Overview of NASA's Solar Irradiance Science Team #2 (SIST-2) Program

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Abstract

The Solar Irradiance Science Team #2 (SIST-2) program is a competitively solicited National Aeronautics and Space Administration (NASA) Earth Science Division (ESD) science research program providing three-year awards beginning in July 2018 to quantify and understand the solar irradiance and its variability. A key motivation for the SIST-2 program is to understand the solar radiation variability and implications for Earth's climate and atmospheric composition. The purpose for the SIST-2 program is limited to the accurate specification of the incoming solar irradiance into the Earth system considering the 43-year satellite data record as well as proxies to which the satellite record can be tied. The SIST-2 program funded eight research grants to study the variability of the total solar irradiance (TSI) and solar spectral irradiance (SSI) and to develop improved space-based data sets, solar proxies, and variability models of the solar irradiance. The SIST-2 projects are briefly introduced.

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Key Points:

- The Solar Irradiance Science Team #2 (SIST-2) program is a research program from July 2018 to July 2021 for NASA's Earth Science Division.
- The SIST-2 program has eight projects to study the variability of the total solar irradiance (TSI) and solar spectral irradiance (SSI).
- The SIST-2 project teams develop improved space-based data sets, solar proxies, and variability models of the solar irradiance.

Abstract

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Plain Language Summary

NASA's Earth Science Division has a dedicated research program to understand the solar brightness and how much the solar radiation can vary over time scales of days to years to centuries. This program is called the Solar Irradiance Science Team (SIST), which started in 2015 with a set of 3-year research grants, and then extended as the SIST-2 program for 2018-2021. There are eight research grants to quantify and model the solar irradiance for the SIST-2 program. Satellite observations of the solar radiation are analyzed to understand how much the solar radiation can vary, as well as how those results are combined with solar proxies to develop models of the solar variability for times when satellite observations are not available.

1 Introduction to NASA's SIST Program

The solar irradiance is the principal energy input to the global climate system and is critical for studying the radiative energy balance, atmospheric photochemistry, and solar influence on global and regional climate change (e.g., see reviews by Ermolli et al., 2013; Lean and Rind, 2008). Collecting accurate solar irradiance data spanning multiple years is crucial for understanding how much solar radiation is deposited in Earth's atmosphere and at the surface, and thus how much energy is available to influence weather, climate, the cryosphere, atmosphere dynamics, and ocean currents. For example, solar-related changes in global surface temperature have been about 0.1^{o}C during the recent 11-year solar activity cycles and are superimposed on a longer-term trend driven by increasing greenhouse gas concentration (Lean and Rind, 2008). The solar spectral irradiance (SSI) and the total solar irradiance (TSI, being the SSI integrated over all wavelengths) have been measured from space since the 1970s. The solar irradiance varies on all time scales, but the variability most important for Sun-climate studies include the 11-year solar activity cycle and longer term variability over centuries. The early measurements of the SSI focused on the ultraviolet in the 115-400 nm range, such as to study ozone photochemistry with the Upper Atmosphere Research Satellite (UARS: 1991-2005) and Solar Backscatter Ultraviolet (SBUV and SBUV/2). The current requirements for SSI observations for the Sun-climate record is for the 200-2400 nm range. NASA's Solar Radiation and Climate Experiment (SORCE) satellite provided SSI and TSI observations during its 17 years of operations from March 2003 to February 2020 (Woods et al., 2021), and the Total and Spectral Solar Irradiance Sensor (TSIS-1) mission continues the SSI and TSI climate records starting in March 2018 (Richard et al., 2020). As illustrated in Figure 1, another NASA mission overlapping with SORCE and TSIS-1 was the TSI Calibration Transfer Experiment (TCTE) mission with only TSI observations. In addition, the Aura Ozone Monitoring Instrument (OMI) has provided SSI observations in the 265 nm to 500 nm range since its launch in July 2004 (Marchenko et al., 2019).

