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Editor's Corner

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After nearly 29 years in orbit, the longest operational satellite mission in history has come to an end. One of Landsat 5's three operational gyroscopes failed on November 4, 2012, and the U.S. Geological Survey (USGS) and NASA subsequently made the decision to end the mission—since control of the satellite would be impossible if another gyro fails. On January 15, the USGS's Flight Operations Team successfully executed the first in a series of maneuvers that will lower Landsat 5 from its operational orbit.

By any standard, Landsat 5 was an extraordinary success. The satellite's Multispectral Scanner (shut down in 1995, and briefly reactivated near the end of the mission) and Thematic Mapper instruments achieved an unprecedented multi-decadal record of Earth observations, helping us to gain a better understanding of land surface changes and the human impact on the planet. Landsat 5 completed over 150,000 orbits and transmitted over 2.5 million images, and its sun-synchronous low Earth orbit eventually became home to other missions. This group of satellites became known as the *Morning Constellation*—referring to their morning overpass times.

While Landsat 5 ends, current and upcoming missions continue to grow the Landsat legacy. Landsat 7, launched in 1999, continues to operate well beyond its projected five-year mission lifetime (despite a long-standing anomaly with the Scan Line Corrector). The next launch is imminent; the Landsat Data Continuity Mission (LDCM[1]) is scheduled to launch on February 11 from Vandenberg Air Force Base in southern California. Discussions are underway regarding the follow-on mission to continue this important record of Earth observations.

Meanwhile, many satellites in NASA's Earth observation fleet continue to reach well beyond their prime mission lifetime. The Solar Radiation and Climate Experiment (SORCE) celebrated the tenth anniversary of its 2003 launch on January 25. SORCE observes solar irradiance, a critical quantity needed for understanding the impact of solar variability on climate. SORCE instruments measure the solar spectral irradiance (SSI) in the ultraviolet, visible, and near/shortwave infrared as well as the total solar irradiance (TSI). SORCE has exceeded all science objectives. Most notably, SORCE's state-of-the-art Total Irradiance Monitor (TIM) instrument established a new lower TSI level near 1361 W/m^2. The mission has also developed reference SSI spectra for use in Earth's atmosphere and climate models to better understand Sun-climate changes. *"The SORCE observations have been*

[1] Following launch, the LDCM satellite will be renamed Landsat 8.

continued on page 2

This composite map of the Earth at night was assembled from data acquired by the Suomi NPP satellite in April and October 2012, and can be found online at *earthobservatory.nasa.gov/NaturalHazards/view.php?id=79765.* **Image credit:** NASA Earth Observatory image by **Robert Simmon**, using data Suomi NPP VIIRS data provided courtesy of **Chris Elvidge** from NOAA.

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critical to continue on the Sun-climate records that NASA missions helped to start back in the 1970s," says **Tom Woods** [Laboratory for Atmospheric and Space Physics, University of Colorado —*SORCE Principal Investigator*].

SORCE observed the peak of activity in Solar Cycle 23 and captured solar irradiance changes during one of the largest solar eruptions yet witnessed—the "Halloween Storm" in October 2003. Then SORCE observed continuously as solar activity declined into a prolonged, anomalously quiet minimum that lasted from 2008 to 2010. Now SORCE observations indicate a significantly lower maximum for Solar Cycle 24 (with the peak seen in November 2011) then that which was observed for cycle 23. On **page 3** of this issue we are pleased to feature an article on SORCE and some of its major accomplishments.

The Advanced Mircowave Scanning Radiometer-EOS (AMSR-E) on Aqua had its antenna stop spinning back in October 2011, most likely due to aging lubricants in the mechanism. *The Earth Observer* has periodically updated our readers on the progress of efforts to spin up the AMSR-E[2] antenna. I am happy to report that on December 4, 2012, the Japan Aerospace Exploration Agency (JAXA) operations team, together with the Aqua Flight Operations Team (FOT), safely executed "Stage 3" of the recovery effort[3] and were able to successfully achieve their rotation goal of 2 rpm. AMSR-E instrument performance is currently nominal and performance parameters (in particular, *jitter*) remain well within acceptable margins. Thus far, there appears to be no impact to the science of the other Aqua instruments. The data obtained from AMSR-E will be used for radiometric inter-comparison with the similar AMSR-2 instrument on the Global Change Observation Mission–Water (GCOM-W1) [a.k.a., *Shizuku*]. This overlap is essential for establishing data record continuity across the two missions. The plan is to have AMSR-E collect data for at least two months.

