# The total solar irradiance as measured from space since 1978

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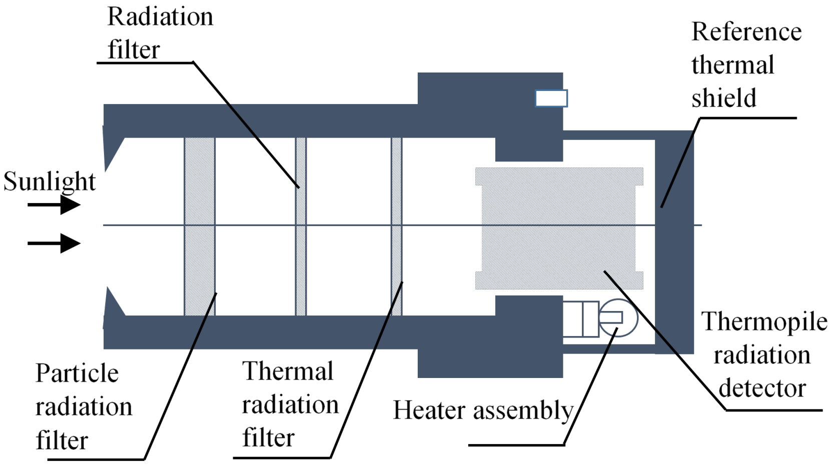
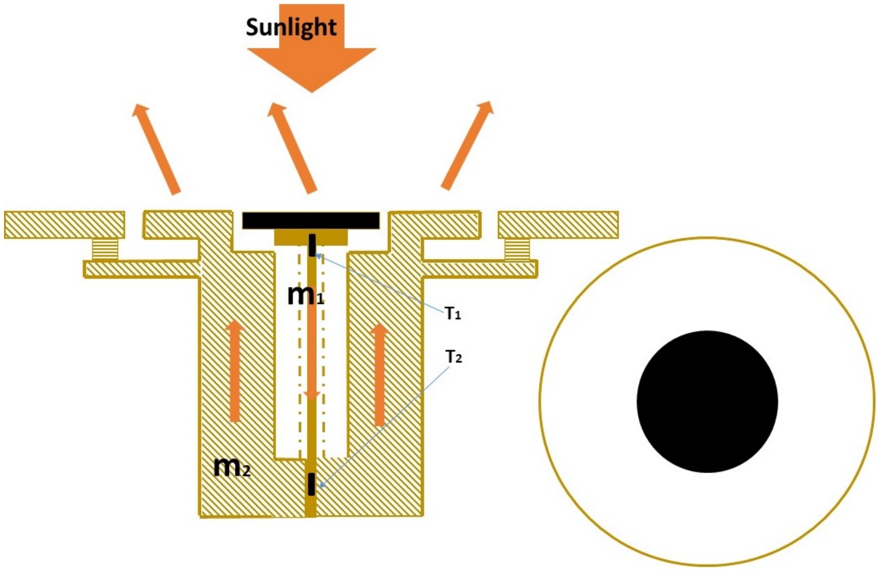
## Abstract

Sun is the key driver of the Earth's climate system, it is essential to understand the interaction between the Sun and the Earth. In this paper, the past space based Total Solar Irradiance (TSI) measurement is presented. According to the instrument operation mode and whether there is a sun tracking platform or not, the space based TSI measurements are divided into three groups: passive sun tracking, dedicated TSI missions and the experiment with an accurate sun tracking system. The configuration and characteristics of solar radiometers of each kind is introduced in detail. The TSI value, which used to be named as solar constant normalized at one astronomical unit is changed from 1365 W/m-2 to 1361 W/m-2 (during the 2008 solar minimum period). The justification of the new lower TSI value is briefly recalled and discussed. A series of solar irradiance references such as International Pyrheliometric Scale (IPS) 1956, World Radiometric Reference (WRR), and the TSI Radiometer Facility (TRF) are also separately recalled. The WRR has an estimated accuracy of 0.3% and guarantees the worldwide homogeneity of radiation measurements within 0.1% precision, which is 0.34%$ higher than the international system of units (SI), while the uncertainty of the TRF facilities to the SI is evaluated and both systems agrees in $0.01\%$. The Solar Irradiance Monitoring (SIM) experiment on FY-3C meteorological satellite measured a TSI value consistent with the new lower values after tracing to the SI scale.

% Please include a maximum of seven keywords \keywords{TSI, WRR, SI, Absolute Radiometer}

