International comparison of the SIAR measurement and the WRR standard*

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We experimentally compare the solar irradiance absolute radiometer (SIAR) measurement with the world radiometric reference (WRR) standard to improve the accuracy of instrument. The SIAR joined in the international pyrheliometer comparison (IPC) in 2000. The comparison results show that the calibration factors for SIAR to WRR are 0.999 220, 1.001 694, 0.998 334 and 0.997 439 in the 9th IPC, the 10th IPC, the 11th IPC and the 12th IPC, respectively. These results are added to the measurement uncertainty budget of SIAR. The repeatability of the SIAR-type absolute radiometers is also investigated. The relative error introduced by two SIAR-type absolute radiometers is within 0.25%.

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It is important and necessary to set up the long-term and accurate monitoring of solar irradiance in the world[1,2]. In order to establish the worldwide reference scale for total solar irradiance (TSI) measurement, the world radiometric reference (WRR) was introduced in the 4th international pyrheliometer comparison (IPC) in 1975. It was realized by the world standard group (WSG) which consists of 15 absolute radiometers with 9 different types[3]. The WRR standard was adopted by the world meteorological organization (WMO) as the official reference standard for TSI measurement in 1979. The uncertainty of the WRR standard with respect to the international system of units (SI units) was estimated to be 0.3% [4,5].

In our country, the absolute radiometer has been developed in Changchun Institute of Optics, Fine Mechanics and Physics (CIOMP) since 1990s[6-9]. In the field of solar irradiance measurement, CIOMP has created a lot of records in China, and solved the problems of independent solar tracking and high precision active temperature control. For example, the package, solar irradiance absolute radiometer (SIAR) designed by CIOMP was carried on the SHENGZHOU-3 spacecraft to measure the TSI from March to September in 2002. It was the first time to obtain the data of TSI in China[10].

In order to obtain accurate and stable TSI database, two new integrated packages, SIM-1 (solar irradiance monitor-1) and SIM-2 (solar irradiance monitor-2) developed by CIOMP were established to achieve the long-term and continuous monitoring of solar irradiance[11,12]. The SIM-1 and SIM-2 both consisted of three SIARs (SIAR-1, SIAR-2, SIAR-3), where SIAR-1 and SIAR-2 were used to monitor the periodic variation of TSI, and SIAR-3 was used to correct measurement degradation during operation. The difference between SIM-1 and SIM-2 is that the SIM-2 contains a rotatable turntable to adjust the angle to the sun, which ensures SIARs always face the sun and the total measurement time is significantly increased[13].

Every five years, the world radiation center (WRC) will host the IPC in Davos (Switzerland) to establish the new WRR standard used in the following five years[14]. In this paper, the international comparison of SIAR and the WRR is proposed. The results show that the calibration factors for SIAR to WRR are 0.999 220 for the 9th IPC (2000), 1.001 694 for the 10th IPC (2005), 0.998 334 for the 11th IPC (2010), and 0.997 439 for the 12th IPC (2015), respectively. The repeatability of SIAR-type absolute radiometers is also investigated. The results show that the relative error between two radiometers is less than 0.25%.

A schematic diagram of the SIAR series radiometer is shown in Fig.1. It adopts a "back to back" structure to combine the main cavity and compensation cavity, which will eliminate the error caused by temperature drift of the heat sink. The main aperture is located before the main cavity, while the compensation cavity is behind the main cavity and neither absorbs sunlight nor achieves electric heating. The main aperture is shaped as a ring with a hollow, while the outer radius is 7.5 mm and inner radius

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is 2.5 mm. Its material is 40Cr and was electroplated on nickel. The thermocouple consists of 180 pairs of copper constantan, which is used to measure the temperature difference between the heat sink and the main cavity. The main cavity is the key structure of the radiometer, and it mainly consists of silver. In order to avoid the opto-electric nonequivalence phenomenon, the heating wire was embedded in the main cavity with the same area where black paint absorbs solar irradiance. The main cavity is a circular cone with height of 24.3 mm, central angle of 30°, and wall thickness of 0.06 mm. The heat sink is made up of aluminum[15,16].

