Report presented as a requirement for the conclusion of the course "Calibration and Installation of a Pyranometer", Huayao Geophysical Observatory, Geophysical Institute of Peru, July 14-25, 1980. ***Updated on March 12, 2017.***

CALIBRATION AND INSTALLATION OF A PYRANOMETER

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ABSTRACT

This paper presents the methodology, calculations and results used to calibrate a pyranometer using an Eppley pyrheliometer at the Huayao Geophysical Observatory of the Geophysical Institute of Peru in 1980. He author participated in a training on the calibration and installation of pyranometer at Huayao on July 14-25, 1980. A calibration coefficient equal to 11.04 mV/kW/m^2 was determined for a Kipp-Zonen CM5 pyranometer. This pyranometer was used by the author to conduct measurements of total solar radiation at the Machu Picchu Ruins. The report also shows the steps involved in the proper installation of a pyranometer to measure total solar radiation and gives recommendations.

Keywords: Calibration, installation, pyrheliometer, pyranometer, calibration coefficient, direct normal (DNI), diffuse horizontal (DHI) and global horizontal solar irradiance (GHI).

1. INTRODUCTION

Solar radiation is a renewable resource that can meet the energy requirements of several agricultural, architectural, engineering and electricity generation projects, to mention a few. The determination of the solar radiation potential of a region to be utilized in such projects requires measurements and/or computer modeling of the solar radiation.

A pyranometer is a radiometer used to measure both the solar global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) arriving at a particular location on the Earth's surface. A pyranometer needs to be properly calibrated from time to time in order to give the most possible accurate measurement results. The frequency at which a pyranometer needs to be calibrated depends on recommendations from its manufacturer, the type of pyranometer (photodiode or thermopile) and environmental conditions that it is under use. Typical calibration frequency can range from every year or every two years depending on the application of the pyranometer.

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One should always double check with the manufacturer or recommendations of the World Meteorological Organization (WMO) to determine the most appropriate calibration frequency for a pyranometer under use in a particular application. For example, IEC (2017) in its IEC 61724-1:2017 standard for solar photovoltaic (PV) systems performance monitoring specifies that a pyranometer must be calibrated once every year for monitoring in utility scale PV systems while once every two years for monitoring large commercial PV systems.

Despite of the fact that the calibration was conducted in 1980, this update of the report makes reference to reports that were published in later years.

According to the WMO's Guide to Meteorological Instruments and Methods of Observation (CIMO Guide), there are a variety of methods for calibrating pyranometers using the sun or laboratory sources. The following six methods are described in the WMO's CIMO Guide (WMO 2008):

1. By comparison with a standard pyrheliometer for the direct solar irradiance and a calibrated shaded pyranometer for the diffuse sky irradiance.

2. By comparison with a standard pyrheliometer using the sun as a source, with a removable shading disc for the pyranometer.

3. With a standard pyrheliometer using the sun as a source and two pyranometers to be calibrated alternately measuring global and diffuse irradiance.

4. By comparison with a standard pyranometer using the sun as a source, under other natural conditions of exposure (for example, a uniform cloudy sky and direct solar irradiance not statistically different from zero).

5. In the laboratory, on an optical bench with an artificial source, either normal incidence or at some specified azimuth and elevation, by comparison with a similar pyranometer previously calibrated outdoors.

6. In the laboratory, with the aid of an integrating chamber simulating diffuse sky radiation, by comparison with a similar type of pyranometer previously calibrated outdoors.

It is mentioned in the WMO's CIMO Guide that the above-listed methods 1, 2, 3, and 4 are commonly used. However, it is essential that, except for method 2, either the zero irradiance signals for all instruments are known or pairs of identical model pyranometers in identical configurations are used. Ignoring these offsets and differences can bias the results significantly. Method 3 is considered to give very good results without the need for a calibrated pyranometer.

The above-listed methods are not the only ones available to calibrate a pyranometer. For example, ISO describes an iteration method. Other methods include the pseudo and the cloudy sky methods.

It should be pointed out that a pyranometer should be calibrated only in the position that it is going to be used, that is horizontal or inclined at a particular angle.

The next section presents background information about the Huayao Geophysical Laboratory.

2. CALIBRATION SITE LOCATION AND BACKGROUND

The calibration of the pyranometer was conducted at the Huayao Geophysical Laboratory, that is located in the town of Huayao, which is about 12 Km. North of the city of Huancayo in the Department of Junin, South Central Highlands of Peru (Figs. 1-3).

Fig. 1: Map of Peru showing the location of Huancayo.

Fig. 2: Map of the region near Huancayo showing the location of Huayao.

Fig. 3: Panoramic view of the Huayao Geophysical Observatory.

