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University of XXX-Solar Radiation Clearness and Variability Index

Dr. Jaime Ramos P.E., University of Texas, Pan American

Dr Jaime Ramos teaches Power Engineering courses at the University of Texas Pan American since 2005. His current research interests are related to Renewable Energy and Engineering Education. He is an active Professional Engineer in the state of Texas. He is a Senior Member of IEEE, and a Member of the ASEE.

Mr. Jesus Alejandro Valladares, The University of Texas Pan American

University of Texas Pan American Solar Radiation Clearness and Variability Indexes

I- Selected List of Acronyms

DHI- Diffuse Horizontal Irradiance [Watts/m^2]

GHI - The Global Horizontal Irradiance [Watts/m^2]

DNI - Direct Normal Irradiance [Watts/m^2]

G-POA-I: Global Plane of Array Irradiance

CI – Clearness Index

VI – Variability Index

NREL: National Renewable Energy Laboratory

MIDC: Measurement and Instrumentation Data Center

POA: Plane of Array

Δt - Time Interval

SC: Solar Constant = 1,367 Watts/m^2

szA- Sun Zenith Angle

II- Introduction

Solar energy sources without energy storage are only available during daytime for the production of electrical power. Their output power is delivered not in a flux of constant electricity, but in a variable form. These sources vary their power output during the day because of two factors: first, the motion of the Sun in the sky, and second, the presence of clouds, chemicals, aerosols in the atmosphere. The second factor makes the delivery of power a random process.–

Operators of solar farms connected to the electric power grid are in need of analytical – tools to estimate and forecast the amount of output power of the facility; since the input energy is the solar radiation, it is necessary to know the amount of radiation and its characteristics, over the solar farm, in a day to day basis.

Those methods are now available, and their development has been an active area of research [1]. The first step is to measure that radiation; that can be done either locally, from on-site sensors, or distantly, from sensors lodged on satellites. In the University of Texas Pan American we have installed [2] a set of tracking pyranometers and pyrheliometer to measure the global horizontal (GHI), diffuse horizontal (DHI), and direct normal (DNI) irradiances.

Direct Normal Irradiance [1] is the “solar beam radiation available from the solar disk on a planar surface normal to the Sun, as measured by a pyrheliometer with a 5° full-angle field of view”

Diffuse Horizontal Irradiance [1] is the “solar radiation from the sky dome, not including DNI, which has been scattered by clouds, aerosols, and other atmospheric constituents, available on a horizontal surface, as measured by a pyranometer with a 180° field of view”

Global Horizontal Irradiance [1] “is the total hemispheric down welling solar radiation on a horizontal surface, as measured by an unshaded pyranometer”

On the basis of the local, 1-minute averages of GHI measurements the evaluation of the local solar resource is pursued. Calculation and plotting of the daily clearness index (CI) and the variability index (VI) is completed, in order to identify difference over the periods when the solar resource is available.

These methods will be taught in the Renewable Energy course which has been offered four times in the last ten semesters as an elective to engineering majors. The course has been popular with an average enrollment of 30 students / semester.

This paper has been organized as follows: Section I contains a selected list of Acronyms; the Introduction is located in Section II; in Section III, the construction and operation of the Solar Radiation Lab is explained. In Section IV, the *CI* and *VI* indexes are introduced and explained. In Section V, the MatLAB program to calculate and graph the indexes, on a daily basis, is discussed. In Section VI, we explain how these methods will be learned by the students. and in Section VII we discuss how an electric utility may benefit from these calculations. Section VIII is the subject of Assessment and Evaluation Methods. Finally, in Section IX Conclusions are drawn for future work.. Bibliography has been written in Section X.

III- The Solar Radiation Lab

The main components of the Lab are the set of instruments that collect the solar radiation and convert these fluxes into electrical signals, using thermoelectric transducers. Their spectral response is from the ultraviolet to the infrared.