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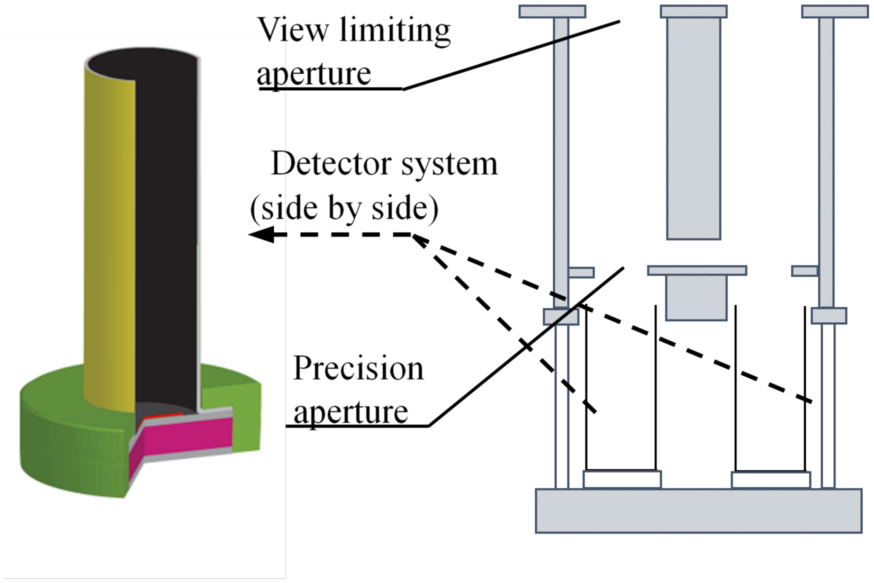
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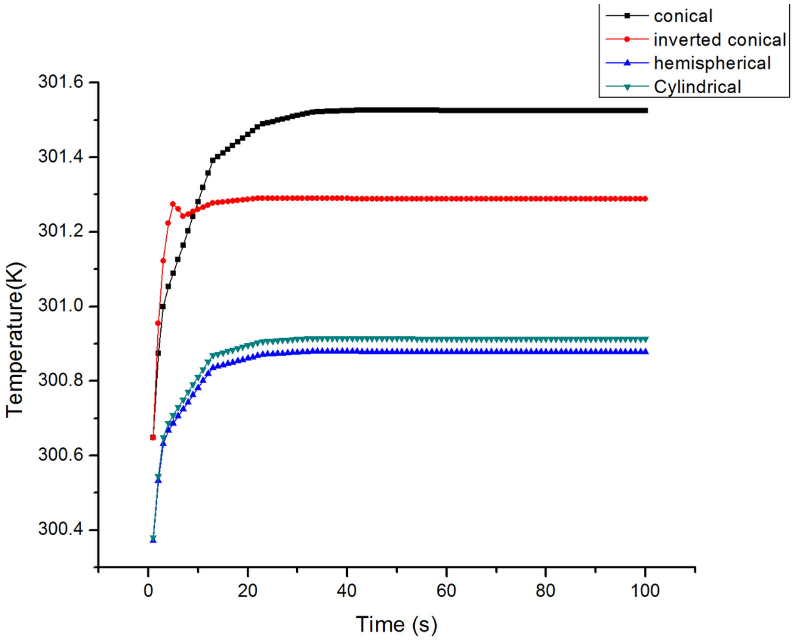

conical
inverted conical
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Cylindrical
Temperature(K)
301.6
301.4
301.2
301.0
300.8
300.6
300.4
Time (s)
0
20
40
60
80
100

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As Sun is the key driver of the Earth's climate system, it is essential to understand the interaction between the Sun and the Earth. In this paper, the past space based Total Solar Irradiance (TSI) measurement is presented. According to the instrument operation mode and whether there is a sun tracking platform or not, the space based TSI measurements are divided into three groups: passive sun tracking, dedicated TSI missions and the experiment with an accurate sun tracking system. The configuration and characteristics of solar radiometers of each kind is introduced in detail. The TSI value, which used to be named as solar constant normalized at one astronomical unit is changed from 1365 W/m$^2$ to 1361 W/m$^2$ (during the 2008 solar minimum period). The justification of the new lower TSI value is briefly recalled and discussed. A series of solar irradiance references such as International Pyrheliometric Scale (IPS) 1956, World Radiometric Reference (WRR), and the TSI Radiometer Facility (TRF) are also separately recalled. The WRR has an estimated accuracy of 0.3% and guarantees the worldwide homogeneity of radiation measurements within 0.1% precision, which is 0.34% higher than the international system of units (SI), while the uncertainty of the TRF facili-

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ties to the SI is evaluated and both systems agrees in 0.01%. The Solar Irradiance Monitoring (SIM) experiment on FY-3C meteorological satellite measured a TSI value consistent with the new lower values after tracing to the SI scale.

**KEYWORDS**
Total Solar Irradiance, World Radiometric Reference, International System of Units, Absolute Radiometer

## 1 | INTRODUCTION

The Sun is the key driver of the Earth's climate system. It continuously transmits radiant energy to the Earth, promotes the evolution of the Earth's environment, and enables the flouring of life, as the most important external energy source of the Earth's climate system. A tiny modulation of the incoming energy may cause a significant change in the Earth's radiation budget [1]. Therefore, it is necessary to establish a long-term and continuous solar irradiance monitoring system both in space and on the ground to better understand the interaction between the Sun and the Earth in terms of radiant energy circulation [2, 3].

More importantly, global warming has become an important issue that cannot be ignored in human society. The driving mechanism of solar activity on the Earth's climate system has been widely studied. In 1950s, the majority of solar physicists and climatologists believed that the energy balance of the Earth's climate system was mainly perturbed by the solar radiation [4]. However, in the past two decades, some studies have shown that massive increases in green-house gas emission are the primary cause of the global warming. It remains a question that whether the secular irradiance variations significantly influence climate change or not. On time scales of decade or multi-decades, the Sun's contribution to the global climate change is controversial [5]. At present, there is no widely accepted conclusion on this topic. One of the reasons is that the space based TSI monitoring is only accumulated about 40 years data, and the accuracy of the measurement is not consistent.