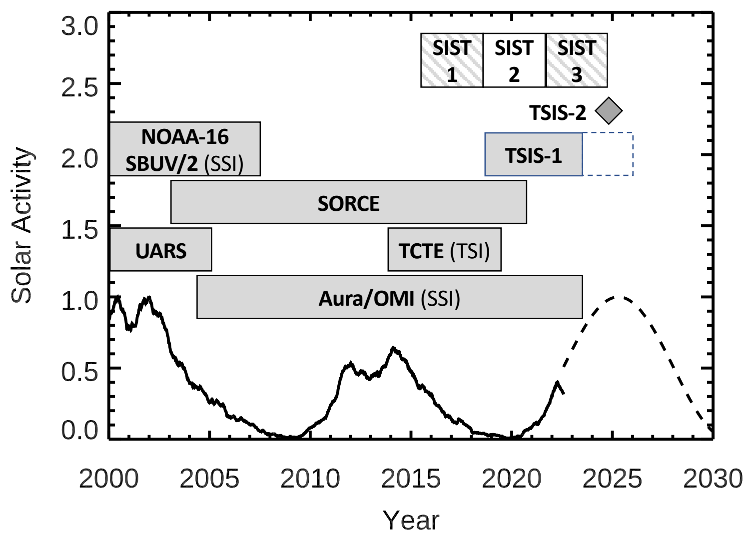

Figure 1. NASA ESD solar irradiance missions during the SIST programs. These missions have both TSI and SSI observations, except that TCTE only has TSI measurements and OMI and SBUV/2 only have SSI measurements. In order to prevent a gap, the TSIS-1 mission could be extended to overlap with the TSIS-2 mission that is anticipated to launch in late 2024. The solar activity time series is the normalized sunspot number smoothed by 243 days, and a rough estimate of the Solar Cycle 25 activity is included as the dashed line.

To support the analyses of the SSI and TSI mission data sets, as well as for extending the solar irradiance records to other time periods through modeling, NASA started the Solar Irradiance Science Team (SIST) program in 2015 as part of NASA's Research Opportunities in Space and Earth Sciences (ROSES) research program. The first SIST program (SIST-1) focused on developing space-based data sets, solar proxies, and variability models of the solar irradiance. Many of the results from the SIST-1 research grants are provided in the AGU Special Collection titled "Results From the Initial NASA Solar Irradiance Science Team (SIST) Program" and as introduced by SIST-1 team leader Matthew DeLand and SIST Program Scientist David Considine (DeLand et al., 2019).

Similar in scope as the SIST-1 program (July 2015 to July 2018), the SIST-2 program has eight 3-year research grants to quantify and understand the variability of the TSI and SSI and to develop improved space-based data sets, solar proxies, and variability models of the solar irradiance. The SIST-2 program started in July 2018 with David Considine continuing as the SIST Program Scientist and Thomas Woods being selected for the SIST-2 team leader. Figure 1 provides a timeline to highlight the SIST programs in context with NASA's solar irradiance missions. As illustrated in Figure 1, the SIST program is further extended for three more years with the SIST-3 program starting in July 2021.

Many of the results from the SIST-2 program are in this AGU Special Collection titled "Science Results from NASA's Solar Irradiance Science Team #2 (SIST-2) Program". Because some of the grants obtained no-cost-extensions, more results from the SIST-2 projects are anticipated in the near future. An overview of the SIST-2 program and its research projects are briefly described in the next section.

2 Overview of SIST-2 Projects

An over-arching goal for the SIST-2 program is to develop improved space-based data sets, solar proxies, and variability models of the solar irradiance. As listed in Table 1, eight research projects were selected for the SIST-2 program to address this over-arching goal, although not every project will develop new data sets, new solar proxies, <u>and</u> new variability models. Instead, each project focuses on one or more of those aspects for studying the solar irradiance and its variability. And not every project will develop results for both TSI and SSI records. For the eight SIST-2 projects, one has a focus for TSI research, five have a focus on SSI research, and two have a focus on improving solar proxies. Each of these projects are briefly described next.

