ERDA/NASA 1022/76/6
NASA CP-2010
Technical Report II-7

SENSITIVITY OF SOLAR-CELL PERFORMANCE TO ATMOSPHERIC VARIABLES
I - SINGLE CELL

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Prepared for
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Office of the Assistant Administrator for
Solar, Geothermal, and Advanced Energy Systems
Division of Solar Energy
Under Interagency Agreement E(49-26)-1022

Presented at Second Annual Photovoltaic Measurements Workshop
Baton Rouge, Louisiana, November 10-12, 1976

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ABSTRACT AND SUMMARY

Measurements of the short-circuit current of a typical silicon solar cell under direct solar radiation were made for a range of turbidity, water vapor content, and air mass to determine the relation of the solar cell calibration value (current-to-intensity ratio) to those atmospheric variables. A modification of a previously developed regression equation was used to describe the relation between calibration value, turbidity, water vapor content, and air mass. Based on the value of the constants obtained by a least-squares fit of the data to the equation, it is found that turbidity lowers the value, while increase in water vapor increases the calibration value. Cell calibration values exhibited a change of about 6% over the range of atmospheric conditions experienced.

INTRODUCTION

Quantitative information on the amount of solar radiation incident upon solar cells and arrays and the subsequent efficiency of conversion of that radiation into electrical energy is essential to the development of improved cells and arrays and the design of cost-effective systems. Standard reference cells can be calibrated so that the incident solar radiation can be determined by measuring the cell short-circuit current. These reference cells then can be used to establish the intensity during the measurement of the performance of other cells, modules or arrays.

It is well known that the spectral distribution of the incident solar radiation is variable, even under clear skies. This variability is due to the effects of Rayleigh and aerosol scattering, and selective absorption (primarily by atmospheric water vapor) as the sunlight passes through the atmosphere. Because the solar cell is sensitive to a limited range of wavelengths (~ 0.3 to $1.2\ \mu m$), its short-circuit current will vary in a manner different from the intensity of the solar irradiance. Thus, the calibration value--the ratio of short-circuit current to the intensity of solar radiation under normal incidence--will be a function of and sensitive to changes in atmospheric turbidity and water vapor content.

The purpose of this work is to determine the effects of turbidity, water vapor, and air mass on the cell calibration value. To do this, measurements over a one-year period were made on a single cell for widely different measured atmospheric conditions. Measurements of turbidity, water vapor and air mass were taken along with current and intensity. The data accumulated were fitted by the least-squares method to a regression equation developed by Majumdar et. al. (Ref. 1) for solar radiation predictions, but modified herein to solar-cell calibration ratio measurements. The regression coefficients obtained are a measure of the sensitivity of the calibration value to the atmospheric variables.

APPARATUS AND MEASUREMENTS

Measurements of the direct solar radiation were obtained using a 10:1 collimation ratio Eppley normal incidence pyrheliometer. The unit is temperature compensated within $\pm$ 1% over the temperature range of -20° C to $+ 40^{\circ}$ C and is calibrated with respect to the IPS 1956 standard.

The solar cell, Z01, used in this study was a commercial 2x2 cm cell mounted in a special holder (Figure 1). The spectral response curve is shown in Figure 2. During measurements, the cell was inserted in a 10:1 collimating tube (slope angle 1.76°) mounted with the pyrheliometer on a sun tracker (Figure 3). The short circuit current of the cell was obtained by measuring the voltage developed across a $0.1\ \Omega \pm .1\%$ resistor located near the cell terminals. The temperature of the cell was controlled to 28° C $\pm$ 2° C.

Two sunphotometers were used to monitor turbidity, water vapor, and relative air mass during cell measurement (Figure 4). The sunphotometer on the right, on loan from the EPA, was used to measure the Schuepp turbidity coefficient, $B = B_o p/p_o$, with the relation:

$$I_\lambda \times S = I_{o\lambda} \times 10^{-(T_{R\lambda} + T_{3\lambda} + B_{o\lambda})\, M_r \frac{p}{p_o}} \qquad \text{Eq. (1)}$$