1. The CHP1 [3] pyrheliometer measures Direct Solar Radiation between 200 nm and 4,000 nm in wavelength.

2. The CMP11 [4] pyranometer measures Global Horizontal Radiation. Its spectral range is 285 to 2,800 nm
3. Diffuse Horizontal Radiation is measured with a shaded pyranometer CMP11
4. The three instruments are mounted on a GPS assisted tracker, SOLYS2[5]. Figure 1 shows the setup at the top of the Engineering building. The top table is maintained horizontally at all times. The two pyranometers lay on this horizontal surface.
5. The pyranometers are equipped with ventilators and heaters to improve the reliability and accuracy of the measurements by reducing dust, raindrops and dews on the domes.
6. The data logger CR1000 [6] functions are to manipulate and communicate the data through an Ethernet port. The units of the three signals are Watts/m².

IV- Solar Resource Clearness and Variability

Clearness Index, *CI*

The Clearness Index is a measure of how clear is the sky during a given period; when the solar resource is available to its full at the ground level the Clearness Index would ideally have a value $CI = 1$; it also possible that $CI > 1.0$, during those periods when the presence of clouds act as concentrators of solar rays. On the other hand, at any given interval of time, when clouds may be casting shadow over the area of interest, the solar resource for Photovoltaic power generation is poor, and CI would be low. If the sun light is fully blocked, then $CI = 0$.

Figure 1 – This photo displays two pyranometers, one pyrheliometer, and the tracker.

In practice the clearness index varies in between these values. A mathematical model is used as a reference [8,11]; this model tells us how much energy, in kWh, from the solar resource is available at ground level. The model is then compared to a set of discrete data measurements taken by a well calibrated *GHI* pyranometer. Once the data from the model and the measurements are obtained, a plot and the index are displayed (Figures 2 and 3) to aid in visualizing the differences between the clear day model and the actual measured data.

To obtain the Clearness Index, two pieces of information are needed:

1. The set of measurements of the local Global Horizontal Irradiance GHI_{MEAS}[k], which can be downloaded from NREL's Measurement and Instrumentation Data Center [7], for later use. The instrument takes measurements every second, writes 1-minutes averages into the database. The time stamp is Standard Central Time. It is also possible to download selected hourly data from MIDC
2. A calculated time-series Clear sky Global Horizontal Irradiance $GHI_{CLEAR\text{-}SKY}$[k], in synchronism with the measured GHI_{MEAS}[k] time series. The former is calculated in solar time; the latter are obtained in standard time. Reference [8] offers a variety of methods to calculate the clear-sky irradiance. We have chosen one due to B. Harwitz, due to its simplicity.

$$CI = \frac{\sum_k GHI_{MEAS}[k]\Delta t}{\sum_k GHI_{CLEAR-SKY}[k]\Delta t} \qquad (1)$$

Given *CI*, Equation (1) allows the calculation of the energy, in W-h, collected by the instrument during one day. For this paper Δt = 1/60 is the 1-minute time interval, written in units of hours. The index k runs over the number of time intervals (minutes) = 960 from 4 AM to 8 PM, in the day. Equation (1) is cast without cancelling Δt to highlight the relation to the energy harvested during the day, in unit of *W-h*. If hourly data is downloaded from MIDC, then Δt = 1 [hour]

Variability Index, *VI*

This index is a measure of the variability of solar radiation, which is primarily caused by two factors: the motion of the sun in the sky, and the presence of clouds, which are also moving and changing, during the day. Solar Resource Variability is explained in References [1], [9]. Variability accounts for the "noise" of the solar radiation graphs, shown in Figure 4. This phenomena is worrisome to (electric power) system operators. A stand-alone solar farm can be knocked out quickly without advanced notice.

In Reference [9] several criteria for detecting clear sky periods are discussed. The criterion selected to be used here measures variability by calculating the length *L* of the line connecting adjacent points of the *GHI* time series:

$$Length\ of\ Interval = \sum_k \sqrt[2]{(GHI_{MEAS}[k] - GHI_{MEAS}[k-1])^2 + \Delta t^2}$$

Here, the strength of the spikes contributes largely, while smooth variations contribute lowly. The *VI* formula is

$$VI = \frac{\sum_k \sqrt[2]{(GHI_{MEAS}[k] - GHI_{MEAS}[k-1])^2 + \Delta t^2}}{\sum_k \sqrt[2]{(GHI_{CLEAR-SKY}[k] - GHI_{CLEAR-SKY}[k-1])^2 + \Delta t^2}} \qquad (2)$$

In (2) *GHI* has units of W/m^2, and Δt has units of minutes. This formula is an algorithm for calculating variation; no other formula are deducted from it.