The one project with a primary focus on TSI is the project with the title of "TSI Reconstructions Based on Updated TSI Composite and Sunspot Records" and with G. Kopp as the Principal Investigator (PI). This project's goal is to develop a long-term TSI record back to the 1700s using the Advective Flux Transport (AFT) model (Ugarte-Urra et al., 2015). The main inputs for the AFT model are bipolar active region information or solar magnetic field images, either being from direct measurements or magnetic-field estimates from other solar images. The reconstruction of the TSI variability is guided by the current TSI climate record. One of the key inputs for this record is the long 17-year TSI measurement from the SORCE mission that is described in detail by Kopp (2021). The AFT model is also useful to make predictions for future solar cycles (Upton & Hathaway, 2018). There are also two other SIST-2 projects studying the TSI variability (project PIs G. Chapman and J. Lean), and those are described below.

Of the five SIST-2 projects focused primarily on the SSI variability, two have a focus on improving SSI measurements for a specific instrument (project PIs S. Beland and H. Warren), one has a goal of improving solar variability models of the SSI and also for the TSI (project PI J. Lean). and two have a goal for developing improved composite records of the SSI over the past four decades (project PIs M. DeLand and T. Woods).

The project with the title "Improved SUSIM Solar UV Spectral Irradiances" (project PI H. Warren) concerns improving the solar ultraviolet (UV) irradiance results from the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) aboard the Upper Atmosphere Research Satellite (UARS). The SUSIM solar UV spectrometers have complex sets of calibration options of multiple redundant optics and on-board deuterium lamps, and their recent analysis involves re-analysis of the in-flight calibrations in order to derive improved instrument degradation trending, which in turn can provide improved SSI variability results. Part of their research has also been the development of a solar magnetic proxy that can be useful for solar variability modeling (Warren et al., 2021).

Table 1. Summary of SIST-2 Projects. The SIST-2 program has eight research grants. The team members, project title, irradiance type (TSI or SSI), and primary products are listed, along with references for some of their research results. The team members include the funded Co-Is but not the many collaborators involved. The product categories include improved mission/instrument data sets, composite data sets, proxy time series, and models of solar variability. The references in bold are in this SIST-2 AGU Special Collection.

Team Members	Project Title	Irradiance Type	Primary Product	Result References
Greg Kopp (PI), Odele Coddington, Lisa Upton	TSI Reconstructions Based on Updated TSI Composite and Sunspot Records	TSI	Model	Kopp, 2021
Gary Chapman (PI), Angie Cookson, Debi Choudhary	Comparing spacecraft TSI and SSI with proxies from space- and ground-based images	TSI SSI	Proxy Proxy	Choudhary et al., 2020
Judith Lean (PI), Odele Coddington, Peter Pilewskie, Marty Snow	Next Generation Solar Irradiance Variability Models	TSI SSI	Model Model	**Coddington et al., 2021** **Lean et al., 2022**
Stephane Beland (PI), Jerry Harder, Erik Richard, Beth Weatherhead	SORCE/TSIS Overlap Analysis: Absolute Scale Comparison, Stability Estimates, and Cycle 23/24//25 Record Construction	SSI	SORCE/SIM TSIS-1/SIM	**Harder et al., 2022a** Harder et al., 2022b
Matt DeLand (PI), Sergey Marchenko	Validation and Continuation of the V2 Composite SSI Data Set	SSI	Composite	Marchenko et al., 2021
Marty Snow (PI), Paul Bryans, Giuliana de Toma	MAGnesium II: Proxy for IrradiancE (MAGPIE). Improving irradiance modeling through better understanding of variability in the facular proxy	SSI	Proxy	Snow et al., 2019
Harry Warren (PI), Linton Floyd	Improved SUSIM Solar UV Spectral Irradiances	SSI	UARS/SUSIM Proxy	**Warren et al., 2021**
Tom Woods (PI)	Decoupling Solar Variability and Instrument Trends over SC 21 to SC 24 to Develop an Improved SSI Composite Record	SSI	Composite	**Woods and DeLand, 2021** Woods et al., 2022

The project with the title "SORCE/TSIS Overlap Analysis: Absolute Scale Comparison, Stability Estimates, and Cycle 23/24//25 Record Construction" (project PI S. Beland) focuses on improving the SSI results from the Spectral Irradiance Monitor (SIM) aboard both the SORCE satellite and the TSIS-1 payload flying on the International Space Station (ISS). Harder et al. (2022a) provides detailed comparison of the SIM SSI observations from SORCE and TSIS-1, and they produced a new version of the SORCE SIM SSI data product that has the SORCE SIM irradiances re-normalized to be consistent with that from TSIS-1 SIM. The SORCE SIM SSI products were also improved with new corrections for SIM instrument trends (Harder et al., 2022b).