where I_λ is the irradiance at wavelength

I_{o_λ} is the AMO irradiance at λ and mean sun-earth distance

S is the correction factor for mean sun-earth distance

$T_{R\lambda}$ is scattering coefficient for air molecules at p_o

$T_{3\lambda}$ is the absorption coefficient for ozone

$B_{o\lambda}$ is the turbidity coefficient at p_o

M_r is the relative air mass

p is the barometric pressure measured at the location

p_o is the standard sea level pressure

Measurements with this instrument are made at a wavelength of 0.5 μm. The sunphotometer provides a current output directly proportional to the irradiance value and is calibrated relative to a standard photometer, routinely calibrated by the Langley Method. The uncertainties in B are believed to be ± 10% (Ref. 2). The second sunphotometer, obtained from Dr. F. Volz, was used to monitor the precipitable water vapor, W, in the atmosphere using the relation (Ref. 3):

$$W = \frac{K}{M_r}\left[\log_{10}\left(\frac{q_o}{q}\right)\right]^2 \qquad \text{Eq. (2)}$$

where K is the calibration constant obtained by comparison with radiosonde measurement of precipitable water.

M_r is the relative air mass

q is the ratio of intensity readings at λ = .940 μm and .880 μm at the location.

q_o is the ratio of intensity readings above the atmosphere at .940 μm and .880 μm.

Here again, the current output of the sunphotometers is directly proportional to the intensity readings. The uncertainty in W is believed to be ± 15%.

BACKGROUND AND METHOD

The sensitivity of the calibration value to variations in atmospheric components can best be demonstrated by theoretical modeling, involving the convolution of spectral irradiance with the cell spectral response curves. However, these methods are fairly elaborate, requiring many computations and accurate data for absorption bands and spectral response. At present, the spectral irradiance curves are generated theoretically and there are few direct comparisons with experimental data to validate the model used.

Also, the measured spectral response curves have errors of about $\pm$ 5%. Thus, calculated calibration values are not reliable at this time.

An alternate way to mathematically describe the sensitivity of solar cell calibration value to the atmospheric variables is through the use of a regression equation. In this method, empirical measurements of the pertinent variables and the solar cell calibration value are made and a curve (or equation) is mathematically fit to the data. This empirical regression equation can then be used to determine calibration values for selected values of the atmospheric variables.

The starting point for this analysis was the regression equation derived by Majumdar et al (Reference 1) to predict the direct solar radiation as a function of air mass and water vapor for clear sky. This equation is:

$$I_n = I_o \times t_1^{M} \times (t_2)^{(WM_r)^{0.25}} \qquad \text{Eq.(3)}$$

where t_1 is the scattering transmission coefficient and t_2 is the water vapor transmission coefficient, and $M = M_r\ p/p_o$ I_0 is the intensity above the troposphere and I_n is the intensity at ground level. Majumdar considered only clear skies with Schuepp turbidity coefficients of around $B = 0.045$. In this report, this equation has been modified to include above and below $B = 0.045$ by use of a short-wave radiation turbidity factor $T = 10B+1$ (Reference 4). This factor is basically the Linke turbidity factor obtained for only the fraction of radiation intensity below the water vapor bands (Reference 5). The turbidity factor was further modified so that at $B = 0.045$, the modified equation reduces to Equation 3.

Thus, the modified equation is:

$$I_n = I_o \times t_1^{\left[10(B-0.045) + 1\right] M} \times t_2^{(WM_r)^{0.25}} \qquad \text{Eq. (4)}$$

The major assumption made by Majumdar and also in this study is that Beer's law, which is strictly valid only for monochromatic radiation, can be extended to the entire solar radiation spectrum through the use of average transmission coefficients for scattering and absorption. In practice, plots of the logarithm of intensity versus air mass (Langley plot) are observed to be nearly linear up to about air mass 3. In a similar manner, the Langley method has been successfully applied in the past to solar cell measurements using the same assumptions (Ref. 6, 7). Therefore, in this study, the solar cell short circuit current was also assumed to have the form:

$$I_{sc} = I_{sc_o} \times f_1^{\left[10(B-0.045) + 1\right] M} \times f_2^{(WM_r)^{0.25}} \qquad \text{Eq. (5)}$$

Dividing eq. 5 by eq. 4 yields the equation for the calibration value:

$$\frac{I_{sc}}{I_n} = C_0 \times C_1^{\left[10(B-0.045) + 1\right] M} \times C_2^{(WM_r)^{0.25}} \qquad \text{Eq. (6)}$$

Taking the logarithm of both sides of equation 6 yields the linear equation:

$$\log\left(\frac{I_{sc}}{I_n}\right) = \log C_0 + \log C_1 \left[10(B-0.045) + 1\right] M + \log C_2 \,(WM_r)^{0.25} \qquad \text{Eq. (7)}$$

Measured values for I_{sc}, I_n, B, W, M_r, and M were used to determine the regression constants C_0, C_1 and C_2 by the method of least squares. C_0 is the "effective" air mass zero coefficient, C_1 is the turbidity coefficient and C_2 is the water vapor coefficient.

