Total solar irradiance data record accuracy and consistency improvements

Greg Kopp¹, André Fehlmann², Wolfgang Finsterle², David Harber¹, Karl Heuerman¹ and Richard Willson³

¹ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303, USA
² Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center, Davos, Switzerland
³ ACRIM, 12 Bahama Bend, Coronado, CA 92118, USA

E-mail: Greg.Kopp@LASP.Colorado.edu

Received 17 September 2011
Published 2 March 2012
Online at stacks.iop.org/Met/49/S29

Abstract

Continuity of the 33-year long total solar irradiance record has been facilitated by corrections for offsets due to calibration differences between instruments, providing a solar data record with precision approaching that needed for Earth climate studies. Recent laboratory tests have (1) improved measurement absolute accuracy to mitigate potential future data gaps, (2) helped explain the causes of instrument offsets and (3) improved consistency between the international references upon which various instrument calibrations are based.

1. Introduction

Total solar irradiance (TSI) is a measure of the spectrally and spatially integrated radiant energy from the Sun, which is the dominant energy source driving the Earth’s climate system. The 33-year spaceborne TSI record is used in climate studies for attributing the portion of global and regional climate effects due to solar variability over modern and—via proxies—historical times [1, 2].

Such studies utilize composite records that are based on the spaceborne TSI instrument measurements shown in figure 1. The offsets between these measurements, which are as large as 0.35% for current instruments, are due to calibration differences, which, along with differing instrumental drifts, must be corrected to create a composite TSI record needed for climate studies.

Because of the instrument offsets and insufficient absolute accuracy, measurement continuity has been imperative and has led to requirements for accuracy improvements and to a desired understanding of the causes of the offsets [3, 4]. Recent tests with ground-based versions of the flight TSI instruments at the new TSI Radiometer Facility (TRF) [5] have provided an improved understanding of the causes of these instrument offsets and suggest higher than stated uncertainties associated with current flight measurements. Internal instrument scatter appears to be the primary cause of erroneously high reported TSI values, favouring a TSI value of (1360.8 ± 0.5) W m⁻² as best representative of solar minimum [6].

2. TRF calibration facility validates measurement accuracy

None of the spaceflight instruments in figure 1 has been calibrated as an end-to-end system for irradiance, as no facility capable of providing the needed accuracies existed prior to launch. The new TRF provides such capability, being the world’s only facility to validate TSI instruments for irradiance directly against a NIST-calibrated cryogenic radiometer at full solar power levels while operating under vacuum. Additionally, control of the incident TRF beam enables diagnostics that help determine the causes of instrument differences.

The TRF creates a uniform incident beam having typical solar irradiance levels (~1361 W m⁻²) and a programmable diameter. This beam enters a vacuum system containing both the TSI instrument under test and a reference cryogenic radiometer. This reference is calibrated by NIST against their Primary Optical Watt Radiometer (POWR) to 98 ppm uncertainty. A NIST-calibrated primary aperture, positioned as the cryogenic radiometer’s foremost element to reduce internal scatter, allows irradiance measurements of incident beams. By translating the defining precision aperture of the
Figure 1. The 33-year TSI record is the result of a number of different instruments. Measurement overlap helps correct for the majority of the differences between instruments shown in this plot from early 2011.

Figure 2. A test TSI instrument (upper right) and NIST-calibrated reference cryogenic radiometer (lower right) are alternately translated into the same portion of the stationary incident TRF’s uniform beam (green) to allow irradiance comparisons at solar power levels in vacuum.

cryogenic radiometer and that of the TSI instrument under test into the same position in the stationary incoming beam, the TSI instrument’s irradiance measurement is compared against that of the reference. A cutaway view of the TRF is shown in figure 2, and a sample irradiance comparison is plotted in figure 3.

Newer spaceflight instruments, particularly the PICARD/PREMOS instrument launched in 2010 and the Glory Total Irradiance Monitor (TIM), a follow-on (that was unfortunately lost in the 2011 Glory launch failure) to the TIM currently flying on NASA’s SORCE mission, benefited from these reference calibrations. Reference [6] reports that the Glory/TIM flight instrument reads lower than the SI-traceable TRF irradiance reference scale by an average of (0.012 ± 0.020)%, while the SORCE/TIM ground unit is lower by (0.035 ± 0.025)%, with both values being consistent within the instruments’ stated accuracies. The PREMOS has now transferred this reference SI-traceable calibration to space. Baselined to the reference TRF, the flight PREMOS instrument may help link the existing on-orbit instruments with future TSI instruments compared on the TRF, helping mitigate potential future—and still undesirable—measurement gaps.

