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Radiometer Measurement Intercomparison using Absolute Cavity Radiometer in Regional Radiometer Center at Tsukuba, Japan

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ABSTRACT Solar radiation measuring instruments are generally more sensitive than other meteorological instruments. The standard reference for solar radiation measurements is maintained by the WRC (World Radiation Center) in Davos, Switzerland. The world radiometric standard reference was determined from the weighted mean of the measurements of group of 15 absolute cavity radiometers every 5 years. The reference instruments of the RRC (Regional Radiation Center) were calibrated through the WRC standards reference. Recently, intercomparison observations were performed using the standard instruments at Mt. Tsukuba in Japan in January, 2012. Several standard instruments (absolute cavity radiometer: PMO6 and AHF, pyranometer: CMP22) of KMA (Korea Meteorological Administration) participated in this program and were calibrated from the reference instruments of WRC and RRC. The errors of PMO6, AHF, and CMP22 were reported to be 0.02%, 0.3%, and 1.87%, respectively, compared to reference instruments. RRC is smaller in scale than WRC, using only five pieces of standard equipment and having only a 10-day observation period. Therefore, direct participation in IPC of WRC is needed to secure the technology related to domestic solar radiation observations.

Key words Solar Radiation Measurement, World Radiation Center, Absolute Cavity Radiometer, Pyrheliometer, Pyranometer, Intercomparison

Nomenclature

I : total solar radiation, W/m^2

I_{Glo} : global solar radiation, W/m^2

I_{Dir} : direct solar radiation, W/m^2

I_{Dif} : diffuse solar radiation, W/m^2

V : measurement voltage, mV

C : sensitivity constant, $W/m^2/mV$

subscrip

θ : solar zenith angle

P_c : power of close

P_o : power of open

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1. Introduction

According to data released by the New Renewable Energy Center of the Energy Management Corporation of Korea,[1] the number of photovoltaic houses increased from 310 in 2004 to over 26,000 houses in 2010, and 45,530 houses in 2012, resulting in 141,408 houses in total that are powered by photovoltaic power generation. This reflects a worldwide increase in the utilization of solar energy as basic energy and the largest natural source of energy on Earth. In particular, this quantity is massive in that the utilization worldwide is still under 0.1%.[2] However, because power production from photovoltaic power generation depends on local solar radiation, the research on analysis and prediction of solar radiation with respect to the location of photovoltaic power generation is very important.[3]

The solar radiation model is a model for the calculation of energy reaching the Earth's surface through the process in which energy from the Sun is absorbed and reflected by clouds and gases in the atmosphere.[4] This model has the advantage of being capable of calculating and analyzing surface solar radiation for vast areas when input data exist.[5,6] However, as the equations used in the solar radiation model calculation may vary across regions, surface solar radiation data that can make calibrations for the variation are needed. The equipment for the observation of surface solar radiation is called a radiometer, which is not capable of observing large areas, but is capable of continuous observation of one station.

The radiometer was invented by Pouillet in 1837, and a great deal of research and development on the equipment has been conducted to date.[7] In addition, the radiometer is significantly influenced by equipment performance and the surroundings at the time of observation.[8] First, equipment performance means equipment-specific sensitivity constant, balance of equipment, and cleanliness of the dome. Among these, equipment-specific sensitivity is a value specific to the equipment obtained from an indoor test when the radiometer is manufactured, and must be tested through a comparison measurement with standard instruments before observation. Second, the influence of surroundings, include blockings and surface conditions (e.g., reflection). In Korea, studies on the equipment include KMA[9] and Jee et al.,[10] which used pyranometer measurement data from 22 stations operated by KMA.

In this study, a comparison measurement conducted at the Regional Radiation Center (RRC) organized by the World Radiation Center (WRC) is explained and the results of comparison measurements are analyzed.

