# CALCULATED SOLAR CELL ISC SENSITIVITY TO ATMOSPHERIC CONDITIONS UNDER DIRECT AND GLOBAL IRRADIANCE

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## ABSTRACT

Using a new solar spectral irradiation computer model, a procedure has been devised which allows the calculation of short-circuit current ($I_{sc}$) sensitivity to atmospheric variables. This procedure, which has applications for photovoltaic reference cell calibrations, clearly shows the $I_{sc}$ sensitivity to spectral distribution changes without the influence of the total irradiance level. Example outputs are presented for four different solar cell types.

## METHODOLOGY

The short-circuit current of a linear, single-junction solar cell can be expressed as

$$I_{sc} = A \int_a^b E_i(\lambda)R(\lambda)d\lambda \qquad (1)$$

where A is the active area of the device, $R(\lambda)$ the spectral response (A/W), $E_i(\lambda)$ is the incident spectral irradiance ($W/m^2/nm$), and $\lambda$ the wavelength (nm). Varying $Ei(\lambda)$ in equation 1 will show variations in $I_{sc}$ but the resulting $I_{sc}$ changes will be due to both spectral and total (integrated) irradiance changes. To isolate the two effects, equation 1 can be divided by the total irradiance, or

$$CN = \frac{A \int_a^b Ei(\lambda)R(\lambda)d\lambda}{\int_a^b Ei(\lambda)d\lambda} . \qquad (2)$$

The ratio of $I_{sc}$ to the total incident irradiance is defined as the calibration number (CN), which is independent of total irradiance changes. An added benefit of using CN is that absolute spectral irradiance is not needed because $Ei(\lambda)$ appears in both the numerator and the denominator of equation 1. Because absolute measurements of active area and spectral response are difficult to obtain, it would be useful if these could be normalized as well. This can be accomplished by normalizing the calibration number to a fixed set of reference atmospheric conditions, or

$$\overline{CN} = \frac{\int_a^b E_i(\lambda)R(\lambda)d\lambda}{\int_a^b E_i(\lambda)d\lambda} \div \frac{\int_a^b E_{ref}(\lambda)R(\lambda)d\lambda}{\int_a^b E_{ref}(\lambda)d\lambda}, \qquad (3)$$

where $\overline{CN}$ is the normalized calibration number and $E_{ref}(\lambda)$ is the spectral irradiance which corresponds to the reference atmospheric conditions. Notice that the active area has been eliminated and all spectral quantities appear in both the numerator and the denominator. Therefore, changes in $\overline{CN}$ which occur from varying $E_i(\lambda)$ are due to spectral changes alone and are relative to $E_{ref}(\lambda)$.

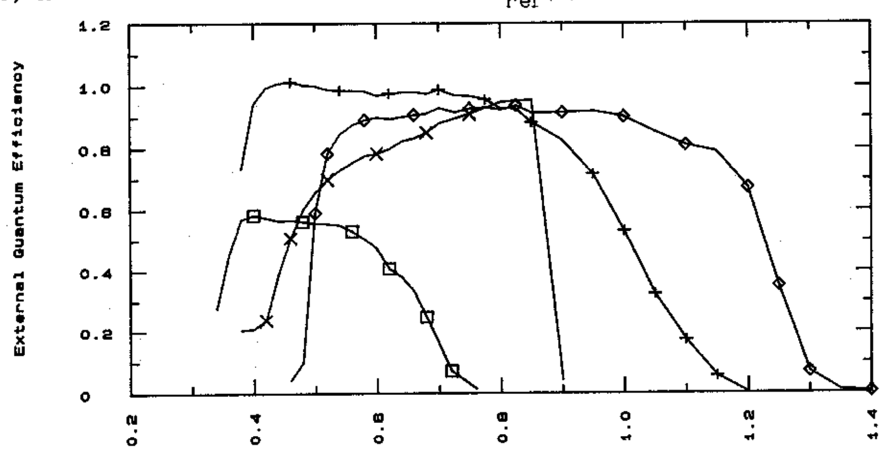


**Figure 1. External quantum efficiency vs. wavelength for silicon (+), GaAs (x), CdS/CuInSe$_2$ (diamond) and a-Si:H (box) devices used in this study.**



