

THE TOTAL IRRADIANCE MONITOR (TIM): SCIENCE RESULTS

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Abstract. The solar observations from the Total Irradiance Monitor (TIM) are discussed since the SOLar Radiation and Climate Experiment (SORCE) launch in January 2003. The TIM measurements clearly show the background disk-integrated solar oscillations of generally less than 50 parts per million (ppm) amplitude over the ~ 2 ppm instrument noise level. The total solar irradiance (TSI) from the TIM is about 1361 W/m^2 , or $4\text{--}5 \text{ W/m}^2$ lower than that measured by other current TSI instruments. This difference is not considered an instrument or calibration error. Comparisons with other instruments show excellent agreement of solar variability on a relative scale. The TIM observed the Sun during the extreme activity period extending from late October to early November 2003. During this period, the instrument recorded both the largest short-term decrease in the 25-year TSI record and also the first definitive detection of a solar flare in TSI, from which an integrated energy of roughly $(6 \pm 3) \times 10^{32}$ ergs from the 28 October 2003 X17 flare is estimated. The TIM has also recorded two planets transiting the Sun, although only the Venus transit on 8 June 2004 was definitive.

1. Introduction

Attempts to measure the total solar irradiance (TSI) began in earnest in the 1830s, with independent ground-based measurements by Claude Pouillet and John Herschel. Their results were low by nearly a factor of 2 because of absorption by the Earth's atmosphere. Even balloon-borne measurements in the 1900s lacked the instrumental accuracy to detect the $\sim 0.1\%$ short-term changes due to solar activity, let alone the similar level of TSI variations over an 11-year solar cycle. It was not until multi-year measurements from space were available that changes in the TSI were accurately measured and the misconception of a "solar constant" changed. This space-borne TSI record has been uninterrupted since 1978, thanks to overlapping measurements from different missions (see Figure 1). While instrument offsets are large, each instrument has high precision and is able to detect small changes in the TSI caused by variability in solar activity. Increases of 0.1% in TSI during times of high solar activity over the 11-year solar cycle are unambiguous. Short-term changes of $\sim 0.3\%$ appear directly attributable to variations in solar magnetic activity (Fligge, Solanki, and Unruh, 2000). However, from the two solar minima observed to date, possible secular changes in the TSI are at low enough level to be difficult to discern (Willson and Mordvinov, 2003; Fröhlich, 2002). Determination of such long-term solar variability will rely on longer-duration measurements of high accuracy, for which continued space-borne TSI measurements are essential.

