations are presented in Table IV. The spacecraft data given in column 2 are averages for June 1969. The third and fourth columns are surface measured and adjusted values at each of the stations. The adjusted values represent corrections made by the National Weather Service to bring all data to the same level of calibration, as stated in the records of the National Climatic Center. The final column gives the average of 10 years. In three out of the four cases the spacecraft values are near or between the measured and adjusted values. The difference between measured and adjusted values gives an idea of the confidence which can be placed in these ground measurements. The large difference for Laramie is probably due to local cloudiness peculiar to Laramie which is not representative of the 210 km<sup>2</sup> area surveyed by Nimbus 3. There is strong reason to believe that higher resolution data as provided by the more recently launched spacecraft and more accurate calibration of the ground station instruments will minimize the disagreements between the two sets of values.

Table IV. Preliminary Results for Insolation (joules/day)  
from Nimbus 3, June 1969

Station	Satellite 210 × 210 km	Pyranometer		Mean 10 years
		Measured	Adjusted	
Ground Junction	2548	2544	2289	2741
Laramie	2544	2008	-----	2385
Dodge City	2326	2565	2310	2590
Albuquerque	2833	2837	2552	3054

#### CONCLUSION

The data recorded by spacecraft concerning cloud cover provides a means for determining the insolation on the ground. Work is now in progress on digitizing the imagery from SMS/GOES spacecraft. When this work is completed we will be in a position to give the equations of correlation between ground insolation for solar energy conversion and spacecraft records of Earth albedo.

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