Currently, solar radiation measurement is focused on two aspects: Direct Solar Radiation (DSR) measurement and Total Solar Irradiance (TSI) measurement. The DSR refers to the solar radiation flux received per unit area at the Earth's surface, and the TSI refers to the solar radiation flux received per unit area at one astronomic unit (1AU) from the sun. All of them represent the electromagnetic radiation input from the Sun to the Earth. Accurate and stable monitoring of DSR and TSI is of a great interest for the study of the Earth's energy imbalance. Therefore, it is extremely important to continuously monitor those parameters.

## 2 | THE PAST SOLAR IRRADIANCE MEASUREMENT

The earliest measurements of solar irradiance were obtained by the Smithsonian Institution in 1902 [6]. It is the institution with the longest record of DSR monitoring, lasting from 1902 to 1962. Solar irradiance measurements can be divided into two periods, corresponding to the DSR and TSI definitions: the ground measurement period and the on-orbit measurement period. The ground measurement is represented by Smithsonian Institution, together with measurements made by other institutions using balloons, airplanes, rockets, and other platforms etc. Table 1 summarizes the experimental results of the past solar radiation measurements, which have been revised according to

**TABLE 1** Experimental data of past DSR measurement

| Year | Source | Platform | DSR (W/m$^2$) |
|---|---|---|---|
| 1902-1962 | Smithsonian | Ground | 1346 |
| 1962-1968 | Kondratyev | Balloon | 1376 |
| 1967-1968 | Murcray | Balloon | 1373 |
| 1967 | Drummond | Aircraft | 1387 |
| 1968 | McNutt | Aircraft | 1375 |
| 1968 | Kendall | Aircraft | 1373 |
| 1968 | Willson | Balloon | 1370 |
| 1969 | Plamondon | Space-craft | 1362 |
| 1969 | Willson | Balloon | 1368 |
| 1975 | Hickey | Space-craft | 1389 |
| 1976 | Willson | Rocket | 1368 |

the average distance between the Sun and the Earth. However, the measurement errors among different platforms are still as high as 25W/m$^2$ [1].

However, due to the influence of atmospheric reflection, absorption, and scattering, there are great differences between the DSR values measured at different times and locations. In some cases, the accuracy requirements of solar radiation measurement cannot be met even after accounting for the inconsistency between instruments. In order to reduce the atmospheric perturbation, since 1978 the number of space based solar radiations measurements is increasing. In 1978, the Nimbus 7 satellite developed by National Aeronautics and Space Administration (NASA) was the first spacecraft to be equipped with an Earth Radiation Measurement Instrument (Hickey-Frieden, electrically self-calibrating, thermopile based, cavity radiometer, HF radiometer) [7, 8] to measure the solar irradiance in space. In the following 30 to 40 years, missions such as SMM/ACRIM (Solar Maximum Mission/Active Cavity Radiometer Irradiance Monitor) [9, 10, 11, 12, 13], SOHO/VIRGO (SOlar and Heliospheric Observatory /Variability of Solar Irradiance and Gravity Oscillations) [14, 15, 16, 17, 18, 19], SORCE/TIM (Solar Radiation and Climate Experiment/Total Irradiance Monitor) [20, 21], PICARD/SOVAP (PICARD/SOlar VAriability Picard) [22, 23], and FENGYUN/SIM (FengYun satellite/Solar Irradiance Monitor) [24, 25, 26, 27, 28, 29] have been launched in space to monitor the TSI. Most solar radiometers can directly monitor solar irradiance and are calibrated to the International System of Units (SI).

With the various aforementioned solar radiometers launched by different institutions, the inconsistency of measurements between each radiometer is huge and have to be studied in detail. In order to eliminate this error and establish a unified monitoring reference for solar radiometers, the World Radiation Center (WRC) was established in DAVOS (Switzerland) at the fourth International Pyrheliometer Comparison (IPC) held in 1975. The TSI reference is defined as the average value of 15 solar radiometers from seven types attended the meeting at that time [6]. From the space based measurement, the absolute TSI value at 1 AU was established as 1365.4 ± 1.3W/m$^2$. However, in the past few years, a new, lower value of 1360.8 ± 0.5W/m$^2$ measured by TIM came to be considered to be more accurate [30]. The TSI values measured with different missions are given in figure 1. The major discrepancies were solved [31] after the fourth World Radiometric Reference (WRR)-to-SI comparison with three transfer radiometers at

