DOE/NASA/1022-78/32
NASA TM-78921

VARIATION OF SOLAR CELL SENSITIVITY AND SOLAR RADIATION ON TILTED SURFACES

Thomas M. Klucher
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

(NASA-TM-78921) VARIATION OF SOLAR CELL SENSITIVITY AND SOLAR RADIATION ON TILTED SURFACES (NASA) 10 p HC A02/MF A01 CSCL 10A

N78-26547

Unclas
G3/44 23347

Work performed for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Solar Energy

TECHNICAL PAPER presented at the
Thirteenth Photovoltaic Specialists Conference
sponsored by the Institute of Electrical and Electronics Engineers
Washington, D.C., June 5-8, 1978

DOE/NASA/1022-78/32
NASA TM-78921

VARIATION OF SOLAR CELL SENSITIVITY AND SOLAR RADIATION ON TILTED SURFACES

Thomas M. Klucher
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Prepared for
U. S. Department of Energy
Office of Energy Technology
Division of Solar Energy
Washington, D. C. 20545
Under Interagency Agreement E(49-26)-1022

Thirteenth Photovoltaic Specialists Conference
sponsored by the Institute of Electrical and Electronics Engineers
Washington, D. C., June 5-8, 1978

E-9661

VARIATION OF SOLAR CELL SENSITIVITY AND SOLAR RADIATION ON TILTED SURFACES

Thomas M. Klucher

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

An empirical study was performed (1) to evaluate the validity of various insolation models used to compute solar radiation incident on tilted surfaces from global data measured on horizontal surfaces and (2) to determine the variation of solar cell sensitivity to solar radiation over a wide range of atmospheric condition. Evaluation of the insolation data indicates that the isotropic sky model of Liu and Jordan underestimates the amount of solar radiation falling on tilted surfaces by as much as 10%. An anisotropic-clear-sky model proposed by Temps and Coulson was also evaluated and found to be deficient under cloudy conditions. A new model, formulated herein, reduced the deviations between measured and predicted insolation to less than 3%. Evaluation of solar cell sensitivity data indicates small change (2-3%) in sensitivity from winter to summer for tilted cells. The feasibility of using such global data as a means for calibrating terrestrial solar cells as done by Treble is discussed.

INTRODUCTION

Accurate design predictions of the output power from tilted solar cell arrays in terrestrial sunlight are complicated by (1) insufficient knowledge of the exact amount of global (total hemispheric) solar radiation falling on the tilted surface and by (2) uncertainties in solar cell sensitivity (ratio of the cell short-circuit current to insolation). The problem of accurately computing solar radiation falling on a tilted surface arises because the array designer must combine the available radiation data on horizontal surfaces with some insolation model to calculate the radiation on a tilted surface. Because of the variety and complexity of terrestrial sunlight, a common assumption made in many models, such as the widely used Liu-Jordan model (1) is that the sky light distribution is isotropic. This assumption considerably simplifies the calculation, but is unrealistic in many instances and may lead to inaccurate results. Alternate models (2), which assume an anisotropic sky light distribution, are primarily developed for use under clear sky conditions and may also be inaccurate under many atmospheric conditions. Neither type of model has been thoroughly examined experimentally, nor attempts made to improve them.

Even if the global solar radiation falling on the tilted surface were accurately known, array output predictions would still remain uncertain because of a lack of information on the variation of solar cell sensitivity with atmospheric variations. It is well known that the spectral distribution of sunlight, and hence solar cell sensitivity, changes with variation in cloud cover, air mass, water vapor and turbidity. However, the extent of the variation in cell sensitivity is still uncertain because of a lack of empirical data on cell sensitivity variations under widely varying conditions including tilted surfaces. Thus, in the case of cell sensitivity, as well as insolation modeling, there is an evident need for an extensive data base for evaluation and reduction of the above uncertainties.

An activity was started to accumulate such a data base as part of the Tests and Applications Project performed by the NASA Lewis Research Center for the Department of Energy National Photovoltaic Program. The objectives of the work were (1) to test the validity of and to improve the insolation models used to compute solar radiation on tilted surfaces and (2) to measure the variation in solar cell sensitivity over a wide range of atmospheric conditions and several tilted surfaces. The approach taken to achieve these objectives was to establish a data set of hourly averages of insolation and concurrent hourly averages of solar cell short-circuit current, using pyranometers and solar cells at several orientations. Data was taken continuously at the Lewis Research Center in Cleveland, Ohio over a period of ten months from January to October 1977. In addition, this data also conveniently allowed an assessment of the global calibration method used by Treble (3) to calibrate reference cells.