A new cloud-free view of the entire Earth at night, made with data from the Visible Infrared Imaging Radiometer Suite (VIIRS) day-night band onboard the Suomi National Polar-orbiting Partnership (NPP) satellite[4] was unveiled at a press conference during the AGU conference. Nicknamed the *Black Marble*, this new image shows the glow of natural and human-generated light sources in greater detail then ever before—see **pages 1** and **49**. Also at AGU, scientists revealed an animation showing *plant stress* from January 2010 through September 2012, using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites as well as NOAA satellites. There was also a release about the likelihood of increased wildfire activity in coming decades based on NASA data. To learn about these topics, we refer you to the news stories on **pages 44** and **46** respectively.

As usual, it is an exciting time for Earth science at NASA. We look forward to the many challenges, opportunities, discoveries, and advancements in the year to come. ■

[2] The "Editor's Corner" in previous issues of *The Earth Observer* chronicles the progress of these efforts.
[3] "Stage 1" of the recovery effort took place in February 2012; initial observations—with no rotation—were taken to test the instrument. In mid-September, "Stage 2" spin-up tests were conducted with a plan to spin up to 4 rpm (original rotation rate was 40 rpm) and then spin back down several times. The antenna did move, but there was friction; they only obtained about 1 rpm with maximum current applied.
[4] Suomi NPP is a joint NASA/National Oceanic and Atmospheric Administration (NOAA) mission.

The SORCE Mission Celebrates Ten Years

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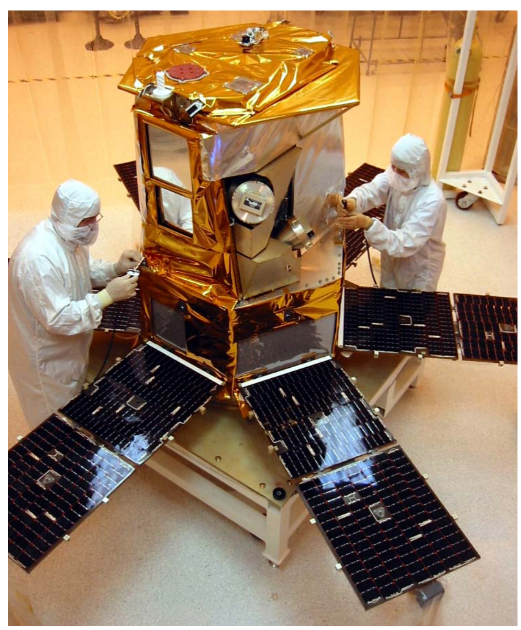
Introduction

The Sun is the solar system's "furnace." Solar radiation carries energy to Earth and beyond, fueling planets and driving a myriad of radiative, chemical, and dynamical processes in Earth's environment that influence natural climate variability. Light at visible wavelengths carries most of the Sun's energy to Earth (82% of the total energy comes from visible wavelengths from 390 to 750 nm). On average only about 50% of the solar radiation directly reaches the surface, due to reflection and attenuation by the overlying atmosphere. Variations in solar irradiance, which occur on all time scales from seconds to centuries and longer, can only be accurately measured from space-based platforms such as SORCE. Decades-long attempts to measure the *total solar irradiance* (TSI[1]) from the ground and rockets have failed to detect the true variability: Historic satellite measurements of TSI and ultraviolet (UV) *solar spectral irradiance* (SSI) date back to 1978—see **Figure 1** (next page).