The coordinates of the Huayao Geophysical Observatory are:

- Latitude: 12° 02′ 18″ S
- Longitude: 75° 19′ 22″ W
- Altitude: 3.350 meters.

The Observatory was founded by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in 1919 as the Magnetic Observatory of Huancayo. The name was changed to Geophysical Observatory of Huancayo in 1947, which 15 years later added other Peruvian institutions to become the Geophysical Institute of Peru.

The Huayao Geophysical Observatory is a WMO Regional Radiation Center of Region III: South America.

The Huayao Geophysical Observatory houses facilities and instrumentation for monitoring and studying geophysical phenomena, including Earth magnetism, climate, solar and seismic activity. It has a standard meteorological station (Fig. 4) with continuing monitoring of the climate, which has the longest series of climate data for Peru.

Fig. 4: View of the meteorological station at Huayao.

The methodology, calculations and results of the procedure used to calibrate a Kipp&Zonen pyranometer using an Eppley pyrheliometer at the Huayao Geophysical Observatory of the Geophysical Institute of Peru on August, 14-25, 1980 is presented in the next section.

3. CALIBRATION OF PYRANOMETER

As before-mentioned, a pyranometer is a radiometer used to measure both the solar global horizontal irradiance (GHI) and diffuse horizontal irradiance (DHI) arriving at a particular location on the Earth's surface. A pyranometer needs to be properly calibrated from time to time in order to give the most possible accurate measurement results.

As before-mentioned, despite of the fact that the calibration was conducted in 1980, this update of the report makes reference to reports that were published in later years, such as the WMO's CIMO Guide (WMO 2008) and the ISO9846:1993 international standard (ISO 1993).

The method presented in the training session to calibrate a pyranometer at the Huayao Geophysical Observatory on July, 14-25, 1980 is the one listed in the WMO's CIMO Guide (WMO 2008) as by reference to a standard pyrheliometer, which is a radiometer used to measure the direct normal irradiance (DNI) arriving on a surface. This method is also called the shade/unshaded calibration technique.

ISO (1993) describes best the calibration of a pyranometer using a pyrheliometer. It lists two methods:

1. Alternating sun-and-shade method (ASSM)
2. Continuous sun-and-shade method (CoSSM)

According to ISO (1993), the fundamental difference between the two methods is the use of direct solar radiation in the ASSM method and the hemispherical solar radiation in the CoSSM method. ISO (1993) also presents the advantages and disadvantages of these two methods in terms of instrument cost, data acquisition system, selection of site, operational procedure, data rate, measurement conditions and applicability of calibration factors. A discussion of these advantages and disadvantages is outside the scope of this report.

The method employed to calibrate the pyranometer using a pyrheliometer at Huayao is the alternating sun-and-shade method (ASSM) as presented in later years by ISO (1993).

According to ISO (1993), the general principle of the ASSM is that the pyranometer under test is compared with a pyrheliometer measuring direct solar radiation. The voltage values from the pyranometer that correspond to direct solar irradiance are delivered from the difference between the measured values of the hemispherical solar irradiance and the diffuse solar irradiance. These values are measured periodically by means of a movable sun shade disc. For the calculation of the responsivity, the difference in irradiance components is divided by the measured direct solar irradiance normal to the receiver plane of the pyranometer.

This method is similar to the method by reference to a standard pyrheliometer and a shaded reference pyranometer (CoSSM), except that the diffuse sky irradiance signal is measured by the same pyranometer. The direct component is eliminated temporarily from the pyranometer by shading the whole outer dome of the instrument. The period required for occulting depends on the steadiness of the radiation flux and the response time of the pyranometer, including the time interval needed to bring the temperature and long-wave emission of the glass dome to equilibrium; 10 times the thermopile 1/e time-constant of the pyranometer should generally be sufficient.

Both the direct and diffuse components will change during the comparison, and care must be taken with the appropriate sampling and averaging to ensure that representative values of the shaded and unshaded outputs are used for the calculation. To reduce uncertainties associated with representative signals, a continuous series of shade and unshade cycles should be performed and time-interpolated values used to reduce temporal changes in global and diffuse sky irradiance. Since the same pyranometer is being used in differential mode, and the difference in zero irradiance signals for global and diffuse sky irradiance is negligible, there is no need to account for zero irradiances. A full description of this pyranometer calibration method is outside the scope of this report.

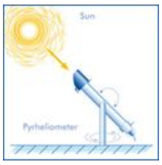
This method gives an accurate calibration coefficient for a pyranometer. It is widely used throughout the world. Some of the well-known laboratories that calibrate pyranometers are the World Radiation Center of the Physikalisch-Meteorologische Observation Davos (PMOD/WRC) in Davos, Switzerland, the US National Weather Service, National Bureau of Standards and National Renewable Energy Research Laboratory (NREL) in the United States, as well as in private laboratories of the companies that manufacture pyranometers.