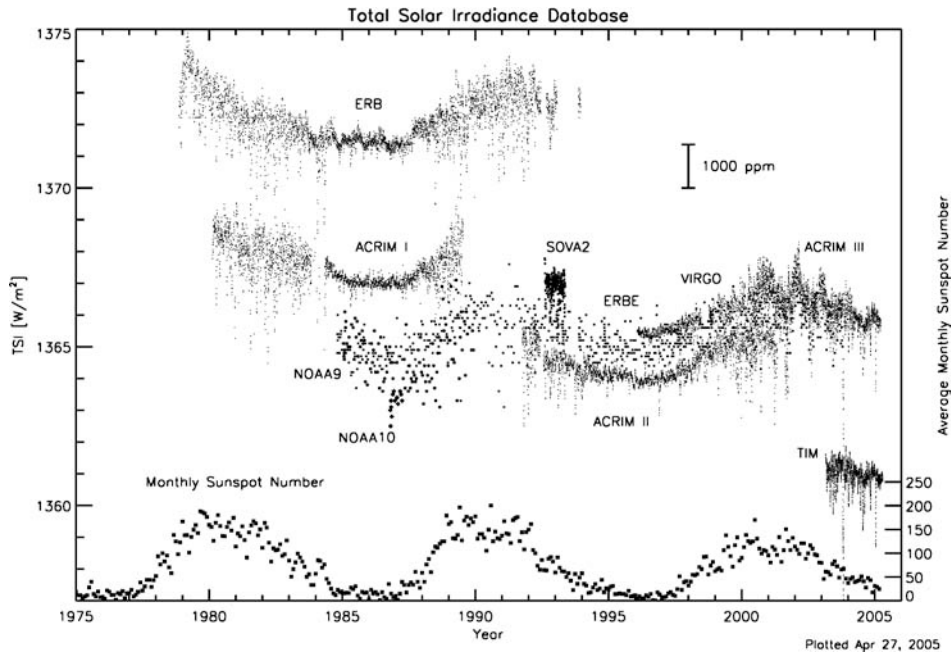


Figure 1. The space-borne TSI database. Space-borne measurements of the TSI show $\sim 0.1\%$ variations with solar activity on short and long time scales. The TIM values are lower than those reported by other instruments. Early instruments showed even larger offsets, and these may be indicative of current capabilities of space-borne radiometry. (These data are available from the following sources: the space-borne TSI plot is available via spot.colorado.edu/~kopp/TSI. The solar irradiance data from SORCE are available via lasp.colorado.edu/sorce/tsi_data.html. The solar irradiance data from VIRGO are courtesy of the VIRGO team via www.pmodwrc.ch/. The solar irradiance data from ACRIM are courtesy of Dr. Richard Willson via www.acrim.com. The solar irradiance data from ERBE are courtesy of Robert B. Lee III. The monthly sunspot data and the NOAA and ERB spacecraft TSI data are courtesy of www.ngdc.noaa.gov/stp/SOLAR/solar.html.)

Very simplistically, short-term decreases in the TSI can be largely attributed to dark sunspots, while values above normal are generally due to bright faculae. The actual Sun displays a much greater continuum of activity however; example solar atmosphere models by Fontenla *et al.* (1999) include eight components describing solar activity, including average supergranules, faint supergranules, average network, bright network, average plage, bright plage, sunspot umbrae, and sunspot penumbrae. It is the spatial and spectral integral of the continuum of solar activity type, each with some center-to-limb variation, that contributes to the TSI measurement.

The TSI measured by the Total Irradiance Monitor (TIM) is plotted in Figure 2. These data have been corrected for instrument degradation, background thermal emission, and instrument position and velocity. On time scales of a few minutes, the TIM measures small fluctuations in the TSI (see Figure 3) having typical amplitudes

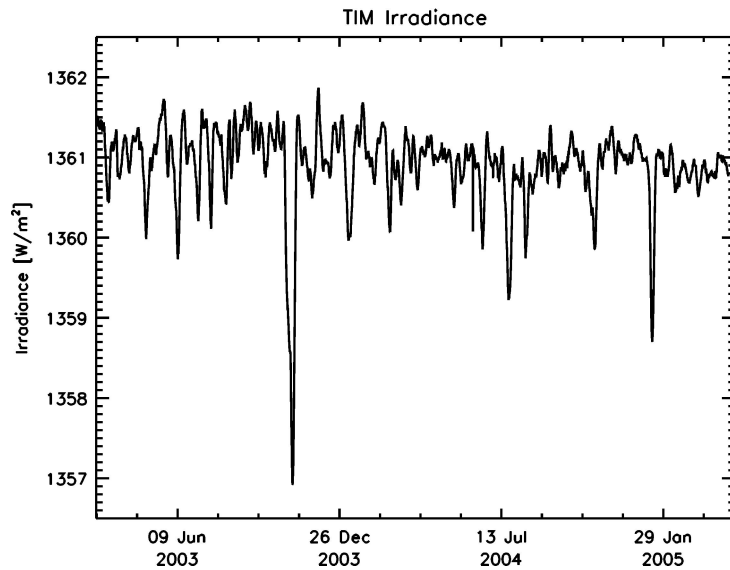


Figure 2. TIM TSI record. This plot shows the TIM Version 4 data of total solar irradiance since launch. The gradual decrease with time is from the Sun approaching solar minimum. The short-term decreases are due to the passage of sunspots.