"As there is only one object in the sky on whom we utterly depend, there can be no astronomical question of more practical significance to mankind than that of the Sun's variability. To determine whether the solar constant is varying…requires long-term monitoring of both the bulk solar radiation and its terrestrially important spectral components. This assignment is not an easy one, for it demands a capability of sensing changes of no more than 0.1% in a decade, carried out over many decades. In the real world of science the greater challenge may be that of insuring the continuance of such a program."
***—John A. "Jack" Eddy**, 1977*

Variations in solar irradiance, which occur on all time scales from seconds to centuries and longer, can only be accurately measured from space-based platforms such as SORCE.

On January 25, 2003, NASA's Solar Radiation and Climate Experiment (SORCE) spacecraft was launched into space on a Pegasus XL vehicle that carried four instruments: the Total Irradiance Monitor (TIM), Solar Stellar Irradiance Comparison Experiment (SOLSTICE), Spectral Irradiance Monitor (SIM), and Extreme Ultraviolet Photometer System (XPS). The primary objectives for SORCE are to measure important solar input to Earth's radiation budget and to relate how solar variability influences our atmosphere and climate. SORCE continues the precise measurement of TSI that began with the Earth Radiation Budget (ERB) instrument onboard the Nimbus-7 satellite in 1978 and have continued to the present with the Active Cavity Radiometer Irradiance Monitor (ACRIM) series of measurements. To learn the history of how SORCE came to be, see *The Sources of SORCE* on the next page.



This image shows the SORCE spacecraft with the solar arrays deployed during integration and testing at Orbital Sciences Corporation. **Image credit:** Orbital Sciences Corporation

[1] The *total solar irradiance* (TSI) is defined as the solar energy per unit time over a unit area perpendicular to the Sun's rays at the top of Earth's atmosphere.

Ten years of observations from SORCE's TIM and SOLSTICE instruments have extended the critical Sun-climate records of TSI and UV SSI measurements. SORCE's SIM instrument made the first continuous space-based observations of SSI at visible and infrared (IR) wavelengths, forming the basis for a new climatological record of the visible and IR SSI. SIM was designed for continuous spectral measurements through the near UV, visible, and near IR with the stability needed to determine, for the first time, true changes in SSI in these wavelengths. The XPS instrument measures high-energy UV radiation and lower-energy X-ray wavelengths. These measurements yield valuable information about the Sun's corona, solar events that impact satellite communications, and the Sun's effects on the very outermost layers of Earth's atmosphere.

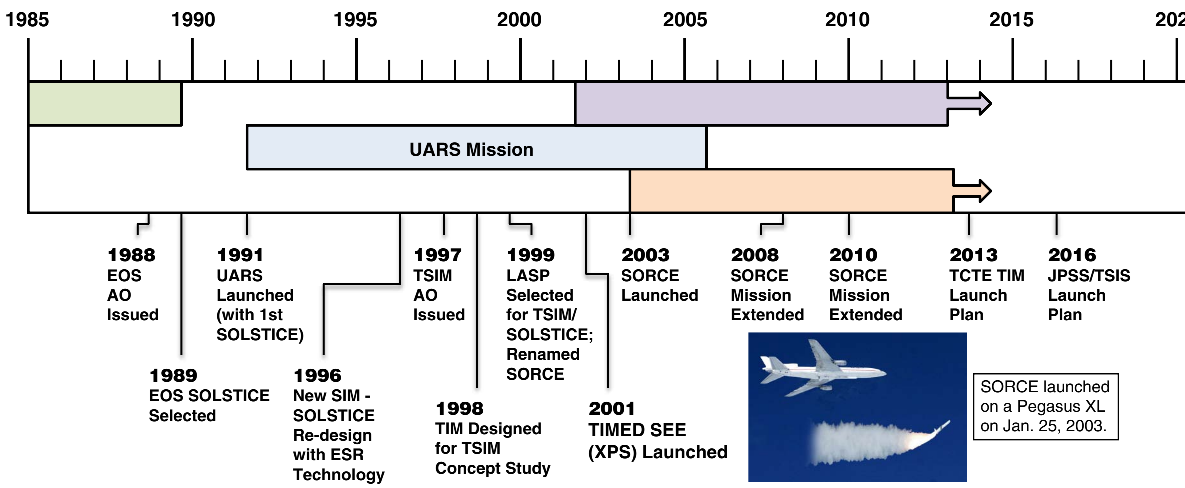


Figure 1. This timeline shows various milestones in the development of solar irradiance measurements relevant to the SORCE mission. **Image credit:** LASP/NASA