In Brazil, calibration of pyranometer is done at the Laboratory of Meteorological Instrumentation (LIM) of the CPTEC/INPE. LIM does not calibrated pyranometers using a pyrheliometer according to the ASSM or CoSSM. The method of calibrating pyranometers used at LIM is the calibration of field pyranometers by comparison to a reference pyranometer, as outline in the ISO9847:1992 international standard (ISO 1992).

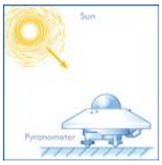
This report details the calibration procedure carried out at Huayao in 1980.

The instruments used in this calibration were:

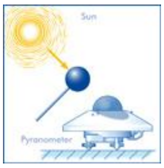
- Eppley standard pyrheliometer
  (Direct Normal Irradiance: DNI)



- Kipp&Zonen CM5 pyranometer
  (Global Horizontal Irradiance: GHI)



- Shading disk
  (Diffuse Horizontal Irradiance: DHI)



- Digital voltmeters
- Thermometer
- Watch and Stopwatch

The following points must be carefully checked during the calibration process:

- A clear day is essentially needed.
- Recommended solar altitudes: 25° as a minimum and 45° as ideal (Figure 5).

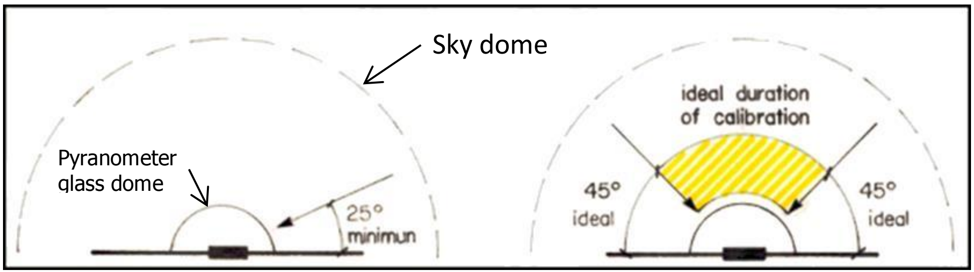


Fig. 5: Recommended solar altitudes for calibration process of a pyranometer.

- Calibration table must have properly leveled and orientated facing due South or North, depending on the Earth's hemisphere.
- Installation all instruments (pyrheliometer, pyranometer, voltmeters, etc.) must follow the manufacturer's instructions.
- Verify if the connection between the sensing elements-insulated wires-voltmeters are electrically and mechanically sound.
- The sensor of the pyrheliometer and pyranometer must be properly exposed to sunlight throughout the period of calibration. The sensors must be above all surrounding obstacles which would provide shade, such as trees, buddings or mountains, during the time period of calibration. It is highly recommended to survey the calibration site prior to calibration in order to verify obstruction from surroundings.

The instruments were set up side-by-side on the calibration table to perform the calibration of a Kipp&Zonen CM5 pyranometer, as shown below in Figure 6.

Fig. 6: Calibration table showing with the following instruments: Eppley pyrheliometer, Kipp&Zonen CM5 pyranometer to be calibrated, shading disk, and voltmeter.

The following steps of the calibration process took place:

1. The output of the pyrheliometer was recorded each minute.
2. The output of the not shaded pyranometer was recorded each eight minutes.
3. The output of the shaded pyranometer was recorded each four minutes after the output of the not shaded pyranometer was recorded
4. Air temperature was recorded when the output of the not shaded pyranometer was recorded, due to the fact that the pyranometer output depends on ambient temperature.
5. Table 1 shows how the data was recorded.
6. Graph 1 presents a plot of the data collected throughout the calibration process.
7. One must carry the calibration long enough to obtain more than one calibration coefficient (k) that must be arithmetically averaged out in order to get a final accurate calibration coefficient.