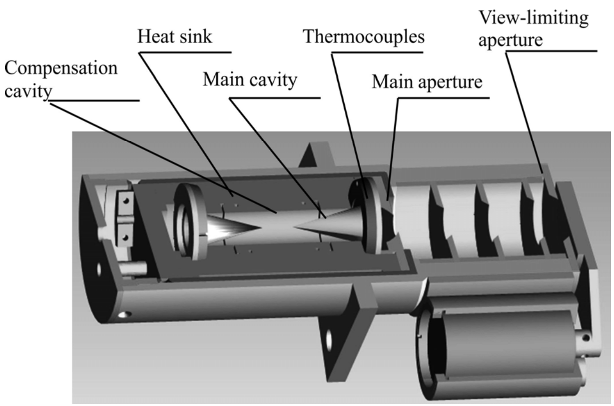

Fig.1 Schematic of SIAR

The measurement process of SIARs consists of radiation heating stage and electric calibration stage[17,18]. However, the responsivity of the main cavity is pre-calibrated before testing. Usually, we apply a low electrical power P_L and a high electrical power P_H in the main cavity, respectively. The thermocouples detect the temperature difference between main cavity and heat sink, and then output the corresponding electric signal (V_L and V_H). Assuming that the responsivity maintains a constant and electric signal increases with radiation power linearly in the measurement, the responsivity of the main cavity would be given by

$$S=(P_H-P_L)/(V_H-V_L). \quad (1)$$

(a) Radiation heating stage. In order to remove the measured deviation introduced by temperature gradient in main cavity, the cavity is preheated by P_H before the measurement. Then, shutter is opened and main cavity begins to receive the radiation power P_O. In order to shorten the measurement time and keep the equilibrium voltage of radiation heating stage still at V_H, a compensation electric power P_{OE} is provided (its value is calculated by the equilibrium temperature of P_O), which finally leads to the equilibrium voltage to T_O.

(b) Electric calibration stage. Close the shutter, and the main cavity is supplied by P_H again (via embedded electric heater), resulting in the voltage returns to V_H. Due to the opto-electric nonequivalence and prediction error of equilibrium temperature, there is a difference between V_O and V_H. The responsivity S is used to eliminate this error, then the radiation power P_O is given by

$$P_O=P_H-P_{OE}+S\times(V_O-V_H). \quad (2)$$

However, considering the drift of responsivity, the responsivity in narrow power range should be measured, too. It is given by

$$S_1=(P_{H1}-P_{L1})/(V_{H1}-V_{L1}), \quad (3)$$

where P_{H1} and P_{L1} are the power values in the vicinity of P_O, and V_{H1} and V_{L1} are the corresponding electric output signals.

Comparing Eqs.(1) and (3), we can find that S and S_1 have the same measurement accuracy. The responsivity S was obtained before the measurement and characterizing the response of the wide power range from P_L to P_H. The responsivity S_1 is obtained in the radiation heating stage, and representing the response of the narrow power range from P_{L1} to P_{H1}, which is near the radiation power P_O. Actually, responsivity S_1 is closer to the true value and its corresponding radiation power P_O could be given by

$$P_O=P_H-P_{OE}+S_1\times(V_O-V_H). \quad (4)$$

Then, the solar irradiance needed to be measured is given by

$$E=\frac{NP_O}{\alpha A}=N\times\frac{P_H-P_{OE}+S_1\times(V_O-V_H)}{\alpha A}, \quad (5)$$

where N is the calibration coefficient, α is the absorptivity of main cavity[19,20], and A is the area of main aperture[21,22].

Originally, the WSG consists of 15 instruments. However, many instruments became unstable in the past 30 years, so the current WSG is reduced to only with six pyrheliometers. The WRR factor $WRR_{i,\mathrm{IPC}}$ for the WSG instrument i, $i\in$ {PMO2, CROM2L, MK67814, HF18748, PAC3, PMO5}, is defined as the radio of the WRR to the WSG instrument i averaged over the duration of the IPC:

$$WRR_{i,\mathrm{IPC(K)}}=\left\langle\frac{WRR(t)}{WSG_i(t)}\right\rangle_t, \quad (6)$$

where $WRR(t)$ is the reference irradiance, $WSG_i(t)$ is the irradiance measured by WSG instrument i at the time t, $\langle x(t)\rangle_t$ denotes the temporal average of $x(t)$, and IPC(K) denotes the Kth IPC in Davos. The reference irradiance $WRR(t)$ is defined as the mean value of the simultaneous readings of six WSG instruments, multiplied by their corresponding WRR factors from the previous IPC:

$$WRR(t)=\langle WSG_i(t)*WRR_{i,\mathrm{IPC}(K-1)}\rangle_i. \quad (7)$$

Therefore, for each WSG instrument i, the new WRR factor is calculated as:

$$WRR_{i,\mathrm{IPC}(K)}=\left\langle\frac{\langle WSG_i(t)*WRR_{i,\mathrm{IPC}(K-1)}\rangle_i}{WSG_i(t)}\right\rangle_t. \quad (8)$$