2. Radiation Center and Solar Radiation Measurement

2.1 Radiation Center

Since 1909, the radiometer standard around the world has been defined by the mean of observed data from 15 types of Absolute Cavity Radiometers (Fig. 1) of the WRC in Switzerland, and determined by a comparison measurement every five years.[11,12] Fig. 2 is the schematic diagram on the WRC's comparison measurement of solar radiation. The International Pyrheliometer Comparison is conducted in Davos,

Fig. 1. Absolute cavity radiometer comparison to the WRC (Source: http://www.pmodwrc.ch)

Switzerland, every five years, the most recent being in 2010.[13,14] In addition, the Regional Pyrheliometer Comparison (RPC) is also conducted there using the RRC's calibrated radiometers.[15] In this comparison, the standard radiometer of each country is calibrated through a comparison measurement, and then the participants calibrate radiometers in their countries when they return to their countries.

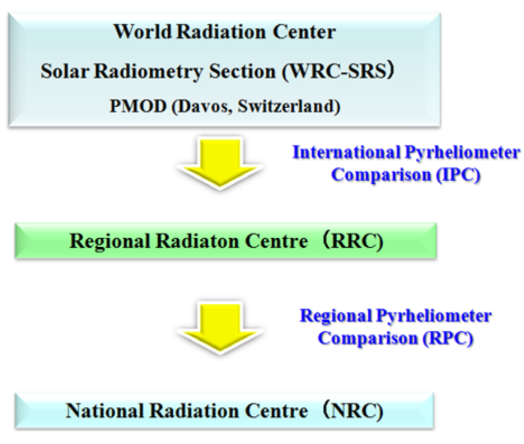
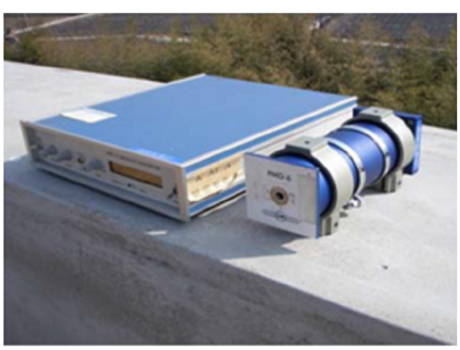
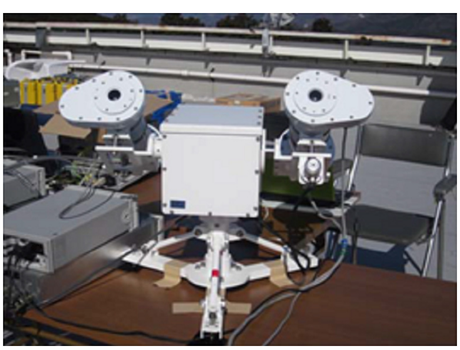


Fig. 2. The schematic diagram of international pyrheliometer comparison (Source:http://www.pmodwrc.ch)

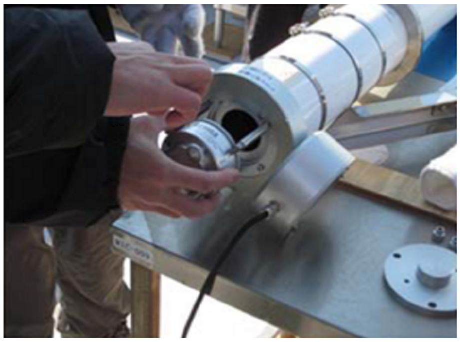
RRC of Asia was established in Tsukuba, Japan in 1964, and includes 34 countries. RRC of Asia has personnel and an environment very suitable for solar radiation measurement to the extent that it operates an observation site for Baseline Surface Radiation Network (BSRN). In addition, Japan has two Asia standard absolute cavity radiometers, and the equipment is also calibrated at the IPC. The calibrated standard absolute cavity radiometers play a role in calibrating standard absolute cavity radiometers of Asian countries along with RRC's standard absolute cavity radiometer. Recently from January 24 to February 2, 2012, a comparison measurement was conducted on the rooftop of the Keisei Hotel (latitude: 36.13°N, longitude: 140.07°E, altitude: 560 m), which is located on Tsukuba Mountain in the City of Tsukuba, Japan. At the time, the standard absolute cavity radiometers of Korea (Fig. 3 (a) and (b)) and