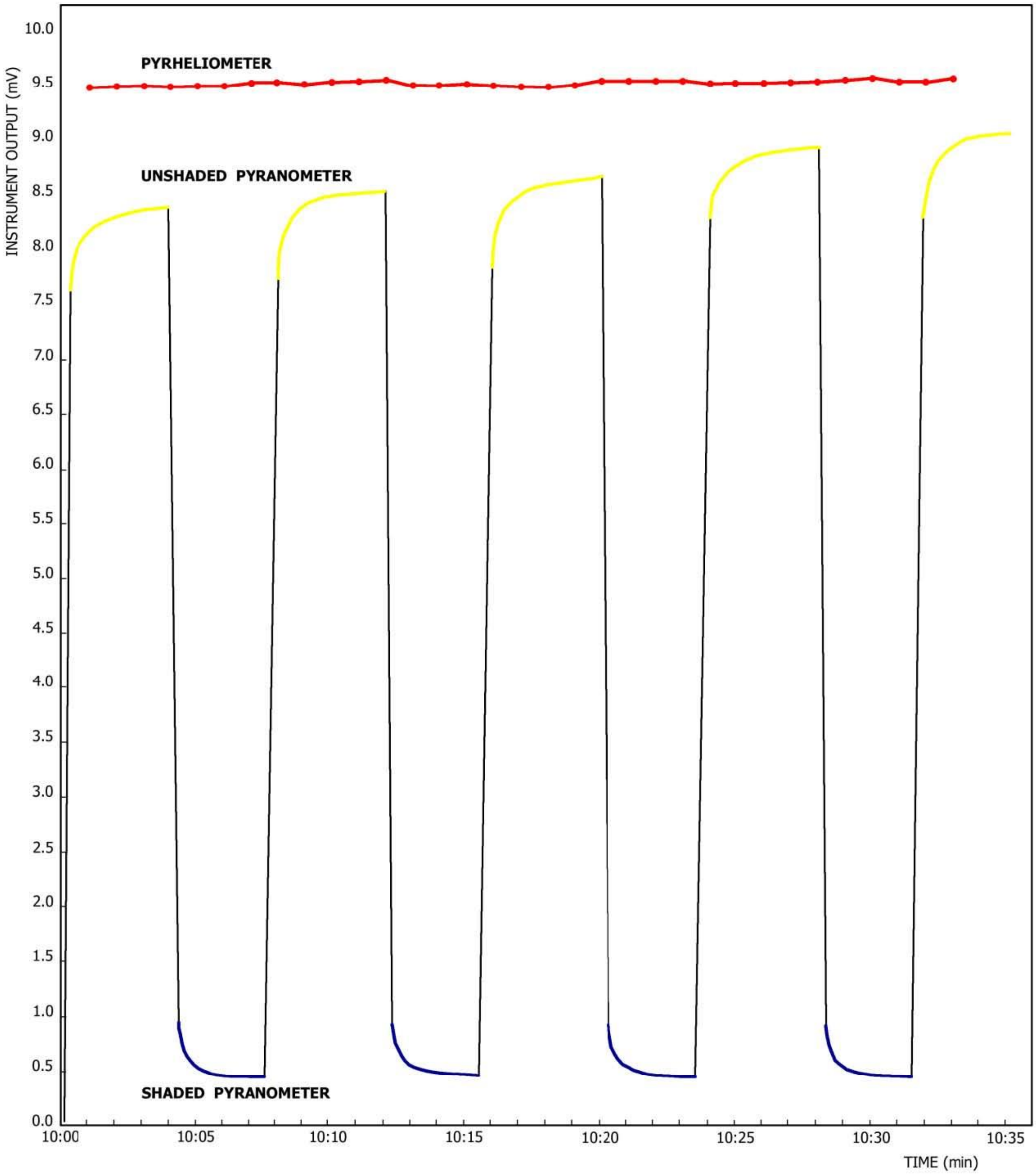
The data collected during this calibration procedure is shown below in Table 1.

AMBIENT AIR TEMPERATURE (°C)	LOCAL TIME (HOUR:MIN)	UNSHADED PYRANOMETER OUTPUT (mV)	SHADED PYRANOMETER OUTPUT (mV)	PYRHELIOMETER OUTPUT (mV)	AVERAGE TO BE TAKEN
	10:01	8.23		9.50	
	10:02			9.51	
	10:03			9.53	
	10:04			9.52	
11.6	10:05		0.53	9.52	1
	10:06			9.52	
	10:07			9.54	
	10:08			9.55	
	10:09	8.42		9.54	
	10:10			9.55	
	10:11			9.56	
	10:12			9.56	
11.0	10:13		0.52	9.53	2
	10:14			9.52	
	10:15			9.53	
	10:16			9.53	
	10:17	8.64		9.51	
	10:18			9.51	
	10:19			9.54	
	10:20			9.56	
11.5	10:21		0.52	9.56	3
	10:22			9.56	
	10:23			9.58	
	10:24			9.55	
	10:25	8.83		9.55	
	10:26			9.55	
	10:27			9.55	
	10:28			9.58	
11.7	10:29		0.54	9.59	4
	10:30			9.60	
	10:31			9.58	
	10:32			9.58	
	10:33	9.00		9.60	

Table 1

Graph 1 illustrates the three solar irradiance components collected during the calibration period:

1. Direct Normal Irradiance (DNI: red line)
2. Global Horizontal Irradiance (GHI: yellow lines)
3. Diffuse Horizontal Irradiation (DHI: blue lines)

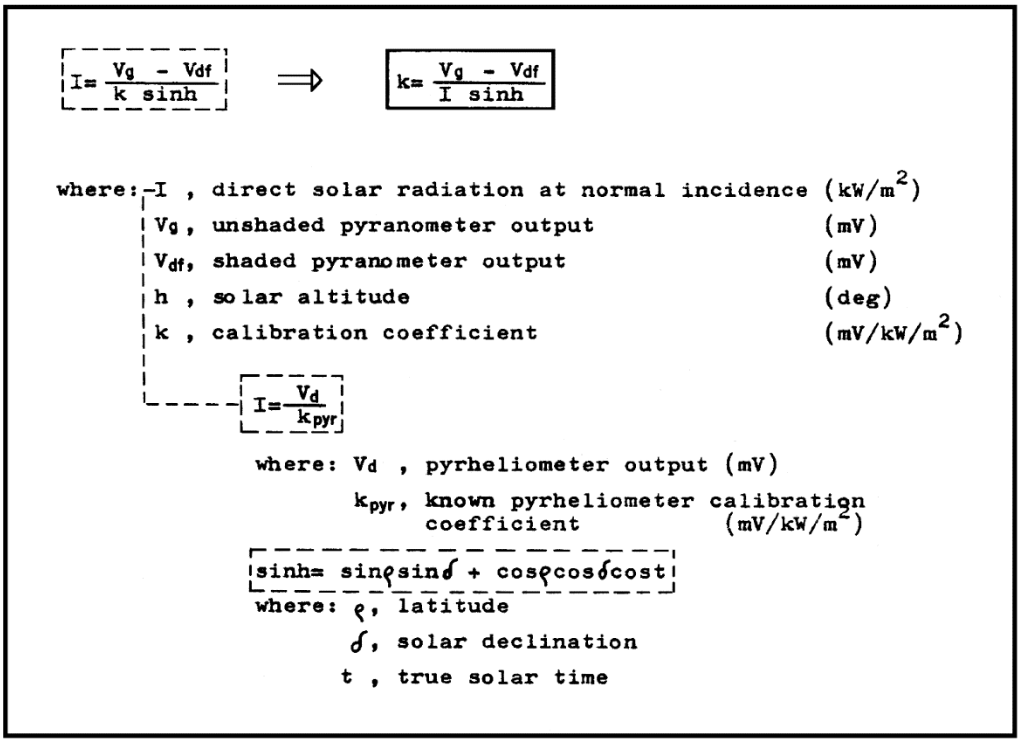


Graph 1: Plot of the data collected during calibration.

The slight variations in the pyrheliometer output (red line) are directly related to variations in the atmosphere turbidity during the calibration process. The black lines indicate the drop or rise in the pyranometer output when the shading disk was placed on or removed from the pyranometer sensor, respectively.

Diffuse solar radiation is a result of the direct solar radiation being scattered by the air molecules and dust in the atmosphere. Diffuse solar radiation comes from all parts of the sky. Due to the fact that the site used for this calibration process was located in a privileged area with very clear atmosphere and high altitude, that is a thin atmosphere, the output of the shaded pyranometer (blue line) is very low being only 6% of the unshaded pyranometer output (yellow line). Therefore, the total solar radiation, which is the sum of the direct and diffuse solar radiations reaching a horizontal surface, for this site is made up mostly of the direct solar radiation component. This is often the case for sites located at high altitudes with clear atmosphere. On the other hand, total solar radiation has a much greater percentage of the diffuse solar radiation at lower altitudes (thicker atmosphere) where scattering is higher.

The calibration coefficient (k) determined by the method by reference to a standard pyrheliometer at Huayao is the ratio of the difference in output from a shaded and not shaded pyranometer to the direct normal solar irradiance multiplied by sine of h (solar altitude). The equations to compute the calibration coefficient (k) using the calibration method described here are presented below in Figure 7.



$$I = \frac{V_g - V_{df}}{k \sin h} \Longrightarrow \boxed{k = \frac{V_g - V_{df}}{I \sin h}}$$

where: I , direct solar radiation at normal incidence $(\mathrm{kW/m^2})$
V_g , unshaded pyranometer output (mV)
V_{df} , shaded pyranometer output (mV)
h , solar altitude (deg)
k , calibration coefficient $(\mathrm{mV/kW/m^2})$

$$I = \frac{V_d}{k_{pyr}}$$

where: V_d , pyrheliometer output (mV)
k_{pyr} , known pyrheliometer calibration coefficient $(\mathrm{mV/kW/m^2})$

