Solar Phys (2017) 292:9
DOI 10.1007/s11207-016-1027-6

Initial In-flight Results: The Total Solar Irradiance Monitor on the FY-3C Satellite, an Instrument with a Pointing System

Hongrui Wang[1,2] · Jin Qi[3] · Huiduan Li[4] · Wei Fang[1]

Received: 26 September 2015 / Accepted: 18 November 2016 / Published online: 12 December 2016

Abstract The total solar irradiance (TSI) has been recorded daily since October 2013 by the *Total Solar Irradiance Monitor* (TSIM) onboard the FY-3C satellite, which is mainly designed for Earth observation. The TSIM has a pointing system to perform solar tracking using a sun sensor. The TSI is measured by two electrical substitution radiometers with traceability to the World Radiation Reference. The TSI value measured with the TSIM on 2 October 2013 is 1364.88 $\mathrm{W\,m^{-2}}$ with an uncertainty of 1.08 $\mathrm{W\,m^{-2}}$. Short-term TSI variations recorded with the TSIM show good agreement with SOHO/VIRGO and SORCE/TIM. The data quality and accuracy of FY-3C/TSIM are much better than its predecessors on the FY-3A and FY-3B satellites, which operated in a scanning mode.

Keywords Instrumentation · Space observations · Total solar irradiance

1. Introduction

Under normal conditions, most of external energy input to the Earth system is provided by the Sun through solar radiation. The solar radiation, the Earth albedo, and outgoing long-wave infrared radiation emitted from the Earth surface and the atmosphere establish a delicate thermal balance that is generally referred to as the Earth radiation

This article is a companion of the article available at doi:10.1007/s11207-016-1026-7.

Electronic supplementary material The online version of this article (doi:10.1007/s11207-016-1027-6) contains supplementary material, which is available to authorized users.

✉ W. Fang
tsim01@sina.com

1 Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Dong Nanhu Road 3888, Changchun 130033, China

2 Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Dorfstrasse 33, 7260 Davos Dorf, Switzerland

3 National Satellite Meteorological Center, No. 46, Zhongguancun Nandajie, Beijing 100081, China

4 Chuxiong Normal University, Lu Cheng Nan Road 546, Chuxiong 675000, China

budget; it defines the basic climate process on and above the Earth's surface. Changes in solar irradiance may have delicate, even uncertain impacts on the energy input to the Earth system, producing subtle effects on the climate system (Ermolli *et al.*, 2013; Solanki, Krivova, and Haigh, 2013). Knowing the variability of solar irradiance is essential to evaluate all climate-forcing items, including both natural and anthropogenic causes (Rind, 2002). To establish a continuous and accurate record of solar irradiance, it is vital to understand the solar driving of the Earth climate. The record of solar irradiance is also helpful to obtain some insight into the internal processes in the Sun's core.

The total solar irradiance (TSI) is the radiative solar power flux at the top of the atmosphere, defined over the entire solar spectrum and at 1 astronomical unit (AU). Accurate and continuous measurements of the TSI are essential quantitative records to find the Sun's signature in climate change and to understand the solar driving mechanism in the current or historic records of climate change.

Spaceborne measurements of the TSI have been made continuously for about 38 years, based on contributions from a number of spaceborne instruments (Fröhlich *et al.*, 1997; Kopp *et al.*, 2012; Meftah *et al.*, 2014b). Temporal variations in the TSI have been detected over Solar Cycles 21 to 23. However, the current TSI observation is facing unprecedented challenges; only a few spaceborne experiments with instrumentations using absolute radiometers have currently been approved.

The FY-3 missions (the FY-3A, FY-3B, and FY-3C satellites, so far) had been planned to record the TSI using electrical substitution radiometers (ESR) of one type that is referred to as the SIAR-type radiometer (Yang *et al.*, 2012; Wang *et al.*, 2015). Observations of the TSI using SIAR-type radiometers will also be performed on future FY-3 satellites in order to provide overlapping measurements with the current FY-3 satellites. However, FY-3 satellites are spacecraft that are mainly designed for Earth observation, not solar-dedicated missions like the *Solar Dynamics Observatory* (SDO; Hoeksema *et al.*, 2014; Wieman, Didkovsky, and Judge, 2014) or the *Picard* mission (Meftah *et al.*, 2014a). Therefore, a new *Total Solar Irradiance Monitor* (TSIM) with a pointing system was developed for the FY-3C satellite in order to achieve accurate solar pointing (Wang *et al.*, 2016). This article presents the first results of FY-3C/TSIM in space flight.