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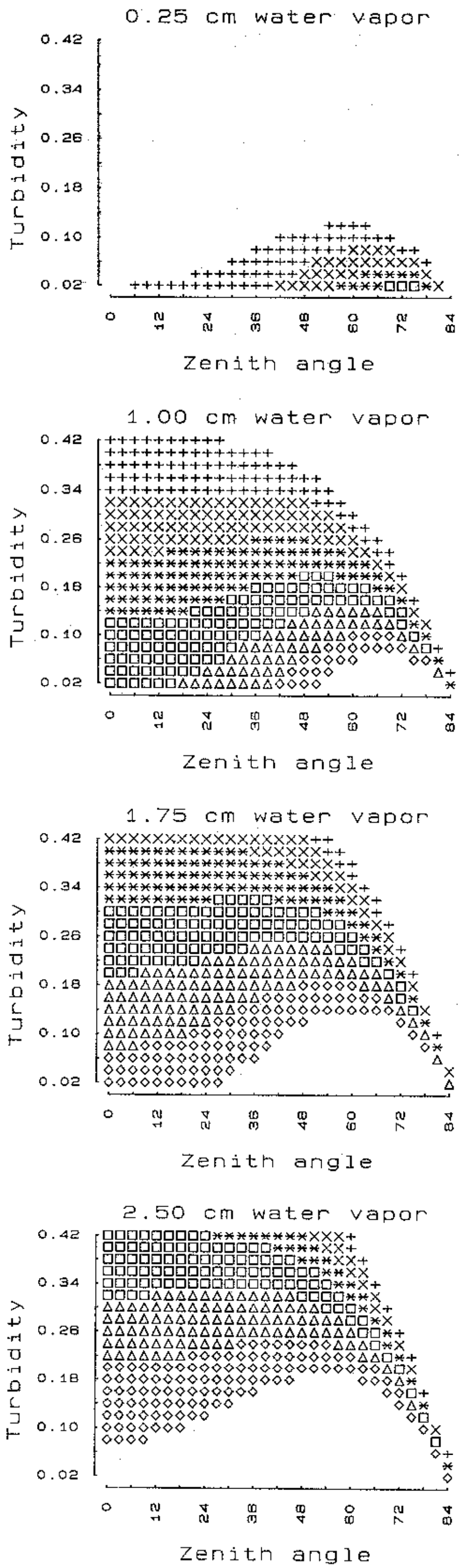


Figure 2. $\overline{CN}$ vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for silicon device under direct irradiance

