THE FUTURE OF SOLAR SPECTRAL IRRADIANCE MEASUREMENTS FROM SPACE: ISS TSIS AND BEYOND

Erik Richard[(1)], Dave Harber[(1)], Joel Rutkowski[(1)], Matthew Triplett[(1)], Peter Pilewskie[(1)], Steven Brown[(2)] and Keith Lykke[(2)]

[(1)]*Laboratory for Atmospheric and Space Physics (LASP), 1234 Innovation Drive, University of Colorado, Boulder, Colorado 80303, (303)-735-6629, erik.richard@LASP.colorado.edu, (303) 492-1387, dave.harber@LASP.colorado.edu, (303)-492-6067, joel.rutkowski@LASP.colorado.edu, (303)-492-4997, matt.triplett@LASP.colorado.edu, (303)-735-5589, peter.pilewskie@LASP.colorado.edu*

[(2)]*National Institute of Standards and Technology (NIST), 100 Bureau Drive, Sensor Science Division, Gaithersburg, Maryland 20899, (301)-975-5167, swbrown@NIST.gov , (301)-975-3216, lykke@NIST.gov*

In order to advance understanding of how natural and anthropogenic processes affect Earth's climate it is critical to maintain accurate, long-term data records of climate forcing. These climate data records are a time series of key measurements of sufficient accuracy, consistency, and continuity to determine true climate variability and change. The dominant driver of Earth's climate is the incoming solar radiation, powering the complex and tightly coupled physical and chemical processes that establish the interactions among the atmosphere, oceans, land, and ice. While accurate measurements of the total solar irradiance (TSI) quantify the total energy available to drive the climate system, it is the measurement of solar spectral irradiance (SSI) that provides the wavelength dependent details necessary to elucidate the underlying mechanisms and terrestrial interactions responsible for solar induced climate changes. Ultimately, accurate, long-term SSI measurements are vital for interpreting how solar variability impacts climate and for validating climate model sensitivities to spectrally varying solar forcing.

Previous space-based SSI measurements, while crucial in evaluating and improving spectral models on short time scales, are not yet of sufficient accuracy and stability to definitively establish the long-term (decadal) solar impact on wavelength-dependent climate processes. The strong reliance on radiative transfer modeling for interpretation and quantification of the deposition of solar radiation in the atmosphere makes it imperative that the SSI be known to a high degree of absolute accuracy – tied and maintained to international standard units (SI) – where complete characterization of measurement uncertainties are known.

Table 1: Solar Spectral Irradiance (SSI) measurement requirements

Specification	Requirement	Justification
Irradiance Range Limits	$10^{-4} – 10^{1}$ $Wm^{-2}nm^{-1}$	Full scale bounds on SSI
Spectral Range (continuous)	200 – 2400 nm	96% of TSI
Measurement Uncertainty (k=1) (SI-traceable in irradiance)	0.2%	Climate modeling input: radiation budget solar attribution
Long-term Stability*	$0.05\%yr^{-1}$ ($\lambda \leq 400$ nm) $0.01\%yr^{-1}$ ($\lambda > 400$ nm)	Solar cycle variability UV: 10%-0.1% (Chromospheric) Vis-IR: ≤ 0.05% (Photospheric)

* Long-term stability limits represent 10-25% of total expected variability

The recently completed *Total and Spectral Solar Irradiance Sensor* (TSIS) *Spectral Irradiance Monitor* (SIM) is the next generation, space-borne SSI radiometer that is scheduled to be operational on the International Space Station (ISS) in late 2017. The instrument has been designed, characterized and calibrated to achieve unprecedented levels of absolute accuracy (u_c<0.25% combined standard uncertainty) and high spectral stability (0.01-0.05% per year relative uncertainty) across a continuous wavelength region spanning 200 – 2400 nm. Full radiometric characterization and calibration of TSIS SIM follows a measurement equation approach at the unit-level with validation of the end-to-end performance at the instrument-level. Following this approach, we establish the instrument as an "absolute" sensor with SI-traceability provided by full radiometric analysis of measurement uncertainties through calibrations tied to primary standards in power and irradiance.