V- How are the graphs generated? Below is a sample code implemented in MATLAB.

```
meanModelGI = sum(globalHorizontal)/k;
meanMeasuredGI = sum(wm2)/k;
ci = meanMeasuredGI/meanModelGI;    %Daily Clearness Index
```

The software of use here has its advantages over a writing the code in C,C++ or java, this is because MATLAB uses a vectorized method for input and output calculations. This reduces the size of the code by using less control structures and iterative loops to handle matrices like the ones described in this example.

For the variability index: Let ‘irradianceVariability’ and ‘calculatedVariability’ be quantitative measures of how the measured and modeled *GHI* varies with time. In the sample code below we see the “ones(***,***)” operator this is for memory allocation purposes, this is good practice when working with vectors that manage large amounts of data. This code shows how the *VI* is calculated.

```
irradianceVariability = ones(1,k);
calculatedVariability = ones(1,k);
for count = 2:k
   irradianceVariability(count) = sqrt((wm2(count-1)-wm2(count))^2 + 1^2);
  calculatedVariability(count) = sqrt((globalHorizontal(count-1)-
  globalHorizontal(count))^2 + 1^2);
end
vi = sum(irradianceVariability)/sum(calculatedVariability); % Daily Variability Index
```

Figures 2 to 4 display selected days during 2013 with clear and overcast skies. Figure 3 shows a “noisy” *GH* irradiance, and therefore has a high variability index *VI*. Figure 5 displays one of the monthly calendars that can be obtained from many of the solar Labs associated to NREL’s MIDC [7]

Up until today there is not a known exact model for calculating the solar radiation reaching ground level. This is due to variations in the solar resource at the point where the light is emitted but mostly, this is due to the variations in the atmospheric conditions. Climate changes throughout the globe make these models even harder to develop as they will tend to change with the years.

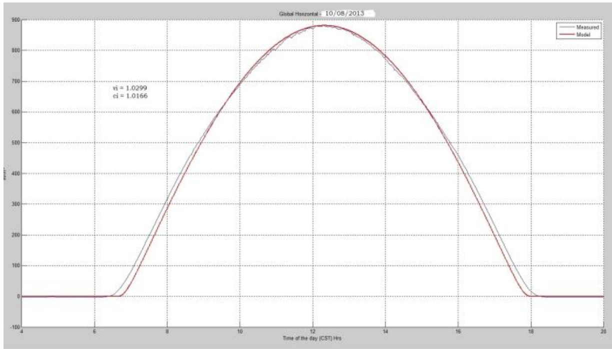

Fig 2- October 8th, 2013, a clear day with low variability ci = 1.0166, vi = 1.0299

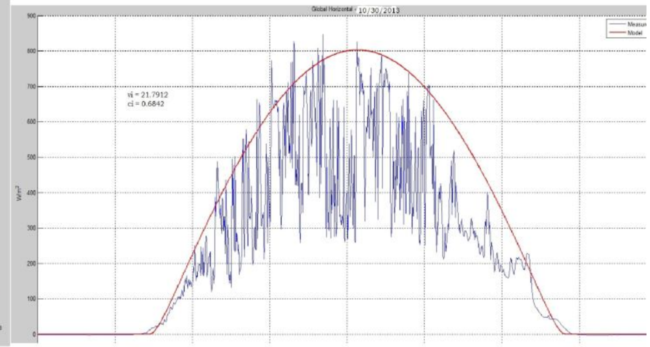

Fig 3- November 30th, 2013, was less clear and had high variability. ci = 0.6842, vi = 21.7912

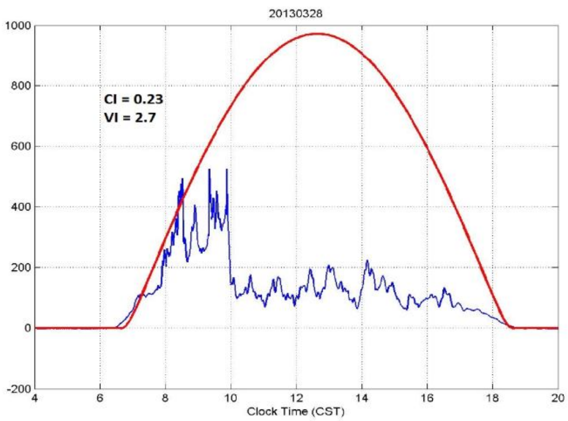

Fig 4- March 28th, 2013 was overcast by clouds, most of the day, therefore the vi is low, as well as the clearness index