Apparatus and Measurements

The insolation and solar cell sensors used in the experiment are shown in Figure 1. Three pyranometers, facing due south, measure global insolation received at 0°, 37°, and 60° tilt angles (measured from the horizontal). A fourth pyranometer, also at 0° and equipped with a shadow band, measures the diffuse component and is used as an aid to estimate the type of day by comparison of the diffuse and total insolation. Each pyranometer is temperature compensated to ±1% over the temperature range of -20° to $+40^\circ$ C and is calibrated with respect to the IPS 1956 Standard Scale.

Solar cell short-circuit current under global radiation is determined with three sensor packages oriented identically to the pyranometer. The solar cell sensors, virtually identical in spectral response (Fig. 2), are 1 cm^2 in area, soldered onto Kovar blocks, and mounted in housings identical to the pyranometer housings. Solar cell temperature is measured with a thermocouple inserted in the Kovar block and is used to correct the cell output to a common temperature (25° C). The tilted sensors are equipped with artificial horizons to eliminate surface reflection effects.

METHOD OF ANALYSIS

Insolation Models

The starting point for the evaluation of the insolation models is the isotropic sky model described in Liu and Jordan (1). In this model, the insolation on a surface tilted toward the equator at an angle ϵ to the horizontal is given by:

$$I_T = \underbrace{\frac{(I_H - I_D)}{\sin\alpha}\cos\psi}_{\text{Direct radiation}} + \underbrace{I_D\left(\frac{1+\cos\epsilon}{2}\right)}_{\text{Diffuse radiation}} \qquad (1)$$

where I_T is total insolation received by tilted surface, I_H is total insolation received by horizontal surface, I_D is diffuse insolation received by horizontal surface, α is solar elevation angle, ψ is angle between sun direction and normal direction of sensor surface, and ϵ is tilt angle of tilted surface measured from horizontal.

In this effort the insolation terms inserted into eq. (1) were hourly average values of insolation obtained from sunrise to sunset during each day. The insolation I_H and I_D were measured by the pyranometers and used in eq. (1) to calculate the total insolation received on the surfaces tilted at 37° and 60°. These calculated insolation values were then compared with the insolation I_T measured at 37° and 60° to determine how well the Liu-Jordan model predicted the insolation on each tilted surface.

The data were also compared with the anisotropic-clear-sky model developed by Temps and Coulson (2). In their model Temps and Coulson combined correction factors with the isotropic diffuse radiation term to account for anisotropy in the diffuse radiation field. They determined that a factor, $1 + \sin^3(\epsilon/2)$, accounts for the increase in sky light observed near the horizon during clear days; similarly, sky brightening near the sun could be approximated by the factor $1 + \cos^2\psi\sin^3(90 - \alpha)$. Applying the Temps and Coulson correction terms to the Liu-Jordan model, then, the anisotropic-clear-sky model has the form:

$$I_T = \frac{(I_H - I_D)}{\sin\alpha}\cos\psi + I_D\left(\frac{1+\cos\epsilon}{2}\right) \times \left[1 + \sin^3\frac{\epsilon}{2}\right]\left[1 + \cos^2\psi\sin^3(90-\alpha)\right] \qquad (2)$$

The final model evaluated was an anisotropic model developed in this effort based upon preliminary results found with the previous two models. This last model involves an adjustment to the Temps-Coulson factors by a simple function containing the ratio of diffuse to total insolation on the horizontal plane. As will be shown in the RESULTS AND DISCUSSION, the Liu-Jordan model worked well for overcast days and the Temps-Coulson model worked well for clear days. The purpose of the new function was to modulate the Temps-Coulson factors as the skies varied from clear to overcast. This anisotropic, "all sky" model thus takes the form:

$$I_T = \frac{(I_H - I_D)}{\sin\alpha}\cos\psi + I_D\left(\frac{1+\cos\epsilon}{2}\right) \times \left[1 + F\sin^3\frac{\epsilon}{2}\right]\left[1 + F\cos^2\psi\sin^3(90-\alpha)\right] \qquad (3)$$

where $F = 1 - (I_D/I_H)^2$ is the modulating function described above. Under overcast conditions, when the ratio of diffuse to total insolation, I_D/I_H, is unity, the all-sky model reduces to the Liu-Jordan isotropic model. Under clear sky, when the ratio of diffuse to total is observed to be small, the all-sky model approximates the Temps-Coulson anisotropic-clear-sky model.

