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Solar irradiance absolute radiometer with ability of automatic solar tracking

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Abstract: To measure total solar irradiance accurately, the solar irradiance absolute radiometer SIAR-3a with the ability of automatic solar tracking is designed and constructed. The principle and structure of the solar irradiance absolute radiometer SIAR-3a are presented in this paper and its control scheme for automatic double-axis solar tracking is proposed. The solar irradiance absolute radiometer SIAR-3a imposes electricity to calibrate the total solar irradiance, which is able to measure the total solar irradiance and follow the sun simultaneously. In the calibration experiments, the corresponding rms error limit of SIAR-3a amounts to 0.06% at the 3σ level, which has been calibrated to World Radiometric Reference stored in World Radiation Centre (WRC) in Davos, Switzerland. The experiment results indicate that SIAR-3a works reliably and accurately.

Key words: solar irradiance; total solar irradiance; absolute radiometer; solar tracking; irradiation calibration

自动寻日的太阳辐照绝对辐射计

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摘要：为了准确测量太阳总量辐射，研制了具备自动跟踪能力的太阳辐照绝对辐射计 SIAR-3a。介绍了 SIAR-3a 的原理，提出了双轴太阳跟踪的控制方法。SIAR-3a 采用电来标定待测量的太阳总量辐射，可以在测量太阳总量辐射的同时较为准确地跟踪太阳。标定实验中，SIAR-3a 在 3σ 范围内的相对均方根误差是 0.06%，已经标定到了保存在瑞士达沃斯世界辐射中心的世界辐射基准。太阳辐照实验结果表明，SIAR-3a 工作可靠，测量结果准确。

关　键　词：太阳辐射；太阳辐射总量；绝对辐射计；太阳跟踪；辐射标定

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1 Introduction

The solar radiation drives nearly all the dynamic process on the Earth's surface and atmosphere. Tiny changes of the solar radiation can have long-lasting effects on the climate of the Earth[1,2]. The World Climate Research Programme (WCRP), the World Meteorological Organization (WMO), *etc* have initiated the Baseline Surface Radiation Network (BSRN) to monitor the radiation budget including total solar irradiance. One objective of BSRN is to obtain high accuracy, long-term, surface-based measurements of total solar irradiance. BSRN required that pyrheliometers for solar irradiance measurement should have traceability to the World Radiation Centre (WRC) in Davos, Switzerland.

Numerous solutions have been proposed to measure total solar irradiance[3-7]. Two basic types of radiometers have been developed for measuring solar irradiance. One is an absolute typed referred as absolute radiometer and the other is the relative one. Measurement results of the absolute radiometer could be related to International System of Units, while the relative type can't be. Existing absolute radiometers for measuring total solar irradiance are active cavity radiometers[3], PMO6 absolute radiometers[4], SIAR absolute radiometers[6] and so on.

Measurement techniques for solar irradiance with high accuracy, precision and stability are desired for climate study, weather reports, solar energies and so on. When sun light can't enter the radiometer incidentally, measurement results for direct solar irradiance are no longer accurate. Thus, calibration for off-optical-axis angle should be introduced and calibration process is not easy. It is essential for radiometers to follow the sun accurately. However, available instruments for measuring total solar irradiance are generally provided without solar tracking devices. In order to make the radiometers always point to the sun, users of solar irradiance absolute radiometers have to purchase or develop solar tracking devices. Specific parts for fixing radiometers to the solar trackers should be designed and produced according to the size of radiometers. Products of solar tracker probably need reconstructions to fix radiometers to the solar tracking devices. These reconstructions may be somewhat complicated for the end-users such as meteorological staff. The instrument for measuring total solar irradiance should be integrated with solar tracking ability.

Inspired by the cases mentioned above, a pyrheliometer named as SIAR-3a with solar tracking ability is designed and constructed by the authors' team. Solar tracking devices with specific parts for fixing the radiometer are also developed. An absolute radiometer is integrated with solar-tracking device to measure solar irradiance, which is implemented by using an automatic double-axis solar tracker[8-10]. Description, principle and experimental results of SIAR-3a are illustrated in this paper. The SIAR-3a is able to measure the total solar irradiance and follow the sun simultaneously, and it had been calibrated to the World Standard Group (WSG) of pyrheliometers. Motivation of the development for SIAR-3a is to provide a standard instrument for measuring total solar irradiance. Pyrheliometer SIAR-3a has traceability to the World Radiation Centre (WRC) and ability of solar tracking. And SIAR-3a had been exported to Cuba as the national standard for measuring solar irradiance.