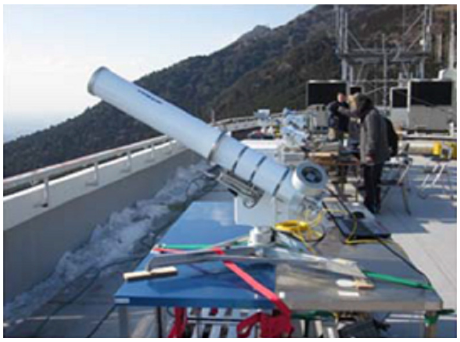
(a) PM06



(b) AHF



(c) CMP22



(d) Observation

Fig. 3. Installment and observation of Korea's standard instruments at RRC (Regional Radiation Center)

pyranometer (Fig. 3 (c)) were calibrated. Among them, as the pyranometer did not have a standard pyrano-meter, the comparison measurement was conducted by converting it into a pyrheliometer using a column as shown in Fig. 3 (c). In other words, as shown in Equation (1), global solar radiation (I_{Glo}) is calculated with direct solar radiation (I_{Dir}), diffuse solar radiation (I_{Dif}), and solar zenith angle (θ). Here, when converting global solar radiation to direct solar radiation, diffuse solar radiation becomes 0 W m^{-2}, and direct solar radiation can be calculated using global solar radiation as shown in Equation (2).

$$I_{Glo} = I_{Dir} \times \cos\theta + I_{Dif} \tag{1}$$

$$I_{Dir} = \frac{I_{Glo}}{\cos\theta}(I_{Dif} = 0) \tag{2}$$

At this time, the inside of the column is painted black as in a black body to enable observation of only direct solar radiation, preventing diffused solar radiation from reaching the pyranometer. In addition, the sun-tracker makes the Sun and the equipment perpendicular to one another, making it precisely so only direct solar radiation can be observed.

2.2 Solar Radiation Measurement

Absolute cavity radiometers that observe direct solar radiation are precision pieces of equipment, with less than five units being manufactured per year. In Korea, two types of absolute cavity radiometers are used, including the PMO6, developed by the WRC (Fig. 3 (a)) and the AHF (Fig. 3 (b)) developed by Eppley in the United States. Absolute cavity radiometers are designed to maintain a certain level of standard heater power the entire time when opening and closing the shutter. In other words, when closing the shutter, it heats up to standard heater power by the heater as there is no absorbed direct solar radiation, but when opening the shutter, it heats up the amount subtracted by solar radiation from standard heater power, and therefore, direct solar radiation for the moment is determined as the value of heater power with the shutter closed (P_C) from which heater power with the shutter open (P_O) is set.

$$I = K(P_c - P_o) \tag{3}$$

Here, K denotes instrument constant.

As absolute cavity radiometers have long observation intervals and are costly, they cannot be used in general observation. The radiometers used in actual observations are the equipment collecting micro-currents caused by solar energy. In other words, when solar energy reaches a radiometer, the temperature of the sensor increases, resulting in the difference in temperature between the sensor and the radio-meter case. At this time, a micro-current occurs which varies across radiometers, and accordingly, the sensitivity of different radiometers are determined separately. In other words, the observed value of a radiometer (I) is represented by the simple equation shown in Equation (4).

$$I = V \times C \tag{4}$$

Here, V denotes the current that occurs as solar energy reaches a radiometer (unit: mV), and c denotes the sensitivity constant (unit: W m^{-2} mV^{-1}) of each piece of equipment.