RESULTS AND DISCUSSION

During the course of a year, eighty-two (82) concurrent measurements of direct normal incidence solar radiation, I_n, solar cell short circuit current, I_{sc}, turbidity, B, water vapor, W, and air masses, M and M_r, were obtained under clear skies, or through clearings in a partly cloudy sky. The data collected had the following range of values: turbidity, 0.031 to 0.30; water vapor, 0.15 to 1.4 cm; and air masses, 1.05 to 4.2. Turbidity values greater than B = 0.300 and water vapor values greater than 1.4 cm were arbitrarily excluded. The sensitivity coefficients were determined to be:

$$C_0 = 1.017 \text{ mA/mW/cm}^2$$

$$C_1 = .991$$

$$C_2 = 1.114$$

These coefficients are specific for only the single cell studied here. The standard deviation of the difference between measured calibration values and the prediction value is 0.011 mA/mW/cm^2 or about 1%. Figure 5 illustrates the comparison between the measured calibration values and those calculated by the regression equation.

Based on the results of the data set examined here of the regression analysis, the cell calibration value exhibits a change of about 6% over the range of atmospheric conditions experienced. As can be seen from equation 7, regression constants less than 1 indicate a decrease in cell calibration value with increase in the associated atmospheric variable, while constants greater than 1 indicate an increase in calibration value with increase in the atmospheric variable. Thus for cell Z01, the water vapor and turbidity sensitivity factors have opposite effects for concurrent increase or decrease in turbidity, water vapor, and air mass.

SUMMARY OF RESULTS

The regression analysis performed on data for a single, but typical, solar cell has determined that the ratio of cell short-circuit current to solar intensity exhibits a change of about 6% over a typical range of atmospheric turbidity, water vapor, and air mass conditions. Thus, the measurement of these atmospheric variables is essential to providing an accurate measurement of cell performance even under clear-sky conditions. With the instruments used, the standard deviation of the difference between measured ratio and predicted ratio was found to be about 1%. This simple regression equation may be used as an aid in correcting the calibration value of solar cell standards for a variety of atmospheric conditions.