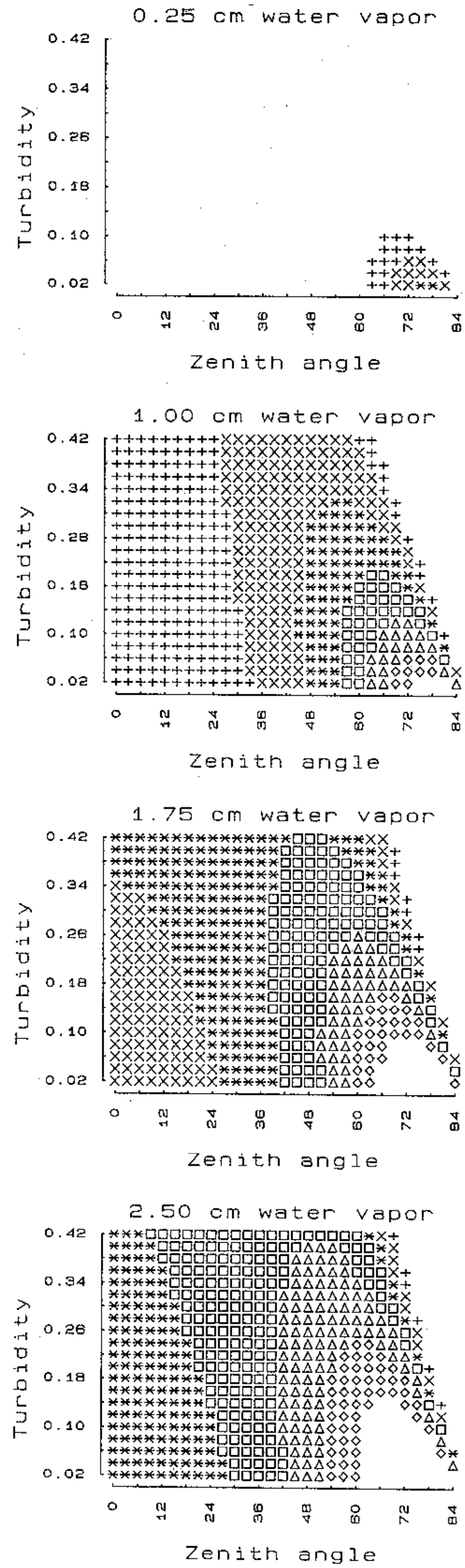


Figure 3. $\overline{CN}$ vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for silicon device under global irradiance.

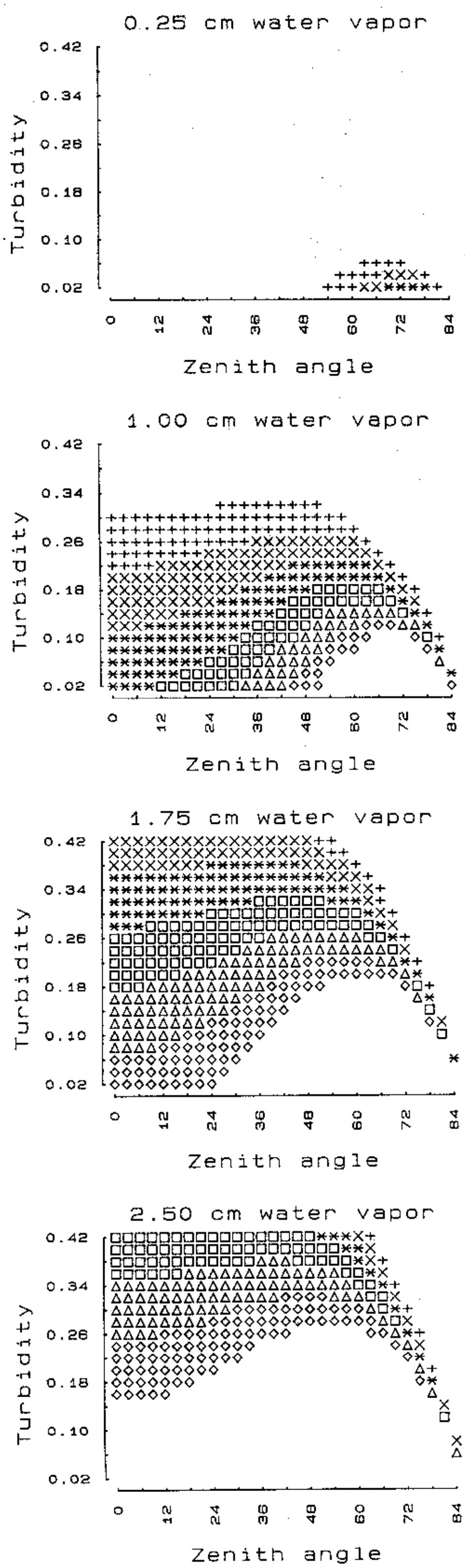


**Figure 4.** $\overline{CN}$ **vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for GaAs device under direct irradiance.**

