

SORCE Team Organizes Solar Spectral Irradiance Intercomparison Workshop

Martin Snow, Laboratory for Atmospheric and Space Physics, University of Colorado, snow@lasp.colorado.edu

Jerald Harder, Laboratory for Atmospheric and Space Physics, University of Colorado, harder@lasp.colorado.edu

Bill McClintock, Laboratory for Atmospheric and Space Physics, University of Colorado, mcclintock@lasp.colorado.edu

Tom Woods, Laboratory for Atmospheric and Space Physics, University of Colorado, woods@lasp.colorado.edu

Overview

A one-day workshop was held in association with the Solar Radiation and Climate Experiment (SORCE) Science Team Meeting on September 19, 2006, to discuss measurements of the solar spectral irradiance (SSI) from different instruments. The heart of the conversation was the comparison of the two spectrometers on SORCE to other observations. The SORCE measurements are from the SOLar-STellar Irradiance Comparison Experiment (SOLSTICE) and the Solar Irradiance Monitor (SIM). These two instruments in combination measure the solar irradiance from 115 nm to 2.7 microns. Variation in the solar irradiance over this wavelength range influences a wide range of processes from the upper atmosphere to the whole climate system. The long-term data record of the solar radiative output is made of a composite of measurements from a variety of sensors, and understanding the instrumental effects in each dataset is crucial to assembling a meaningful composite time series.

The morning session of the workshop covered the ultraviolet portion of the spectrum, while the afternoon was devoted to the visible and infrared.

Ultraviolet Session:

There were four presentations in the morning session, all concerned with measurements of SSI from about 115 to 300 nm. This region of the solar spectrum is highly variable on both short and long time scales. Radiation from these wavelengths is predominately absorbed by molecular oxygen and ozone in the upper atmosphere and is the major driver of chemical and dynamical processes in the thermosphere, mesosphere, and stratosphere.

The first presentation was from **Matt Deland** [Science Systems and Applications, Inc. (SSAI)] on his work to create a composite of solar UV measurements from 1978 to the present. He showed some of the challenges of this undertaking, which range from gaps in the data record (not enough data) to conflicting simultaneous measurements (too much data), and he reviewed the progress he has made in assembling a unified composite. Deland also noted that greater involvement from the SOLSTICE and SUSIM instrument scientists would aid in the construction of this reference spectrum.

The next speaker was **Linton Floyd** [Interferometrics, Inc.] who discussed the responsivity calibration of the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) on the Upper Atmosphere Research Satellite (UARS). This instrument measured SSI from 108 to 412 nm

from September 1991 through August 2005. Changes in responsivity were tracked with onboard deuterium lamps and duty cycling of redundant optical elements.

Martin Snow [LASP, University of Colorado] gave a presentation on the calibration of SOLSTICE instruments on both the UARS and SORCE platforms, as well as a comparison of SOLSTICE and SUSIM time series. Long term changes in responsivity of SOLSTICE are tracked via comparison with stellar irradiances, but the UARS instrument lost its capability to routinely observe stars at the end of 1999. Both Snow and Floyd noted that an important source of uncertainty in tracking degradation is the different field-of-view for the Sun and calibration sources (lamps or stars). The absolute irradiance measured by SORCE SOLSTICE is in agreement with the other UV SSI measurements at the 1 sigma level, as shown in **Figure 1**.