Solar radiation is divided into direct or beam solar radiation, diffuse or sky solar radiation, and global or total solar radiation, and the devices for the observation of solar radiation are called pyrheliomter and pyranometer. Pyrheliometer is the equipment designed such that direct sunlight penetrates a small space of a cylinder and is detected by the sensor located vertically to the path of sunlight, and usually used for observation of 290–4000 mm wavelength. Pyranometer is the equipment for simultaneous measurement of direct and diffuse radiations of the sun, and used for observations of about 290–2800 mm wavelength, and the sensor must be installed horizontally in a glass dome.[16] Diffuse radiometers are the same equipment as pyranometer, but are the equipment for measurement of only diffuse solar radiation in the atmosphere by blocking direct solar radiation using a shutter.

3. Radiometer Measurement Intercom–parison and Calibration

3.1 Radiometer Measurement Intercomparison

Fig. 4 is a time table of the comparison measurement method of absolute cavity radiometers. The observation interval is 30 minutes, with the observation being conducted for 18 minutes from the beginning, and the equipment check and preparation for the observation for the next time during the rest of the time. In addition, as absolute cavity radiometers need to observe energy when opening and closing the shutter, they make repeated observations by repeating the opening and closing of the shutter with 1 minute 30 seconds for stabilization time. In other words, the WRC's absolute cavity radiometer comparison measurement uses only the data for the time with direct solar radiation over 800 W m^{-2}, and considering the characteristics of absolute cavity radiometers, data is created for three minutes (repeated observations after 1 minute 30 seconds from opening the shutter, and after 1 minute 30 seconds from closing the shutter).

While the WRC uses a total of 15 standard absolute cavity radiometers, the RRC usually uses five standard absolute cavity radiometers. Three of the five are standard absolute cavity radiometers of the WRC, and the remaining two are the RRC's standard absolute cavity radiometers. The standard absolute cavity radiometer used in this study is shown in Table 1. A

Table 1. Standard absolute cavity radiometers participated in regional pyrheliometer comparison from world and regional radiometer center

Instruments		Serial Number
WRC	PMO6 PMO6 AHF	0401 0803 32455
JMA	PMO6 AHF	0406 32446
Korea	PMO6 AHF CMP22*	951202 36014 090081

*CMP22 is Korea Standard Pyranometer

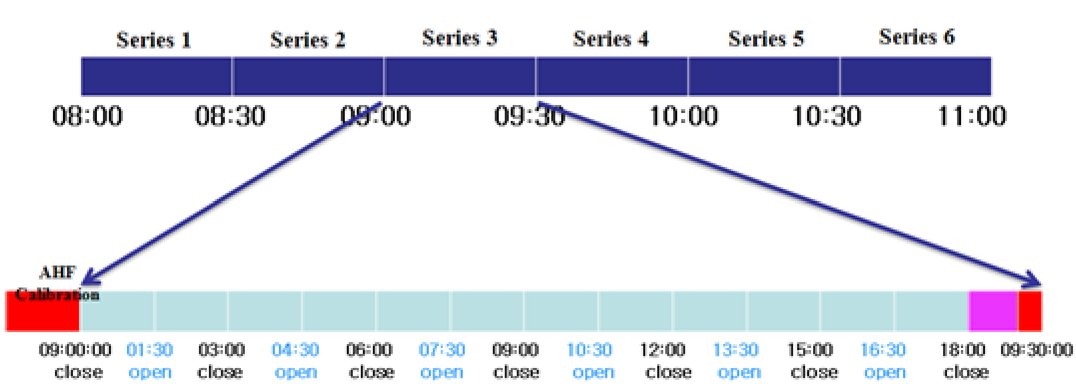


Fig. 4. The time table for absolute cavity radiometer comparative measurement

comparison measurement was conducted from January 24 to February 2, 2012, from 8:00 AM to 4:00 PM, with the times when observation was impossible due to clouds or precipitation having been excluded.