Solar Cell Sensitivity

The study of solar cell sensitivity (ratio of short-circuit current to insolation) was performed by means of a regression analysis of monthly data sets. These data sets consisted of hourly average insolation and corresponding hourly average cell short-circuit current for each cell. Plots showing the variation of short-circuit current, I_{SC}, with global insolation, L_T, for each cell-pyranometer orientation (0^o, 37^o, and 60^o) and for each month demonstrated a simple linear relation between current and insolation, with the curve extending through the origin. The linear relation suggests that a single mean value for sensitivity, represented by the slope of the curve, may be used for each month. Therefore, a least squares fit procedure was employed to fit a regression line through each monthly data set using the equation

$$I_{SC} = S_{SC} \, L_T$$

where the regression constant, S_{SC}, is the mean sensitivity of a cell for each month. Variations of S_{SC} from month to month were determined for each cell to evaluate the long term variations in sensitivity; the standard deviations of hourly sensitivity about the monthly means sensitivity were also determined to evaluate variations in sensitivity due to short term variations in atmospheric conditions.

RESULTS AND DISCUSSION

Insolation Model Study

Figures 3(a), (b), and (c) illustrate typical results found for each of the three insolation models studied in this effort. The trends illustrated by these figures are applicable to results to both the 37^o and 60^o tilt angles so only the 37^o results are shown for the sake of brevity. A complete set of monthly plots for each model over the first 6 months of the study are found in Reference 4.

Figure 3(a) shows that the Liu-Jordan isotropic-sky model provides a good fit to experimental data at the low intensity conditions (<20 to 30 mW/cm^2). This is to be expected, since the low intensities are primarily associated with the occurrence of overcast sky conditions which have uniform diffuse insolation and little direct insolation. At the higher intensities (>50 mW/cm^2), however, the isotropic-sky model underestimates the amount of solar radiation falling on tilted surfaces.

In contrast to those results, the results from the Temps-Coulson anisotropic-clear-sky model demonstrate a good fit to the experimental data on clear days, regardless of intensity level. This can be seen in Figure 3(b) in which the data for clear skies (shaded symbols) fall along the unity slope line. However, during cloudy and overcast days (open symbols in Fig. 3(b)) the Temps-Coulson model overestimates the insolation on tilted surfaces. Figure 3(b) shows predicted values exceeding measured by as much as 10 mW/cm^2 in March. Such overestimates ranged from about 12 mW/cm^2 in the winter months to about 3-5 mW/cm^2 in the summer. Thus, this model, developed for clear sky conditions, is obviously not applicable to all atmospheric conditions.

Figure 3(c) illustrates the fit of the anisotropic-all-sky model to the data. The model predictions correlate very well with empirical data at all intensity levels and all sky conditions. The primary effect of the correction terms used in the all sky model was to reduce the systematic error previously observed in the Liu-Jordan model at high intensity levels without the advere effects of overcorrections produced by the Temps-Coulson clear-sky model during cloudy and overcast days.

Data for all ten months at 37^o and 60^o are summarized in Table I. Tabulated are the differences between measured and calculated values obtained at 75 mW/cm^2 using the isotropic-sky model and the anisotropic-all-sky model. The differences ranged from 2 to 10% for the isotropic-sky model and are less than 3% for the anisotropic-all-sky model. It is apparent that the anisotropic-all-sky model provides a better prediction of solar radiation on tilted surfaces than does the isotropic-sky model throughout the test period.

