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Solar Irradiance: Instrument-Based Advances

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Abstract. Variations of the total solar irradiance (TSI) over long periods of time provide natural Earth-climate forcing and are thus important to monitor. Variations over a solar cycle are at the 0.1 % level. Variations on multi-decadal to century timescales are (fortunately for our climate stability) very small, which drives the need for highly-accurate and stable measurements over correspondingly long periods of time to discern any such irradiance changes. Advances to TSI-measuring space-borne instruments are approaching the desired climate-driven measurement accuracies and on-orbit stabilities. I present a summary of the modern-instrument improvements enabling these measurements and present some of the solar-variability measurement results from recent space-borne instruments, including TSI variations on timescales from solar flares and large-scale convection to solar cycles.

Keywords. Sun: irradiance, TSI, variability; instrumentation: radiometry

1. Climate-Driven Requirements of Solar-Variability Measurements

Solar forcing is one of the natural influences of climate change on the Earth. While the climate system cannot respond quickly to short-term solar variability, changes over the 11-year solar cycle are evident in climate records, causing radiative forcings of $\sim 0.1°$C (Lean 2017), or a climate sensitivity of $\sim 0.6\ C\ W^{-1}\ m^2$. Longer-term changes, which allow the Earth's climate system more time to equilibrate, should have at least as great a radiative-forcing sensitivity. Detecting small, potential solar variations over multi-decadal to century timescales drives stringent total solar irradiance (TSI) accuracy and stability requirements. Measuring such variability requires the uncertainties shown in Table 1.

2. Instrument Improvements Enabling Required Solar-Variability Measurements

All TSI instruments prior to the SORCE Total Irradiance Monitor (TIM), launched in 2003, measured erroneously high values largely because of internal instrument scatter due to aperture placement (Kopp & Lean 2011). Those instruments had a large view-limiting aperture at the front of each radiometer, which allowed two to three times the amount of sunlight intended to be collected into the interior on all non-TIM instruments. Ground-based estimates have now been applied to correct most of the afflicted instruments.

Including the scatter-eliminating aperture layout, the TIM introduced several innovations to improve TSI-measurement accuracy:

- Precision apertures located at front of instrument
- Nickel Phosphorus black absorptive cavity interiors demonstrate the best on-orbit stability of any TSI instrument
- Phase sensitive detection reduces sensitivity to out-of-band noise in the instrument's servo system and in ground-based data processing

Table 1. Climate-Driven TSI Measurement Requirements

Parameter	Requirement
Radiometric Uncertainty (Accuracy)	10^{-4}
Stability (Long-term Precision)	10^{-5} yr^{-1}
Noise (Short-term Precision)	$<10^{-5}$

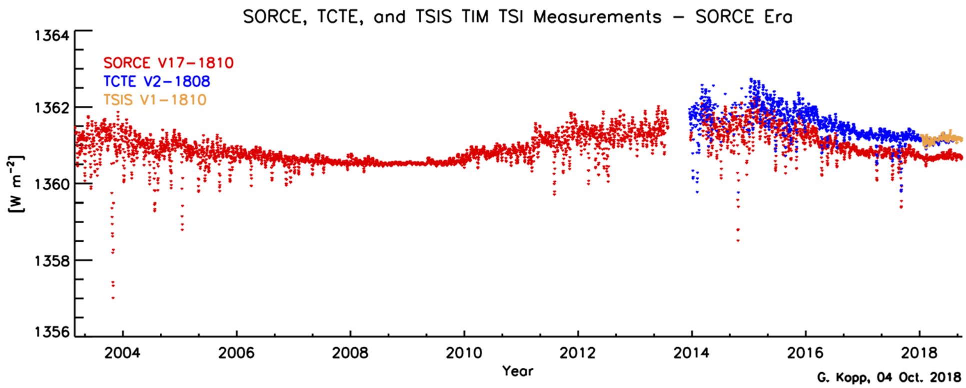

Figure 1. TIM TSI instruments show calibration consistency over many years

• Feedforward maintains cavity thermal stability and servo balance
• The instrument's thermal background is both measured on-orbit and modeled
• Pulse-width modulation of precision DC constant-voltage references applies power linearly (rather than as V^2, as is the case in varying-voltage references)
• Digital servo system with proportional-integral-derivative control allows servo tuning

Three on-orbit TIMs calibrated independently over a 15-year span show good consistency (see Fig. 1). Many of these TIM-introduced improvements are now being incorporated into other new instruments.