Table 2 shows the observation data from the standard absolute cavity radiometers for one interval among the observation data. These were observations made over 18 minutes from 10:00 AM on January 29, 2012, creating a total of 6 data points for each piece of equipment, as one observation was obtained every three minutes. Fig. 5 shows variations among observed values from Table 2, and the differences were mostly under ±0.10% (±0.001; medium dash line). S/N 0803 and 0406 overestimated compared to the mean, S/N 0401 and 32455 underestimated, and S/N 32446 showed a larger difference than the other equipment. These differences may increase with the service life of the equipment, and can be influenced by location. Although all equipment is connected to a sun-tracker and perpendicular to the Sun, differences may occur as each device has a different optical path. The factors that influence such optical paths include clouds and aerosol, and the large differences among devices at 10:18 occurred because stratus clouds were included in the optical path of the devices.

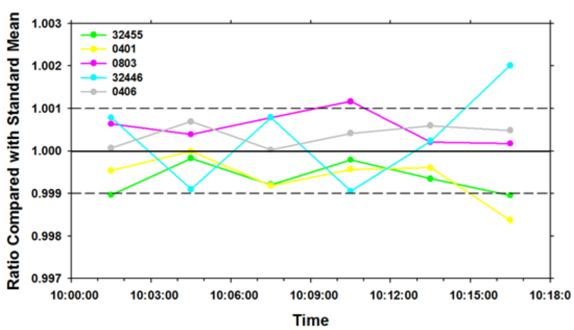


Fig. 5. Time series of ratio for direct solar radiations compared to mean, respectively

Fig. 6 shows time-series data from January 31, 2011 for which the largest amount of data were collected among observed days. Red dots indicate standard solar radiation as well as the mean of the solar radiation observed from RRC's five absolute cavity radiometers, blue dots (AHF) and green dots (PMO6) indicate absolute cavity radiometers, and pink dots indicate observed values from the pyranometer

Table 2. Sample measurement data of standard absolute cavity radiometers from Table 1. The measurement performed from 09:00 to 09:30 on 29 January 2012 in Fig. 4

Status	Time (minute : sec)	PMO6 (0401)	PMO6 (0803)	AHF (32455)	PMO6 (0406)	AHF (32446)
Close	00 : 00					
Open	01 : 30	927.09	928.11	926.56	927.58	928.24
Close	03 : 00					
Open	04 : 30	929.55	929.92	929.40	930.20	928.72
Close	06 : 00					
Open	07 : 30	830.84	832.33	930.86	931.62	632.33
Close	09 : 00					
Open	10 : 30	928.30	929.79	928.51	929.09	927.83
Close	12 : 00					
Open	13 : 30	907.78	908.33	907.55	908.68	908.36
Close	15 : 00					
Open	16 : 30	919.03	920.70	919.57	920.98	922.39
Close	18 : 00					

(CMP22) converted to direct solar radiation. While absolute cavity radiometers did not show significant differences from the RRC mean, the pyranometers have some differences. For quantitative analysis, standard deviations are shown in Figure 7 using a scatter plot. Two absolute cavity radiometers of both the AHF and PMO6 showed standard deviations of 0.775 W m^{-2} and 0.381 W m^{-2}, respectively, similar to the RRC values, while the CMP22 showed over-estimated values compared to other observation data, with a standard deviation of 1.781 W m^{-2}. The data from the CMP22 used in the observation were the first observations after its production, requiring an accurate sensitivity constant based on the comparison measurement.