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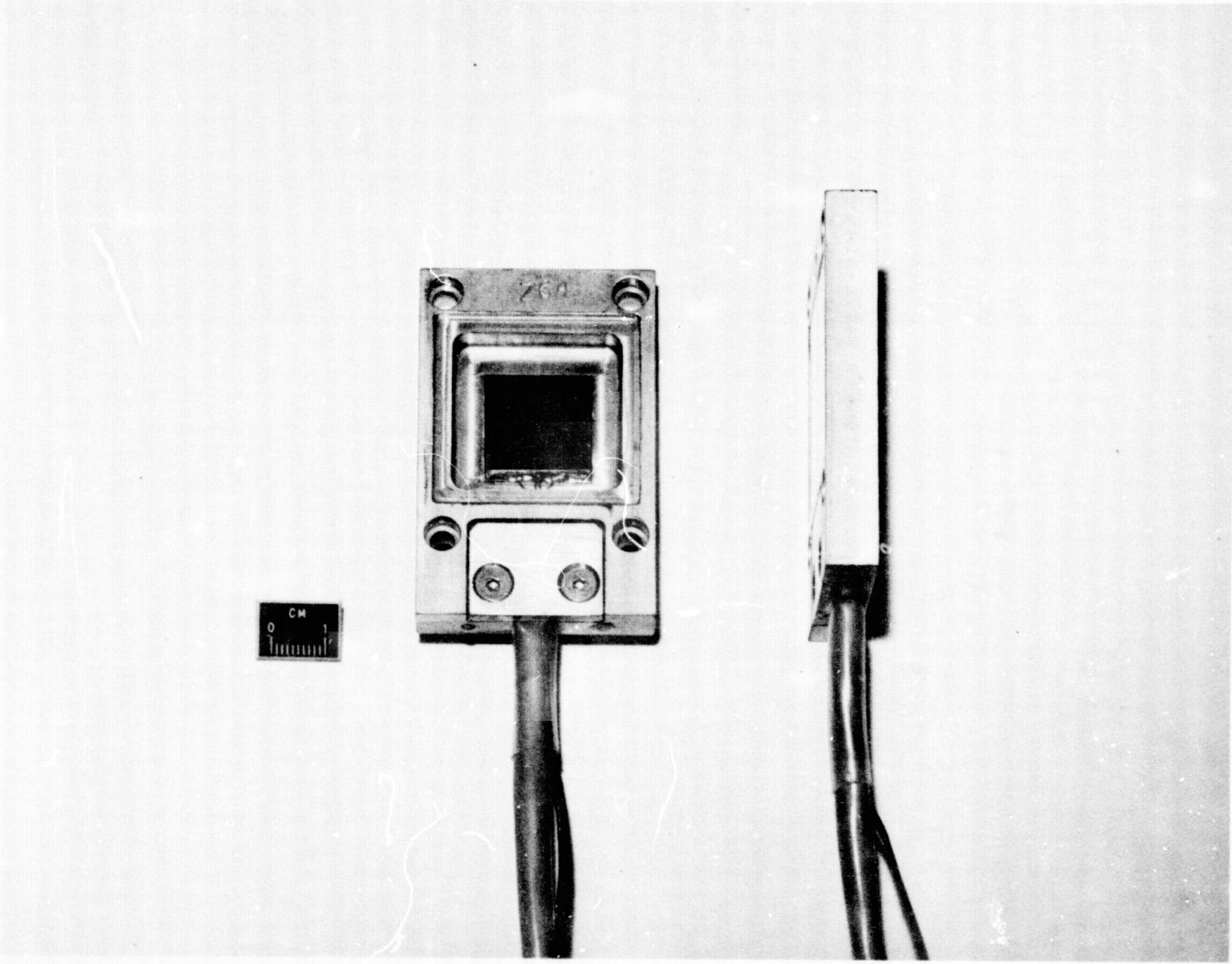