Cell Sensitivity Study

Figure 4 illustrates the variation in monthly mean sensitivity, S_{SC}, over the 10-month period studied. The mean sensitivity of the tilted cells exhibit a variation of less than 3%, while the sensitivity variation of the cell at 0^o tilt is somewhat greater (~5%). Some of this variation, particularly for the horizontal cell, may be attributed to optical surface reflection losses. For example, the low sensitivity of the horizontal cell in January and February can be explained by the deviation of cell response from an ideal cosine response as the sunlight at low winter elevation angles strikes the cell surface at far from normal incidence angles. To determine the horizontal cell's sensitivity variation to atmospheric variations only, reflection losses as a function of incidence angle were determined empirically and adjustments made to the hourly average short circuit current data sets. As shown in Figure 4 the adjusted results show a slight reduction in sensitivity variation for the horizontal cell (~3.3%). Thus, it appears from this study that sensitivity variations due to several variations in atmospheric conditions alone are less than 3%.

The standard deviations of hourly sensitivity values about the regression curve were also obtained in order to determine the variation in cell sensitivity with hourly variations in atmospheric conditions. Table II illustrates the minimum and maximum standard deviations (in percent) found over the ten month test period, irrespective of cell tilt angle. Since these standard deviation are a measure of the closeness with which monthly mean sensitivity values represent the hourly variations in cell sensitivity, they indicate the percentage errors which would be incurred if a single sensitivity value (monthly mean) were assumed in hourly design calculations. It can be seen but the maximum standard deviation in Table II was 1.8% at 80 mW/cm^2 and 5.8% at 25 mW/cm^2. In absolute terms, the standard deviations of the short circuit current is essentially constant at all intensity levels.

Feasibility of Global Calibration

The constancy of monthly mean sensitivity and the good precision obtained in hourly sensitivity measurements at high intensities suggest the possibility that a global calibration technique may be used to establish reference cells for performance measurements of field arrays. As pointed out in the Introduction, a global calibration procedure has been used for several years by at least one investigator, Treble (3); in that method, calibrations are performed for solar cells on a horizontal plane under special conditions. According to Treble, insolation, solar elevation angle and atmospheric conditions must meet the following conditions:

(1) global irradiance on horizontal surface $\geq 80\ mW/cm^2$

(2) solar elevation angle ≥ 54

(3) clear sky with diffuse to global irradiance ratio, ≤ .25

This global calibration method was evaluated using the monthly data sets described previously. The restrictions recommended by Treble dealing with the solar elevation angle and the diffuse to global radiation were followed in order to reject unwanted data points from each data set. It was felt that these two restrictions allowed sufficient data to permit a good evaluation of the global technique. Also, the limit on elevation angle was transformed to a limit on the solar incidence angle ($\leq 35^o$) to permit use of the data from the tilted cells.

Mean sensitivity values of the restricted mostly data sets were obtained by regression analysis of each cell-month combination; these sensitivity values are the calibration values which would be obtained during a global calibration of reference cells. The results of the regression analysis of data which meet the restrictions of $\alpha \leq .25$ and solar incidence angles equal to or less than 35^o are shown in Table III. The results in Table III show that, except for the January and February results of global calibrations of the 37^o tilt cell, month to month reproducibility of cell calibration is within ±1% of the overall average calibration value; the deviations in January and February (37^o) were within +1.5%. Treble indicates a reproducibility within ±1% for cells calibrated yearly by the global technique (3). Thus, the global calibration method appears to be a fesible calibration technique for standardizing solar cells in the Terrestrial Photovoltaic programs and warrants further consideration.

CONCLUSIONS

This paper describes the results of an evaluation of a data base of hourly averages of insolation and solar cell short circuit current taken continuously over a period of ten months in Cleveland, Ohio. Tests of the validity of certain insolation models for tilted surfaces and a determination of the variation in solar cell sensitivity led to the following conclusions:

1. The isotropic-sky insolation model of Liu-Jordan provides a good fit to empirical data at low intensities (<30 mW/cm^2) but underestimates the amount of solar radiation falling in tilted surfaces at intensity levels above 50 mW/cm^2.

2. The anisotropic-clear-sky model of Temps and Coulson provides a good correlation between measured and predicted insolation on tilted surfaces for clear skies but overestimate the insolation for mostly cloudy and overcast conditions.

3. The anisotropic-all-sky model formulated in this effort provides a better prediction of solar radiation on tilted surfaces than either the isotropic or anisotropic-clear-sky models.

4. A mean solar cell sensitivity was calculated for each month. The variation of monthly solar cell sensitivity due to atmospheric variation was about 3% over the period of this study. Effects of optical surface reflection losses increased the variation of the horizontal cell sensitivity to 5%. Hourly sensitivity variation (Std. deviation) are less than 3% at intensities greater than

50 mW/cm^2 but increase to ~6% at lower intensities (25 mW/cm^2).