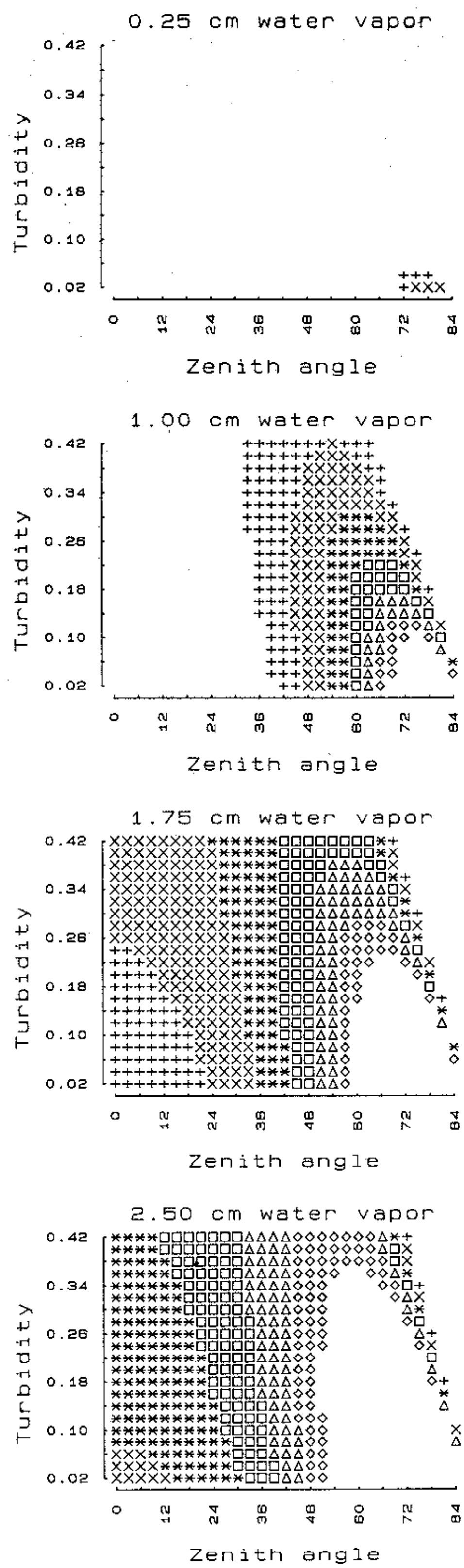


**Figure 5.** $\overline{CN}$ **vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for GaAs device under global irradiance.**