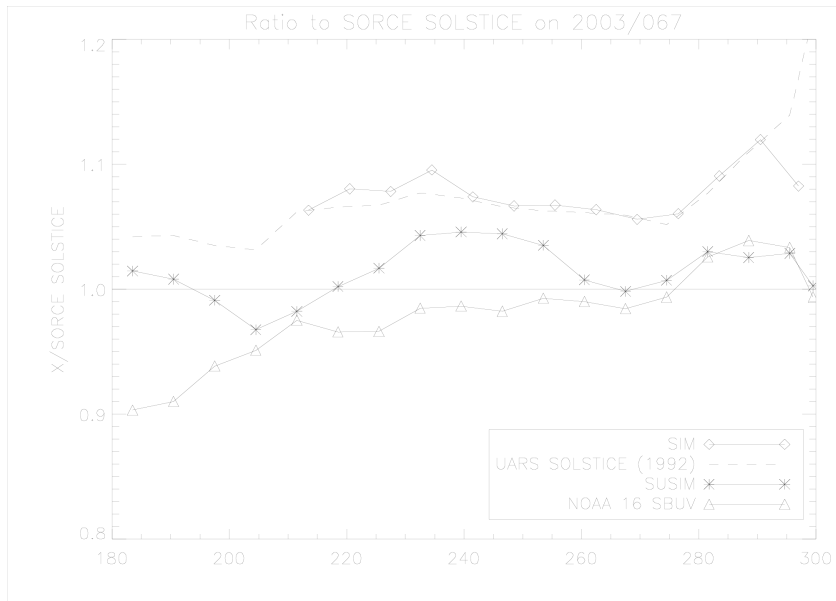


Figure 1. Preliminary analysis of calibration differences in the middle ultraviolet. The four curves shown in this figure are the ratio of measurements from SORCE SIM, UARS SOLSTICE, UARS SUSIM, and NOAA 16 SBUV to SORCE SOLSTICE. The published uncertainties of each instrument are on the order of a few percent, so agreement at this level is to be expected.

Wrapping up the morning session, **Francis Eparvier** [LASP, University of Colorado] gave a summary of how SOLSTICE and SUSIM data are used in analysis of the Solar EUV Experiment (SEE) on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. The SEE team uses a combination of SUSIM, SORCE SOLSTICE, and rocket underflights to measure the degradation rate of their instrument.

Ultraviolet Conclusions:

In addition to the ultimate goal of having consistent composite time series dating back to 1978, it was determined that a set of UV reference spectra should be produced in the near future. Just two spectra, one for solar maximum and one for solar minimum levels, have often been used by climate modelers in the past. A solar proxy measurement such as the Mg II index or F10.7 radio flux could then set the scaling between them for any given date. While this approximation is useful for long-term climate studies, we encourage the atmospheric community to directly use the more accurate measurements, such as from SORCE.

The UV solar irradiance presenters also had some very fruitful discussions about technical aspects of each mission's data products. Small details such as the time of day for measurements and wavelength binning were examined and noted for further analysis, as well as the larger issues of long-term trends and calibration offsets.

It was recognized that atmospheric and climate modelers are currently upgrading some of their radiative transfer modules (such as the transition from CAM3 to CAM4), and that the time is ripe for encouraging use of more detailed solar measurements. **Peter Pilewskie** [LASP, University of Colorado] presented a summary of a workshop that was held in Boulder, Colorado in August 2006. At that workshop, the SORCE scientists met with climate modelers from National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration (NOAA), Naval Research Laboratory (NRL), Atmospheric and Environmental Research, Inc. (AER), Jet Propulsion Laboratory (JPL), and the University of Colorado, to share information about what measurements were available from the instruments as well as what types of SSI inputs for the models were desired. There is a compelling need to include realistic solar variability in these models, and continued work with the modeling community is necessary to find workable solutions to include these measured data sets in the current climate modeling efforts.

Visible and Infrared Session:

The afternoon session began with a talk by **Gerard Thuillier** [Service d'Aéronomie du CNRS (Centre national de la recherche scientifique), France] on his SOLar SPECtral Irradiance (SOLSPEC) composite spectrum. This bridged the morning discussion of the UV with the topic of the afternoon, the visible and infrared, since his composite goes from the x-ray region to the IR. It is composed of rocket measurements below 120 nm, UARS SOLSTICE and SUSIM data in the far ultraviolet (120-200 nm), a combination of UARS and Atmospheric Laboratory for Applications and Science (ATLAS) measurements in the middle ultraviolet and near UV (200-400 nm), SOLSPEC ATLAS (400-870 nm), and SOLSPEC on the European Retrieval Carrier (EURECA) from 870 to 2400 nm. These measurements combine to produce two reference spectra for different levels of solar activity.

Claus Fröhlich [Physikalisch-Meteorologisches Observatorium Davos, Switzerland] presented a comparison of the WRC85 spectrum with SOLSPEC. The WRC85 spectrum is, like Thuillier's spectrum, a composite of different observations. Four spectra are combined and scaled to produce an integrated irradiance of 1367 Wm^{-2} . Comparisons with the Thuillier spectrum are within the stated uncertainties in the visible, but are larger than the published uncertainties in the UV and IR. These differences are on the order of 10% at 200 nm and at 2000 nm.