FY-3C/TSIM is developed by Changchun Institute of Optics, Fine Mechanics and Physics for the China Meteorological Administration (CMA). The TSIM is called *Solar Irradiance Monitor* (SIM) in CMA documents and data sites.

2. Mission Summary

The primary objective of the FY-3C/TSIM experiment is to obtain accurate measurements of the TSI at the top of the Earth's atmosphere, the same as the previous two TSIMs. However, the instrument requirements for FY-3C/TSIM are much stricter than the previous two. The TSI should be measured with higher accuracy because accurate solar pointing and better thermal stabilities are provided in the FY-3C mission. The nominal lifetime of the TSIM experiment for the FY-3C satellite is five years, the same as the spacecraft.

The FY-3C/TSIM instrument was designed to work under stable solar pointing and good thermal stabilities of the radiometers' heatsink. As defined by its routine mode, the instrument is able to follow the Sun in the daytime portion of each orbit, near the North Pole of the Earth. The routine observing mode provides observations of the Sun twice per orbit. The stable solar pointing permits a smaller field of view compared with the previous instrument FY-3B/TSIM (Girshovitz and Shaked, 2014), eliminating complex corrections of solar pointing errors. In addition to the normal closed-loop servo using the sun sensor, other backup operation modes were designed for the pointing system to make the instrument operate still normally without image feedback from the sun sensor. A lens-free design is used for the sun sensor to simplify its system design. The sun sensor consists of an optical module with a single aperture and a digital image sensor (Cetin *et al.*, 2014).

After the pre-launch test, the FY-3C satellite with the TSIM onboard was launched into orbit. After the launch, a science test of the TSIM instrument began and lasted for about three months. The main purpose of the science test is to verify that the TSIM instrument is compliant with the instrument requirements in space. A variety of instrument operations were performed for the post-launch validation of TSIM data products, including solar observation, solar tracking, temperature regulations, and so on.

After the period of the science test was concluded, the data quality of the instrument has been assessed routinely at all levels of data processing. Nearly all of the instrument data are analyzed routinely to ensure that the instrument is in a healthy state. System parameters of the instrument are generally compared to the acceptance ranges determined before launch or from historical space experiences. When any instrument parameter is out of the normal range, the instrument team is informed to determine what affects the instrument data.

3. Pre-launch Tests

The system assembly and integration of the TSIM flight product were completed in 2012. Afterwards, the instrument was tested by a specific program of performance verification to ensure that the TSIM satisfies the required levels. The pointing system had been tested on the ground, using a solar simulator to provide in-orbit conditions of sunlight.

The area of the primary apertures, the reflectance of the cavity detector from ultraviolet to infrared wavelengths (Kopp, Heuerman, and Lawrence, 2005; Witte *et al.*, 2014), and the output of the voltage reference has been measured in the pre-launch calibration. A comparison experiment was performed to obtain TSIM's traceability to the World Radiometric Reference (Wang, Li, and Fang, 2014). The time used for the comparison experiment was no more than two weeks. The radiometer package of FY-3C/TSIM was then pointed to the Sun by a sun tracker, with the standard radiometers SIAR-1a and SIAR-2c in operation simultaneously. These two radiometers had been calibrated to the World Radiometric Reference (WRR) in the 11th International Pyrheliometer Comparison (IPC-XI), 2010. The on-ground comparison experiment was performed only in the air, not in vacuum, under conditions of ambient temperature and pressure. Unfortunately, FY-3C/TSIM was not end-to-end calibrated, like the *Precision Monitoring Sensor* (PREMOS; Schmutz *et al.*, 2013) experiment using the TSI Radiometer Facility (TRF). No cryogenic radiometer, high-stable laser, or other instruments were available for the TSIM calibration.

After the comparison experiments for instrument calibration, the TSIM was integrated into the FY-3C spacecraft. The performance of the TSIM instrument was validated further by extensive pre-flight tests on the spacecraft level, under ambient or thermal vacuum conditions.