The Sources of SORCE

In early 1988 NASA issued an Announcement of Opportunity (AO) for the Earth Observing System (EOS), seeking proposals to fly instruments onboard a polar-orbiting platform—then known as EOS-A—to study Earth's systems from space. At that time, the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP) was operating the Solar Mesosphere Explorer (SME), which was launched in 1981. In addition to atmospheric ozone experiments, SME carried a solar irradiance spectrometer to collect data between 115 and 300 nm. LASP had also completed the design and fabrication of the Solar Stellar Irradiance Comparison Experiment (SOLSTICE). In 1991 SOLSTICE was in its calibration phase and awaited integration to launch onboard NASA's Upper Atmosphere Research Satellite (UARS). Given this previous experience, it was quite appropriate and natural that LASP responded to the EOS AO with a proposal to provide a second-generation SOLSTICE (EOS SOLSTICE) to fly on the polar-orbiting platform.

NASA received 458 proposals in response to the EOS AO, and EOS SOLSTICE was one of the 30 Instrument Investigations selected. The NASA selection specified that SOLSTICE would become a Flight of Opportunity (FOO) and NASA's Goddard Space Flight Center would be responsible for finding an appropriate means for launch. The search seemed as if it would never end (with all possible large and small, national and international, high- and low-risk missions considered) until finally, in 1998, the small, free-flying SORCE mission that exists today began to materialize. The original NASA selection process and frequent restructuring of the EOS program during the early- and mid-1990s determined the future of the SORCE mission[1].

After launch in 1991 it became apparent that the UARS SOLSTICE technique of comparing the Sun to bright, blue stars worked very well—at the 1% accuracy level. This level of accuracy was more than adequate to determine solar variability at wavelengths below 240 nm and acceptable out to 300 nm, but provided only an upper limit at longer wavelengths. The EOS SOLSTICE needed to push this accuracy limit, so LASP developed an entirely new optical channel with a single figured prism and a miniature *electrical substitution radiometer* (ESR).

[1] Numerous articles in *The Earth Observer* have described various aspects of the evolution of the Earth Observing System from its original conceptions to its present reality. Ghassem Asrar's article in the May–June 2011 issue [**Volume 23**, **Issue 3**, pp. 4-14] includes a very-well written summary of that evolution with references to many other relevant articles.

The electronics of the new ESR were game changing, although somewhat similar to those of previous radiometers. ESR incorporated a revolutionary phase sensitive detection that improved precision by more than a factor of 10. This new channel became a separate instrument on SORCE—the Solar Irradiance Monitor (SIM).

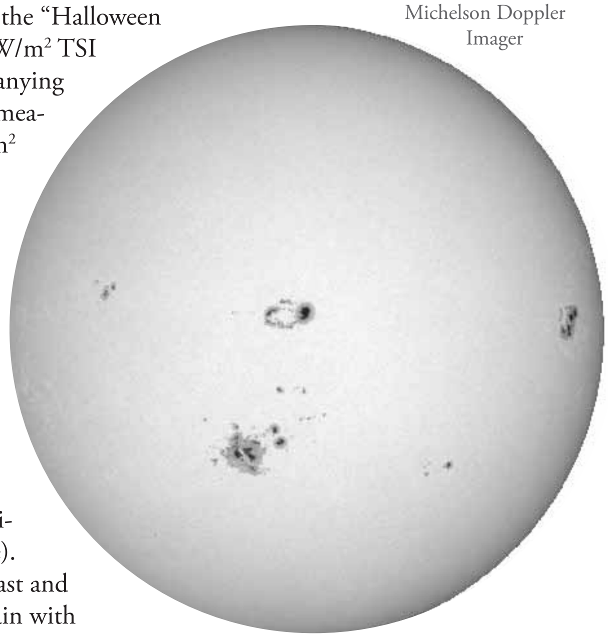
Another of the 30 EOS instruments selected in 1989 was the Active Cavity Radiometer Irradiance Monitor (ACRIM) that would measure TSI. This instrument was also relegated to the FOO category, but—unlike SOLSTICE—it fast-tracked as a small free-flyer named ACRIMSAT, and was launched in 1999. ACRIMSAT was the first of three, five-year TSI missions. To procure the second and third missions, NASA issued an AO in 1997 for a Total Solar Irradiance Monitor (TSIM). LASP was confident in its ongoing development of the ESR for SIM, and felt the phase-sensitive detection approach would provide a far-more-accurate TSI device. LASP proposed for TSIM, and was selected in 1999.