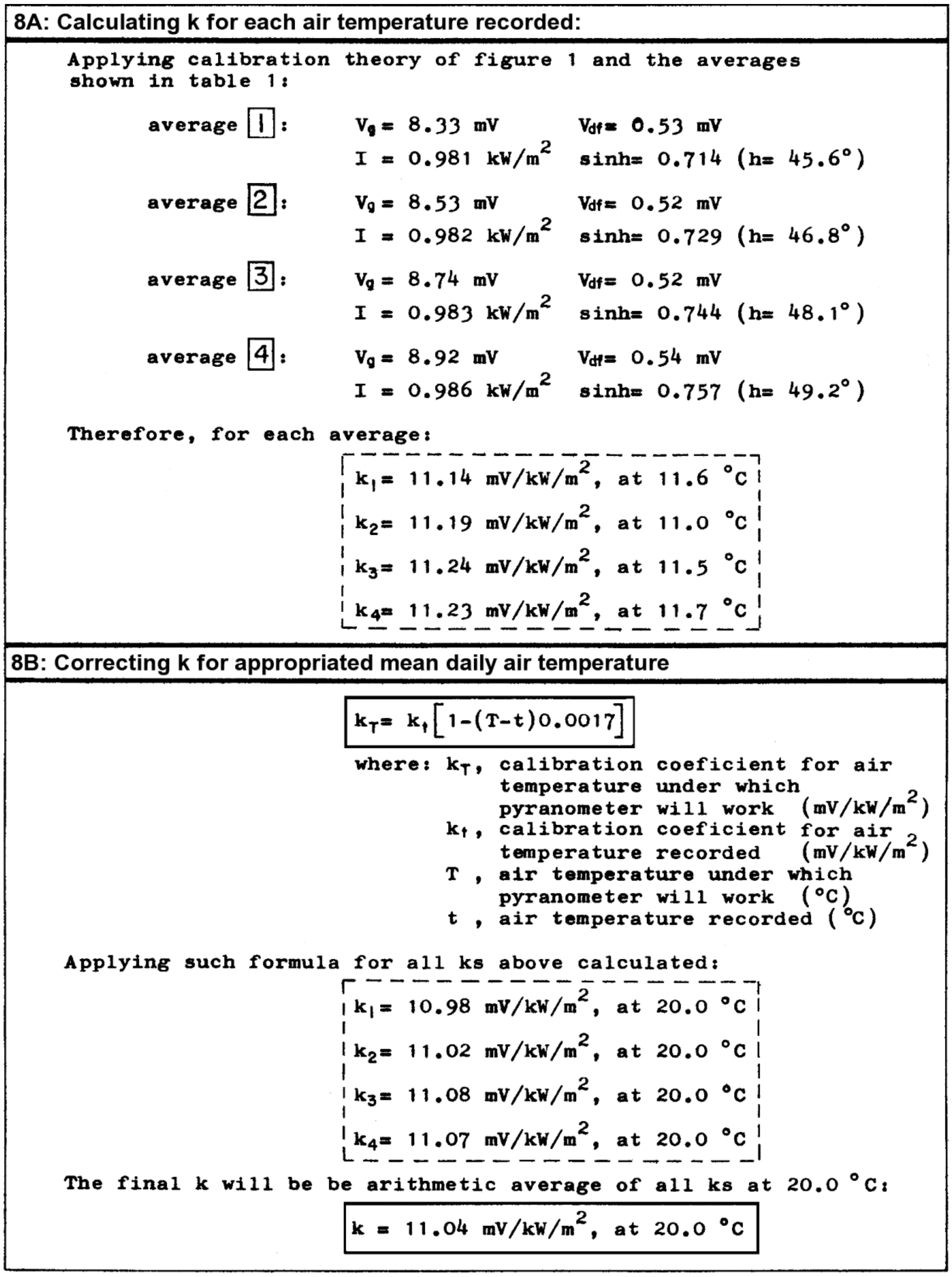
$$\sin h = \sin\varrho \sin\delta + \cos\varrho \cos\delta \cos t$$

where: ϱ , latitude
δ , solar declination
t , true solar time

Fig. 7: Equations used to calculate the calibration coefficient k.

Four calibration coefficients, k, that is one for each temperature recorded, were calculated in this calibration. Arithmetic averages were taken of the two unshaded pyranometer output corresponding to the nine pyrheliometer output (See Table 1).

Figure 8A shows the steps used to determine the calibration coefficient for each of the air temperatures recorded. Then, these calibration coefficients must be corrected to the mean daytime air temperature under which the pyranometer being calibrated will be working on permanent basis. The mean daytime air temperature used in this case was considered to be 20° C. The temperature correction was applied following the steps in Figure 8B. The final calibration coefficient, k, was determined by the arithmetic average of the four temperature corrected coefficients. The final calibration coefficient for this calibration was determined to be 11.04 mV/kW/m2.