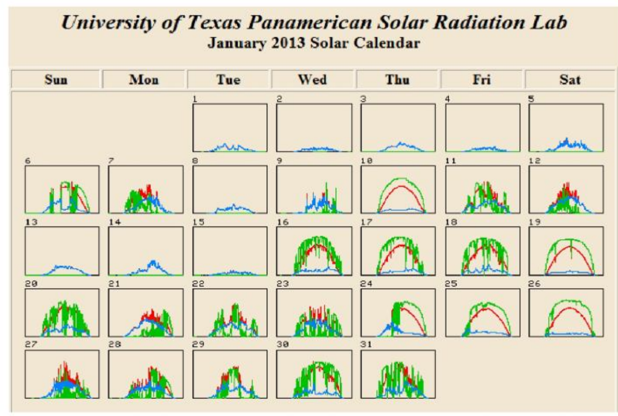

Fig 5- This calendar graph display an exampleof the quality of service given by NREL's Measurement and Instrumentation Data Center

Some of the most imprecise models will give an over-estimate of the clear sky irradiance. The most advanced models that take the atmospheric absorption into consideration give an under estimate with a high degree of accuracy.

Given this fact, we would expect that the *CI* might reach values that exceed unity. Cloud focus which might cause the measure to pike well over the clear sky model will also contribute for these values to reach higher values than unity.

VI- How are we going to teach this?

Our objective is to add new instructional strategies and content to the ELEE 4373 course about Renewable Energy. The textbook for this course [11] includes a Chapter about the Solar Resource. It is in this context that we plan to add homework set to calculate the Clearness and Variability Indexes. As it is clear that the relevant knowledge has already been discovered, we must focus on the scholarship of application [10]

The calculation of the *CI* the participant must have a clear understanding of the solar trajectory in the sky. The instructor can rely on textbooks to discuss such fundamentals of solar energy, such as solar and standard times, meridians, azimuth, altitude angles, and declination. For example, Masters [11] in his textbook includes a Box 4.1 *"Summary of Solar Angles"* and its equations. Then the trajectory of a sunray from outside the atmosphere, where the solar constant SC is 1377 W/m^2, is followed through the atmosphere, with an air mass ratio AM, suffering absorption and dispersion until it hits the horizontal collector with an incident angle. Formulae for all these variables can be found in Box 4.2 *"Summary of Clear Sky Insolation Equations"* of Chapter 8, Reference [11]

An excellent tool for the process of learning fundamentals of solar energy is the sundial site at the University grounds. It has a 6 meter slender column, a photo of which is shown in Figure 6, and the local meridian line running in the South to North direction (as shown in the photo) can be easily found. During a session of the ELEE 4373 Renewable Energy course, participants measure the length of the shadow, at solar noon, and calculate the height of the column, using the solar altitude angle. To demonstrate the difference between solar and civil times, the participants witness the daily passage of the Sun over the meridian line, in the University sundial, as it is shown in Figure 6.

After the participants have acquired the fundamental knowledge, the next outcome of the course is to learn about the real conditions of the Earth atmosphere, which hinder the output of power from solar farms. At this stage of the course, they practice downloading the relevant data from one or more of the Labs in the MIDC network [7]. Using the MATLab software developed by one of the authors, the participants proceed to analyze the solar resource at given locations. Finally, at the evaluation and assessment stages the instructor and participants investigate how

well the data has been analyzed and summarized, and connected their findings to the implications for practice

VII- How are the utilities going to benefit from this?

It is relevant to the grid's operators to study the frequency with which high variability index days occur and how reliable the Solar Resource is at a given site during high demand periods and Power Plant down time.