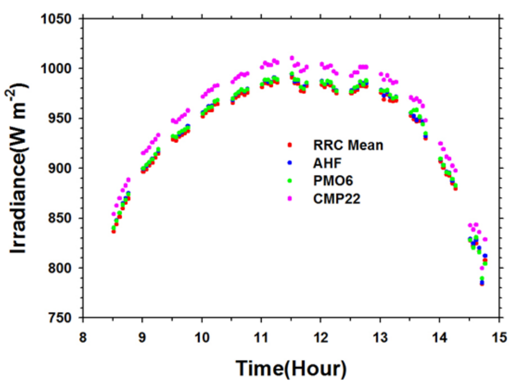


Fig. 6. Time series of solar radiation for RRC mean and Korea instruments (AHF, PMO6, CMP22) on 31 January 2012 (red point: mean of RRC standard instruments, blue point: AHF, green point: PMO6, and pink point: CMP22)

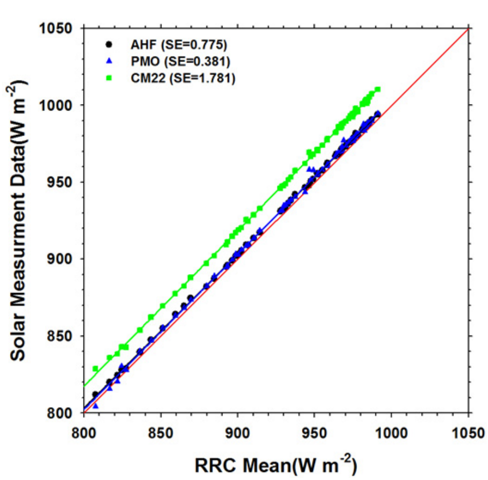


Fig. 7. Scatter plot of solar radiation from Fig. 6 (black circle: AHF, blue triangle: PMO6, and green square: CMP22)

3.2 Calibration

A new calibration constant for domestic standard equipment (absolute cavity radiometer 2EA, pyrano-meter 1EA) was obtained from the RRC. Calibration constants as shown in Table 3 were reported from the WRC and RRC based on the results of a com-parison measurement using five standard absolute cavity radiometers in total. All equipments overesti-mated compared to the observation of the RRC's standard absolute cavity radiometer, and in particular, the first domestic standard absolute cavity radiometer, PMO6, overestimated by 0.02%, while the AHF that has been used since 2010 overestimated by 0.3%. In addition, it was found that CMP22, which will be the standard pyranometer in Korea, overestimated by 1.87%. These results are similar to the results described in section 3.1, created by the use of numerous observation data over 10 days.

4. Conclusions

As radiometers are very sensitive equipment com-pared to other types of meteorological observation equipment, their condition needs to be frequently inspected, and calibration needs to be made regularly based on comparison measurements with standard radiometers. The international standard radiometer

Table 3. The reduction factor between WRC and Korea standard instruments in Table 1

Instruments	Reduction Factor
PMO6	−0.02%
AHF	−0.30%
CMP22	−1.87%

is created based on the mean observations of a total of 15 absolute cavity radiometers at the WRC every five years, and based on the data, the RRC's equipment is calibrated and then the standard radiometer of each country is calibrated. Korea participated in the solar radiation comparison measurement program conducted at the RRC of Asia in Japan in January 2012, and conducted comparison measurements for two absolute cavity radiometers (PMO6 and AHF) and one pyranometer (CMP22). As a result, it was found that the PMO6 and AHF overestimated by 0.3% and the CMP22 overestimated by 1.87%. The PMO6 showed a small difference from the reference value as it has been regularly calibrated in Japan as the standard radiometer of Korea since the 1990s. On the other hand, the AHF and CMP22 that will be newly used as standard radiometers showed larger difference compared to the PMO6.

Solar radiation comparison measurements at the WRC were conducted when the sky is clear and cloud-free, with no environmental factors that may have influenced solar radiation being present near the observation site. In addition, the differences among standard absolute cavity radiometers are ±0.1%, which is converted into about 1 W m^{-2} in solar radiation. However, compared to the WRC, the RRC has a smaller number of standard absolute cavity radiometers and a shorter observation period. Thus, direct involvement with the WRC, where numerous researchers analyze solar radiation observation data together and conducting observations, will contribute significantly to the technological advancement of domestic meteorological observation equipment. In addition, the foundation for development and research of solar radiation observation equipment using domestic technology needs to be established.

Acknowledgments

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