

Engr 300 : Engineering Experimentation – Lab

Solar Panel

Rob Roberts

Camilo Jimenez

Naji Ghosseiri

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Prof. Mutlu Ozer

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Abstract:

During the Solar Cell Energy lab three flexible solar cells were combined in series and exposed to solar radiation at different angles in one axis of rotation. The cells were attached to a levered plane with a protractor that acted like a “see-saw” to adjust the angle of the solar cells to the Sun. Around the plane, a column of cardboard was constructed with black fabric covering the inside and bottom surfaces to prevent unwanted reflections. The time of day, temperature, voltage, and current was collected for every one-degree change in angle. Using Microsoft Excel, the data (voltage, current and calculated power) was graphed with respect to angle. All three parameters displayed a pattern close to a logarithmic function, similar to half a bell curve.

Summary:

The objective of this experiment is to find a distinct relationship between a solar cell’s power output and its angle of incident with Sunlight. In order to get readings that encompassed the full range of the multi-meter three solar cells were attached in series, their voltages add. Because the Sun takes approximately 6 hours to move 90 degrees [relative to one spot on the earth, it was thought that changing the angle of the solar cells in a short period of time would yield better results than taking measurements at timed increments during one day. In order to do that, the solar cells were attached to a pivot able-plane which was able to pivot 360 degrees. Call this the apparatus. A transparent protractor was secured in a way that made it easy to read the angle at which the solar panel was facing with respect to the Sun. (see pictures) To keep ambient light (ie. light not coming directly from the Sun) from activating the solar cell a 3 foot tall column (like a blackened chimney) was put in place surrounding the solar cells. The solar apparatus and column were secured to a heavy base lying in the plane perpendicular to the Sun. To make sure the column was pointed directly at the Sun, its shadow was constantly monitored. Black fabric on all interior surfaces of the column minimized ambient light that may have reflected off the interior walls of the column. The cells were then connected to a fluke multimeter and voltages and currents were collected at each whole-degree of rotation from 0-90 degrees¹. To make changes to the angle, a door was cut out of the side of the column (like the opening at the base of a fireplace) to allow access to the cells and attached protractor. Rays of light from the Sun were assumed to be parallel².

¹ Actual measurements went up to 135 degrees, but data past 90 was not used due to higher uncertainties above 90 deg.

² *Small Angle Approximation Theorem: at small angles the hypotenuse and second longest leg of a triangle are assumed equal.*

Introduction:

The energy extracted from solar radiation by solar cells is vital to expanding our source of energy. Alternative sources of energy are being sought out constantly and solar energy has already been a primary source as solar cells have been in existence for many years. By figuring out how to maximize the efficiency of solar cells, engineers can build better cells and models for usage in homes and businesses. The purpose of this lab is to gain a better understanding of the relationship between solar cell voltage output and the angle of incidence with the Sun's rays. Since the Sun is never stagnant, an understanding of this relationship will help in designing practical positioning of solar cells.

Theory:

Engineers and solar cell manufacturers have already determined that solar cells are most efficient when placed exactly perpendicular to the Sun's rays. The question in mind is how much power can be generated in other angular arrangements and what relationship exists between angle of incidence and power. The expectation is that the solar cell will collect power very well for a certain range after its perpendicular position and then quickly fall eventually giving no power at all. Although temperature does affect the solar cells' ability to absorb energy, the majority of energy is dependent on the intensity of the Sun's rays (its self a function of angle). A logarithmic function is expected to describe the relationship between angle and voltage output, current and power.

Apparatus and Procedure:

The apparatus consisted of three solar cells in series, glued to a plastic plane. The plane had an axel and was able to pivot through two rubber grommets drilled in two vertical triangles. A red needle was glued to the end of one side of the axel, as the cells were rotated the needle would rotate with it, always denoting the exact angle of incidence. This apparatus was secured to a solid base, and around the apparatus was placed a tall black column. The purpose of the column was to block most (if not all) ambient light from hitting the solar cells. The leads from the solar cells were extended through a small hole on the bottom of the column and were then attached to the multi-meter according to respective measurement. For voltage: the leads from the cells were connected directly with the leads of the multimeter. For measuring current: one lead of the solar cell was connected to a small light bulb (11.1 Ω), the other lead of the light bulb was connected to the multimeter, the other lead from the solar cells was connected to the multimeter. After the apparatus was completed the following procedure was followed to collect data:

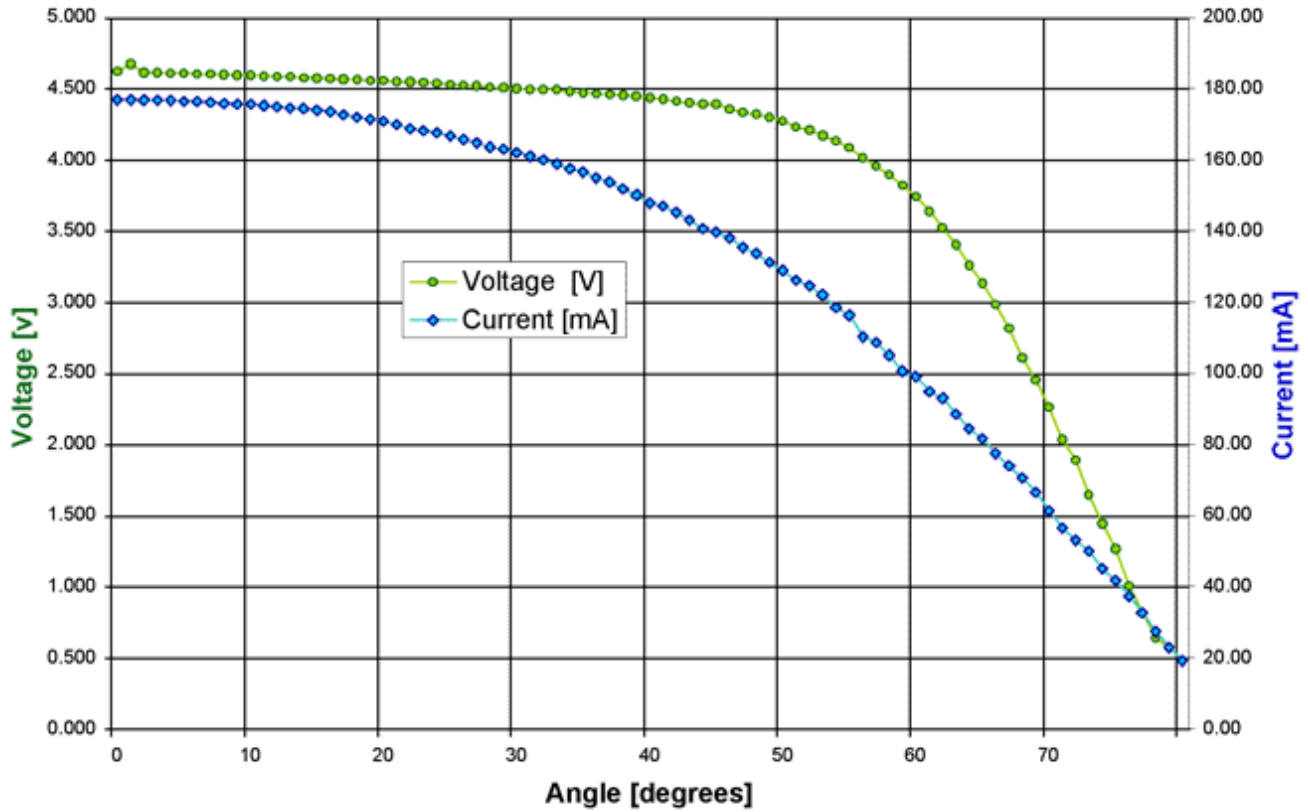
1. [On a cloudless day] An area with open access to the Sun was selected and the column with the solar cells inside was secured to the ground facing directly toward the Sun.
2. The column (attached to its base) was then shifted around until the shadow of the column disappeared.
3. The cells were aligned to 0 degrees (perpendicular to the Sun's rays) according to the protractor and the leads from the cells were clipped to the multi-meter.
4. The temperature and time of day was recorded before data was collected.
5. Voltage and current readings were collected at 1 degree angle increments between 0-90 degrees. Note: Actual readings were taken from 0 to 100 degrees and additional points taken at 135 and 180 degrees.