4. Post-launch Tests

The meteorological satellite FY-3C was launched on 23 September 2013 and was successfully placed in a sun-synchronous polar orbit. During the initial days in orbit, most of the

TSIM instrument modules were not allowed to work, except for the thermal control system. The radiometer package was not enabled until the temperature of the heatsink was stabilized.

After the radiometer package was enabled to measure the TSI, instrument science data were examined to validate the performance of the instrument in flight. The science test lasted for about three months. The commissioning phase began in October 2013 and ended in January 2014.

Various experiments were performed during the commissioning phase, including electrical substitution of the TSI, solar tracking control, temperature regulation, and so on. Some functions of the instrument can only be validated when the instrument is located on the spacecraft in space. For example, the solar tracking experiments on the ground were not able to completely validate the real pointing performance without the real sunlight in orbit.

In the commissioning phase, the radiometers in FY-3C/TSIM were commanded to operate in a special test mode, slightly different from their routine mode. In the routine mode, the radiometers record the TSI with a cadence of 10 minutes in the sunlight portion of the orbit. In the commissioning phase, the measurement time of each radiometer for the reference phase was changed from 5 min to 3 min in order to reduce the measurement time for a single observation.

The degradation effect of the cavity detector in the radiometers should be monitored in the space experiment, in order to make corrections for science data products. In the commissioning phase, the two radiometers in the radiometer package were enabled to measure the TSI simultaneously for nearly two months in order to determine whether their performance meets the instrument requirements. In the routine mode of the instrument, one radiometer is supposed to perform daily observation, while another radiometer will only occasionally observe the Sun and rarely as the backup channel. However, channel AR2 in FY-3C/TSIM was selected finally for occasional observation to investigate degradation had not been shut off until December 2013 since it was turned on in October 2013. Therefore the radiometer AR2 had been exposed to too much sunlight over two months. This has made the investigation of degradation for the cavity detector somewhat complex. The detector degradation will be studied in the future.

All functions of the instrument in its routine mode were tested in space. The most critical test was solar-tracking of the pointing system when the satellite leaves the eclipsed portion of the orbits. The mission operation of the TSIM experiment may be extended if the in-flight performance of the pointing system remains satisfactory. As the solar pointing errors showed puzzling behaviors on the TSIM on FY-3A and FY-3B, the solar tracking performance of the pointing system had been taken as a focus of the commissioning. The pointing system ran well in the mode of closed-loop servo control. The backup modes of the pointing system had not been tested in the commissioning phase. The performance of the thermal control system had been tested without human interference, after the initial days in orbit. The thermal control system was tested in only a constrained small temperature range, not over the full operating temperature range.

Determining the exact characteristics of the instrument, such as its precision and accuracy, is another goal of the validation activities. The instrument uncertainty was also evaluated during the test period, using the results of in-flight experiments.

From the results of space experiments, it is found that the operation of the instrument FY-3C/TSIM is stable and the instrument response is repeatable. The performance of FY-3C/TSIM is as expected, satisfying instrument requirements in system design.

5. Thermal Control Experiments

Since the instrument TSIM is a thermal system, the thermal stability of the radiometer system is critical to achieve accurate measurements of the TSI. Before TSIM was enabled to measure the TSI with solar pointing, the thermal control system had to establish a stable thermal environment for the instrument. The temperature of the radiometers' heatsink is regulated through active thermal control of the instrument, with 13 separate heating regions, including the pitch motor and the yaw motor for solar tracking, the gears, and so on. The temperature reference of each heating region can be changed by telemetry commands.

After the thermal control system was turned on, the temperature reference of each heating region in the thermal control system was carefully changed from its design value to the operational value several times, in order to establish a proper thermal state for the instrument. The heatsink temperature was stabilized around 300 K as required in the routine mode of the instrument before October 2013. Control errors in the heatsink temperature had been negligibly small. As soon as the expected instrument thermal stability was achieved, the pointing system was commanded to obtain first light for the radiometer package by telemetry commands from the ground station.

6. Solar Pointing Experiments

In order to survive the launch vibration, the motors and the gears inside the pointing system were not allowed to move by using the locking unit. Before the pointing system began its solar pointing in space, telemetry commands were sent to the TSIM, and the locking unit was released. As soon as the satellite left the eclipsed portion of the orbit, the pointing system tracked the Sun in the closed-loop servo-mode using the sun sensor, just as was required in the system design.