He also talked about observations from the SPM filter-radiometers on SOHO VIRGO that measure solar irradiance at 402, 500, and 862 nm respectively. After correction for degradation, time series data from these three photometer channels could be compared to SIM.

The spectrum from the UV through the near infra-red measured from GOME (Global Ozone Monitoring Experiment) and SCHIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric ChartographY) was shown by **Mark Weber** [University of Bremen, Germany].

This instrument measures the reflected sunlight relative to the solar input, so an absolutely calibrated measurement of the SSI is not required. Therefore there is only a limited capability for in-flight degradation measurements. Even so, their observations agree with other spectra discussed at this workshop at the 5% level. The combined GOME and SCHIAMACHY mission provide a measurement of solar spectral variability throughout the 240-790 nm region over 1 full solar cycle (1995 to present) and SCHIAMACHY has been providing additional information in the 790-2400 nm range since its launch in 2002.

Jerry Harder [LASP, University of Colorado] discussed the in-flight long-term precision and absolute calibration of the SIM instrument. His presentation showed how measurements of prism degradation and comparisons of the two independent spectrometers of SIM are used to correct for long-term drifts of the instrument. **Figure 2** shows the ratios between SIM, SCHIAMACHY, and WRC85 composite with SOLSPEC composite 3 at the SIM resolution in the 300-2400 nm range. The plot shows two curves for SIM: one with the current long wavelength ESR efficiency correction based on comparison with SOLSPEC, and the other shows the data as measured without this correction. The plan is to replace this bias correction with measurements at NIST's Spectral Irradiance and Radiance Calibrations with Uniform Sources (SIRCUS) facility using the SIM ESR (electrical substitution radiometer) flight spare. The plot shows that in the visible part of the spectrum, the four measurements agree to about the 2-4% level in the visible part of the spectrum (300-1000 nm) with larger deviations in the infrared. More work and comparisons must be done to understand these differences.

Later, **Joe Rice** of NIST presented a progress report on the calibration of the SIM flight spare ESR detector and engineering model spectrometer using the NIST SIRCUS facility. The laser system provided valuable characterization of the SIM slit instrument profile and scattered light response of the instrument function. Most importantly, the measurement campaign provided promising preliminary information on the calibration of the ESR's wavelength responsivity function. A second campaign is planned to repeat these measurements to extend the spectrometer's slit scatter function measurements into the UV and IR, and to repeat the ESR calibration with closer wavelength sampling, extend the measurement further in the UV and IR, and establish better the uncertainty of the measurement. **Figure 3** shows the preliminary results from the ESR calibration study. The solid curve is the correction factor used in **Figure 2**. These new results show that the measured efficiency of the ESR in the infrared matches the empirical correction factor that has been previously applied to SIM data.