The project with the title "Next Generation Solar Irradiance Variability Models" (project PI: J. Lean) seeks to improve their solar variability models using the more recent TSI and SSI observations. These models are called the Navy Research Laboratory Total Solar Irradiance (NRLTSI) for the TSI variability and the Navy Research Laboratory Solar Spectral Irradiance (NRLSSI) for the SSI variability. The NRLTSI and NRLSSI models of solar variability have been used for many Sun-climate studies, as well as, they have been adopted by NOAA for their official TSI and SSI climate records (Coddington et al., 2016). Both models include two proxies with one primarily representative of the dark sunspot effects for the solar irradiance and one primarily representative of the bright faculae contribution to the solar irradiance. The version 2 of the NRLTSI and NRLSSI models include many improvements as part of their SIST-1 project research (Lean et al., 2020), and a higher resolution version of NRLSSI is described by Lean et al. (2022). In addition, Coddington et al. (2021) have developed an even higher spectral resolution solar reference spectra based on TSIS-1 SSI observations.

Composite records of the solar irradiance combine several different solar irradiance measurements along with estimates from the solar variability models to fill temporal and spectral gaps. The various measurements are usually scaled to a reference data set in order to provide consistency over the full period of the composite record. The composite records can provide improved estimates of the solar cycle variability than possible with individual data sets and also provide decades-long climate record appropriate for use in Sun-climate research. Both of the SIST-2 projects developing composite SSI records (project PIs M. DeLand and T. Woods) start with the GSFCSSI2 Composite SSI record (DeLand et al., 2019b), and they are expanding out the SSI composite record in time and also in wavelength. For example, Woods and DeLand (2021) have a new SSI-3 composite record that is expanded in time using primarily the SORCE SIM data and also expanded in wavelength down to 0.1 nm and up to 1600 nm using SORCE SSI data. As part of the SSI-3 development, proxy models of the solar variability are also generated, and those proxy model results are also provided by Woods and DeLand (2021). In addition, more detailed analysis of the Aura OMI solar SSI data has revealed improved understanding of the solar activity for the hydrogen Balmer lines (Marchenko et al., 2021).

The remaining two SIST-2 projects have a focus on improving solar proxies useful for modeling solar variability. The project with the title "Comparing spacecraft TSI and SSI with proxies from space- and ground-based images" (project PI G. Chapman) is about improving and extending their solar proxies derived from the solar images obtained at the ground-based San Fernando Observatory (SFO) (Chapman et al., 2012). They are also studying similar solar visible images from the space-based Helioseismic and Magnetic Imager (HMI) instrument to derive similar solar proxies. In addition, they are studying the TSI variability in comparison to their solar proxies (Choudhary et al., 2020).

The project titled "MAGnesium II: Proxy for IrradiancE (MAGPIE)" (project PI M. Snow) is about improving the solar Mg II 280-nm proxy that is commonly used for solar UV variability and for the bright faculae component (such as used as input for the NRLTSI and NRLSSI models). Snow et al. (2019) provide improvements for the composite solar Mg II proxy, and they have also been studying the solar physics of how the chromospheric Mg II emission changes with solar activity through analysis of spectral images from the Interface Region Imaging Spectrograph (IRIS) satellite.

Although each SIST-2 project has its own unique objectives, there are many common elements shared between the projects. Obviously, the TSI and SSI observations over the past four decades are critically important for the SIST program. The solar proxies, such as the sunspot number and Mg II proxy, are also very important as input for the solar variability models to be able to fill observational gaps and extending backwards in time to as early as the 1700s. The solar proxies are also useful to help validate solar variability of the TSI and SSI direct measurements, and can even help to validate instrument degradation trends in some analyses (e.g., Woods et al., 2018).