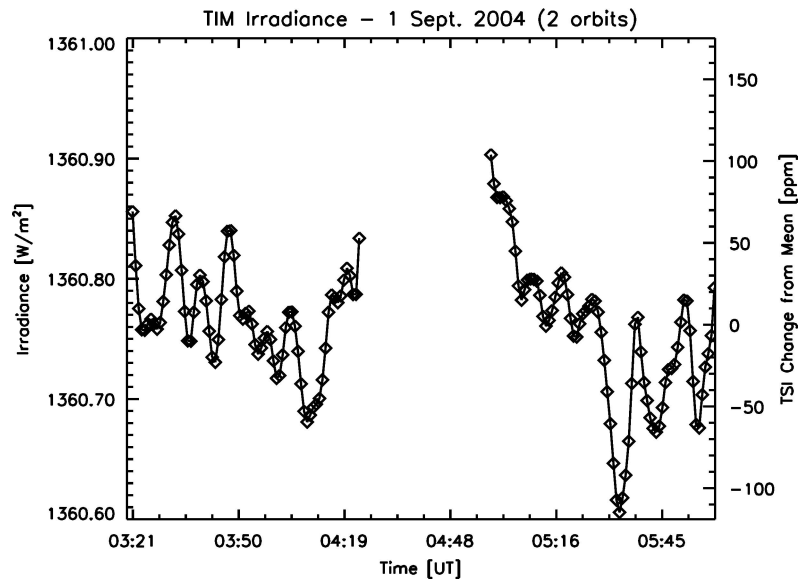


Figure 3. Solar oscillations in TSI. Changes of several tens of ppm in the TSI time series are due to globally averaged solar oscillations. The gap in these data is when the SORCE spacecraft was in the Earth's shadow.

of a few tens of parts per million (ppm). These are the disk-integrated signals due to solar oscillations, the superposition of millions of modes of trapped acoustic waves with periods near 5 min. These oscillations have been observed by other TSI instruments (Fröhlich and Lean, 2004).

2. Comparison with Other TSI Instruments

The TIM TSI data and that from other space-borne TSI instruments are plotted in Figure 1. One major result is that the TIM's measured value of TSI at 1 AU is lower than that measured previously; a solar minimum value of 1361 W/m^2 is estimated from the current TIM data. An actual measurement during the upcoming solar minimum, a period in the Sun's 11-year cycle with very little magnetic activity, will be acquired in a couple of years. This lower value of TSI may affect Earth climate models that have been using higher values of solar input.

The TIM measures TSI values 4.7 W/m^2 lower than the VIRGO¹ and 5.1 W/m^2 lower than ACRIM III.² This difference exceeds the $\sim 0.1\%$ stated uncertainties on each instrument, and continues to be a source of discussion. Differences between the various data sets are solely instrumental and will only be resolved by careful and detailed analyses of each instrument's uncertainty budget. Unfortunately documentation and test samples from the earliest missions may no longer be accessible.

Having recently completed a thorough examination of the TIM calibrations, uncertainties, and processing algorithms, we find no causes that could contribute to the TIM value being in error at this level. The TIM calibrations and the intra-instrument agreement between all cavities indicate a $1\text{-}\sigma$ standard deviation on the TIM TSI values of 300 ppm, or 0.4 W/m^2 .

The internal TIM consistency, measured by the 270 ppm deviations between the four TIM radiometers, is plotted in Figure 4 as a function of time without any corrections for instrument degradation. The common-mode fluctuations are due to changes in the Sun's TSI that affect each channel equally. That the differences between each radiometer remain constant with time at the 90 ppm level of the primary ESR's degradation over the first two years on orbit indicates good stability. This intra-instrument comparison shows a maximum spread of 640 ppm between all four cavities, with three falling within a spread of only 290 ppm. This consistency is better than that published for any other space-borne TSI instrument. Such intra-instrument consistency is a necessary, but not sufficient, condition for demonstrating low combined standard uncertainty.

¹Unpublished Version 6 data from the VIRGO experiment on the cooperative ESA/NASA Mission SOHO is courtesy of the VIRGO team through PMOD/WRC, Davos, Switzerland.

²ACRIM data are courtesy of Dr. Richard Willson via www.acrim.com.