The solar pointing error for a single solar measurement, as the angle between the incoming sunlight and the optical axis of the radiometer package, is shown in Figure 1. The solar pointing errors were taken from the sun sensor.

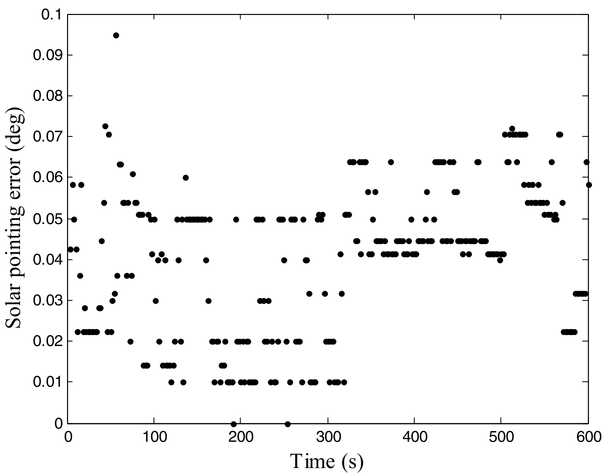

Figure 1 The solar pointing error for a single solar measurement of FY-3C/TSIM recorded at 12:00 UT, 2 October 2013.

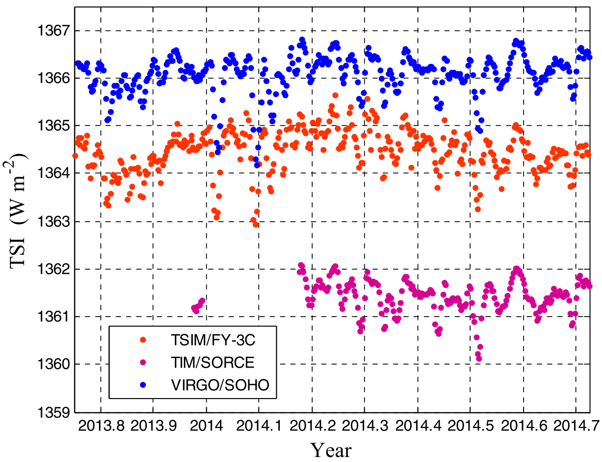

Figure 2 TSI data from FY-3C/TSIM with primary corrections (Sun–Earth distance, thermal background, and solar pointing errors).

7. TSI Observations on Orbit

The TSI data from FY-3C/TSIM are normalized by applying corrections of the Sun–Earth distance, thermal background emission, and solar pointing errors as

$$T_{\mathrm{c}} = (E - E_{\mathrm{b}}) f_{1\,\mathrm{AU}} f_{\mathrm{pointing}} f_{\mathrm{c}}, \tag{1}$$

where T_{c} is the normalized TSI at 1 AU and zero velocity, E is the original irradiance measured with each ESR in TSIM, E_{b} is the irradiance of the thermal background measured in space, $f_{1\,\mathrm{AU}}$ is a factor for Sun–Earth distance correction, f_{pointing} is a correction factor for solar pointing error, and f_{c} is a correction factor for traceability to WRR.

Since accurate spacecraft position in space is still under study, the correction for the Sun–Earth distance is used instead of the correction for the spacecraft-Earth distance, and Doppler correction is neglected in the primary corrections of TSI data.

A degradation correction (BenMoussa *et al.*, 2013) will be performed later to find a proper method to determine the degradation of the radiometer AR2, which is the channel left for occasional observation. The radiometer AR2 was exposed to sunlight for two months in the initial performance test period of the experiment. Sufficient TSI measurement data of radiometer AR2 are needed to build a mathematical model of degradation to correction for the TSI data produced by the radiometer AR1 in FY-3C/TSIM.

The TSI data of FY-3C/TSIM with these primary corrections are shown in Figure 2. Compared with TSI data from the *Variability of solar Irradiance and Gravity Oscillations* instrument on the *Solar and Heliospheric Observatory* (SOHO/VIRGO; Fröhlich *et al.*, 1997) and the *Total Irrandiance Monitor* instrument on the *Solar Radiation and Climate Experiment* mission (SORCE/TIM; Kopp and Lean, 2011), short-term TSI variations detected with FY-3C/TSIM show a nearly identical trend in a one-year period. Some TSI data from FY-3C/TSIM with primary corrections are shown in Figure 3 together with data from previous FY-3B/TSIM.