The Spectral Radiometry Facility (SRF) was developed at LASP in collaboration with the National Institute for Standards and Technology (NIST) in order to characterize unit-level uncertainty contributions and validate the end-to-end performance of the SIM instrument. This comprehensive

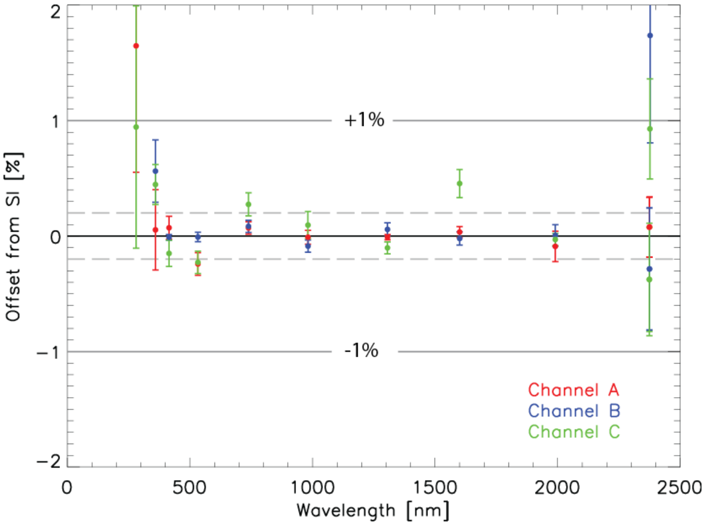

Figure 1: Results of end-to-end TSIS SIM spectral irradiance measurement equation validation through a NIST-traceable cryogenic radiometer. Individual error bars represent random laser intensity fluctuations in the measurement (Type-A uncertainty) and offsets reflect a systematic error in comparison process (Type-B uncertainties predominantly at extreme UV and IR wavelengths). The dashed lines represent the ±0.2% (k=1) irradiance uncertainty limits.

facility includes a large thermal-vacuum test chamber with a 5-axis precision manipulator for the SIM instrument. The illumination source is provided by a NIST *Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources* (SIRCUS) laser system. This laser system provides narrow, continuously tunable light from 210-2700 nm. Central to this facility is an *L-1 Technologies* cryogenic radiometer traceable to the NIST Primary Optical Watt Radiometer (POWR), the primary US standard for radiant power measurements. This cryogenic radiometer includes a NIST calibrated precision aperture and is used to measure the absolute irradiance of the illumination light. The SRF thus allows us to illuminate the instrument with a known (and highly stable) irradiance, wavelength, and polarization. Furthermore, the 5-axis manipulator permits us to fully quantify the pointing sensitivity and off-axis performance of the instrument over the full operational envelope of external driving factors. A series of detailed calibrations of the SIM instrument in this facility allowed us to fully characterize the instrument wavelength scale, spectral response functions, pointing sensitivity, and radiometric accuracy to better than 0.25% combined standard uncertainty.

With respect to establishing a continuous SSI record, observational continuity is key – without sufficient mission overlap of SSI data records, measurement uncertainties will preclude tying them together with the necessary accuracy to observe true climate signatures. Delays in the implementation of TSIS to assure future continuity of solar irradiance records are further compounding the problem of introducing large measurement gaps in achieving a long-term SSI record. Given these concerns, we have recently started a new development program for an instrument concept that will mitigate potential risks associated with large mission delays resulting in observational data gaps by developing a cost effective, reduced-size SSI radiometer. This compact SSI instrument offers significant implementation flexibility for future alternative flight opportunities, including CubeSat missions. The instrument will be a cost-effective and lower risk alternative to obtain high-priority SSI measurements and, through calibration with the SRF, will provide an SI-traceable tie to existing and future satellite records.

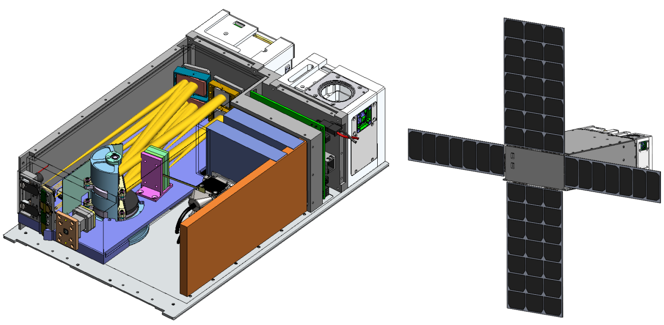

Figure 2: Diagram of the Compact Spectral Irradiance Monitor (CSIM) instrument under development. Shown here is a detailed view of the 6U instrument package with a folded, 2-channel prism spectrometer design. Also shown is the fully deployed CubeSat configuration.