Figure 1. - Solar cell mounted in holder

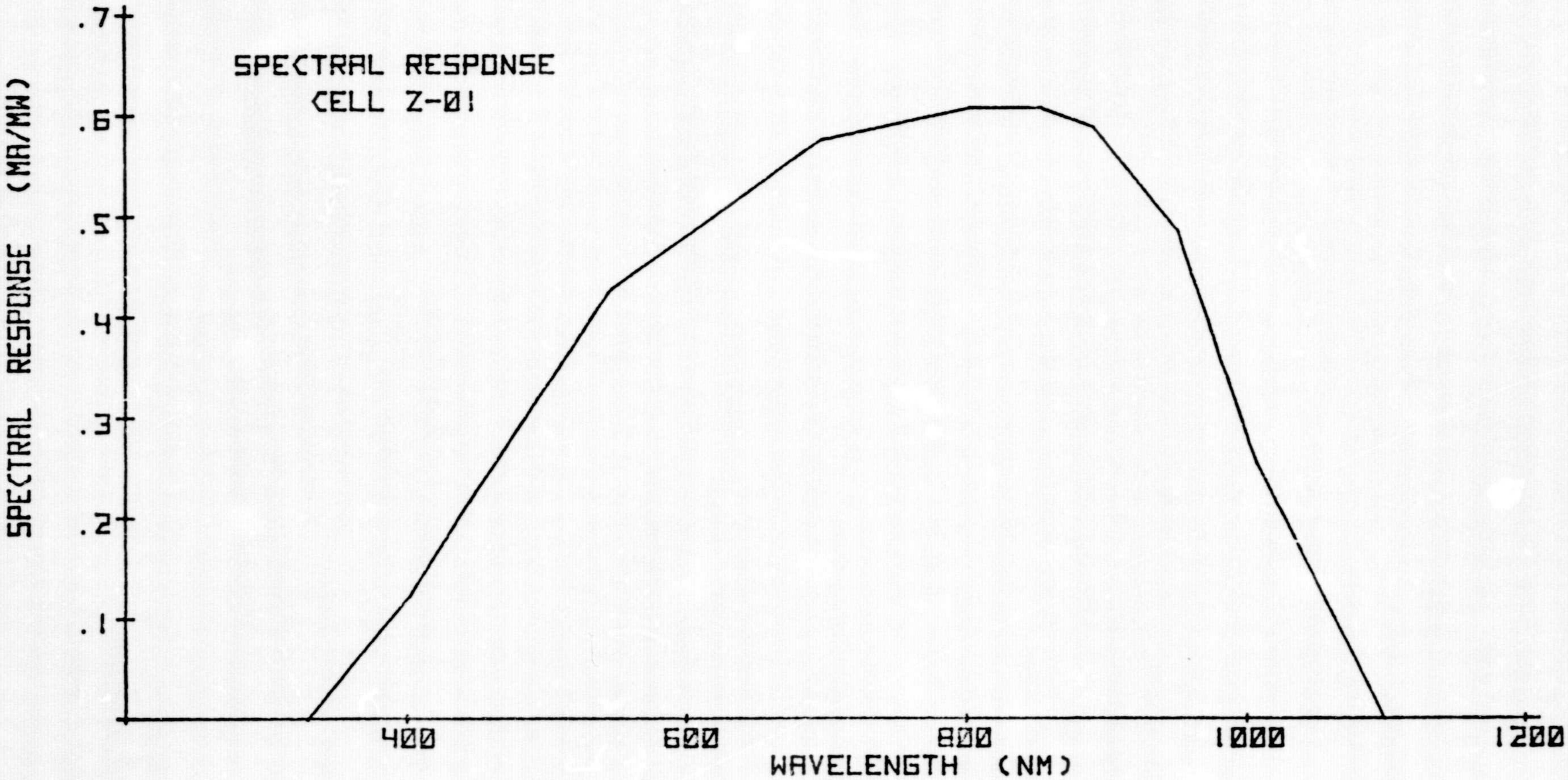

Figure 2. - Spectral response curve of cell Z 01