The TSI offset values between FY-3C/TSIM and SOHO/VIRGO are shown in Figure 4. In order to make comparisons with the previous TSIM operating in the scanning mode, the TSI offset values between FY-3B/TSIM and SOHO/VIRGO are also given in Figure 4. The TSI data from FY-3C/TSIM are generally smaller than those from SOHO/VIRGO; the same is true for FY-3B/TSIM. However, the TSI differences between

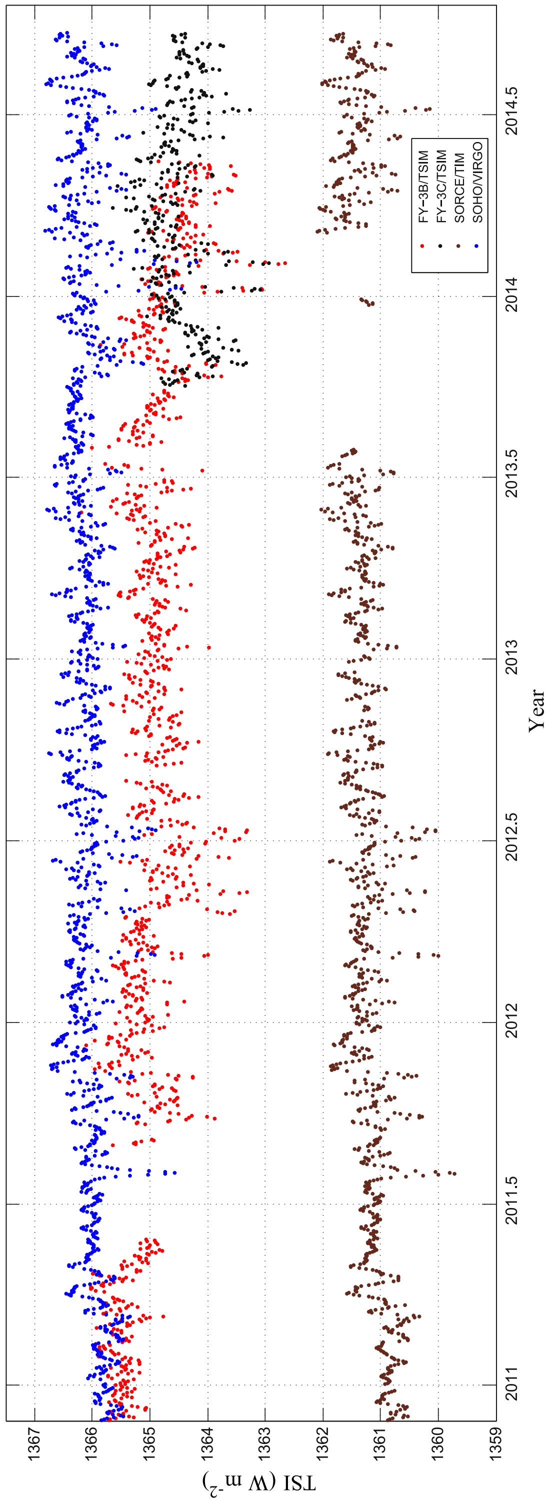

Figure 3 TSI data series of FY-3C/TSIM, FY-3B/TSIM, SOHO/VIRGO, and SORCE/TIM. The instrument FY-3B/TSIM is still operating well in space after nearly five years of operation. However, correction works for the data from FY-3B/TSIM are not completely concluded yet, and its data are only updated to May 2014.

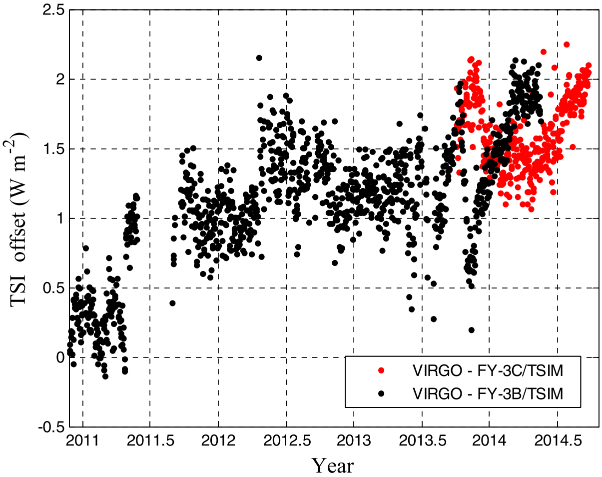

Figure 4 Offset values of TSI data between FY-3C/TSIM and SOHO/VIRGO (red) and between FY-3B/TSIM and SOHO/VIRGO (black). Some data gaps are due to instrument failure.