Meanwhile, throughout the 1990s the LASP extreme UV (EUV) irradiance program was becoming extremely robust. A highly successful sounding rocket program at LASP, and the Student Nitric Oxide Explorer (SNOE) and Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) missions had developed exceptional EUV photometers. An outgrowth of these programs, the X-ray Photometer System (XPS) was developed and added to the planned EOS SOLSTICE mission.

By the late 1990s EOS SOLSTICE was being studied as a possible free-flyer; the recently awarded TSIM was also considered a free-flyer. It made sense to combine the two missions into what became the SORCE mission. SORCE would combine the instruments planned for SOLSTICE and TSIM on a single platform, and operate as a principal investigator (PI)-led program with LASP as the lead institution and Gary Rottman as the SORCE PI. LASP selected Orbital Sciences Corporation (OSC) to build the spacecraft. Since launch the entire program has been on schedule. SORCE was under budget, so in 2008 the University of Colorado returned $2,997,000 to NASA after successfully completing its prime mission.

Overall SORCE Accomplishments

SORCE's state-of-the-art solar radiometers (i.e., SOLSTICE, TIM, SIM, and XPS) have successfully characterized simultaneous changes in TSI and SSI that occur in concert with the Sun's ever-changing activity. The SORCE mission began near the peak of activity in Solar Cycle 23 and captured solar irradiance changes during one of the largest solar eruptions ever witnessed—nicknamed the "Halloween Storm"—in October 2003. In addition to observing a 4-W/m^2 TSI decrease from October 18-29 and measuring the accompanying spectral changes, SORCE's TIM recorded the first direct measurement of a solar flare in TSI that increased by 0.2 W/m^2 for approximately 10 minutes on October 28.



The largest sunspots in 50 years appeared in October 2003 as part of "The Halloween Storm." **Image credit:** Solar and Heliospheric Observatory-Michelson Doppler Imager

During its ten-year mission, SORCE monitored solar irradiance continuously during the decline of solar activity into the prolonged, anomalously quiet minimum that began in 2008. Combining SOLSTICE and SIM spectral measurements during this period, along with those at shorter EUV wavelengths made by SORCE's XPS and the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) mission's Solar EUV Experiment (SEE), produced the most accurate *reference spectrum* of solar irradiance for the nominally inactive "quiet" Sun—shown in **Figure 2** (next page). This spectrum is a unique benchmark and reference for past and future solar variability. Solar activity began to increase again with the onset of a new solar cycle (Solar Cycle 24), and SORCE continues to track the solar irradiance fluctuations that are expected to peak in 2013 at a modest level. Solar Cycle 24 is exhibiting notable differences from the three prior, more active cycles for which TSI and ultraviolet SSI observations exist—and SORCE will be there to observe it as it evolves.