2 System overview

The pyrheliomete SIAR-3a includes an absolute radiometer and a solar tracker. It is pictorially shown in Fig. 1. The absolute radiometer SIAR-3a imposes electricity to calibrate the total solar irradiance[3-6]. The solar tracker is integrated in the measurement system. And it is employed to ensure the sun light fall into the primary cavity of the absolute radiometer incidentally.

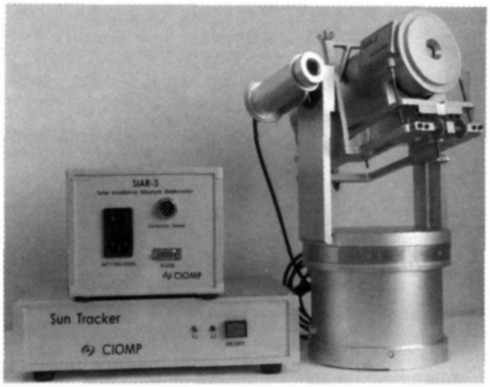

Fig. 1 Solar irradiance absolute radiometer SIAR-3a

Fig. 3 Control unit of absolute radiometer

3 Absolute radiometer

The absolute radiometer consists of a detector and a control unit as shown in Fig. 2 and Fig. 3. Schematic of the detector is shown in Fig. 4. Interior surface of the primary cavity is coated with pure silver whose effective absorptance for solar radiant flux is quite high. Field of view for the primary cavity is confined

Fig. 2 Detector of in absolute radiometer

by the primary aperture. A heater winding with low temperature coefficient is embedded into the wall of primary cavity corresponding to incoming solar irradiance. Both primary cavity and reference cavity are equipped with temperature sensors. Heat produced in the primary cavity due to the solar irradiance is conducted to the heat sink of the instrument. And the resulting temperature difference between the primary cavity and the heat sink is sensed by the passive temperature sensors.

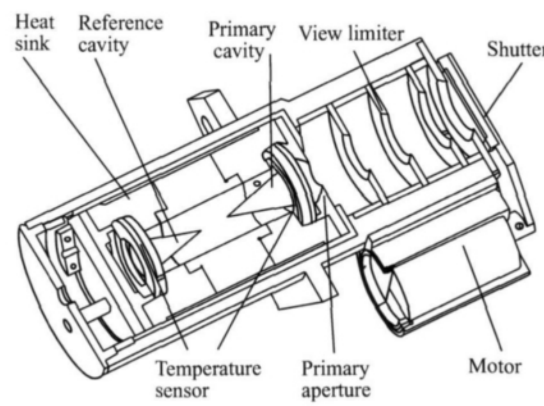

Fig. 4 Schematic of detector

The primary cavity is heated by electrical power to maintain a constant temperature. The shutter opens periodically over the precision view limiters. When the shutter is opened, sunlight is allowed to fall incident on the inside of the primary cavity and the radiometer is operating in the observation phase. Less electrical power is applied as heat is produced by the solar irradiance in the observation phase. The accurately measured reduction of electrical power compensates for the incoming solar radiant energy. When the shutter is closed, the radiometer is operating in the reference phase. Primary cavity is no more heated by sun light in this phase. Electricity has to be supplied again to maintain the same temperature for primary cavity. The changing electrical power is equivalent to the incident radiant power from the sun. As a result, an accurate estimation of the solar irradiance is obtained.

If the radiant power from the sun is perfect substituted by the electrical power, abstraction of the radiometer's operation has the form as follows,

$$S = \frac{P_r - P_o}{A \cdot \alpha}. \quad (1)$$

where S is the measured solar irradiance, A is area of the primary aperture, α is the absorptance of primary cavity for solar irradiance, P_r is the electrical power applied to the primary cavity in the reference phase, and P_e is the electrical power applied to the primary cavity in the observation phase.

More details of the absolute radiometer will be found in Ref. [5].

4 Solar tracker

Single axis and double-axis solar tracking schemes are available for the solar tracker [7-10]. Main difference between single and double-axis trackers is that the latter could follow the sun with varying weather and changing altitude angle. Two-axis tracking mechanism is employed here. The solar tracker includes a turntable and a control unit. The solar tracker follows the sun with changing solar altitude angle and solar azimuth angle. Solar altitude angle is defined as the angle between the central ray from the sun and a horizontal plane containing the observer. Solar azimuth angle is the angle, measured clockwise on the horizontal plane, from the north-pointing coordinate axis to the projection of the sun's central ray.