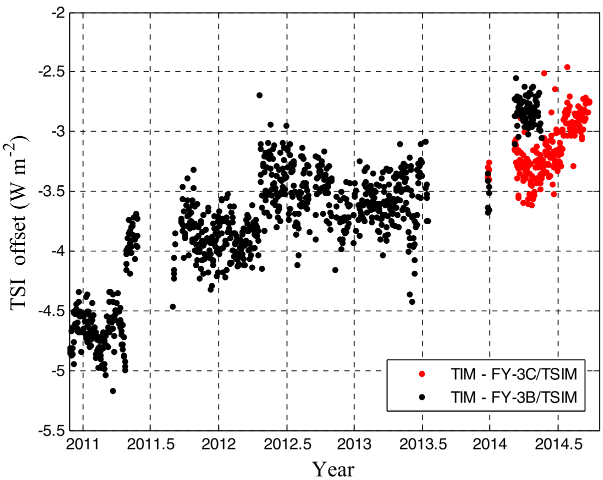

Figure 5 Offset values of TSI data between FY-3C/TSIM and SORCE/TIM (red) and between FY-3B/TSIM and SORCE/TIM (black). SORCE/TIM was switched off from July 2013 to February 2014 due to a power problem of the spacecraft, so that no data were available there.

FY-3C/TSIM and SOHO/VIRGO vary in a smaller range than those between FY-3B/TSIM and SOHO/VIRGO. The larger and time-varying differences between FY-3B/TSIM and SOHO/VIRGO may be due to incomplete corrections of solar pointing errors for FY-3B/TSIM. The TSI difference between FY-3C/TSIM and SOHO/VIRGO is about 1.5 $\mathrm{W\,m^{-2}}$, which may be attributed to instrument calibration and as yet uncorrected cavity sensor degradation of the radiometers in FY-3C/TSIM.

The TSI data from FY-3C/TSIM are generally larger than those from SORCE/TIM. The TSI differences between the two TSIMs and SORCE/TIM are presented in Figure 5. The TSI differences between FY-3B/TSIM and SORCE/TIM vary in a wider range compared with those between FY-3C/TSIM and SORCE/TIM. Again, the larger differences between FY-3B/TSIM and SORCE/TIM may be attributed to incomplete solar-pointing corrections for FY-3B/TSIM. The TSI difference between FY-3C/TSIM and SORCE/TIM is about 3 $\mathrm{W\,m^{-2}}$, which is larger than the difference between FY-3C/TSIM and SOHO/VIRGO. Both FY-3C/TSIM and SOHO/VIRGO use the same arrangement of the apertures in the radiometers (the precision apertures of the radiometers are located behind the baffles and

Table 1 Uncertainties in FY-3C/TSIM measurements. Most of the data for the uncertainty evaluation are obtained from the regular channel AR1 in October 2013.

Parameter	Value	Relative uncertainty (3σ)
E (original irradiance)	1352.837 W m^{-2}	592 ppm
E_{b} (thermal background)	-1.820 W m^{-2}	6624 ppm
$f_{1\,\mathrm{AU}}$ (correction factor for Sun–Earth distance)	1.001 611 594	200 ppm
f_{pointing} (correction factor for solar pointing error)	1.000 000 288	400 ppm
f_{c} (correction factor for traceability)	1.005 926 773	781 ppm
T_{c} (normalized TSI)	1364.882 W m^{-2}	739 ppm

view-limiting aperture), which is different from the configuration of SORCE/TIM (Kopp and Lean, 2011; Kopp, 2014).

Fehlmann *et al.* (2012) found that WRR-traceable radiometers generally agree with the SOHO/VIRGO TSI level, whereas SI-traceable radiometers agree with SORCE/TIM. This finding is now further validated by the measurements of WRR-traceable FY-3C/TSIM, as shown clearly in smaller TSI differences with respect to SOHO/VIRGO.