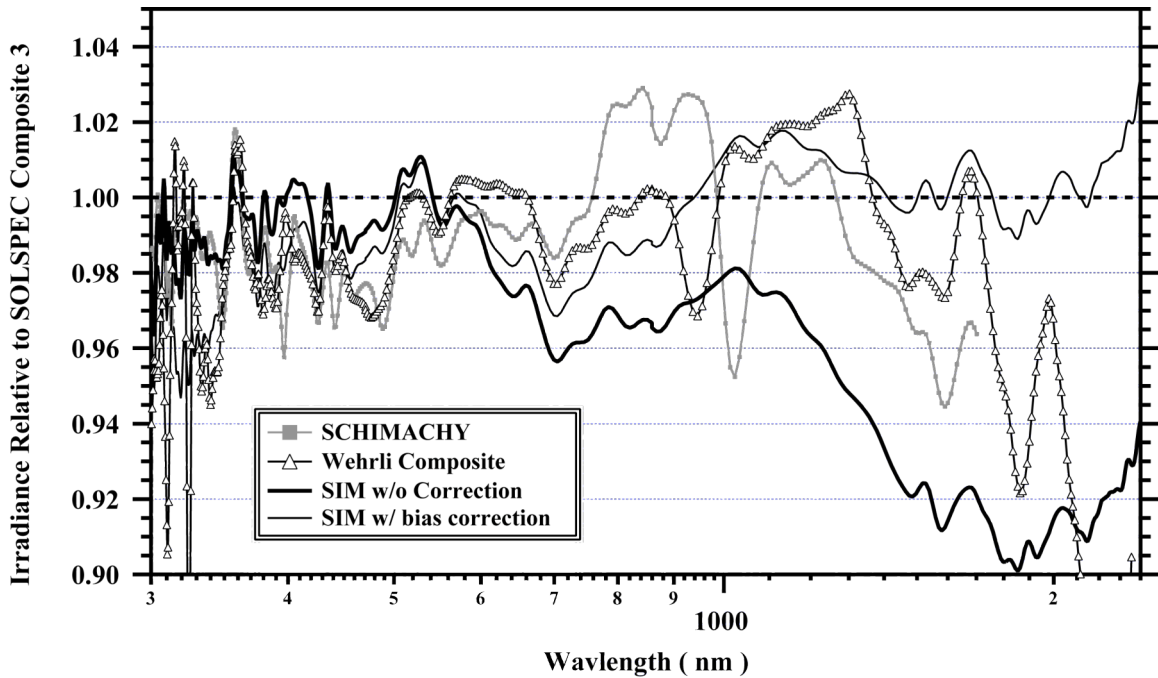


Figure 2. Comparison of visible and infrared spectra to the SOLSPEC composite for the spectra used in this workshop. Each spectrum has been convolved with the SIM instrument function for comparison. Two curves are shown for SIM, one with the current long wavelength ESR efficiency correction, and the other without. Figure 3 shows laboratory measurements of this correction factor.

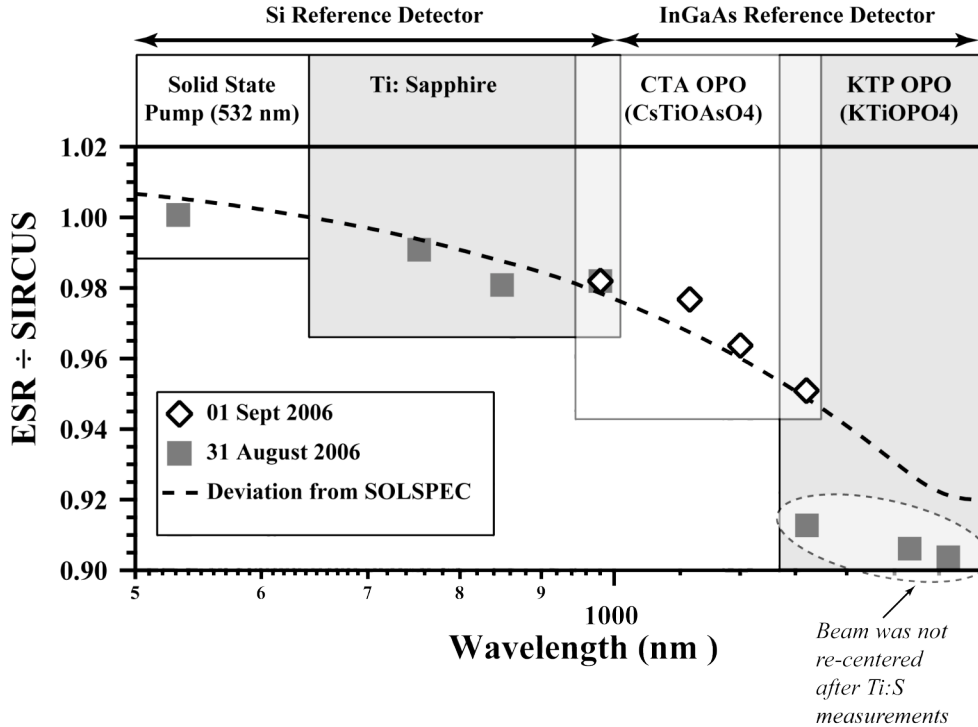


Figure 3. The efficiency of the SIM ESR measured at SIRCUS. The symbols indicate measurements from the flight spare ESR on the given dates. The dashed curve is the empirically determined correction factor needed to bring the SIM spectrum into agreement with SOLSPEC. The SIRCUS measurements confirm this correction factor with laboratory measurements.