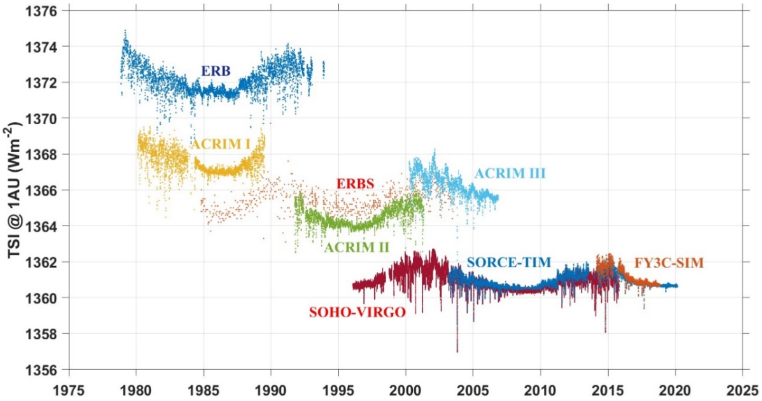

**FIGURE 1** The TSI values measured in space are plotted together. The latest version of SOHO/VIRGO, SORCE/TIM and FY3C-SIM are in a good agreement. The FY3C-SIM has been traced to the SI scale.

the National Physical Laboratory and at the TSI Radiometer Facility (TRF) located at the Laboratory for Atmospheric and Space Physics (LASP) in Boulder, Colorado. It has reported the WRR is 0.34% higher than the SI scale [32]. In this review, we have taken this into account for the FY3-C measured TSI values. After applying this correction, the FY3C TSI series is in an agreement with the value of TIM at the level of 1 W/m$^2$.

By comparing the TSI value of ERB, ERBS, SOHO-VIRGO, ACRIM-I/II/III, SORCE-TIM, and FY3C-SIM in figure 1, one can founds that due to the differences in instrument configuration, cavity types, and the procedure to correct the ambient noise, the TSI measured with different instruments at the same period do not agree with each other. The maximum inconsistency among these instruments is 0.4%. In order to keep a coherent and traceable measurements among reference radiometers, an IPC is held at Davos, Switzerland to disseminate the reference scale and to validate its stability by comparison to a large group of approximately fifty external instruments. The solar radiometer in the World Standard Group (WSG) continuously measures the DSR on the ground to reduce the inconsistency among different instruments, and to maintain the primary standard for solar irradiance.

## 3 | INSTRUMENTS

The TSI instruments are usually called Absolute Radiometers (ARs). In the development of solar irradiance, ARs are separated into two groups according to their measurement principles. The first group is the Solar Absolute Radiometers (SARs), whose measurement principle can be traced to the WRR or the international unit system. The other group is composed of the Electrical Substitution Radiometers (ESRs). The earliest SARs were proposed in Switzerland and called Angstrom radiometer in the late 19th century [6]. The second radiometer type is the Relative Radiometer, which records the temperature changes due to the solar heating effect. This kind of radiometer is more flexible to test and easy to use. However, the drawback of the system is that it needs to be calibrated with SARs to obtain the absolute value. The Relative Radiometer, then called a Pyrheliometer first was proposed by Pouillet in 1837 [6]. The measurement principle of this instrument is based on the calorimeter. Recently, a fast response bolometer type radiometer (a type of a relative radiometer) has been developed at the Royal Observatory of Belgium, and has been used to monitor the rapid changes in the solar irradiance [22]. The first experiment has been realized with the PICARD mission [23]. For space-based TSI measurement, almost all solar radiometers use the first kind of SARs to monitor

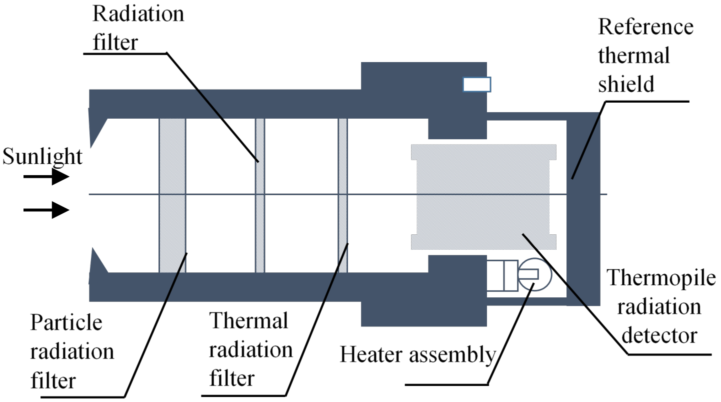

**FIGURE 2** The schematic of HF radiometer. It shows a cross-sectional drawing of one typical channel. Note, that the incoming radiation enters the sensor through a protective window. When the energy through the spectral filter, it still needs to pass through a second window and then strikes the surface of black-painted thermopile detector.

the absolute value of solar irradiance. In this paper, if there is no special statement, the solar radiometer refers to the ARs.

We summarized the space based solar radiation observations into three categories according to their operation mode:

a) Passive Sun tracking. Here, "passive" means that the working mode of the solar radiometer is passive, and the satellite carrying the solar radiometer is generally an Earth observation satellite, that is, the main mission of the satellite is remote sensing and monitoring various parameters related to the climate of Earth. There is no accurate pointing ability towards to the Sun, and the solar radiometer itself does not have a solar tracking system.

b) Dedicated solar missions. it means that the solar radiometer can accurately point to the Sun through the attitude control system of the spacecraft. This type of solar radiometer is usually designed for certain solar missions. For instance, the SOHO is a benchmark NASA-ESA solar observation mission, which has been continuously observing the Sun more than 20 years at the first Earth-Sun Lagrange point (L1) [14, 15].

c) Accurate Sun tracking. It means that the solar radiometer itself has a solar tracking system. This type of radiometer is commonly used in experiments where the main task is space experiments or solar observation.