As indicated in Figures 4 and 5, the data quality and accuracy of FY-3C/TSIM are improved compared to the previous FY-3B/TSIM and FY-3A/TSIM instruments. Complex corrections of non-negligible and time-varying solar pointing errors that FY-3B/TSIM had suffered from are now removed from FY-3C/TSIM. The TSI recorded by FY-3C/TSIM is hoped to provide important data to study medium- and short-term solar variability in the design lifetime of the instrument.

The VIRGO TSI data used here (data file: virgo_tsi_h_6_004_1502.dat, data version 6.4) were downloaded from the ftp server ftp.pmodwrc.ch. The TIM data used here (SORCE Level 3 TSI 24-h data, data version 17) were downloaded from the SORCE data website at http://lasp.colorado.edu/home/sorce/data/tsi-data/.

Relative uncertainties given in Table 1 are evaluated using data obtained from the routine channel AR1 of FY-3C/TSIM in October 2013, except for the original irradiance (E). Since the incoming sunlight is always changing, it is difficult to evaluate the uncertainty in the original solar irradiance. The uncertainty in the original irradiance is not evaluated in space, but in the ground experiments, and the radiometer was set to run in its test mode in the ground experiments (Fang *et al.*, 2014).

The values given in Table 1 are the solar observation data obtained by AR1 at 13:23 UT on 2 October 2013. Any variation in light sources (such as the laser as the simulation light source) was removed in the test mode to obtain the real characteristics of the radiometer (Rubenchik, Fedoruk, and Turitsyn, 2014). The relative uncertainty in TSI data from FY-3C/TSIM is 739 ppm, which is smaller than the 910 ppm of relative uncertainty in TSI data from FY-3B/TSIM.

TSI Level-1 data products of FY-3C/TSIM can be downloaded from the CMA website http://satellite.cma.gov.cn/PortalSite/Data/Satellite.aspx. TSI Level-1 data products of FY-3B/TSIM can also be found there. It should be noted that the TSIM is called ‘SIM’ instead in the data site. In addition, the correction methods for TSI data given in this article are somewhat different from those used by CMA to produce the Level-1 data product available at the CMA data site.

8. Summary

As of November 2016, FY-3C/TSIM has made daily observations of the TSI for more than three years. Accurate solar pointing has been achieved by the TSIM itself using the pointing system in a narrow time window no more than 20 min on the FY-3C satellite, which has mainly been developed for Earth observation. The TSI value derived from the measurement made on 2 October 2013 without correction for the cavity degradation is 1364.88 $\mathrm{W\,m^{-2}}$ with an uncertainty of 1.08 $\mathrm{W\,m^{-2}}$ after correcting for the Sun–Earth distance, thermal background emission, and solar pointing errors. The effects of diffraction and backscattering of the view-limiting aperture were not included.

The TSIM has been operated normally in the closed-loop servo-mode in the daytime portion of the orbit using the sun sensor. Short-term TSI variations recorded with FY-3C/TSIM show good agreement with SOHO/VIRGO and SORCE/TIM. Since the accurate solar pointing is achieved by the sun sensor with a smaller field of view in the case of FY-3C/TSIM, the TSI data quality from FY-3C/TSIM is much better than from the previous FY-3B/TSIM instrument, which is running in scanning mode. The TSI differences between FY-3C/TSIM and SOHO/VIRGO and SORCE/TIM are continuous in time and smaller than the previous FY-3B/TSIM. FY-3C/TSIM is expected to record the TSI in the next three years or even longer, overlapping in time with its predecessors SOHO/VIRGO and SORCE/TIM.

Acknowledgements This work is supported by Development Plan Project for Science and Technology of Jilin Province (No. 20130101044JC), Basic Research Project for application of Yunnan Province (No. 2012FD050), and Natural Science Foundation of China (No. 61077080, No. 21643006). The China Scholarship Council also provides financial support and international-travel support to this work. Numerous people have contributed to this work in the Changchun Institute of Optics, Fine Mechanics and Physics, satellite teams, the China Meteorological Administration, and other organizations. The constructive remarks, suggestions, and help from the referee are highly appreciated by the authors. The TSI dataset of SORCE/TIM was provided by the TIM team, Laboratory for Atmospheric and Space Physics, University of Colorado, through the SORCE website. The unpublished TSI data of SOHO/VIRGO were provided by the VIRGO team through its FTP site at PMOD/WRC, Davos, Switzerland.

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