The turntable is shown in Fig. 5. The control unit drives the turntable to follow the sun. Key components of the control unit are a sun sensor, amplification circuits, Micro Control Unit (MCU) C8051F020 with built in A/D, two steppers with driver circuits and so on. Hardware block diagram of control unit is shown in Fig. 6. A four-quadrant photodiode is used to provide precise information about relative sun displacement as the sun sensor and it is shown in Fig. 7. Drawing schematic of the four-quadrant photodiode is shown in Fig. 8.

Fig. 5　Turntable of sun tracker

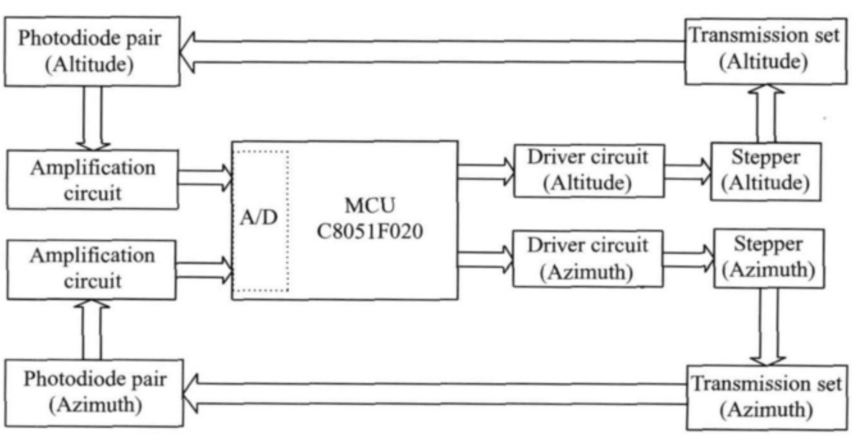

Fig. 6　Hardware block diagram of control unit

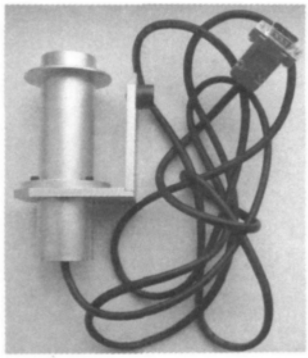

Fig. 7 Sun sensor

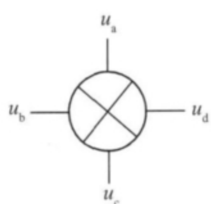

Fig. 8 Drawing schematic of the four-quadrant photodiode, u_a, u_c are voltages produced by photodiode pair corresponding to altitude angle, and u_a, u_c are voltages produced by photodiode pair corresponding to azimuth angle.

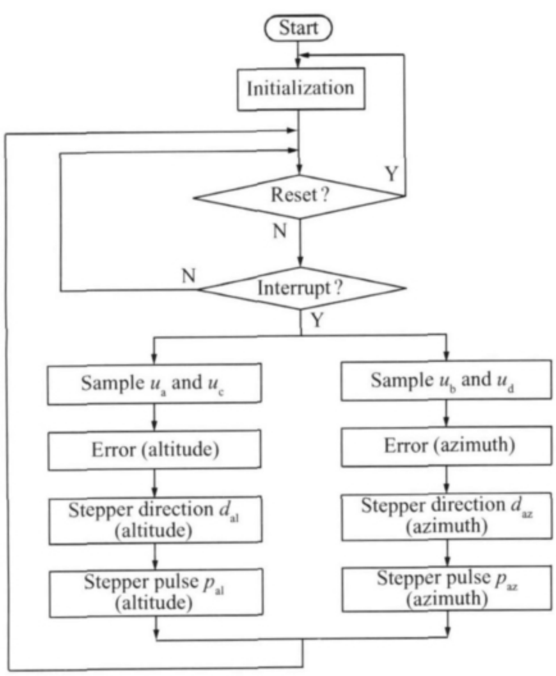

Fig. 9 Flow chart of software for solar tracker

The control software for the solar tracker is written in C language with Keil μVision 3. Fig. 9 shows the flow chart of the control scheme for the sun tracking.

Direction and number of the pulse sent to the stepper corresponding to altitude angle are calculated as below,

$$p_{al} = \begin{cases} k_{al}\,|u_a - u_c| & |u_a - u_c| > g_{al} \\ 0 & \text{otherwise} \end{cases}. \quad (2)$$

where p_{al} is pulse number, k_{al} is proportional gain, g_{al} is a specific value.

$$d_{al} = \begin{cases} 1 & u_a - u_c > 0 \\ 0 & \text{otherwise} \end{cases}. \quad (3)$$

where al denotes direction of the stepper corresponding to altitude angle.