## 3.1 | The passive Sun tracking

The earliest passive sun tracking radiometer was the HF radiometer carried on the Nimbus7 satellite [7, 8]. The HF was part of the Earth's Radiation Budget experiment (ERB). The configuration of the HF radiometer was relatively simple compared with current designs. It contained an inverted cone cavity, with its surface coated with high absorptivity black paint. The inner wall of the cavity was embedded with a heating wire resistance, and its schematic is shown in figure 2. The measurement frequency of HF radiometer is 1Hz, the integration time is 0.8s, and the uncertainty of measurement is about 0.5% [7]. In the orbital measurement stage, the HF radiometer can only observe the Sun for a few minutes when the satellite was in the proximity of the South Pole of the Earth. The angular velocity of the Sun sweeping through the HF radiometer is 4 deg/min [7].

In October 1984, NASA launched a new ERB/ACRIM-I satellite to measure the Earth's radiation budget, by mon-

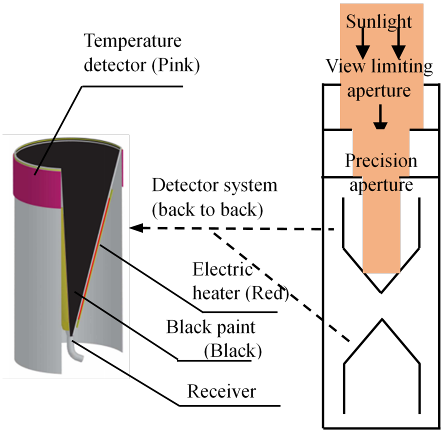

**FIGURE 3** The schematic of ACR-IV's detector system. The detector's field-of-view is defined by the secondary (view limiting) aperture at the top of an extension of the heat sink. The heat sink assembly is thermally isolated from the outer case.

itoring the solar radiation reflected by the Earth at a wave-length of 0.2-5.0 $\mu m$ and long wave radiation at a wave-length of 5.0-100.0 $\mu m$ [33, 34, 35]. In order to calibrate the measurements, the satellite has been equipped with an absolute solar radiometer called ACRIM-I. The working principle and mode of this instrument is similar to that of HF radiometer on Nimbus7 satellite, but due to the needs of other observation experiments, the ACRIM-I in ERB was only activated every two weeks. However, like the HF radiometer, ACRIM-I had the same limitation of the observation time being too short and the deviation from the pointing towards to the Sun being larger than expected.

## 3.2 | The dedicated solar missions

ACRIM-I [9, 10, 11, 12, 13] was also launched onboard the Solar Maximum Mission (SMM) Satellite. It is classified as a dedicated solar mission mode radiometer because the SMM satellite is designed for the solar irradiance monitoring and has its own pointing system towards the Sun. SMM/ACRIM-I, launched in February 1980, was the first radiometer to measure the TSI with an approximate zero solar pointing deviation in space. The ACRIM-I consists of three ACR-IV (Active Cavity Radiometers-IV) of the same type, as shown in figure 3. The first ACR sensors, types I, II and III were designed primarily to measure TSI on high altitude balloon flight experiments (1968-70) [11]. The design of each ACR-IV radiometer is the same. The on-orbit measurement time of ACRIM-I is about 9.75 years. Compared with the HF radiometer on Nimbus7, the uncertainty of the TSI measured by ACRIM-I is greatly reduced. This is mainly due to the precise solar pointing ability of the SMM satellite. Therefore, a large number of continuous, high-quality measurement data has been obtained in this experiment. However, it also caused some technical risks. For example, from November 1980 to April 1984, the stabilization system of the SMM satellite becomes insensitive, cause the deviation of the solar pointing system increased, and consequently the data quality of the TSI measurement degraded. The data quality returned to normal after the altitude control system was repaired during a Space Shuttle mission in March 1984 [36].

In December 1995, SOHO/VIRGO (SOlar and Heliospheric Observatory /Variability of solar Irradiance and Gravity Oscillations) [14, 15, 16, 17, 18, 19] was jointly developed and launched by NASA and ESA (European Space Agency). This instrument carried two solar radiometers to measure the TSI at the Earth-Sun Lagrange point (L1).