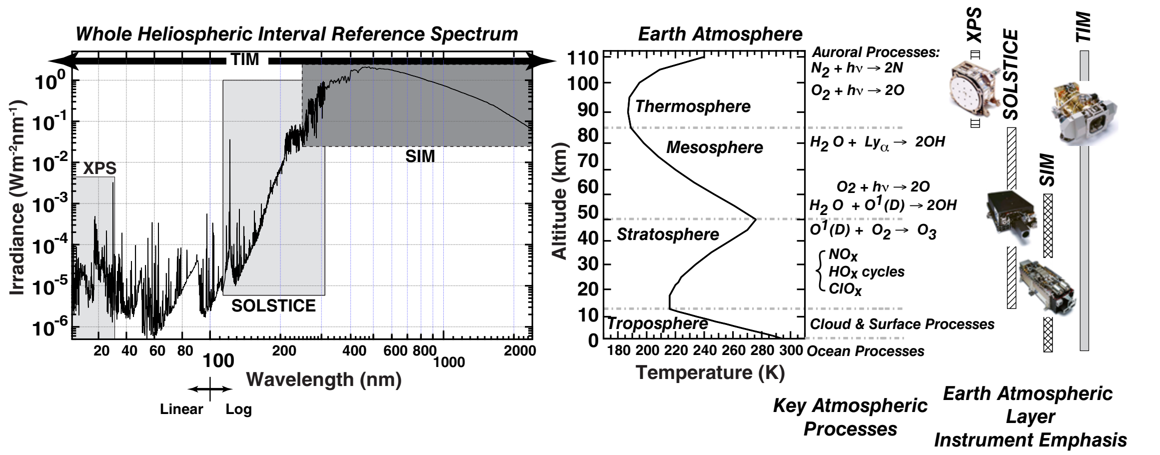


Figure 2. This figure represents a synopsis of the primary studies with SORCE data. The SORCE total and spectral radiometers measure the spectrum of the Sun and its variability daily. Solar energy establishes the structure of Earth's atmosphere through a series of key chemical reactions and thermodynamic processes. The SORCE instruments were designed to provide input for studying different layers of Earth's atmosphere and influences on climate change. **Image credit:** LASP

Results from the SORCE mission show that solar irradiance varies continuously at all wavelengths across the electromagnetic spectrum. The changes are tightly connected to solar activity, which generates both dark and bright magnetic features (*sunspots* and *faculae*[2] respectively) on the Sun's disk. These features alter the local emissions from the Sun's surface in different ways and at different wavelengths, depending on where the emissions originate within the Sun's atmosphere. Solar irradiance changes continuously as these magnetic features appear, evolve, and decay, while the Sun's rotation alters their location on the disk as seen from Earth. SORCE's measurements have characterized these changes in TSI and SSI on time scales from minutes to years. Clarifying the spectral contributions to the total irradiance variation on longer time scales of the solar cycle is underway, taking into account the wavelength-dependent changes in instrument sensitivity that are ubiquitous in space-based observations, which SORCE's instruments monitor via redundant optical channels and periodic observations of stars.

Even as the SORCE instruments have reliably and routinely tracked the Sun's irradiance, they have also recorded exciting serendipitous phenomena, detecting signatures as both Venus and Mercury transited the disk of the Sun, which each occurred twice during the mission.

As the ability to model Earth's climate and atmosphere has advanced, so too has the need for improved specification of solar irradiance inputs—as illustrated in Figure 2. Most, if not all, state-of-the-art models of Earth's climate and atmosphere, such as those used for the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC AR5) and the Ozone Assessment, now require the SSI—not just the total (spectrally integrated) quantity. Analysis of SORCE spectral irradiance observations and development and validation of models of spectral irradiance variability for use in global change studies is a key science objective of SORCE.

Even as the SORCE instruments have reliably and routinely tracked the Sun's irradiance, they have also recorded exciting serendipitous phenomena, detecting signatures as both Venus and Mercury transited[3] the disk of the Sun, each of which occurred twice during the mission. Additionally, the fundamental metrological scale that the SORCE instruments carried into space, traceable through careful characterization and accurate calibration to National Institutes of Standards and Technology (NIST) standards, is being transferred to other astronomical objects—e.g., stars and the Moon.

[2] A *facula* is literally a "bright spot" on the Sun's photosphere that burns hotter than the surrounding area that often, but not always, occurs in proximity to dark (cooler) regions known as *sunspots*.

[3] For more information about how TIM observed the 2012 transit of Venus, read *SORCE/TIM Views the 2012 Transit of Venus* in the July-August 2012 issue of *The Earth Observer* [**Volume 24**, **Issue 4**, pp. 36-37].