There is still on-going work to get more of the SIST-2 research results published, so this overview of the SIST-2 program is more of an introduction to the SIST-2 program. The SIST-2 program builds upon the previous SIST-1 program (2015-2018) (DeLand et al., 2019a), and the new SIST-3 program (2021-2024) will be able to extend the progress towards better understanding of the solar irradiance and its variability in time and in wavelength as is needed for a myriad of Sun-climate studies.

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https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1944-8007.NASASIST2

Open Research

There are no datasets or software used for developing this manuscript, but we note that many of the SIST data products are available from the University of Colorado Laboratory for Atmospheric and

Space Physics (LASP) Interactive Solar Irradiance Data Center (LISIRD) (https://lasp.colorado.edu/lisird/).

References

Chapman, G.A., Cookson, A.M., & Preminger, D.G. (2012), Comparison of TSI from SORCE TIM with SFO Ground-based Photometry, *Solar Physics*, 276, 35-41. https://doi.org/10.1007/s11207-011-9867-6

Choudhary, D. P., Cadavid, A. C., Cookson, A., & Chapman, G. A. (2020), Variability in Irradiance and Photometric Indices During the Last Two Solar Cycles, *Solar Physics*, 295, id. 15. https://doi.org/10.1007/s11207-019-1559-7

Coddington, O., Lean, J. L., Pilewskie, P., Snow, M., & Lindholm, D. (2016). A solar irradiance climate data record. *BAMS*, *97*(7), 1265-1282. https://doi.org/10.1175/BAMS-D-14-00265.1

Coddington, O. M., Richard, E. C., Harber, D., Pilewskie, P., Woods, T. N., Chance, K., Liu, X., & Sun, K. (2021), The TSIS-1 Hybrid Solar Reference Spectrum, *Geophysics Research Letters*, 48, id. e091709. https://doi.org/10.1029/2020GL091709

DeLand, M. T., Kopp, G., & Considine, D. B. (2019), Overview of the NASA Solar Irradiance Science Team (SIST) Program Special Section, *Earth and Space Sciences*, 6, 2229-2231. https://doi.org/10.1029/2019EA000773

DeLand, M. T., Floyd, L. E., Marchenko, S., & Tiruchirapalli, R. (2019). Creation of the GSFCSSI2 Composite Solar Spectral Irradiance Data Set. *Earth and Space Science*, *6*(7), 1284-1298. https://doi.org/10.1029/2019EA000616

Ermolli, I., Matthes, K., Dudok de Wit, T., Krivova, N. A., Tourpali, K., Weber, M., Unruh, Y. C., Gray, L., Langematz, U., Pilewskie, P., Rozanov, E., Schmutz, W., Shapiro, A., Solanki, S. K., & Woods, T. N. (2013). Recent variability of the solar spectral irradiance and its impact on climate modelling. *Atmospheric Chemistry and Physics*, *13*(8), 3945-3977. https://doi.org/10.5194/acp-13-3945-2013

Harder, J., Béland, S., Penton, S. V., Richard, E., Weatherhead, E., & Araujo-Pradere, E. (2022a), SORCE and TSIS-1 SIM Comparison: Absolute Irradiance Scale Reconciliation, *Earth and Space Sciences*, 9, id. e02122. https://doi.org/10.1029/2021EA002122

Harder, J. W., Beland, S., Penton, S., & Woods, T. N. (2022b), Long-term Trend Analysis in the *Solar Radiation and Climate Experiment* (SORCE) / *Spectral Irradiance Monitor* (SIM), *Solar Physics*, 297, 69. https://doi.org/10.1007/s11207-022-02001-9

Kopp, G. (2021), Science Highlights and Final Updates from 17 Years of Total Solar Irradiance Measurements from the *SOlar Radiation and Climate Experiment/Total Irradiance Monitor* (SORCE/TIM), *Solar Physics,* 296, 133. https://doi.org/10.1007/s11207-021-01853-x.