Tab.1 The WRR factors for SIAR-type absolute radiometers since 2000

Type	Component	WRR factor	σ (ppm)	N_1 used	N_2 total
IPC-IV (2000)	SIAR-1A	0.999 220	1 140	5	5
	Average	0.999 220	1 140		
IPC-V (2005)	SIAR-1A	1.001 928	815	753	945
	SIAR-2A	1.006 230	490	906	1 210
	SIAR-2B	0.998 620	507	979	1 318
	SIAR-2C	1.000 016	933	761	956
	Average	1.001 694	339		
IPC-VI (2010)	SIAR-1A	1.002 401	994	440	1 505
	SIAR-2A	0.991 696	737	495	2 107
	SIAR-2B	1.000 286	668	427	2 107
	SIAR-2C	0.999 839	1 124	441	1 505
	Average	0.998 334	448		
IPC-VII (2015)	SIAR-2A	0.991 432	2 535	221	*N/A*
	SIAR-2B	1.000 941	2 227	210	*N/A*
	SIAR-2C	0.998 949	753	392	*N/A*
	Average	0.997 439	957		

For each participating instrument *j*, like SIAR, the new WRR factor is calculated as:

$$WRR_{j,\mathrm{IPC}(K)} = \left\langle \frac{WRR(t)}{Irr_j(t)} \right\rangle_t , \tag{9}$$

where $Irr_j(t)$ is the irradiance measured by the instrument *j* at the time *t* and $WRR(t)$ is the coinstantaneous reference irradiance.

Four SIAR-type absolute radiometers SIAR-1A, SIAR-2A, SIAR-2B and SIAR-2C were used as transfer instruments in the comparison experiments[23]. With respect to Eqs.(7) and (9), the WRR factors for SIAR are listed in Tab.1. The N_1 (used) is the available measurements number used in the calculation of WRR factor, and N_2 (total) is the total measurements number. Outliers are successively removed to make sure the WRR to SIAR ratios maintain within a certain range of mean value. The results show that the calibration factors for SIAR to WRR are 0.999 220, 1.001 694, 0.998 334 and 0.997 439 for the 9th, 10th, 11th and 12th IPCs, respectively. Because SIAR-1A suffered from inexplicable jumps, it was not used in the 12th IPC. The WRR calibration factors are added to the combined standard uncertainty in the measurement of TSI. There are many standard uncertainties, but only a few dominant factors are considered in this analysis. The uncertainty budget of TSI measurement of SIAR is summarized in Tab.2. Detailed discussions were presented in Ref.[24].

The repeatability of SIAR-type absolute radiometers is also investigated. The measurement results of direct solar radiation of SIAR-1A and SIAR-2C are compared to test the repeatability, as shown in Fig.2. The direct solar radiation is the ground based definition of TSI. We choose a very good measurement day to set up the comparison experiment, for no absolute radiometer is available with bad weather, such as rain or cloud. The abscissa in Fig.2 is denoted as time, where the time of one day is assumed as a value of 1. The comparison results show that the relative error between two SIAR-type absolute radiometers is less than 0.25%. It is enough for the requirement of TSI measurement.

Tab.2 Uncertainty budget of TSI measurement of SIAR

Parameter	Value	σ (ppm)
A_m	$5.047\,9\times10^{-5}$ m^2	290
α	0.999 7	120
f_a (correction factor for the sun-earth distance)	1.029 425	200
f_b (correction factor for the solar pointing error)	1.005 679	700
f_{WRR} in the 9th IPC (2000)	0.999 220	1 140
f_{WRR} in the 10th IPC (2005)	1.001 694	339
f_{WRR} in the 11th IPC (2010)	0.998 334	448
f_{WRR} in the 12th IPC (2015)	0.997 439	957
E_b (thermal background irradiance)	−20.571 W/m^2	1 354

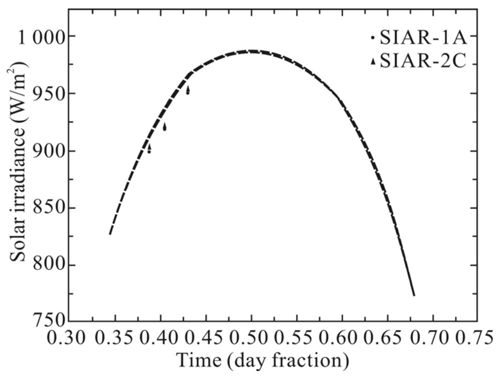

Fig.2 Measurement results of direct solar radiation of SIAR-1A and SIAR-2C over one day

In conclusion, accurate measurement of solar irradiance requires scientific calibration system. In this paper, the international comparison between SIAR measurement and WRR standard is proposed. Four different calibration factors for SIAR to WRR are taken into consideration in the uncertainty budget of TSI measurement. For example, the SIAR in FY-3C was set into space on 23 September 2013. So the calibration factor to WRR is 0.998 334, which was measured in the 11th IPC in 2010. The repeatability of SIAR-type absolute radiometers is also investigated. A relative error of 0.25% is revealed which is in accordance with the accuracy requirement of SIAR and enough for the TSI measurement.

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