3. Scatter, power and diffraction are the causes of instrument differences

Diagnostics during TRF tests have helped explain the causes and magnitudes of the on-orbit differences. Scattering and diffraction within the sensors and errors in basic power measurement are found to be the principal sources of differences between the originally reported TSI results. Instruments tested to date include a ground-based
Total solar irradiance data record accuracy and consistency improvements

Figure 3. Differences between temporally alternating irradiance measurements from a TSI instrument (blue) and the TRF’s cryogenic radiometer (red) allow end-to-end instrument calibration validations. These show the ACRIM3 instrument measuring irradiances 4418 ppm higher than the TRF, an effect attributed to scatter. Alternating measurements accounts for low frequency drifts of incident beam power and thermal effects.

SORCE/TIM, the flight Glory/TIM, a PMO6 radiometer representative of the SoHO/VIRGO, a ground representative of the ACRIMSat/ACRIM3, and a flight and a ground-based PICARD/PREMOS.

A fundamental optical design difference between the TIM and all other radiometers is the position of the precision aperture whose area defines the sunlight collected by the instrument relative to the cavity radiometer measuring the collected radiant power. The TIM locates this small aperture at the front of the instrument, allowing only the light intended for measurement into the instrument, the cavity radiometer measuring the collected radiant power. All other radiometers have a larger entrance aperture at the front and this small precision aperture inside, close to the radiometer cavity itself (see figure 4). This layout allows two to three times the light intended for measurement into the instrument interior, where it can scatter into the radiometer cavity and cause erroneously high signals.

By expanding the uniform light beam entering the TRF from underfilling to overfilling an instrument’s larger entrance apertures, the interior of an instrument with this traditional configuration is progressively illuminated and scatter sources are diagnosed. The PREMOS flight instrument shows scatter effects of 0.04% while a ground-based version has higher measured scatter at 0.10%. The VIRGO ground unit shows measured scatter of 0.15% while the ACRIM3 has scatter contributions as large as 0.51%.

Diffraction effects are present in all these instruments at the ∼0.1% level. Straightforward to estimate via fundamental optical calculations, diffraction was accounted for prior to testing by the TIM, PREMOS and VIRGO instruments. NIST estimates diffraction causes a 0.16% signal contribution in the ACRIM3, and this effect is embedded in the TRF scatter diagnostics reported here for that instrument.

Table 1 provides a summary of the optical power, irradiance and scatter effects for the instruments tested on the TRF. Note the increase in measured irradiance signals for the non-TIM instruments as the entrance aperture is overfilled and the internal instrument sections are illuminated, allowing scattered light to enter the primary aperture and radiometer; this increase is attributed to uncorrected scatter and diffraction, estimated in the fifth column. Principal sources of scale differences for PREMOS and VIRGO include large applied power errors of 0.6% and 0.7%, respectively; for the PREMOS flight instrument, these were calibrated prior to launch, but it is uncertain how such power errors might affect the flight VIRGO results.

The magnitudes of these scatter and optical power effects are comparable to the measured instrument offsets in figure 1, and likely explain the majority of the on-orbit differences between TSI instruments, although applying these monochromatic lab scatter measurements to flight instruments that have been in orbit for several years requires adding large uncertainties to the corrections.

The ACRIM team has applied these TRF calibrations retroactively to their ACRIM3 flight data, correcting for much of the scatter and diffraction in the foremost sections of the instrument. Preliminary data from the PREMOS instrument are now also available. With the TRF corrections, the agreement between the flight TSI instruments is significantly improved over that shown in figure 1. The latest TSI data record, with these corrections applied to ACRIM3 and PREMOS, is shown in figure 5.