Direction and number of the pulse sent to the stepper corresponding to azimuth angle are calculated as below.

$$p_{az} = \begin{cases} k_{az}\,|u_b - u_d| & |u_b - u_d| > g_{az} \\ 0 & \text{otherwise} \end{cases}. \quad (4)$$

where p_{az} is pulse number, k_{az} is proportional gain, g_{az} is a specific value.

$$d_{az} = \begin{cases} 1 & u_b - u_d > 0 \\ 0 & \text{otherwise} \end{cases}. \quad (5)$$

where az denotes direction of the stepper corresponding to azimuth angle.

Both g_{al} and g_{az} should be determined by trials.

5 Experiments

SIAR-3a has been calibrated to World Radiometric Reference (WRR). WRR is the base for solar measurements within the meteorological community around the world [4]. For direct total solar irradiance, WRR is maintained and transferred by World Standard Group (WSG) of pyrheliometers. WSG of pyrheliometers are managed by PMOD/WRC (Physikalisch Meteorologisches Observatorium/World Radiation Center, Davos). Measurement results of SIAR-3a had been compared with those obtained by absolute radiometers SIAR-1a and SIAR-2c [6]. Radiometers SIAR-1a and SIAR-2c had been calibrated with the WSG of pyrheliometers in Davos before.

SIAR-3a, SIAR-1a and SIAR-2c had measured total solar irradiance together for over 100 hours. SIAR-1a and SIAR-2c were pointed to the sun with a solar tracking device. Calibration coefficients of solar irradiance absolute radiometer SIAR-3a is 1.001269133. In the calibration, the corresponding rms error limit of SIAR-3a amounts to 0.06% at the 3σ level.

Measurement results of one experiment for total solar irradiance are shown in Fig. 10. The measurement time is from 9:24:35 (2009.11.19) to 13:57:47 (2009.11.19). Measurement time for one sample of solar irradiance is 90 seconds. Experiment location is in Changchun. And longitude is N23°45′44″. In Fig. 10, measurement results of SIAR-3a for total solar irradiance nearly coincided with those measured by SIAR-2c. The experiment results indicated that the solar irradiance absolute radiometer SIAR-3a worked reliably and accurately.

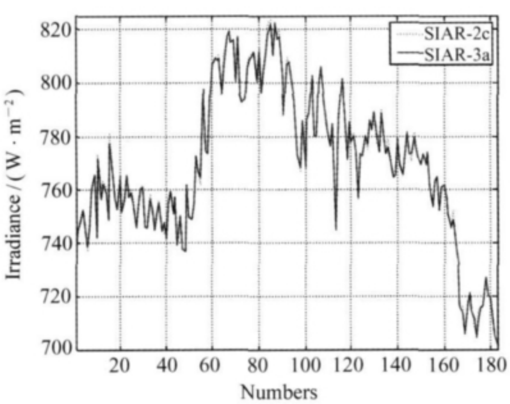

Fig. 10　Measurement results for total solar irradiance

Up to the present, no technique problems of SIAR-3a have been reported by the customer in Cuba. SIAR-3a runs well and it will be used to calibrate pyrheliometers in Cuba.

6 Conclusions

Pyrheliometer SIAR-3a with the ability of automatic solar tracking have been designed and constructed to monitor total solar irradiance accurately. Description, principle and experiments plus calibration of SIAR-3a are illustrated in this paper. A control scheme for the automatic solar tracker is proposed in this paper. SIAR-3a is integrated with an automatic solar tracker. Hardware and software designs of the solar tracker are illustrated. SIAR-3a imposes electricity to calibrate the total solar irradiance, and it includes an absolute radiometer and a solar tracker. Both hardware structure and software of the solar tracker are introduced. SIAR-3a is able to measure the total solar irradiance and follow the sun simultaneously. SIAR-3a has been Calibrated to World Radiometric Reference. In the calibration, the corresponding rms error limit of SIAR-3a amounts to 0.06% at the 3σ level. The experimental results indicate that SIAR-3a works reliably and accurately. SIAR-3a had already been sent to Cuba serving as the national standard for pyrheliometers of direct solar irradiance. Up to now, SIAR-3a works quite well and no problem have been reported yet.

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