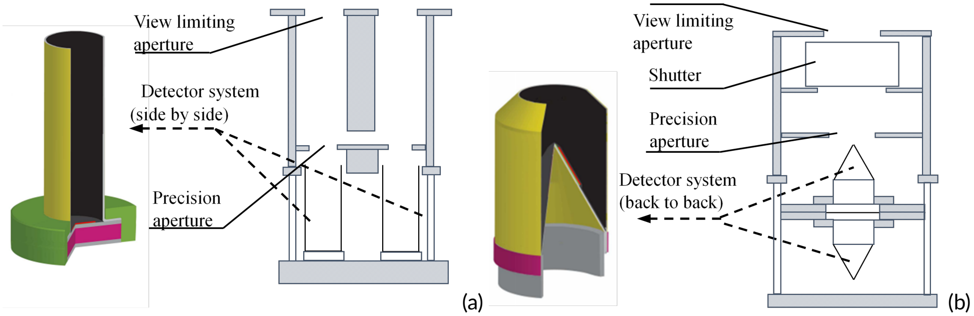

**FIGURE 4** The schematic of (a) DIARAD, and (b) PMO6-V. Although the designs of both radiometers are based on the same principle, the physical realization is different. The different geometries and coatings of the cavities will most likely lead to different degrees of degradation. Note, that the red part is the electric heater, the pink part is the temperature detector, and the black part is the black paint.

VIRGO included two independent solar radiometers, the DIARAD (Dual Irradiance Absolute RADiometer) [37, 38] developed by the Institute Royale Meteorologique Belgique (IRMB) and the PMO6-V (Physikalisch Meteorologisches Observatorium Radiometer6-V) [39] developed by the Physico-Meteorological Observatory Davos (PMOD, which is also the home of World Radiation Center), as shown in figure 4. DIARAD and PMO6-V both include two room temperature solar radiometers with the same configuration, where the reference channel is used to evaluate the materials degradation in space.

VIRGO is the first experiment in which the satellite carries two independent radiometers. For the first time, a reference is introduced to characterize the materials' degradation. This new design was inspired by ACRIM-I's experiments since the data acquired in space indicated that there was a significant attenuation in the later stage of ACRIM-I's on-orbit experiments. The latter studies suggest that the long-term exposure of ACRIM-I to the space environment is the main reason for the degradation of the instrument, so it is necessary to qualitatively or even quantitatively evaluate the degradation properties of the sensor, which must be used to correct from the measured value. PMO6-V has different optical and aperture designs from that of DIARAD. The main cavity and reference cavity of the PMO6-V are arranged back to back. The reference cavity is not exposed to the solar radiation, which serves as a reference. The cavity of DIARAD is a cylindrical, the main cavity and the reference cavity are arranged in parallel "side by side". The advantage of this structure is that the thermal environment and measurement environment of the main cavity and reference cavity are the same.

SORCE/TIM (Total Irradiance Monitor) [20, 21] is a satellite launched by NASA in January 2003, as shown in figure 5. The TIM/SORCE has reached some significant achievements such as finding a new lower solar constant and observing a white solar flare at the first time [6]. SORCE was a special satellite designed to monitor the variation of TSI and Solar Spectral Irradiance (SSI) in space. The measurement characteristics of TIM are as follows: the uncertainty of TSI measurement is less than 100ppm (parts per million), the noise level is 1ppm, and the relative uncertainty is less than 10ppm when the measurement period is one year [20, 21]. This experiment included several significant improvements in solar irradiance measurement such as the inverse precise optical aperture design and ground cryogenic calibrations facilities.

TIM introduces a new optical design which placed precision aperture in front of the view limiting aperture to eliminate stray light. In fact, almost all solar radiometers adopted another optical system before, that is, the viewing aperture was placed in the front, followed by the baffle and the precise aperture. The designers of the TIM believed

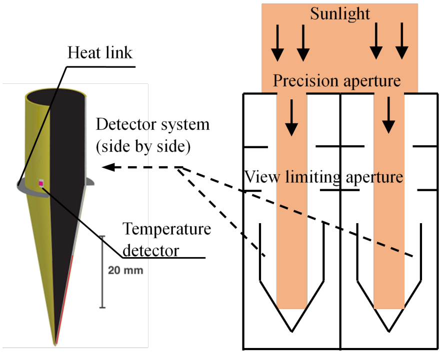

**FIGURE 5** The schematic of TIM's detector system. The surface of the absorption cavity of TIM radiometer is etched with a layer of NiP black paint, where the average absorptivity of NiP paint used is 99.9998% [32, 33]. Note, that The TIM optical layout places the small precision aperture at the front of the instrument so that only light intended to be measured enters.

this will result in too much stray light passing through the precise aperture and entering in the main cavity, which led to a higher TSI value to be measured. Therefore, by using this new optical system, the new solar constant measured by TIM was 1360.8 W/m$^2$, while the VIRGO on SOHO satellite value measured by was 1365.4W/m$^2$ [30] (which has been already traced to the WRR reference). The measurement data of TIM radiometer is considered to be more reliable [21], because this result (a new lower value) was independently obtained by the PREcision MOnitor Sensor (PREMOS) instrument onboard PICARD [40]. Consequently, the 35-year Active Cavity Radiometer Irradiance Monitor (ACRIM) TSI satellite composite time series has been revised [41]. It provides a new absolute value of the TSI (new scale) that is 0.42% lower than the original scale (available at ftp://ftp.pmodwrc.ch/pub/data/irradiance/virgo/TSI/). Finally, space observations with these experiments are consistent with a mean TSI value of 1361 ± 1 W/m$^2$, which is a representative TSI value of the 2008 solar minimum period [42].