Results: (see data table in Appendix)

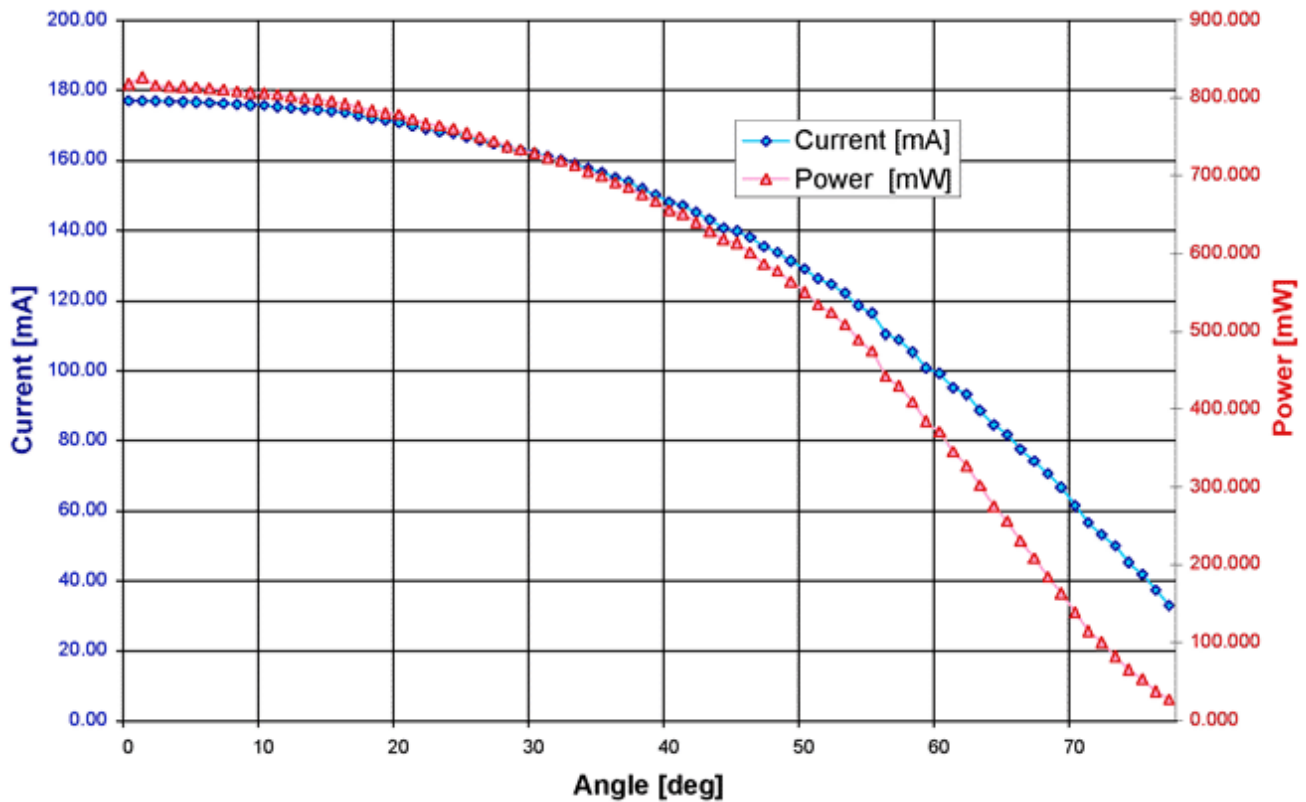
The following graphs and table show the results of the experiment: voltage & current vs. angle of incidence, current & power vs angle of incidence, power & power error vs. angle of incidence, and finally voltage drop vs. angle of incidence. Data includes the numerical data of angle, voltage, voltage \pm error, current, current \pm error, power, power error and power \pm error. Errors for voltage measurements were constant, as were errors for current measurements, both are based on specs provided by *Fluke*, the manufacturer of our multimeter. (see appendix for multimeter specs) The error for the power differed for each data point, it was calculated using the root of sum of squares formula:

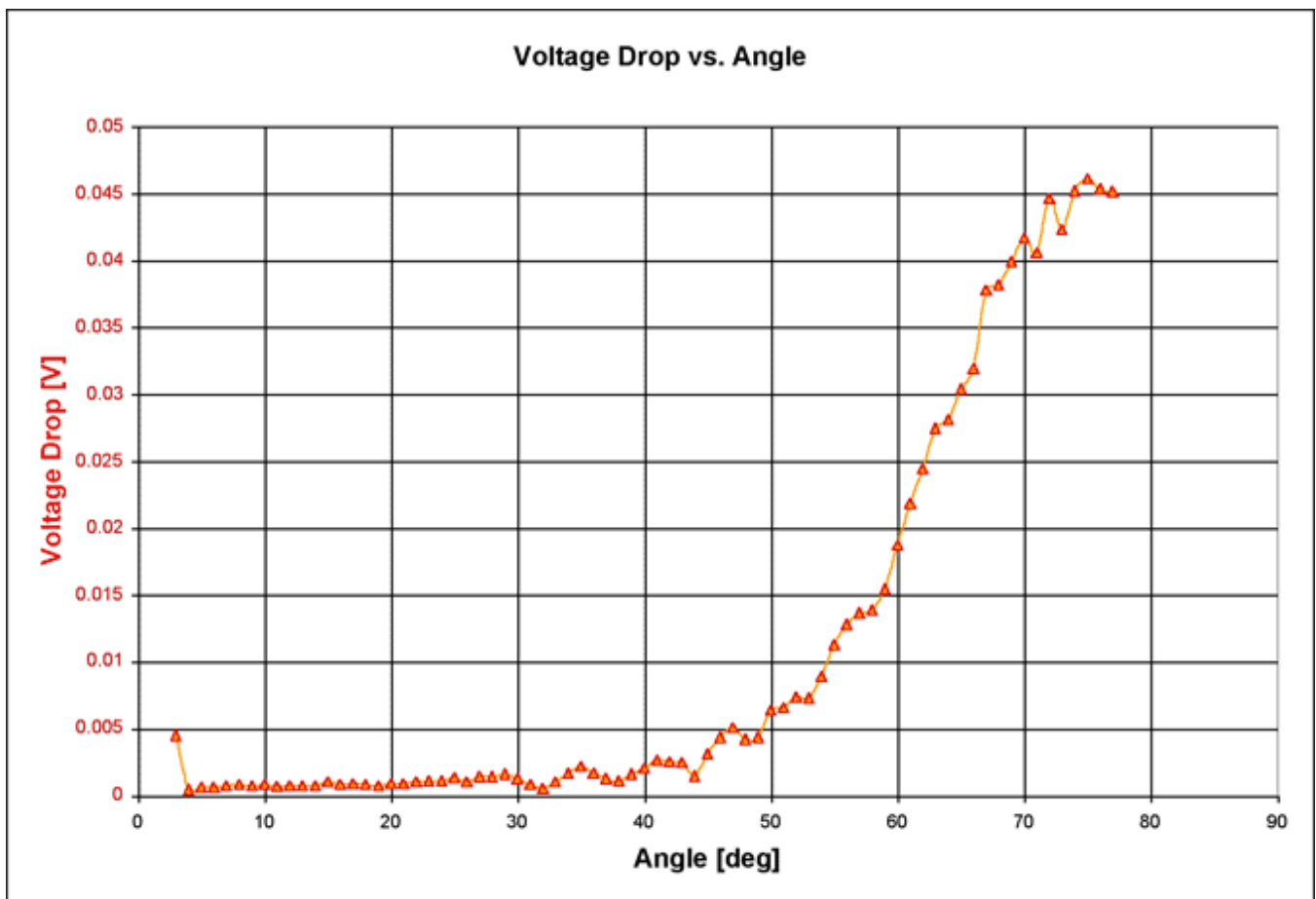
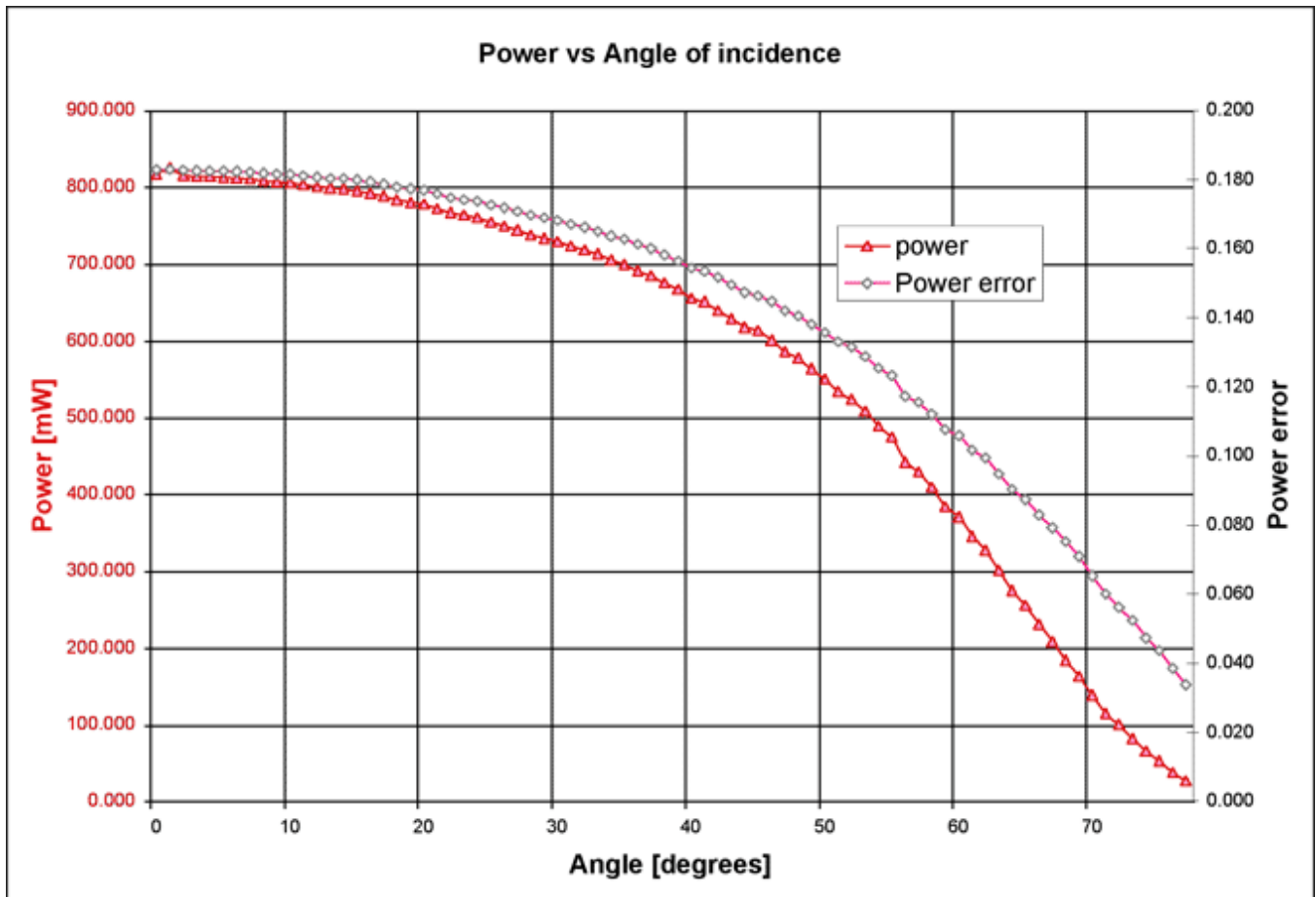
$R = R(X_1, X_2, X_3, \dots, X_n)$	
$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_{x1} \right)^2 + \left(\frac{\partial R}{\partial x_2} w_{x2} \right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} w_{xn} \right)^2 \right]^{1/2}$	$P = IR; \quad \frac{\partial P}{\partial V} = I; \quad \frac{\partial P}{\partial I} = V;$
$W_P = \left[\left(\frac{\partial P}{\partial V} W_V \right)^2 + \left(\frac{\partial P}{\partial I} W_I \right)^2 \right]^{1/2}$	$W_V = 0.001 V; \quad W_I = 0.01 mA$
$W_P = \left[(I * 0.001)^2 + (V * 0.01)^2 \right]^{1/2}$	