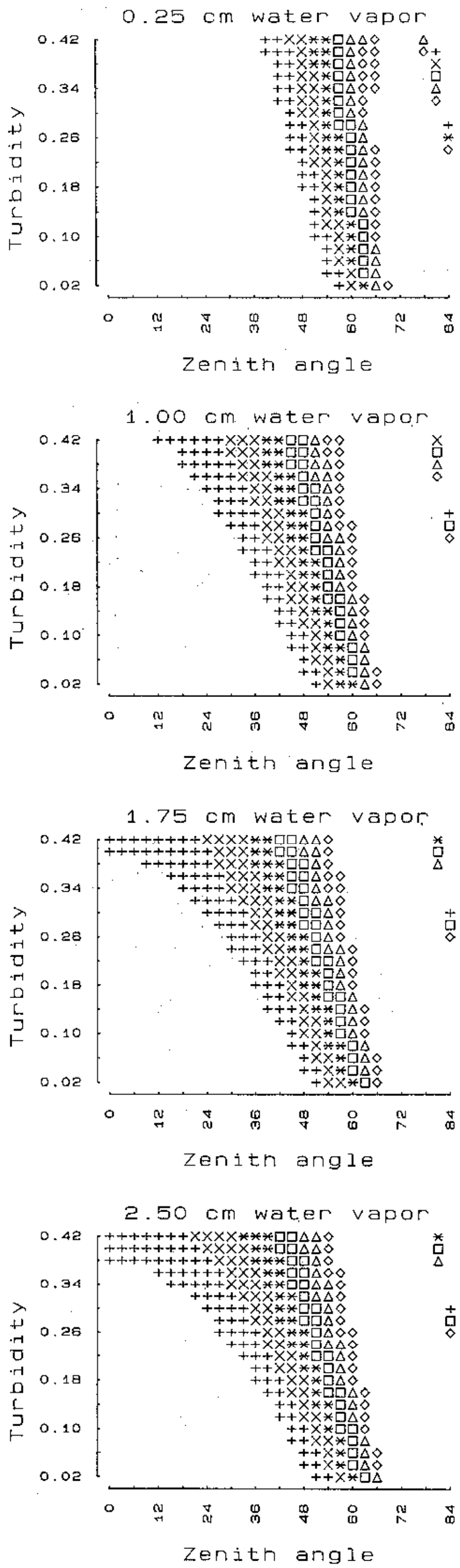


Figure 6. $\overline{CN}$ vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for $CdS/CuInSe_2$ device under direct irradiance.

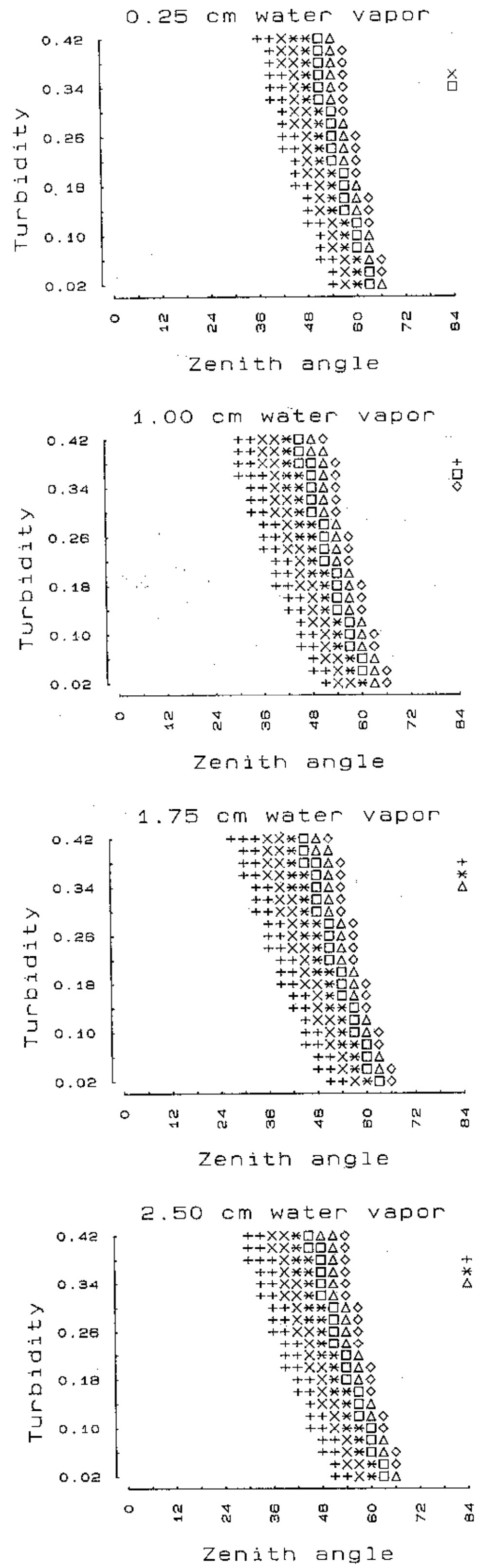


Figure 7. $\overline{CN}$ vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for $CdS/CuInSe_2$ device under global irradiance.