One recent dedicated solar mission is called PICARD mission, named after the French astronomer Jean PICARD (1620-1682). PICARD/SOVAP is a satellite designed to simultaneously measure the size of the Sun, the total and spectral solar irradiance. It was launched on June 15, 2010. SOVAP is an experiment developed by the Belgian STCE (Solar Terrestrial Center of Excellence), as shown in figure 6. The experiment is composed of an absolute radiometer provided by the RMIB (Royal Meteorological Institute of Belgium) to measure the TSI and a bolometer provided by the ROB (Royal Observatory of Belgium) [22]. While SOVAP is a recurrent design, the Bolometric Oscillation Sensor (BOS) has been designed to increase the time resolution in the TSI measurement. BOS measures the Solar Irradiance, and the short and long wave radiation from the Earth with a ten seconds cadence. After carefully modelling the cavity radiation using the temperature measurement, the SOVAP produced a TSI value in close agreement (0.05% higher) with the PREMOS on the same platform and the SORCE/TIM.

## 4 | THE ACCURATE SUN TRACKING

SOVIM [43, 44] (SOlar Variability and Irradiance Monitoring) is a combination of radiometers used to observe the TSI on the International Space Station (ISS). Similar to the VIRGO experiment, the radiometer carried by SOVIM is also the PMO6-V developed by PMOD and DIARAD developed by IRMB, which are used to measure the TSI. Unlike the

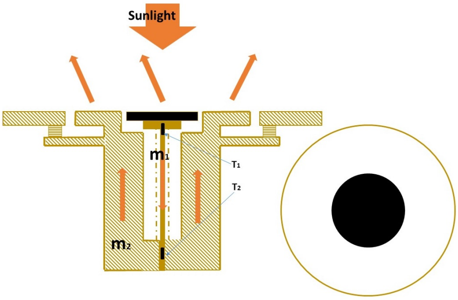

**FIGURE 6** Sketch of the $2\pi$ FoV flat bolometric oscillation sensor.

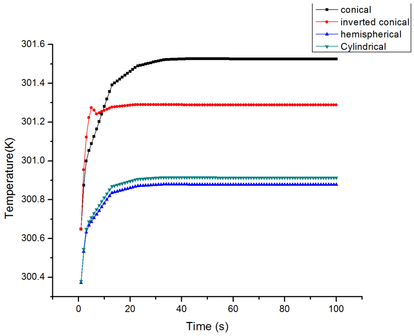

**FIGURE 7** Response diagram of temperature changing with time of each cavity types of BOS

VIRGO experiment, SOVIM itself is equipped with a solar tracking device CPD (Coarse Pointing Device).

The instrument was successfully launched on February 7, 2008. When the sun pointing Beta angle of the International Space Station corresponding to the inclination between the orbital plane of the ISS and the Sun-Earth plane is within the range of 23 °, the solar tracking device CPD can accurately track the sun. With the help of the CPD device, the measuring time of each orbit of SOVIM is up to 15 minutes, while the running time of each orbit of SOVIM is about 90 minutes. Unfortunately, the power supply of the system failed in October 2008, and the SOVIM experiment worked only for eight months.

The Solar Irradiance Monitor (SIM) of FENGYUN-3 operational meteorological satellites comprised the SIAR (Solar Irradiance Absolute Radiometer) [24, 25, 26, 27, 28, 29] series radiometer developed by Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences (CIOMP). In the field of space based TSI measurement, CIOMP has finished several initiatives in China. The SIAR series radiometers were considered for inclusion in the World Standard Group. SIAR participates in the IPC in Davos every five years to establish the solar irradiance reference which will be served as reference in China in the following 5 years.

In June 2008, the SIAR radiometer (as shown in figure 7) onboard FENGYUN-3A entered the LEO (low earth orbit) orbit. SIARs has three identical channels, and each channel is arranged in a fan shape at an angle of 13.3 °. The plane of the three channels is perpendicular to the flight direction of the satellite, and the SIAR forms a solar observation angle of 22.5 ° with the orbital plane of the spacecraft. The schematic of SIAR is shown in figure 8. This successful launch is of great significance, indicating that the solar irradiance monitoring in China has entered a new stage. The

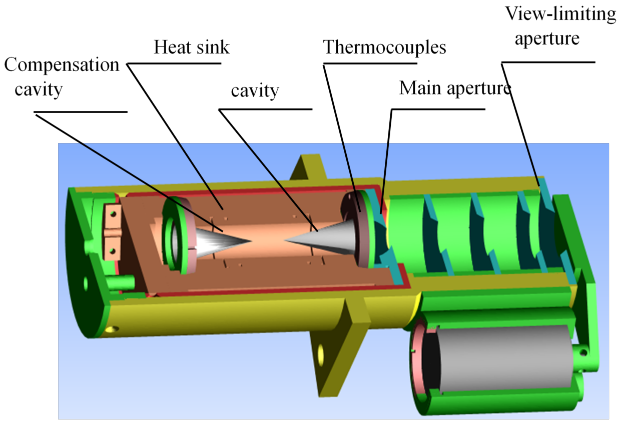

**FIGURE 8** The schematic of SIARs. Note, that it provides the first TSI data support for climate forecast and long-term Earth climate change study in China. The running time of FENGYUN 3A/SIM is from June 2008 to 2011, while for FENGYUN 3B/SIM is from November 2010 to September 2018, and for FENGYUN 3C/SIM is from October 2013 to the present.

life time of FENGYUN-3A/SIM is three years, and it provides TSI data support for climate forecast and long-term Earth climate change study in China.