Lean, J. L., & Rind, D. H. (2008). How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006. *Geophysical Research Letters*, *35*(18), L18710. https://doi.org/10.1029/2008GL034864

Lean, J. L., Coddington, O., Marchenko, S. V., Machol, J., DeLand, M. T., & Kopp, G. (2020), Solar Irradiance Variability: Modeling the Measurements, *Earth and Space Sciences*, 7, e2019EA000645. https://doi.org/10.1029/2019EA000645

Lean, J. L., Coddington, O., Marchenko, S. V., & DeLand, M. T. (2022), A New Model of Solar Ultraviolet Irradiance Variability with 0.1-0.5 nm Spectral Resolution, *Earth and Space Science*, e2021EA002211. https://doi.org/10.1029/2021EA002211

Marchenko, S. V., Woods, T. N., DeLand, M. T., Mauceri, S., Pilewskie, P., & Haberreiter, M. (2019), Improved Aura/OMI Solar Spectral Irradiances: Comparisons With Independent Data

Sets and Model Predictions, *Earth and Space Sciences*, 6, 2379-2396. https://doi.org/10.1029/2019EA000624

Marchenko, S., Criscuoli, S., DeLand, M. T., Choudhary, D. P., & Kopp, G. (2021), Solar activity and responses observed in Balmer lines, *Astronomy & Astrophysics*, 646, id. A81. https://doi.org/10.1051/0004-6361/202037767

Richard, E., Harber, D., Coddington, O., Drake, G., Rutkowski, J., Triplett, M., Pilewskie, P., & Woods, T. (2020), SI-traceable Spectral Irradiance Radiometric Characterization and Absolute Calibration of the TSIS-1 Spectral Irradiance Monitor (SIM), *Remote Sensing*, 12, 1818, https://doi.org/10.3390/rs12111818

Snow, M., Machol, J., Viereck, R., Woods, T., Weber, M., Woodraska, D., & Elliott, J. (2019), A Revised Magnesium II Core-to-Wing Ratio From SORCE SOLSTICE, *Earth and Space Sciences*, 6, 2106-2114. https://doi.org/10.1029/2019EA000652

Ugarte-Urra, I., Upton, L., Warren, H. P., & Hathaway, D. H. (2015), Magnetic Flux Transport and the Long-term Evolution of Solar Active Regions, *Astrophysical J.*, 815, 90. https://doi.org/10.1088/0004-637X/815/2/90

Upton, L. A., & Hathaway, D. H. (2018), An Updated Solar Cycle 25 Prediction with AFT: The Modern Minimum, *Geophys. Res. Lett.*, 45, 8091-8095. https://doi.org/10.1029/2018GL078387

Warren, H. P., Floyd, L. E., & Upton, L. A. (2021), A Multicomponent Magnetic Proxy for Solar Activity, Space Weather, 19, e2021SW002860. https://doi.org/10.1029/2021SW002860

Woods, T. N., Eparvier, F. G., Harder, J., & Snow, M. (2018). Decoupling solar variability and instrument trends using the Multiple Same-Irradiance-Level (MuSIL) Analysis Technique. *Solar Physics*, *293*(5), 76-96. https://doi.org/10.1007/s11207-018-1294-5

Woods, T. N., & DeLand, M. T. (2021), An Improved Solar Spectral Irradiance Composite Record, *Earth and Space Science*, 8, e2021EA001740. https://doi.org/10.1029/2021EA001740

Woods, T. N., Harder, J. W., Kopp, G., McCabe, D., Rottman, G., Ryan, S., & Snow, M. (2021), Overview of the Solar Radiation and Climate Experiment (SORCE) Seventeen Year Mission, *Solar Physics*, 296, id.127, https://doi.org/10.1007/s11207-021-01869-3

Woods, T. N., Harder, J., Kopp, G., & Snow, M. (2022), Solar Cycle Variability Results from the *Solar Radiation and Climate Experiment* (SORCE) Mission. *Solar Phys.*, 297, 43. https://doi.org/10.1007/s11207-022-01980-z.