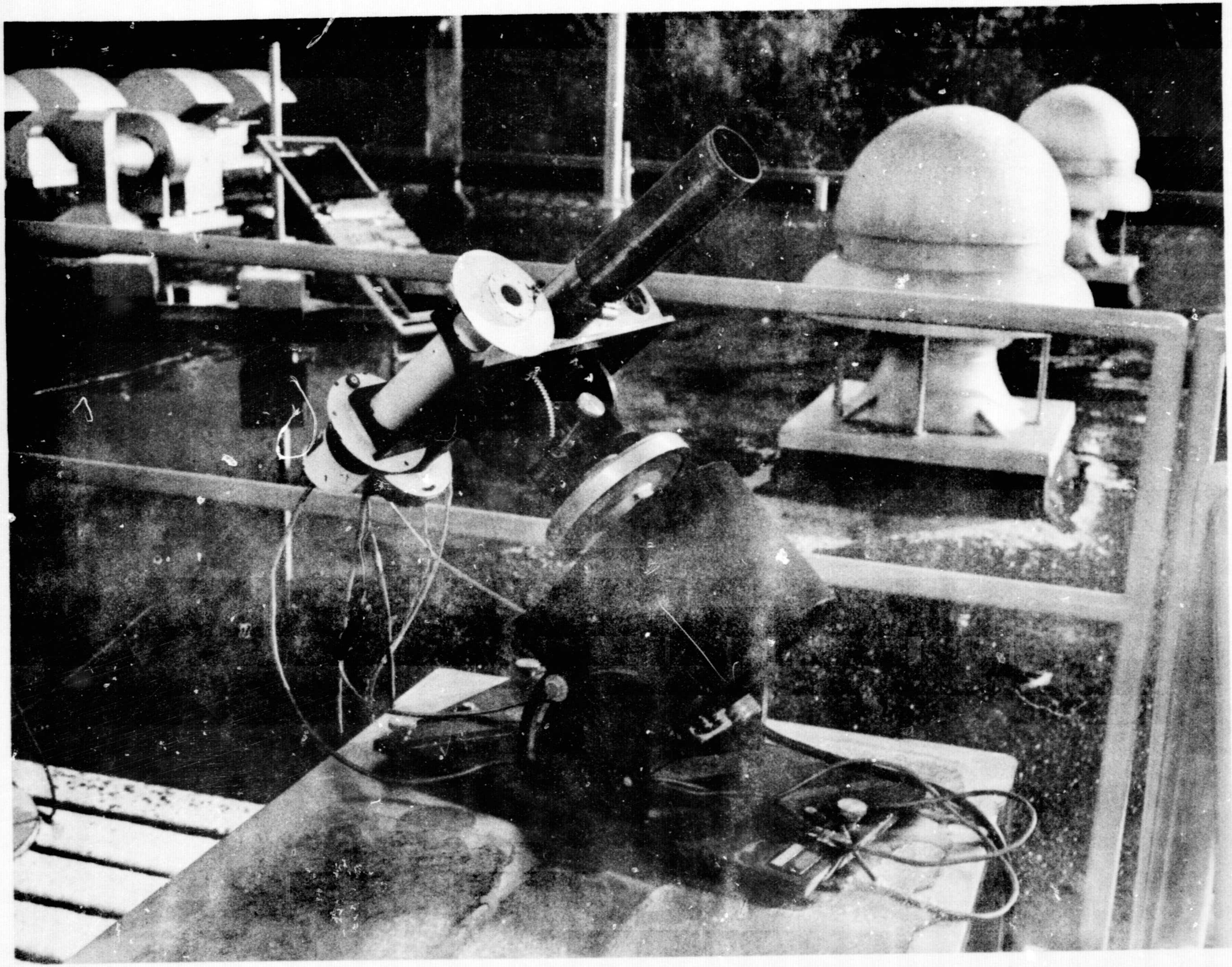

Figure 3. - Solar cell calibration apparatus

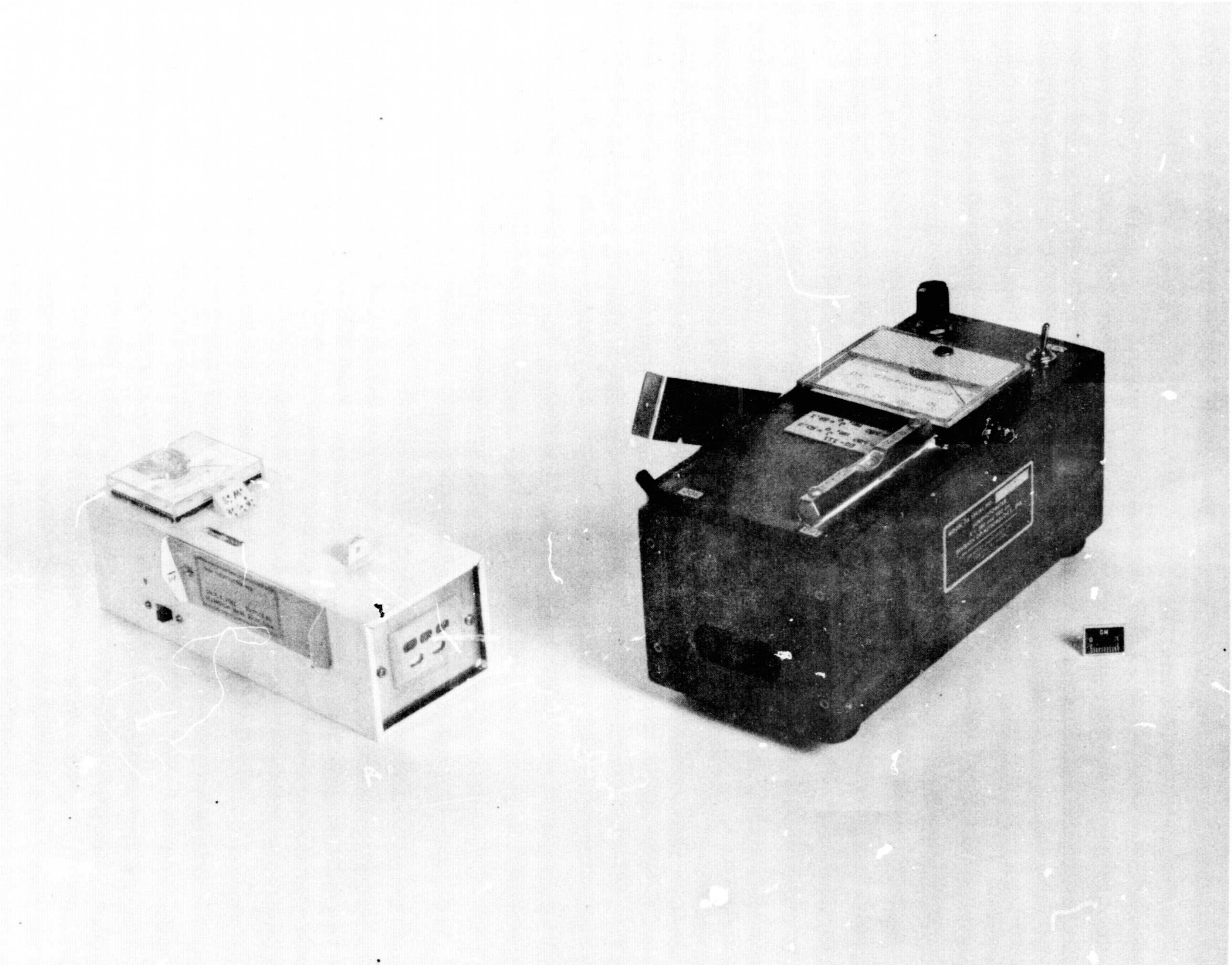

Figure 4. - Sunphotometers used to