With the data obtained from the onsite solar resource measurements, the clear sky model for solar insolation, the clearness and variability indices calculated along with the average electric power that can be collected, we can now estimate the size of a photovoltaic generating plant in the area with certain degree of expectancy for average power output during the different seasons and months of the year. Thus making a feasibility study more reliable.

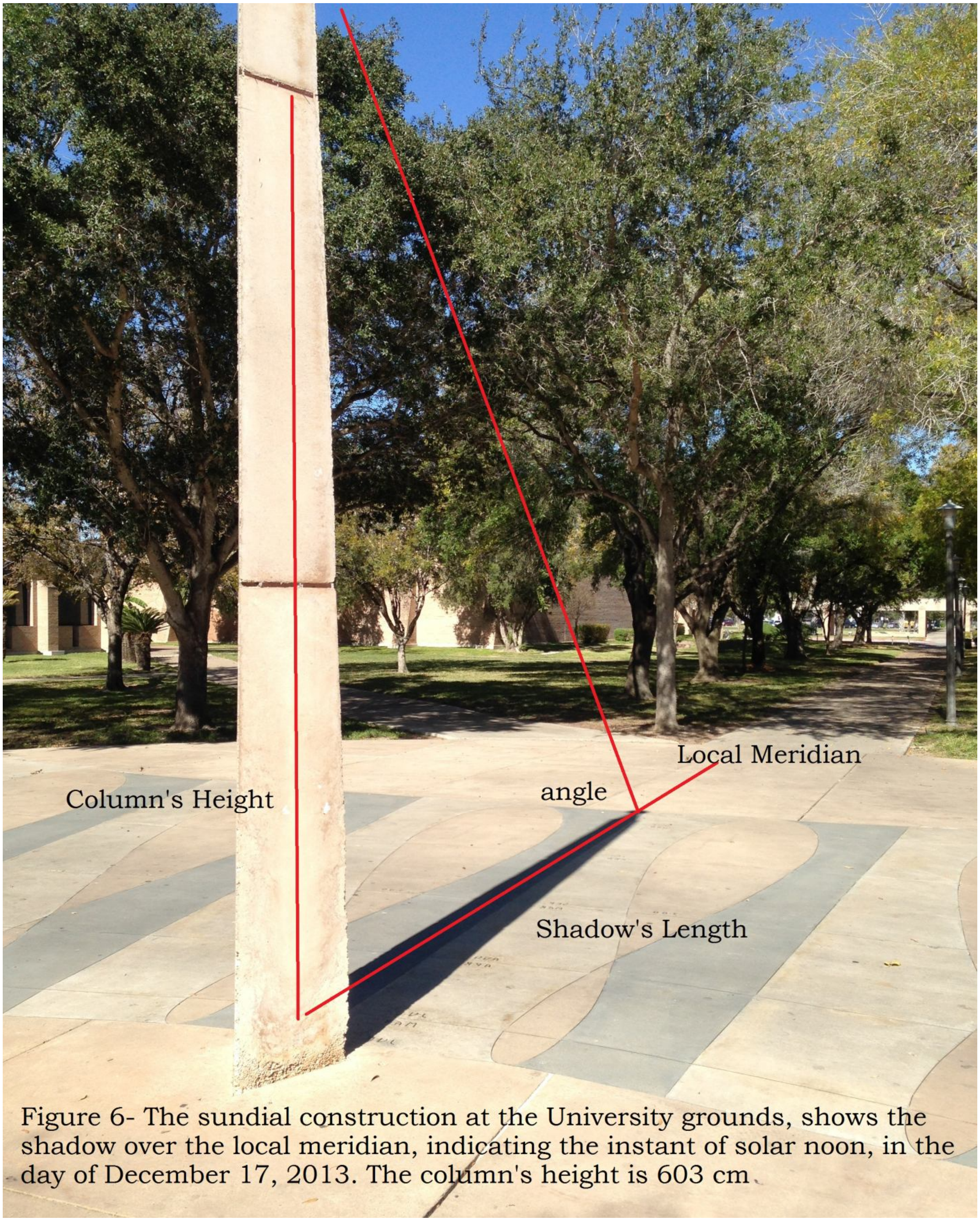

Figure 6- The sundial construction at the University grounds, shows the shadow over the local meridian, indicating the instant of solar noon, in the day of December 17, 2013. The column's height is 603 cm.