8A: Calculating k for each air temperature recorded:

Applying calibration theory of figure 1 and the averages shown in table 1:

average $\boxed{1}$: V_g = 8.33 mV V_{df} = 0.53 mV
I = 0.981 kW/m^2 sinh= 0.714 (h= 45.6°)

average $\boxed{2}$: V_g = 8.53 mV V_{df} = 0.52 mV
I = 0.982 kW/m^2 sinh= 0.729 (h= 46.8°)

average $\boxed{3}$: V_g = 8.74 mV V_{df} = 0.52 mV
I = 0.983 kW/m^2 sinh= 0.744 (h= 48.1°)

average $\boxed{4}$: V_g = 8.92 mV V_{df} = 0.54 mV
I = 0.986 kW/m^2 sinh= 0.757 (h= 49.2°)

Therefore, for each average:

k_1 = 11.14 mV/kW/m^2, at 11.6 °C
k_2 = 11.19 mV/kW/m^2, at 11.0 °C
k_3 = 11.24 mV/kW/m^2, at 11.5 °C
k_4 = 11.23 mV/kW/m^2, at 11.7 °C

8B: Correcting k for appropriated mean daily air temperature

$$\boxed{k_T = k_t\left[1-(T-t)0.0017\right]}$$

where: k_T, calibration coeficient for air temperature under which pyranometer will work (mV/kW/m^2)
k_t, calibration coeficient for air temperature recorded (mV/kW/m^2)
T , air temperature under which pyranometer will work (°C)
t , air temperature recorded (°C)

Applying such formula for all ks above calculated:

k_1 = 10.98 mV/kW/m^2, at 20.0 °C
k_2 = 11.02 mV/kW/m^2, at 20.0 °C
k_3 = 11.08 mV/kW/m^2, at 20.0 °C
k_4 = 11.07 mV/kW/m^2, at 20.0 °C

The final k will be be arithmetic average of all ks at 20.0 °C:

$$\boxed{k = 11.04 \text{ mV/kW/m}^2\text{, at } 20.0\ ^\circ\text{C}}$$

Fig. 8: Steps in the calculation of the calibration coefficient.

Once the calibration coefficient (k) has been determined, one can go ahead and install the pyranometer to get the most accurate possible measurements of total solar radiation.

Aspects related to the uncertainty of the calibration coefficient (k) are presented in the next section of this report.

4. UNCERTAINTY

According to ISO (1993), a basic uncertainty in the determination of the calibration coefficient is inherent in the use of the reference pyrheliometer. This uncertainty is caused initially by the transfer of SI units to the pyrheliometer, which amounts to about 0.7% and 1.0% for a secondary standard and a first class pyrheliometer, respectively. The values are increased to 0.9% and 1.5% because of the permissible range of instrument instability over two years.

The level of uncertainty resulting from carrying out the calibration procedure can be reduced to less than 1% by accurate adjustments, readings and careful operation (ISO 1993).

The sample standard deviation, calculated from the results of all series, is indicative of the variation in meteorological conditions, such as wind, and instrument precision and variabilities, such as azimuthal response of the pyranometer. Its amount depends on the tolerated ranges of the pyranometers (ISO 1993).

As indicated by ISO (1993), the ASSM delivers calibration coefficients which should be preferably applied when scattered cloud conditions are typical. The calibration coefficient determined with the CoSSM, supported by careful zeroing procedures and careful installation of both pyranometers "seeing" the same horizon and foreground, are preferred in clear sky conditions. The calibration coefficient of the CoSSM may be higher by about 0.5% depending on the reading of the theoretical final values.

Uncertainty was not computed for the calibration coefficient determined during the calibration of the two pyranometers calibrated at Huayao in 1980.

The steps involved in the installation of the calibrated pyranometer are presented in the next section.

5. INSTALLATION OF A PYRANOMETER

One of the calibrated Kipp&Zonen CM5 pyranometer and its recorder were installed at a selected location with the Huayao Geophysical Observatory.

There a few important points that one needs to consider in order to properly installing a pyranometer to provide the best possible total solar radiation measurements, such as:

- Survey the site prior to installation to select an area that is free from obstructing elements, such as trees, buildings, mountains, and the like. That is, the sensor of the pyranometer cannot be shadowed at any time during the day at the different seasons of the year.

- The base used to install the pyranometer should be well above ground level.

- The base and pedestal that hold the pyranometer should be properly leveled, both horizontally and vertically.