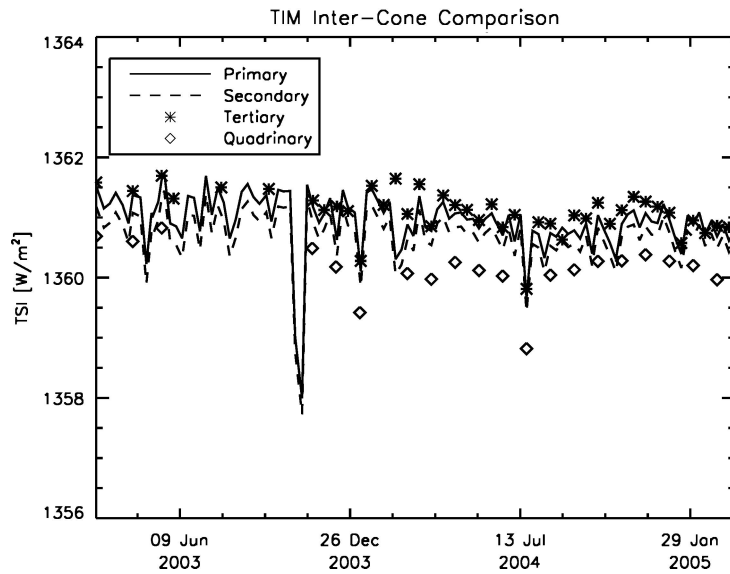


Figure 4. TIM intra-instrument comparison. The four TIM radiometers measure within a standard deviation of 270 ppm of the same value of TSI and show only a 90 ppm change with time due to tracked degradation of the primary ESR. The fluctuations in this plot common to multiple ESRs are due to normal solar variability. Degradation corrections have not been applied to these values, so this plot also indicates good fundamental instrument stability.

On a relative scale, offsetting the data to account for differences between the three currently flying TSI instruments acquiring daily data, the TIM, VIRGO, and ACRIM III instruments agree very well (see Figure 5).

3. Solar Activity during the October to November 2003 Time Frame

The TIM made the first definitive measurement of a solar flare in TSI. This occurred during a two-week period of extraordinarily high solar activity near the end of October 2003. During this time, the passage of two extremely large sunspot groups across the disk caused the largest short-term fluctuation of TSI in the 25-year record of observations (see Figure 6).

Over this two-week period the Sun released several flares, including the largest and the fourth largest X-ray flares ever recorded. These occurred respectively at 4 November 19:44 UT and 28 October 11:10 UT based on NOAA Geostationary Operational Environmental Satellite (GOES) soft X-ray measurements.

Despite the notoriously high energies of flares, they are small compared to the entire energy output of the Sun, and thus are nearly imperceptible in TSI. Indeed, in 25 years of space-based irradiance monitoring, no previous solar flare had been definitively measured in TSI, although studies by Hudson and Willson

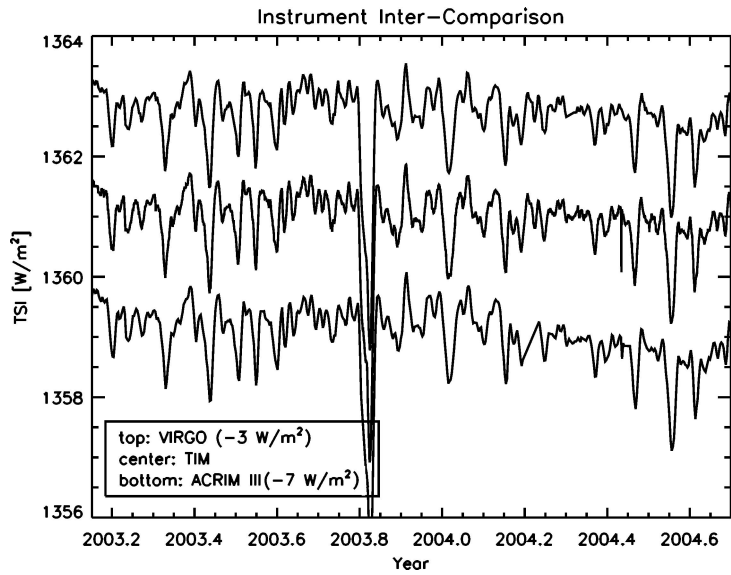


Figure 5. TSI comparison. The three TSI instruments currently providing daily measurements show good agreement on a relative scale. The spike in early June 2004 (2004.44) is from the transit of Venus across the solar disk and was not observed by the VIRGO instrument.