A good example of the use by utilities of the solar radiation indexes can be found in Reference [12]. The scatter plot shown in Fig. 7 reflects the condition of the local atmosphere during selected months of 2013. The main characteristic of the graph is the dispersion of data into three zones, arbitrary labeled “clear”, “overcast” and cloud/sunny”

January is the most extremist of the months as it has clear and overcast skies

The days in April are quite variable, and therefore unpredictable.

July’s days are mostly clear as well as cloudy/sunny

October’s days are quite similar to July’s

Forecasting, or predicting within certain probability bounds, what the solar resource would be in the future is a valuable tool that has been used effectively [12]. However, it requires measuring tools of a different nature: a Total-Sky Imager

Solar panels for power generation are not usually on the horizontal position, as our instruments are (refer to §II.4). The orientations of those panels or collectors are tilted at the plane of the array Angle (POA). What is needed is the G-POA-I Irradiance. The relation among the three irradiances is well know

$$GHI = DNI \cos(szA) + DHI \qquad (5)$$

Where *szA* is the solar zenith angle. From these three basic irradiances it is possible to calculate the irradiance at any tilt angle of the solar farms, that is the POA irradiance [13]

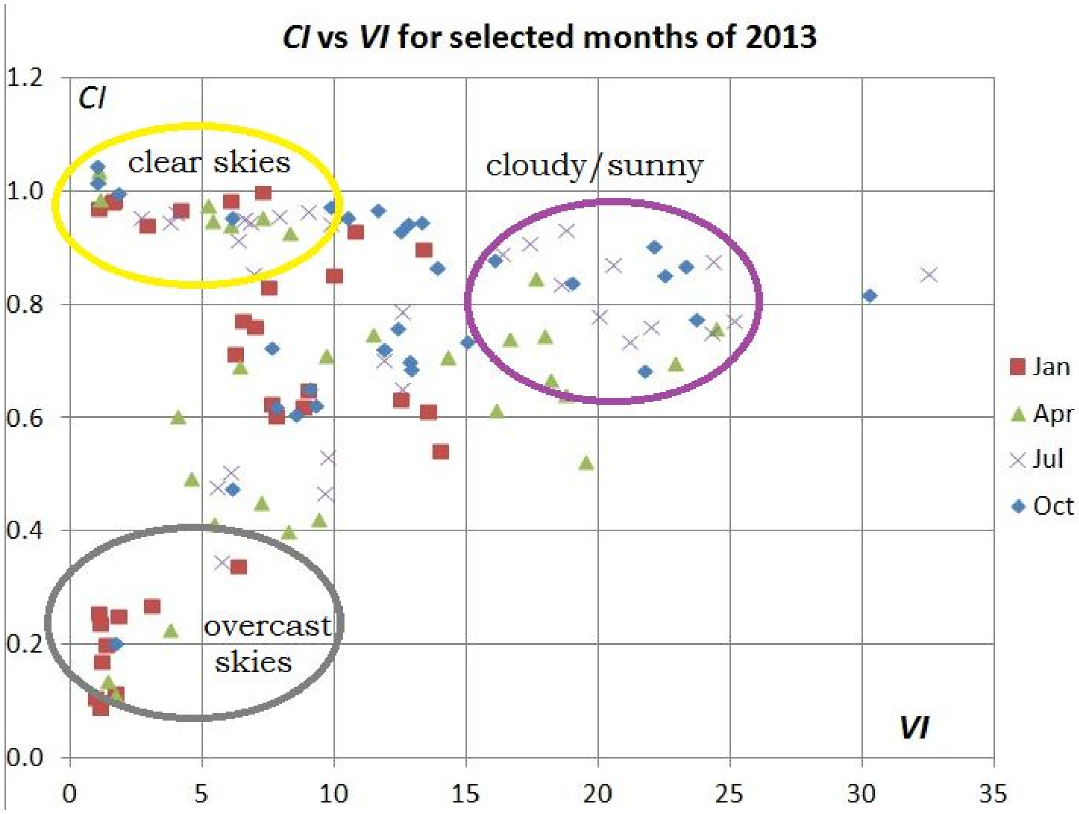

Fig 7- Scatter plot of daily *Clear* and *Variability Indexes* for Edinburg, TX

VIII- Assessment and Evaluation Methods

As mentioned in the Introduction this learning material will be taught to students enrolling in ELEE 4373 Renewable Energy, under a procedure devised to introduce experiential content on the course. A recent editorial on the contributions to a journal on engineering education underline how relevant is the educational content (Froyd 2014)[14] of this article to electrical engineering.