Voltage and Current vs. Angle of Incidence



Current & Power vs. Angle





Discussion:

The results of the experiment were very close to what we expected. The voltage vs angle was very linear until it reached an expected threshold, after which a steep decline in voltage was observed. Also expected was a more predictable current output. It was thought that the current and voltage would behave similarly, but they did not follow the same trend. After calculating the power, it was apparent that the power graph looked very similar to the current graph, and when superimposed one could see a distinct similarity. This was expected however, since the current [range] dominates voltage [range] in the power equation. When the power equation is graphed with the calculated power error, the graph is what we expected. The power graph drops off slightly faster than the graph of the power-error-calculation, this is because even at very low power levels there is still inherent error in the power calculation. The highest power-calculation-error exists at the lowest power values, for this reason it is vital that we used the RSS method of error analysis. Simply multiplying the %error Voltage with the %error current would lead to a false account of error (error would come out to high.) The significance of these graphs is very important to the understanding of solar cells. From the results, it shows that voltage does not change dramatically until an angle of incidence of about 45° is reached, after which voltage drops rapidly. The current and power response to angle do not have a threshold and are non-linear.

Significance of last graph: Voltage Drop vs. Angle – This graph clearly illustrates the linear and non-linear properties of solar panel voltage output. When used in a practical application, a solar panel is commonly connected to a DC->AC converter or DC->DC transformer. What is important is that the voltage stay above a given value, the current may fluctuate depending on solar intensity. For example, a cell phone charger will work properly on 110 VAC and it will draw whatever current it needs. If the current fluctuates a little the charger will still work, but if the voltage drops below 110 VAC the charger may not work properly. Its performance is hinged on voltage much more than current. This is why solar panels have been designed to give a relatively flat voltage output within a certain span, in this case $0^\circ \pm 45^\circ$ (0° = solar panel perpendicular with solar rays). The final graph shows that beyond a $\pm 45^\circ$ angle of incidence the tested solar panels will not provide a reliable voltage.

Conclusion:

The voltage output of a solar panel is approximately linear until a certain angular threshold is reached, in our case this was approximately 45° , after which voltage drops significantly.

Current output fits a cosine trend: $I = I_{max} * \cos(\theta)$.

Power roughly fits the same trend: $P = P_{max} * \cos(\theta)$.

Microsoft excel and Matlab each had problems calculating the proper function for predicting voltage output, however we know from simple inspection this function must be *logarithmic*.

Recommendations:

We felt that this experiment went very well, but it could have been done better. Firstly, we were lucky to have absolutely no clouds in the sky, but by taking our data in November, in San Francisco, we were limited to less than optimal solar luminosity. At high noon on the day of our data collection the sun rose no higher than 31.5° above the horizon. We would recommend performing solar cell data collection at a location closer to the equator. Secondly, we ran into a problem with with reflected light at oblique angles (greater than 70° .) Even though our column was covered in black fabric it still reflected light. Despite it's high cost, we would recommend using black felt instead of fabric. Also, to reduce the quantity of light reflected off the base [inside the column] we recommend suspending the solar panels in the middle of the column instead of close to the base.

References:

Lab Manual - ENGR 300

Text Book – Intro to Engineering Experimentation, 2nd edition, Wheeler & Ganji, 2004

Text Book - Fundamentals of Science and Engineering, Callister, William, 2001

WWW:

<http://www.physicalgeography.net/fundamentals/6i.html> (area vs. angle, solar tracking)

<http://www.macslab.com/optosolar.html> (optimal solar panel placement)

<http://www.susdesign.com/sunangle/> (find the angle of the sun anywhere any time)

<http://www.iowathinfilm.com/products/powerfilm/index.html> (manufacturer of *similar* cells)