5. The global calibration method appear to be a feasible alternative to normal incidence calibration methods currently used and warrants further study.

REFERENCES

1. B. Y. H. Liu, and R. C. Jordan, "Daily Insolation on Surfaces Tilted Toward the Equator," ASHRAE J., vol. 3, pp. 53-59, Oct. 1961.
2. R. C. Temps, and K. L. Coulson, "Solar Radiation Incident Upon Slopes of Different Orientations," Sol. Energy, vol. 19, pp. 179-184, 1977.
3. F. C. Treble, "Recommendations for the Performance Rating of Flat Plate Terrestrial Photovoltaic Solar Panels," NASA CP-2010, pp. 323-336, 1976.
4. T. M. Klucher, "Evaluation of Models to Predict Insolation on Tilted Surfaces," DOE/NASA/1022-78/28, NASA TM-78842, March 1978.

This work was performed for the U.S. Department of Energy under Interagency Agreement E(49-26)-1022.

TABLE I. - COMPARISON MEASURED MINUS PREDICTED INSOLATION ON TILTED SURFACES FOR ISOTROPIC AND ANISOTROPIC-ALL-SKY MODELS (INSOLATION = 75 mW/cm^2)

	Tilt = 37°		Tilt = 60°	
	Isotropic, mW/cm^2	Anisotropic, mW/cm^2	Isotropic, mW/cm^2	Anisotropic, mW/cm^2
Jan	5.5	0.1	8.5	2.5
Feb	7.0	0.3	10.0	2.2
Mar	5.2	0.0	7.0	1.1
Apr	2.9	-0.9	3.7	0.9
May	2.9	0.4	2.6	0.5
Jun	2.2	0.5	2.8	0.5
Jul	3.0	1.5	3.0	1.5
Aug	3.9	1.1	5.0	2.4
Sept	5.7	1.7	8.3	2.6
Oct	5.4	0.5	7.6	2.2

TABLE II. - MINIMUM AND MAXIMUM STANDARD DEVIATION OF HOURLY SENSITIVITY ABOUT MONTHLY MEAN SENSITIVITY

Insolation level, mW/cm^2	Standard deviation (percent)	
	Minimum	Maximum
80	±0.7%	±1.8%
50	1.1%	2.9%
25	2.2%	5.8%

TABLE III. - RESULTS OF CELL CALIBRATION UNDER GLOBAL SOLAR RADIATION USING TREBLE METHOD

	Cell sensitivity - monthly means		
	Cell at 0° tilt, ma/mW	Cell at 37° tilt, ma/mW	Cell at 60° tilt, ma/mW
Jan	*	0.2780	0.2709
Feb	*	.2783	.2737
Mar	*	.2737	.2724
Apr	0.2683	.2727	.2725
May	.2692	.2730	*
Jun	.2700	.2727	*
Jul	.2713	.2735	*
Aug	.2713	.2747	.2723
Sept	*	.2768	.2752
Oct	*	.2767	.2735
Average of all data	0.2702	0.2742	0.2727

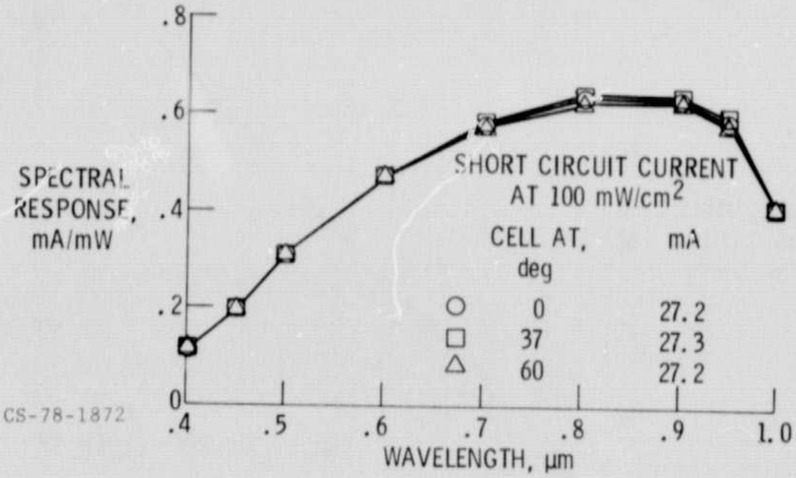
*Sun-cell incidence angle exceeds 35°

TEST FACILITY SENSOR SUBSYSTEM

Figure 1.