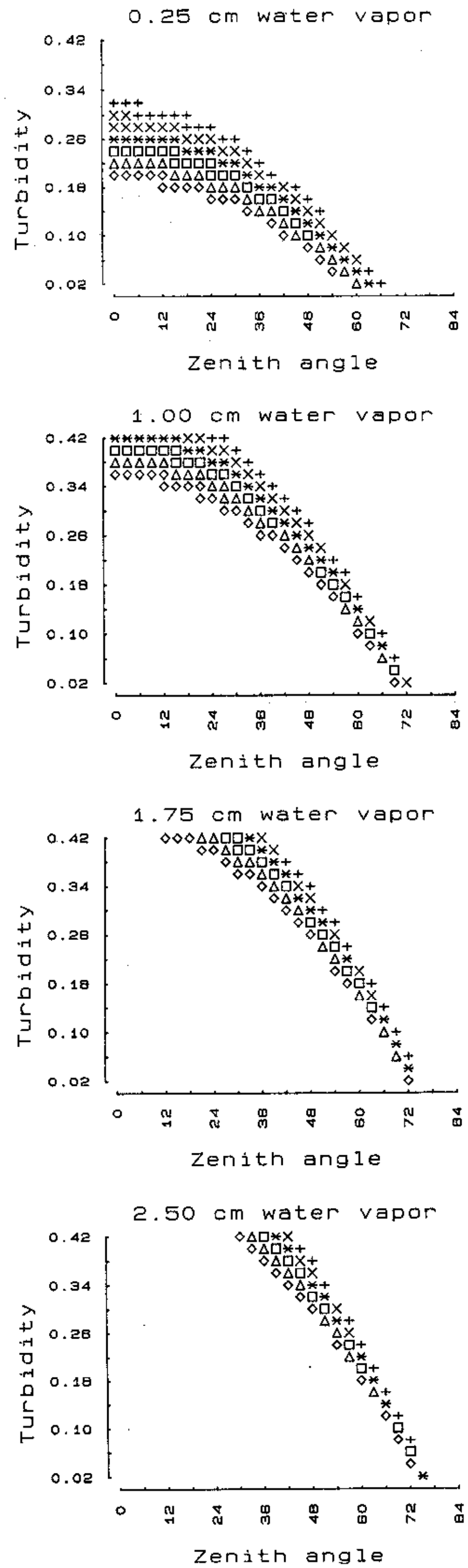


Figure 8. $\overline{\text{CN}}$ vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for a-Si:H device under direct irradiance.