Geoffrey Toon [JPL, Pasadena] presented a summary of the state-of-the-art of the absolute solar spectrum in the infrared (2-16 μm or 600-5000 cm^{-1}) with emphasis on results from the MkIV (balloon) and ATMOS (shuttle) interferometers. There has been less progress on parameterizing the solar continuum irradiance in the IR than there has been in the ultraviolet and visible spectral regions. Infrared instruments with high radiometric accuracy tend to have lower spectral resolution and vice versa. To date, none of the active ground-based, balloon-borne or space-based instruments have a rigorous absolute calibration; all of these instruments are used for detection of atmospheric trace gases, so this calibration effort has not been actively pursued. The best estimate of the solar continuum irradiance will come from a combination of ground, balloon, and space-based instruments. The MkIV interferometer has been calibrated against a commercial 1000C blackbody, but the direct Sun is much brighter than a 1000C blackbody so effects due to detector non-linearity and gain changes become important error sources. The pursuit of this absolute calibration will be important for future missions.

Robert Kurucz [Harvard-Smithsonian Center for Astrophysics] discussed his analysis of combining ground-based high spectral solar observations from Kitt Peak National Observatory in Arizona with both modeled and measured spectra. Kurucz analyzed the Kitt Peak data set to remove telluric contributions to leave only spectral structures associated with the sun. This residual spectrum can then be combined either with a calculated or semi-empirical solar model (for this meeting, the Kurucz ASUN model was used) to give the absolute spectrum, or the residual spectrum can be smoothed and broadened to match the resolution of lower resolution instruments that have a good absolute calibration, such as SIM and SOLSPEC. A study of this kind is very useful in understanding the absolute solar continuum level and evaluating measured spectra.

Juan Fontenla [LASP, University of Colorado] described the Solar Radiation Physical Model (SRPM) that he developed at LASP. His research integrates the results of measured solar spectra (such as SIM, SOLSTICE, SOLSPEC, and SUSIM) with detailed semi-empirical models of the solar atmosphere. The goals of SRPM are to: 1) provide a high resolution solar reference spectrum throughout the UV/Vis/IR spectral regions that is representative of the quiet Sun, 2) provide a variability spectrum at full-resolution for any observed distribution of solar activity for any given mask image of observed solar activity, and 3) understand sources of solar spectral variability at full-resolution. One of the new findings from this study suggests that the temperature minimum in the solar atmosphere is about 400 km higher than previously assumed, and this change produces better agreement with observed spectra.

The afternoon session was capped with discussion on two future missions.

Gerard Thuillier gave a presentation on SOLSPEC-ISS that will be deployed on the International Space Station in late 2007; this instrument consists of three double spectrometer systems that cover the 180-3000 nm range and lamps for in-flight photometric and wavelength calibration.

Hartmut Boesch [NASA JPL] described the Orbiting Carbon Observatory (OCO) scheduled for launch in September 2008 with a two-year life time. OCO will provide global, space-based

observations of atmospheric CO₂ with the needed precision, resolution, and coverage to monitor sources and sinks of this increasingly important atmospheric trace gas. The measurement requires an empirical solar reference spectrum algorithm that must be validated with calibrated solar irradiance spectra from measurements and models such as those discussed in this workshop.

Visible and Infrared Conclusions:

The following items best summarize the needs, plans, and actions for visible and infrared measurements:

- Further and more detailed comparisons among these instruments must be performed and published. For instance comparisons of the absolute scale (accuracy) and solar variability of SIM, SCHIAMACHY, SOLSPEC, and VIRGO SPM are planned and needed. Future comparison activities will continue with launch of SOLSPEC-ISS and the continuing SORCE and SCHIAMACHY missions.
- The greatest uncertainties in agreement between the instruments are in the infrared. Activities like the SIRCUS/SIM ESR calibration are needed to refine the on-orbit SIM calibration parameters. Future missions like OCO require good calibration of the solar continuum in the IR, and other space missions require good calibration further into the IR past 3000 nm. These measurements can be aided and extended by inclusion of solar model calculations such as from SRPM and ASUN.