Top Ten Achievements of the SORCE Mission

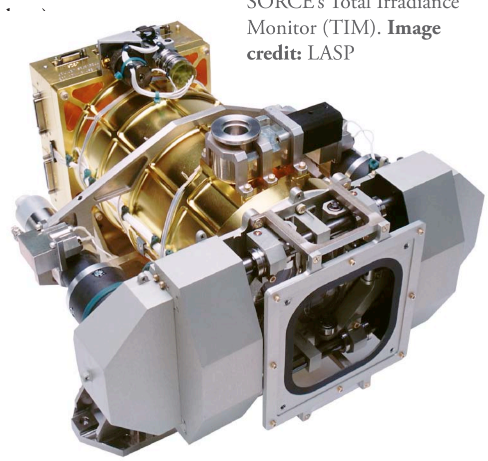
The SORCE mission has:

1. Established a new level of TSI that is 4.6 W/m^2 (0.34%) lower than prior space-based observations.
2. Acquired the first continuous measurements of SSI in the 115- to 2400-nm spectral range.
3. Defined an accurate reference spectrum of the Sun's spectral irradiance from 0.1 to 2400 nm during very quiet solar conditions.
4. Provided total and spectral irradiance inputs to the climate and atmospheric communities, and used in a wide variety of simulations and models.
5. Implemented next-generation instrumentation of spaceflight radiometers for solar irradiance monitoring, with the highest accuracy and precision yet achieved.
6. Seamlessly extended the National Oceanic and Atmospheric Administration's (NOAA's) Mg II index of chromospheric activity.
7. Acquired the first solar flare measurements in TSI, and accompanying spectral variations.
8. Advanced and validated models of the Sun's total and spectral irradiance variability.
9. Observed two Venus transits and two Mercury transits of the Sun, demonstrating exosolar planet detection capabilities and limitations.
10. Validated the white dwarf flux scale for absolute calibration of instruments for UV astronomy and made the first absolute measurement of disk-integrated lunar UV reflectance.

Top SORCE Achievements

The SORCE science team compiled a list of mission results that have been loosely organized—see *Top Ten Achievements.* While cognizant of the fact that there are many other results and details that could have been included, the consensus among the team members was that these ten are the most noteworthy achievements from SORCE's first decade in orbit.

The first five accomplishments are briefly discussed in this article (see b A summary that includes descriptions of all ten is available at *lasp.colorado.edu/sorce/index.htm*.



SORCE's Total Irradiance Monitor (TIM). **Image credit:** LASP

#1 – Established a new level of total solar irradiance (TSI) that is 4.6 Wm^2 (0.34%) lower than prior space-based observations

The SORCE TIM extends the uninterrupted spaceborne measurements of TSI that began in 1978. Offsets between prior measurements due to instrument calibration differences have made construction of a single composite record difficult, and overlapping instruments to provide measurement continuity is imperative. The advanced design and laboratory calibrations of TIM give it an estimated uncertainty of 0.035%—more than a factor of three improvement relative to prior ins ments. By virtue of its unique design and resulting accuracy, the TIM e lished a new baseline TSI level of the net radiative solar energy at Earth's top of atmosphere (TOA) of 1360.8 W/m^2 [0.34% (4.6 W/m^2) lower than previously measured] during the recent solar minimum[4]. This improved absolute accuracy reduces risk from a potential loss in continuity of the solar data record, although detection of solar

[4] Kopp and Lean [*Geophysical Research Letters,* **38,** L01706, 2011] describe this phenomenon.

TIM's innovative new optical design is the primary reason for its improved measurement accuracy, verified by comparisons of a ground-based TIM with international facilities at NIST and the Physikalisch-Meteorologisches Observatorium Davos (PMOD) World Radiometric Reference, as well as at LASP's newly created TSI Radiometer Facility (TRF).

trends at the levels needed for climate studies will continue to rely on TSI measurement overlap until uncertainties are reduced further.