Appendices: Multimeter Specs, Photos, Data

Fluke 179 digital multimeter specs

Function	Range ¹	Resolution	Accuracy ± ([% of Reading] + [Counts])		
			Model 175	Model 177	Model 179
AC Volts ^{2,3}	600.0 mV	0.1 mV	1.0 % + 3	1.0 % + 3	1.0 % + 3
	6.000 V	0.001 V	(45 Hz to 500 Hz)	(45 Hz to 500 Hz)	(45 Hz to 500 Hz)
DC mV	600.0 mV	0.1 mV	2.0 % + 3	2.0 % + 3	2.0 % + 3
	6.000 V	0.01 V	(500 Hz to 1 kHz)	(500 Hz to 1 kHz)	(500 Hz to 1 kHz)
DC Volts	600.0 mV	0.001 V	0.15 % + 2	0.09 % + 2	0.09 % + 2
	6.000 V	0.01 V	0.15 % + 2	0.09 % + 2	0.09 % + 2
Continuity	600 Ω	1 Ω	0.15 % + 2	0.15 % + 2	0.15 % + 2
	600 Ω	1 Ω	Motor beeps at < 25 Ω, beeper turns off at > 250 Ω, detects opens or shorts of 250 μs or longer.		
Ohms	600.0 Ω	0.1 Ω	0.9 % + 2	0.9 % + 2	0.9 % + 2
	6.000 kΩ	0.001 kΩ	0.9 % + 1	0.9 % + 1	0.9 % + 1
	60.00 kΩ	0.01 kΩ	0.9 % + 1	0.9 % + 1	0.9 % + 1
	600.0 kΩ	0.1 kΩ	0.9 % + 1	0.9 % + 1	0.9 % + 1
	6.000 MΩ	0.001 MΩ	0.9 % + 1	0.9 % + 1	0.9 % + 1
Diode test	2.400 V	0.001 V	1.5 % + 3	1.5 % + 3	1.5 % + 3
	2.400 V	0.001 V	1 % ± 2		
Capacitance	1000 nF	1 nF	1.2 % + 2	1.2 % + 2	1.2 % + 2
	10.00 μF	0.01 μF	1.2 % + 2	1.2 % + 2	1.2 % + 2
	100.0 μF	0.1 μF	1.2 % + 2	1.2 % + 2	1.2 % + 2
	9999 μF ⁴	1 μF	10 % typical	10 % typical	10 % typical
AC Amps ⁵ (True RMS)	60.00 mA	0.01 mA	1.5 % + 3	1.5 % + 3	1.5 % + 3
	400.0 mA	0.1 mA	1.5 % + 3	1.5 % + 3	1.5 % + 3
AC Amps ⁵ (45 Hz to 1 kHz)	6.000 A	0.001 A	1.5 % + 3	1.5 % + 3	1.5 % + 3
	10.00 A	0.01 A			

- All AC voltage and AC current ranges are specified from 5 % of range to 100 % of range.
- Frequency is specified from 2 Hz to 99.99 kHz in Volts and from 2 Hz to 30 kHz in Amps.
- Below 2 Hz, the display shows zero Hz.
- For non-analogical waveforms, add ±2% reading + 2% full scale typical, for crest factors up to 3.
- In the 3999 μF range for measurements to 1000 μF, the measurement accuracy is ± 2 % + 2 for all models.
- Amps input burden voltage (typical): 400 mA input 2 mV/mA, 10 A input 37 mV/A.

Function	Range ¹	Resolution	Accuracy ± ([% of Reading] + [Counts])		
			Model 175	Model 177	Model 179
DC Amps ⁵	60.00 mA	0.01 mA	1.0 % + 3	1.0 % + 3	1.0 % + 3
	400.0 mA	0.1 mA	1.0 % + 3	1.0 % + 3	1.0 % + 3
Hz	6.000 A	0.001 A			
	10.00 A	0.01 A			
Temperature	99.99 Hz	0.01 Hz	0.1 % + 1	0.1 % + 1	0.1 % + 1
	999.9 Hz	0.1 Hz			
	9.999 kHz	0.001 kHz			
MIN MAX AVG	-40 °C to +400 °C	0.1 °C	NA	NA	1 % + 10 ¹
	-40 °F to +752 °F	0.1 °F			1 % + 10 ¹

- All AC voltage and AC current ranges are specified from 5 % of range to 100 % of range.
- Frequency is specified from 2 Hz to 99.99 kHz in Volts and from 2 Hz to 30 kHz in Amps.
- Below 2 Hz, the display shows zero Hz.
- Amps input burden voltage (typical): 400 mA input 2 mV/mA, 10 A input 37 mV/A.
- Does not include error of the thermocouple probe.

Photos:

Apparatus



Apparatus in the field



Looking down into column



Taking data



Finding Solar Altitude Angle for San Francisco (31.5°) see references for url

inputs

longitude: 122 West
 latitude: 37.75 North
 date: Nov 24
 year: 2004
 elevation: 20 meters
 time: 12:00 24 hr
 time zone: U (GMT - 8:00)
 time basis: Clock time
 daylight savings: No
 zero azimuth: South

outputs

altitude angle: 31.50
 azimuth angle: -1.43
 clock time: 12:00
 solar time: 12:05
 hour angle: -1.27
 declination: -20.74
 equation of time: 0.22
 time of sunrise: 06:57
 time of sunset: 16:52