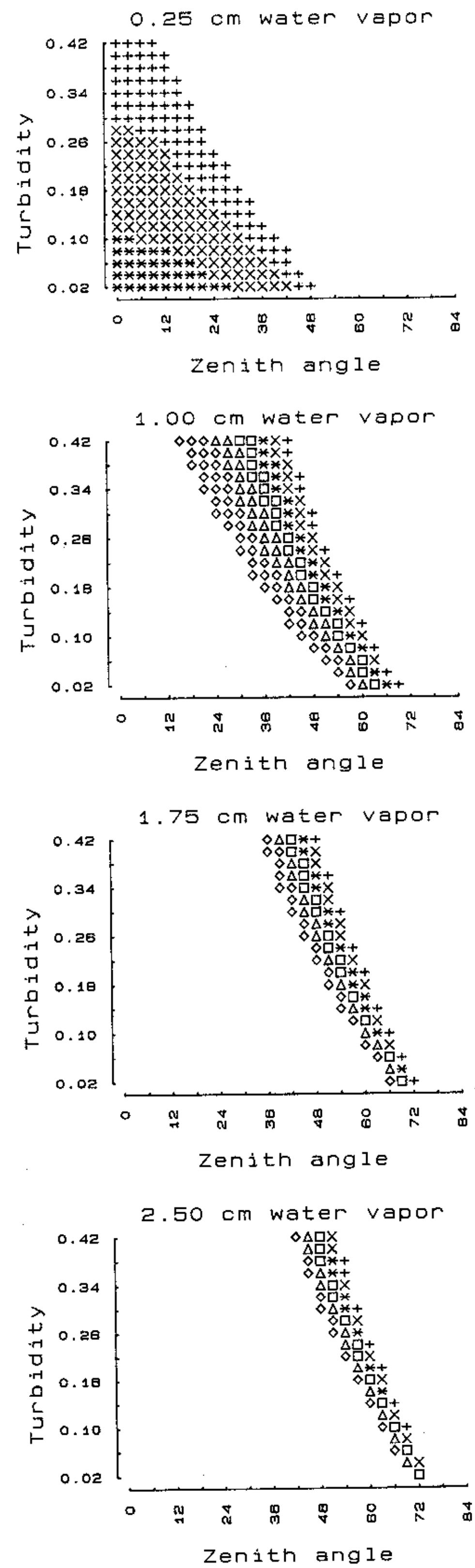


Figure 9. $\overline{\text{CN}}$ vs. water vapor, turbidity at 0.5 µm, and zenith angle (degrees) for a-Si:H device under global irradiance.

## PROCEDURE

The computer model which was used to vary $E_i(\lambda)$ outputs both a direct beam and a global spectrum for a given set of input atmospheric variables (1). Therefore, it was possible to obtain simultaneously the global and direct sensitivities for a given solar cell. The model provides for a large number of variables to be input such as atmospheric turbidity, surface air pressure, water vapor and ozone content, solar zenith angle, and ground albedo for a cloudless sky. In order to restrict the input to three independent variables, it was necessary to fix all other variables except the water vapor content, atmospheric turbidity, and the solar zenith angle. Fortunately, most of the other variables except the air pressure either do not vary much or have a rather small effect on the spectrum. The reference conditions chosen for this study are water vapor, 1.42 cm; atmospheric turbidity at 500 nm, 0.27; air pressure, 1013.25 mb (sea level); ozone, 0.34 cm; ground albedo, 0.2; and zenith angle, 48.19° (corresponding to air mass 1.5) (2).

Four measured spectral responses were chosen for study, and the quantum efficiencies of these devices are presented in figure 1. The input variable matrix used consisted of 21 values of turbidity, 29 zenith angles, and four water vapors, which resulted in 4,872 different spectra. These were used in equation 3 with the spectral resonses to calculate the normalized calibration number for each case. The resulting 19,488 $\overline{CN}$'s are presented in figures 2-9. Each $\overline{CN}$ was sorted into bins as follows:

+ $\overline{CN}$ = 0.9800 to 0.9867;
× $\overline{CN}$ = 0.9867 to 0.9933;
✳ $\overline{CN}$ = 0.9933 to 1.0000;
□ $\overline{CN}$ = 1.0000 to 1.0067;
△ $\overline{CN}$ = 1.0067 to 1.0133;
◇ $\overline{CN}$ = 1.0133 to 1.0200.

Therefore, each character maps a location where the $\overline{CN}$ is within a given range of unity and on any given plot, the total area marked shows the region where $\overline{CN}$ is within 2% of unity.

## DISCUSSION

Some major trends are evident upon examination of Figs. 2-9. From the total number of points marked in each series, it is seen that silicon is the least sensitive while a-Si is the most sensitive. GaAs is very similar to silicon in form although it is slightly more sensitive. In terms of outdoor performance measurements, this means it will be much less likely that a set of conditions will exist that produces the reference calibration number ($\overline{CN} = 1$) for amorphous silicon and $CuInSe_2$/CdS than for silicon or GaAs. As a rule, increasing zenith angle increases $\overline{CN}$ except for a-Si, which decreases. Also, increasing water vapor increases $\overline{CN}$ excluding $CuInSe_2$/CdS for which water vapor has very little effect. The information obtained clearly shows how the $\overline{CN}$ will change under varying atmospheric conditions.

Finally, the form of equation 3 indicates that the normalized calibration number can be used to correct outdoor performance measurements if the atmospheric conditions at the time of measurement are known. Once $\overline{CN}$ has been calculated, the measured calibration number is corrected by dividing by $\overline{CN}$, giving the reference calibration number.

## ACKNOWLEDGEMENT

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## REFERENCES

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2. R.E. Bird, R.L.Hulstrom, L.J. Lewis, "Terrestrial Solar Spectral Data Sets", Solar Energy, Vol. 30, No. 6, pp. 563-73, 1983.