measure turbidity, water vapor and relative air mass

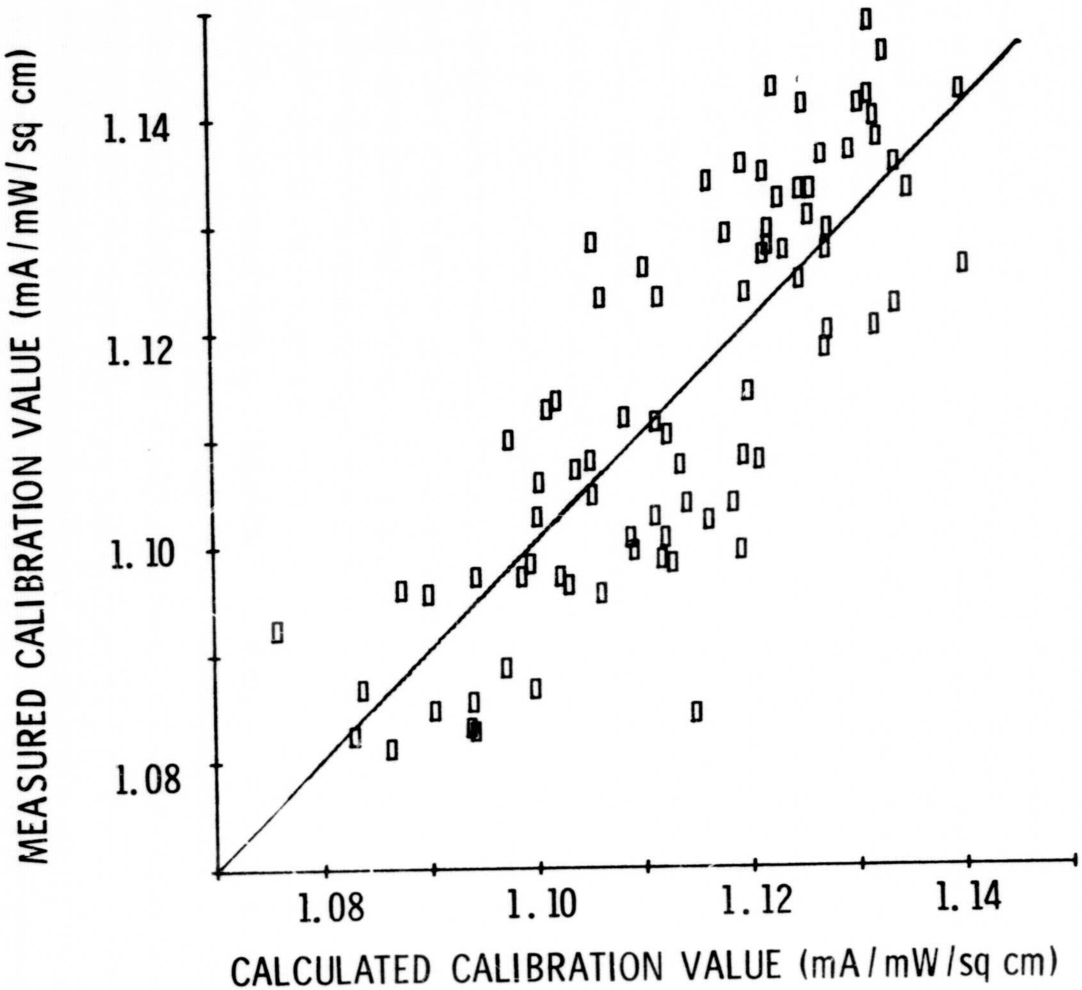

Figure 5. - Measured versus calculated calibration value