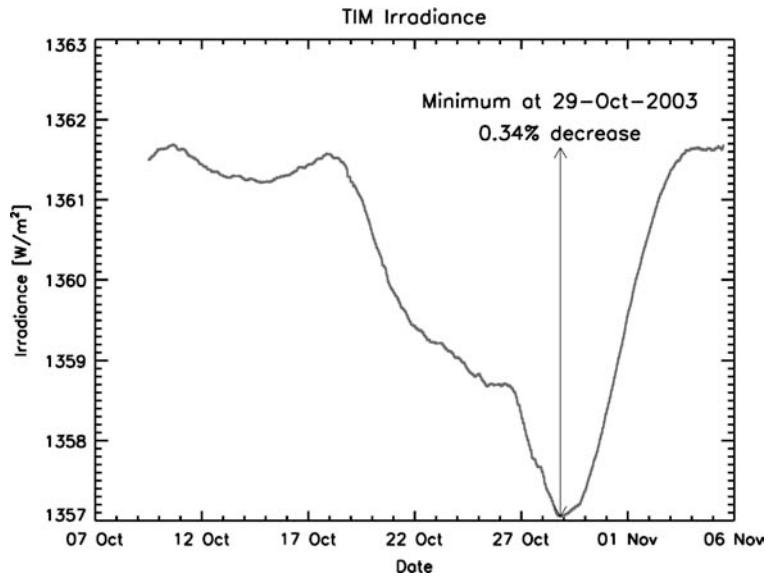


Figure 6. TSI decrease in October 2003. Two extraordinarily large sunspot groups caused the greatest short-term change in TSI on record.

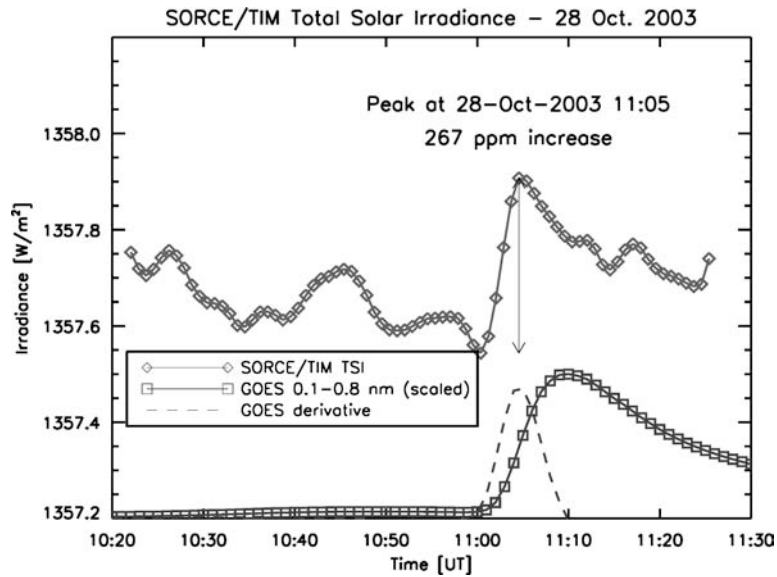


Figure 7. 28 October 2003 X17 flare. The TIM detected this large flare in TSI. The TSI peak is roughly coincident with the estimated hard X-ray peak. The TIM data are reported at a 50-s cadence using the phase sensitive detection algorithm described by Kopp and Lawrence (2005). The GOES data are reported at a 1-min cadence, although measurements are acquired every 3 s.

(1983) established flare energy levels needed for detection in TSI with an early ACRIM instrument.

The 28 October flare was large enough and well enough centered on the solar disk to cause a measurable change in the TSI. This flare came from NOAA's Solar Region Number 10486, a large sunspot group with surrounding intense magnetic activity. The NOAA ranking for this flare was X17.

The soft X-ray signature of the 28 October X17 flare as measured by the NOAA/GOES is shown in Figure 7 with a peak at 11:10 UT. The SORCE/TIM data show a sudden increase of 267 ppm peaking at 11:05 UT; this abrupt increase is the flare's signature in the TSI. The gradual decay in TSI after the flare's peak is characteristic of flares, although the complete relaxation is interrupted at 11:26 UT when the SORCE spacecraft entered the Earth's shadow. While some portion of the TSI increase may be due to normal solar variations, these are generally at the 20 ppm level and are much more gradual, so do not account for the large and abrupt peak observed.

A flare's hard X-ray emission roughly coincides with the derivative of the soft X-ray (GOES) emission, as described by Neupert (1968). As seen in Figure 7, the TSI measurements of this X17 flare coincide with this derivative, both leading the soft X-ray peak by 5 min. This indicates that portions of the visible and UV included in TSI also respond to the sudden initiation of the flare.