In November 2010, another SIM package developed by CIOMP was successfully launched by the FengYun-3B satellite, accomplishing the goal of having multiple solar radiometers measuring the TSI at the same time in China. Through the comparison and verification between two solar radiometers of the same type, the measurement accuracy of the TSI measurement data is greatly improved. In order to further improve the measurement accuracy of SIAR series radiometers, after three years of efforts, a new SIAR type radiometer was developed, overcoming the difficulties of independent sun tracking and high-precision active temperature control. The new generation SIM package was successfully launched by FengYun-3C satellite on September 23, 2013. During more than three years of on-orbit operation, the accuracy of autonomous tracking of the sun was better than 0.1 °and the accuracy of active temperature control was better than 0.1K. The TSI value is consistent in a 99% confidence level with the new version VIRGO's measurements and TIM's value.

## 5 | RADIOMETRY REFERENCE

In order to gain a better understanding of the mechanisms underlying the Sun's contribution to the Earth's climate, the first global solar irradiance reference was established by Commission for Solar Radiation (CSR) in 1905 [6]. One of the original Angstrom pyrheliometers, called the A-Scale, served as reference at a meeting at Innsbruck [6]. Meanwhile, a silverdisk pyrheliometer was used by Smithsonian Institution, which then led to another reference named Smithsonian scale, revised 1913 (S-scale) [6].

However, there persisted a 2.5% systematic error between the A-scale and S-scale. In the subsequent 40 years, many discussions were carried out about the error between the A-scale and S-scale. The question of how to achieve a truly worldwide homogeneity of solar irradiance was raised. Therefore, in order to define a standard, a worldwide international conference on solar irradiance measurement was held in 1956, which resulted in the definition of the

International Pyrheliometric Scale (IPS 1956). The "solution" was that IPS 1956 was materialized according to neither A-scale nor S-scale, but A-scale +1.5% and S-scale −2%. The inconsistencies which were later detected confused the community and gave rise to many discussions in the following years [6]. Because of this discrepancy, the World Radiation Center was created in 1975 to establish the World Radiometric Reference (WRR). The reference consists of seven independent types of room temperature solar radiometers, including PACRAD-III, PMO-2, PMO-5, CROM-2L, CROM-3L, TMI-67814 and HF-14195, which also formed the original World Standard Group [6]. However, it is found that the world radiation standard is 2.2% higher than IPS 1956. Because WRR was defined by the integration of the measured data from multiple solar radiometers, it was considered to be more reliable. Subsequently, WRR was confirmed as a formal standard and proposed as a worldwide reference in July 1980. At this time, the uncertainty of the WRR with regards to the international system of units is 0.3% [32, 45, 46, 47].

Then in the 21st century, a NASA sponsored workshop was held at NIST in order to solve the systematic offsets of Solar Irradiance measurements obtained with different radiometers in space [48]. In this meeting, a continuation and improvement of the comparison method originally recommended by National Physical Laboratory (NPL) and PMOD/WRC was realized at the University of Colorado [49], called the "TSI Radiometer Facility (TRF)". The TRF radiometers are established mainly based on the principle of cryogenic solar radiometer because cooling electrical substitution radiometers to cryogenic temperatures leads to an improvement in absolute uncertainty levels by more than a factor of fifty [50]. The uncertainty of the TRF device with regards to the international system of units is about 0.01% [49].

## 6 | CONCLUSION

Currently, there is an immediate and urgent need for a better understanding of energy circulation in the Earth's climate system, which corresponds to the need of measuring TSI value with an uncertainty at the level of 0.01% [8]. The absolute accuracy of the TSI measurements has been improved significantly after entering the space era, but reducing the uncertainty to the 0.01% level remains a big challenge. Reaching this goal requires analyzing the uncertainty budgets remaining in the TSI measurement and finding a way to realize a periodically absolute calibration. The past experimental results suggest that the background noise of the existing solar radiometer remains significant. It is mainly due to the opto-electric nonequivalence of the solar radiometer and the nonlinear degradation of different parts of the instrument. In order to improve the accuracy, it is necessary to carry out detailed analyses of the thermal characteristics of the radiometer at each stage and apply it to optimize the heat transfer efficiency and in this way to reduce the measurement error from the ambient background radiation. Furthermore, several key parameters must be measured as accurately as possible such as the absorptivity of the main cavity and the area of the main aperture. The last but not the least objective is to set up a space based traceable radiometry calibration facilities. In order to improve the precision and accuracy of the SSI and TSI measurements over time, successive missions were planned by the international space agencies from orbiters, NASA Shuttle missions and rocket flights. In addition, to bring the accuracy of solar and terrestrial radiance and spectral irradiance absolute measurements to the next level, recently, several agencies have initiated their space radiometry traceability missions, for instance, the ESA TRUTHS mission [51], the NASA CLARREO pathfinder mission [52] and the CMA LIBRA mission [53].

*Albert Einstein*

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