A theory of how students learn, and the effectiveness of the teaching methods is necessary for formulating questionnaires to be filled by students. In the context of this article the following sections must be analyzed:

1. The motion of the sun in the sky. To evaluate their learning the following questionnaire will be applied after the visit to the Sun dial:
   "Write the definitions of …….
   1- Ecliptic (Line)
   2- Ecliptic (Plane)
   3- Declination (Angle)
   4- Meridian (Line)
   5- Latitude (Angle)
   6- Longitude (Angle)
   7- Tropic of Cancer Latitude (Angle)
   8- Tropic of Capricorn Latitude (Angle)
   9- Arctic Circle (Latitude)
   10- Solar Altitude (Angle)
   11- Solar Azimuth (Angle)
   12- Solar Zenith (Angle)
   13- Solar noon in the sky
   14- Irradiance W/m2
   15- Insolation kWh/m2/day
2. The instruments in use for measuring irradiance. In this section the following questions can be applied.
   1- What is the value, units and meaning of the Solar Constant
   2- Define Air mass in terms of the solar altitude angle
   3- Define direct normal irradiance
   4- Define global horizontal irradiance
   5- Define diffuse horizontal irradiance
   6- Define ground reflectance
3. The numerical method followed to calculate the indexes. Two exercises will be assigned:
   1- Download 1-Min Data *GHI* data from NREL's MIDC site;
   2- Download *GHI* Hourly data.
   With the data available in csv format, complete exercises 1 and 2 as follows

3- Run MatLAB program to calculate and plot the two indexes, for the case $\Delta t = 1$,
4- Run MatLAB program to calculate and plot the two indexes, for the case $\Delta t = 60$
5- Repeat steps 1..4 for several days, i.e. one calendar week
6- Make a scatter plot, and classify the days according to clear/cloudy/sunny categories

If the question: Are the students engaged by the learning material? Can be positively responded, then a proof will exists about the effectiveness of the experience. A second question is: to what extent quantitatively? Following (A. C. Worcester 2013)[15] a survey will be designed to determine the contribution of the activities to 1) the participants' level of knowledge, 2) to increase their interest and confidence in learning engineering, and 3) the appropriateness of the software/tools in use. Likert scales ranging from -2 ("strongly disagree) to +2 ("strongly agree"), and including 0 points for the "neutral" response.

The following questions will be applied in a survey for assessing their thinking about (1) the knowledge base:

1. I believe the activity was beneficial to my understanding of sun's motion
2. I believe the lectures and simulation have good tools to understand the concepts of air mass
3. To correlate the concept of air mass with absorption of sunrays in the atmosphere

To query the students' thinking about the contribution of the activity to increase the level of (2) their interest in the subject, questions such as the following will be poised:

1. I believe the exercises relate to real-world solar energy industry problems and issues
2. I believe in the numerical methods used to classify days as clear/cloudy/sunny
3. I believe the classification methods helped me to assess the local solar resource

And the last set of questions (3) are intended to gauge the students' opinion about the environment under which they worked

1. The NREL/MIDC site is friendly to the user
2. I believe I have the required background to understand the level of information in this exercise
3. I believe each section helps me understand the following section.
4. I believe the MatLAB programs are well written

IX- Conclusions

Although the attention of the ASEE to Solar Energy has been active for many years [16], today it is even more active because the solar industry has grown steadily, and the interest of the engineering students has grown exponentially. The dissemination of the new knowledge from industry and laboratories to the engineering colleges must be welcomed and returned as we instruct the young professionals that will serve there, in the future.

We have briefly examined the usefulness of the *CI* and *VI* indexes to analyze the intensity of the local solar resource. This work can now be extended to include the analysis of an array with a different POA orientation, using the measured irradiances data. We must also consider the aggregation of solar farm's power output at different locations to reduce the variability of the stand-alone farms.

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