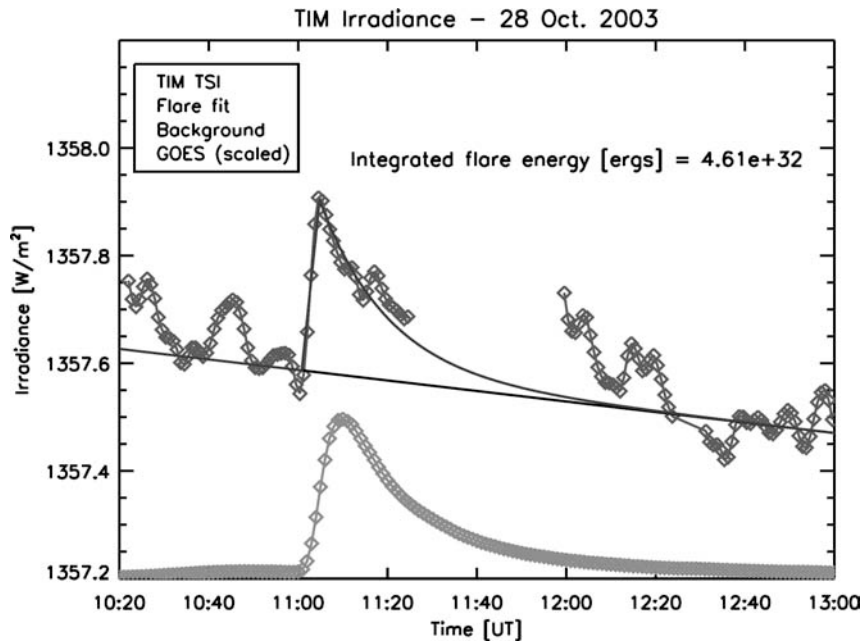


Figure 8. Total flare energy. Since the TSI measurement is sensitive to the entire solar spectrum, the TIM measurement of the X17 flare can be integrated over time to give the total flare energy.

The TIM measures radiant power across the entire solar spectrum from X-ray to far infrared wavelengths. The measurement of a flare in TSI thus provides knowledge of the total flare energy. From the TIM measurements, this X17 flare had an estimated total energy of approximately 5×10^{32} ergs (see Figure 8). A lower energy limit of 3×10^{32} and an upper limit of 9×10^{32} ergs are estimated based on possible background signals due to solar oscillations.

Combined with solar spectral irradiance measurements, we have estimated the spectral distribution of the flare energy to determine the amount released at EUV and at longer wavelengths. Preliminary estimates of the flare energy at wavelengths shorter than 100 nm, based on solar EUV measurements from other SORCE instruments and from a similar instrument on NASA's TIMED mission, only account for roughly 20% of this energy, meaning the majority of the flare's energy was emitted at wavelengths longer than 200 nm (Woods *et al.*, 2004).

The 4 November flare, although larger in X-ray emission with a NOAA ranking of X28, was only faintly detectable in TSI because its position was at or just beyond the solar limb. The correlation of the TIM TSI measurements with disk-integrated GONG intensities by Leibacher *et al.* (2004) shows a sudden increase in the TIM TSI that is likely due to this flare.

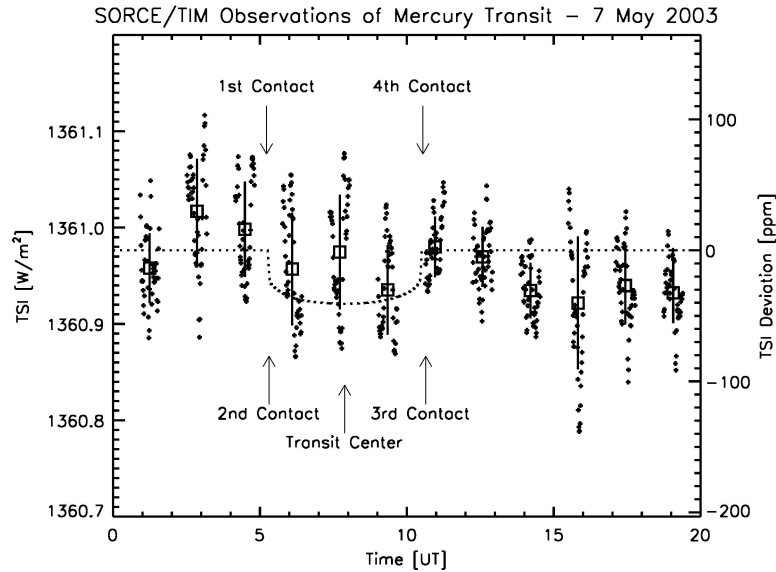


Figure 9. TIM observations of Mercury transit. The TIM observations do show roughly the expected level of decrease in TSI during the times of the Mercury transit (*smooth curve*), but these are indistinguishable from the effects of normal solar fluctuations. High-cadence data are given as *dots* and orbital averages by *squares* with their associated standard deviation error bars.