TIM's innovative new optical design is the primary reason for its improved measurement accuracy, verified by comparisons of a ground-based TIM with international facilities at NIST and the Physikalisch-Meteorologisches Observatorium Davos (PMOD) World Radiometric Reference, as well as at LASP's newly created TSI Radiometer Facility (TRF). All prior spaceborne TSI instruments were of a configuration that was much more susceptible to internal scattered light, which caused erroneously high measurements. TRF comparisons with previous instruments help quantify the scatter in their datasets and establish the needed corrections to their measurements.

Contemporaneous measurements now report TSI values that are very similar to those that TIM first released soon after SORCE's launch. **Figure 3** shows the 34-year long TSI record and the improved measurement agreement with the currently operating instruments.

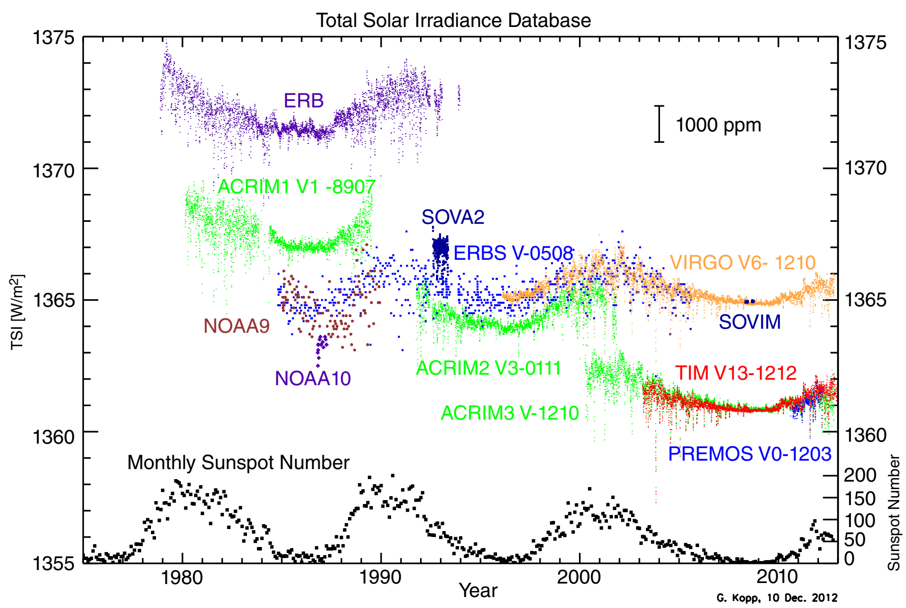


Figure 3. Having lower uncertainties than other flight TSI instruments, the TIM established a new, lower TSI value of 1360.8 W/m². Recently applied corrections for scatter—which causes erroneously high readings in other instruments—have lowered those instruments' values, and the agreement between TSI measurements is now much improved. **Image credit:** LASP

Acronyms Used in Figure: ERB = Earth Radiation Budget [onboard Nimbus 7]; ERBS = Earth Radiation Budget Satellite; ACRIM = Active Cavity Radiometer Irradiance Monitor; SOVA = SOlar VAriability experiment [onboard the Picard satellite]; VIRGO = Variability of solar Irradiance and Gravity Oscillations [onboard the SOlar and Heliospheric Observatory (SOHO)]; NOAA = National Oceanic and Atmospheric Administration; PREMOS = PREcision Monitoring Of Solar Variability [onboard Picard]; SOVIM = SOlar Variations and Irradiance Monitor [onboard the International Space Station]; TIM = Total Irradiance Monitor [onboard SORCE].

"SORCE has set a new standard of accuracy, precision, and wavelength range for the Sun's irradiance, a kind of 'climate gold standard' for the radiative forcing of Earth over the decade of the 2000's, beginning with the dramatic Halloween flares of October-November 2003, through the historically low 2008–2009 minimum of Solar Cycle 23, into the rise of Solar Cycle 24, providing a climate record likely to grow in value for Sun and Earth studies over many decades to come."

*—**Robert Cahalan** [GSFC—SORCE Project Scientist]*