E-9661

COMPARISON OF SPECTRAL RESPONSE AND SHORT CIRCUIT CURRENT OF CELLS USED AS SENSORS



CS-78-1872

Figure 2.

ORIGINAL PAGE IS OF POOR QUALITY

ANISOTROPIC ALL SKY MODEL RESULTS

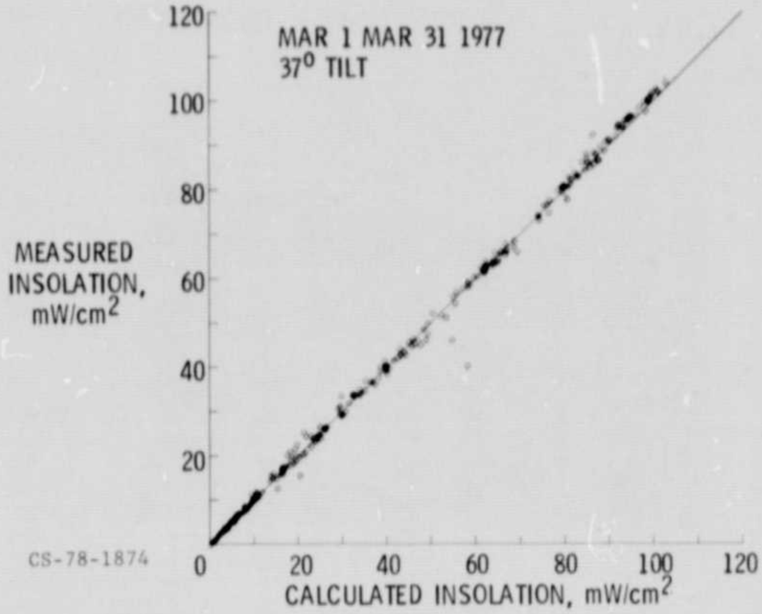


Figure 3(a).

ANISOTROPIC CLEAR SKY MODEL RESULTS

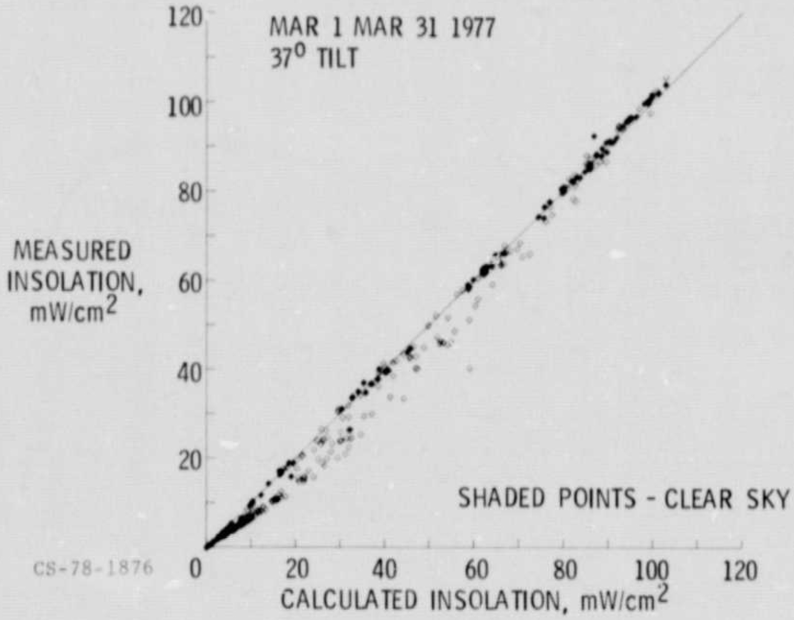


Figure 3(b).