- If necessary, the area selected to install the pyranometer should be fenced and locked to avoid destruction by animals, vandalism and theft.

- The position of installation should meet the one for which the pyranometer was calibrated. That is, the pyranometer should be installed on the horizontal, vertical, 45° or another position, if it were calibrated to operate under such position. In another words, one should never install a pyranometer in the vertical position if it was calibrated to operate on the horizontal position.

- The pyranometer was installed horizontally since it was calibrated to measure total solar radiation arriving at a horizontal surface.

- The pyranometer should be properly leveled, both horizontally and vertically.

- If the pyranometer has a rectangular sensor, it should be installed with the longest side of the sensor oriented North-South. One should refer to the installation manual of the pyranometer being installed to follow the manufacturer's instructions regarding the correct orientation for the installation of the pyranometer.

- One should use screws to should be secure the pyranometer to the cylindrical pedestal.

- The pyranometer should be installed using a flexible mechanism that allows for adjusting its level from time to time.

Figures 9-11 show three steps of the installation of the calibrated Kipp&Zonen CM5 pyranometer at a selected area within the Huayao Geophysical Laboratory.

Fig. 9: Surveying the site to select an area without obstructions to install the pyranometer.

Fig. 10: Preparation of the base to install the cylindrical concrete pedestal.

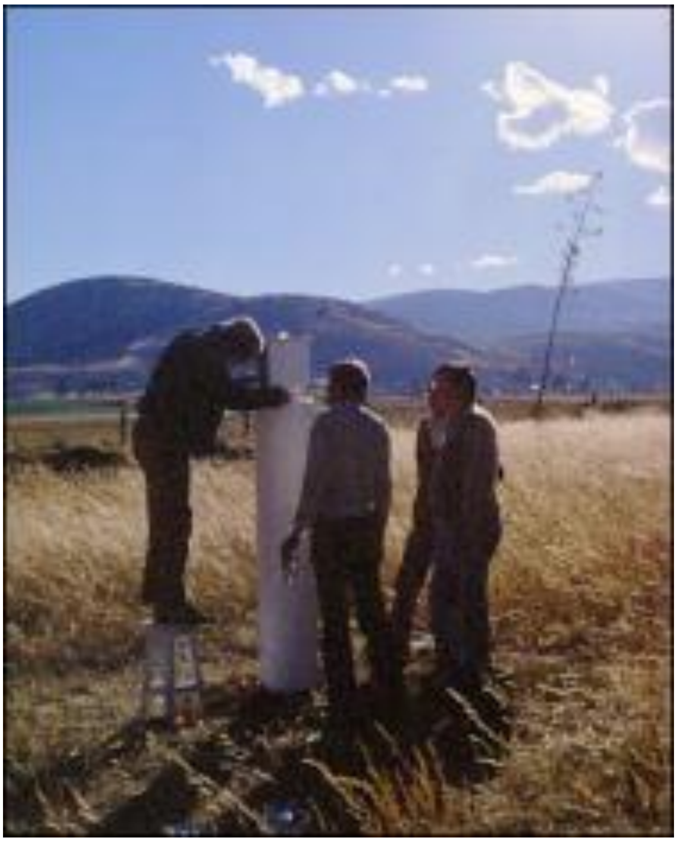


Fig. 11: Final installation of the pyranometer on the cylindrical pedestal.

6. CONCLUSIONS

Calibration of a pyranometer was performed using an Eppley standard pyrheliometer. The method and calculations of the calibration coefficient (k) are straight forward. However, one must take into consideration several points presented in this report in order to properly determine k. The surrounding environment of the Huayao Geophysical Observatory provided ideal altitudinal and atmospheric conditions for the adequate calibration of a pyranometer.

A calibrated pyranometer can be used to provide accurate measurements of total solar radiation to be used in various types of projects or calibrate computer models to compute solar radiation. There were two pyranometers calibrated during this project. One pyranometer was calibrated and installed within the Huayao Geophysical Observatory. The other calibrated pyranometer was taken by the author to measure global horizontal solar irradiation (GHI) at the Machu Picchu Ruins, Peru from August 07 to August 12, 1980, as illustrated in Figure 12. A calibration coefficient equal to 11.04 mV/kW/m^2 was determined for the Kipp&Zonen CM5 pyranometer calibrated to be installed at the Machu Picchu Ruins.

The installation of a pyranometer should be carefully done to obtain the best possible results in GHI measurements. The steps listed in this report can be used to have a successful installation of pyranometers.

Fig. 12: Red arrow points to the pyranometer Kipp&Zonen CM5 that was calibrated at the Huayao Geophysical Laboratory and installed by the author at the Machu Picchu Ruins on August 07, 1980.

7. ACKNOWLEDGMENTS

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