4. Linking international references

Via comparisons at NPL, the NIST-calibrated TRF and the World Radiation Reference (WRR), the PREMOS instrument
Table 1. Difference relative to TSI Radiometer Facility.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measured power offset</th>
<th>Irradiance: precision aperture overfilled</th>
<th>Irradiance: entrance aperture overfilled</th>
<th>Difference attributable to scatter error</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>SORCE/TIM ground</td>
<td>−0.035%</td>
<td>−0.035%</td>
<td>−0.035%</td>
<td>0.000%</td>
<td>0.025%</td>
</tr>
<tr>
<td>Glory/TIM flight</td>
<td>−0.020%</td>
<td>−0.012%</td>
<td>−0.012%</td>
<td>0.009%</td>
<td>∼0.038%</td>
</tr>
<tr>
<td>PREMOS-1 ground</td>
<td>−0.049%</td>
<td>−0.104%</td>
<td>−0.005%</td>
<td>0.037%</td>
<td>∼0.027%</td>
</tr>
<tr>
<td>PREMOS-3 flight</td>
<td>0.631%</td>
<td>0.605%</td>
<td>0.642%</td>
<td>0.037%</td>
<td>∼0.027%</td>
</tr>
<tr>
<td>VIRGO-2 ground</td>
<td>0.730%</td>
<td>0.743%</td>
<td>0.897%</td>
<td>0.154%</td>
<td>∼0.025%</td>
</tr>
<tr>
<td>ACRIM3 ground</td>
<td>0.021%</td>
<td>0.308%</td>
<td>0.534%</td>
<td>0.506%</td>
<td>0.059%</td>
</tr>
</tbody>
</table>

Figure 5. With the TRF corrections, the agreement between flight instruments is much improved over that shown in figure 1.

has linked the national labs at NPL with those at NIST, showing agreement in optical power measurement of 999 989 ± 0.000 297 ($k = 1$) [8]. Similar comparisons indicate that the WRR reads slightly higher than SI in optical power by 1.001 805 ± 0.000 913 ($k = 1$) and higher yet in irradiance (1.003 358 ± 0.000 923, $k = 1$), likely due to internal scatter in the WRR instruments.

SORCE/TIM participation in the 2010 International Pyrheliometer Comparison XI linked the TIM to the WRR, albeit with inconclusively high uncertainties due to the air-to-vacuum and atmospheric scatter corrections needed because the TIM and the WRR have very different fields of view; the TIM acquires light from nearly 2.7 times the total sky area as the WRR based on instrument response functions (plotted in figure 6). The TIM’s larger field of view makes it more sensitive to circumsolar scatter, which was particularly high during the IPC-XI observing campaign because of a large Saharan Dust Event (SDE) that started near the beginning of the campaign. Although the WRR would nominally measure solar irradiances higher than the TIM in the absence of atmospheric scatter due to the internal instrument scatter discussed above, during IPC-XI the TIM actually measured higher signals than the WRR by 1.002 704 ± 0.001 420 [9]. Much of this difference is likely due to the high atmospheric scatter combined with the TIM’s larger field of view, although a portion (0.0015 ± 0.0010) is also due to a thermal background correction that the TIM applies that is not applied by the WRR instruments. The corrections for scatter, thermal background and non-equivalence when operating in air each have high uncertainties, making the uncertainties in this ground-based comparison between instruments having disparate fields of view similarly high. Currently no significant conclusions can be drawn from the TIM IPC-XI comparison.

5. Summary

Recent ground tests with the TSI Radiometer Facility indicate the causes of the offsets between the ACRIM3, PREMOS, VIRGO and TIM TSI instruments are principally internal instrument scatter for ACRIM3 and a combination of scatter and measured optical power for VIRGO and PREMOS. TRF-derived corrections shown in table 1 have been applied by the ACRIM3 and PREMOS teams, and produce agreement of these instruments with the TIM results to within 0.05%. The ground-based VIRGO optical power and scatter corrections, if applicable to the flight instrument, would place its results nearly as much below TIM as they are currently above.
Total solar irradiance data record accuracy and consistency improvements

Figure 6. The TIM has a much broader instrument response profile than the WRR-designed instruments in the IPC, making it much more sensitive to atmospheric circumsolar scatter, which was high during the IPC-XI.

The TRF facility is a unique diagnostic tool for validating TSI instrumentation accuracy. Its use will make the existing TSI climate data record more robust against a potential future data gap. The NPL and NIST radiometric references are in good agreement for measuring optical power, while the WRR reads slightly higher in both optical power and irradiance based on comparisons with the PREMOS radiometers (but currently inconclusive from the TIM’s participation during the ground-based IPC-XI). The on-orbit SORCE/TIM, ACRIMSat/ACRIM3 and PICARD/PREMOS radiometers are now reporting TSI values within instrument uncertainties of each other.

Acknowledgment

NASA’s Glory program supported the development of the TSI Radiometer Facility that enabled this research.

References