4. Planetary Transits Observed

The TIM observed during the transits across the solar disk of both Mercury (7 May 2004 from 5:13 to 10:32 UT) and Venus (8 June 2004 from 5:13 to 11:36 UT). Accounting for solar limb darkening for the off-center transits, expected decreases in the TSI for these transits are 41 and 1005 ppm, respectively.

The Mercury transit (see Figure 9) was not detectable in TIM TSI measurements. While there may be a decrease of the appropriate magnitude over the three orbits during which this transit occurred, normal solar fluctuations during prior and subsequent orbits show similar levels of variability, making any detection here ambiguous.

The Venus transit was much larger and was easily detected. The TIM observed ingress (first to second contact) for this transit, although egress occurred when the TIM was in the Earth's shadow and could not view the Sun. The observed decrease in the TSI during transit closely matches the expected decrease using the solar limb darkening profiles of Hestroffer and Magnan (1998) (see Figure 10). While there is little of scientific value from TIM observations of this transit, it does confirm that Hestroffer and Magnan's limb darkening estimates are correct at the <5% accuracy level limited here by the noise due to solar fluctuations.

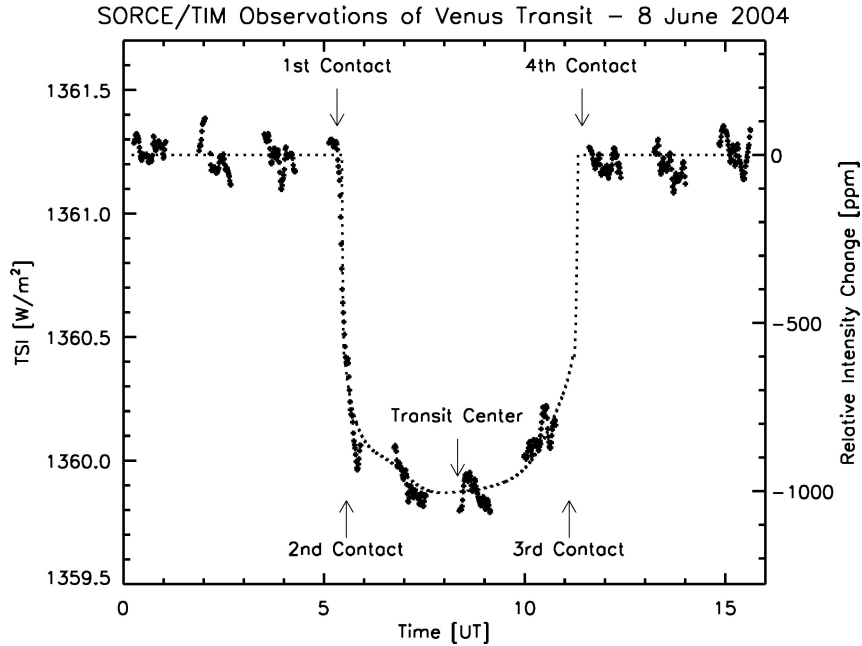


Figure 10. TIM observations of Venus transit. The TIM observations ('+' signs) of the Venus transit match the expected TSI decrease (smooth curve) to the limits of the background disk-integrated solar oscillations.

5. Summary

The SORCE/TIM measures a lower value of total solar irradiance than previous space-borne irradiance measurements. We do not attribute this discrepancy to any known calibration error in the instrument. Based on the TIM data, we predict the TSI input at the top of the Earth's atmosphere at a distance of 1 AU from the Sun during the upcoming solar minimum to be 1361 W/m^2 .

We also report the first measurement of a solar flare in TSI, from which we estimate the total energy of this X17 flare to be 5×10^{32} ergs.

The TIM observed planetary transits of both Mercury and Venus. Measured TSI values closely match the expected decreases in intensity.

Acknowledgement

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