LIU-JORDON ISOTROPIC SKY MODEL RESULTS

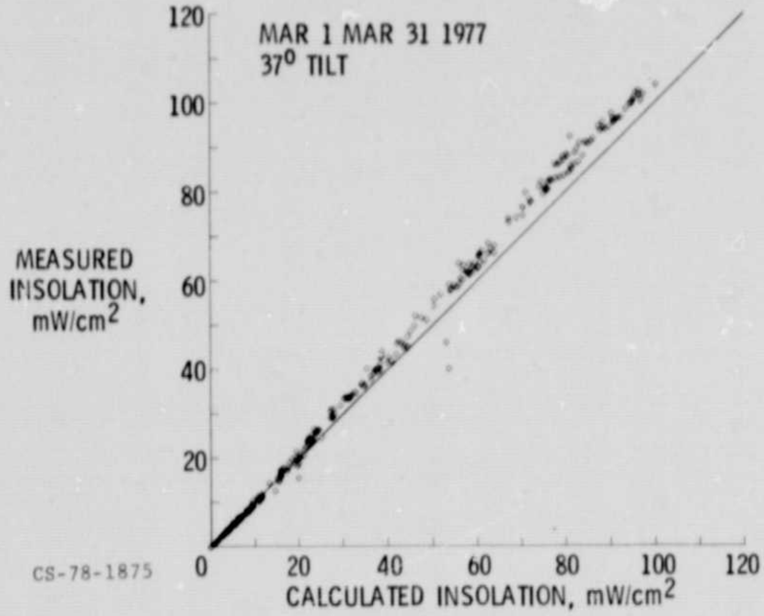


Figure 3(c).

MONTHLY VARIATION IN CELL SENSITIVITY

FOR CELLS TILTED AT 0°, 37°, & 60° ABOVE HORIZON

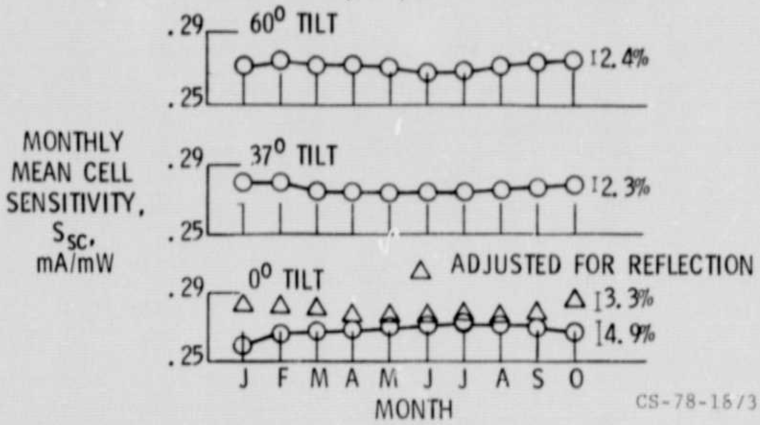


Figure 4.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-78921		

4. Title and Subtitle	5. Report Date
VARIATION OF SOLAR CELL SENSITIVITY AND SOLAR RADIATION ON TILTED SURFACES	
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Thomas M. Klucher	E-9661
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address U.S. Department of Energy Division of Solar Energy Washington, D.C. 20545	14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/1022-78/32

15. Supplementary Notes

Prepared under Interagency Agreement E(49-26)-1022. Presented at the Thirteenth Photovoltaic Specialists Conference sponsored by the Institute of Electrical and Electronics Engineers, Washington, D.C., June 5-8, 1978.

16. Abstract

An empirical study was performed (1) to evaluate the validity of various insolation models used to compute solar radiation incident on tilted surfaces from global data measured on horizontal surfaces and (2) to determine the variation of solar cell sensitivity to solar radiation over a wide range of atmospheric condition. Evaluation of the insolation data indicates that the isotropic sky model of Liu and Jordan underestimates the amount of solar radiation falling on tilted surfaces by as much as 10%. An anisotropic-clear-sky model proposed by Temps and Coulson was also evaluated and found to be deficient under cloudy conditions. A new model, formulated herein, reduced the deviations between measured and predicted insolation to less than 3%. Evaluation of solar cell sensitivity data indicates small change (2-3%) in sensitivity from winter to summer for tilted cells. The feasibility of using such global data as a means for calibrating terrestrial solar cells as done by Treble is discussed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Solar radiation Photovoltaic Solar cells Insolation modeling	Unclassified - unlimited STAR Category 44 DOE Category UC-63

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161