3. Solar-Variability Magnitudes and Timescales

The instrument improvements described above enabled the first solar-flare detection by a TSI instrument thanks to a combination of the SORCE/TIM's low noise and a large flare (Woods *et al.* 2006). While flares are easily detected at ultraviolet and x-ray wavelengths, where the solar disk is very dark, they are nearly insignificant in terms of net contribution to the total radiative solar energy, making them difficult to discern in TSI above the ever-present variations of 0.005 % to 0.01 % due to globally-averaged solar convection and oscillations. The value of a flare detection in the TSI is that the time-integrated TSI enables an estimate of the net radiant flare energy, as shown in Fig. 2.

Low instrument noise also enables observations of Venus and Mercury transits, as shown in Fig. 3, where the effects of limb darkening during the transits are evident. Observations (red) show intrinsic short-term solar variability on 3- to 5-minute timescales due to convection and oscillations. These transit observations are representative of exoplanet transits of Sun-like stars and the potential obscuring effects of stellar variability.

The TSI varies on all timescales over which it has been observed. Kopp (2014) discusses these timescales and variabilities, summarized here in Table 2. Figs. 2 and 3 show solar variability on short timescales and Fig. 1 shows it on daily to solar-cycle timescales.

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Table 2. Solar-Variability Magnitudes and Timescales

Timescale	Magnitude
minutes	0.01%
days	<0.3%
11-yr solar cycle	0.1%
multi-decadal to centuries	0.05-0.3% (unknown)
stellar evolution	10^{-10} yr^{-1}

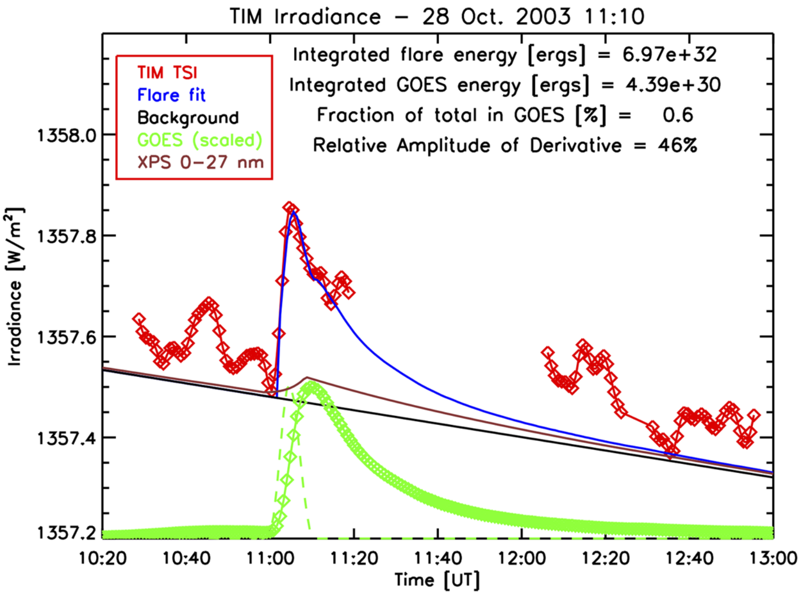

Figure 2. The first solar flare ever detected in TSI (red) enabled flare-energy estimates.

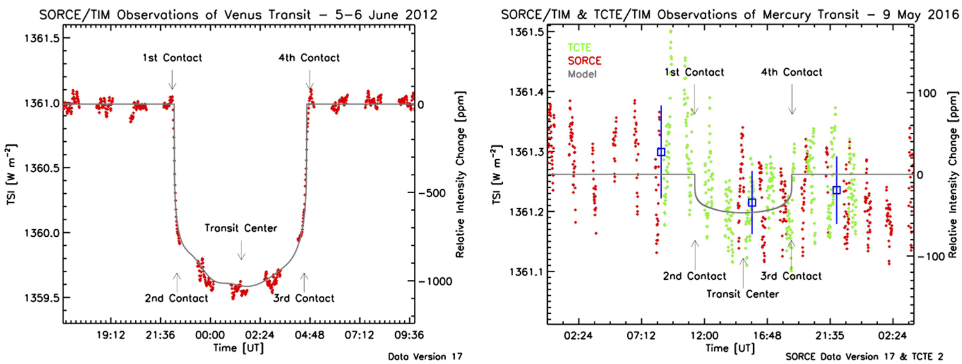

Figure 3. Venus (left) and Mercury (right) transits observed by the SORCE/TIM and TCTE/TIM. Observations (red and green) closely match predictions including limb-darkening effects (grey). The Mercury transit was not significant enough to be considered a "detection."

4. Conclusions

I describe recent TSI-instrument improvements. These have enabled more accurate and stable measurements of the solar variability on short (solar flare and convection/oscillation) and long (daily to solar-cycle) timescales. I summarize the magnitudes and timescales of measured solar variability benefitting from these improved TSI instruments.

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