Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

TSIS-1 SIM V12 Level 3 Data Product Release Notes V3

August 22nd, 2024

Summary

NASA's Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) built by the Laboratory for Atmospheric and Space Physics (LASP) operates on the International Space Station (ISS). TSIS-1 obtains absolute measurements of the total solar irradiance (TSI) and spectral solar irradiance (SSI). TSI and SSI are essential for scientific models of climate change and solar variability. TSIS-1 has two science instruments, the Total Irradiance Monitor (TIM), and the Spectral Irradiance Monitor (SIM).

This document describes Version 12 (V12) of the TSIS-1 SIM Level 3 (L3) data release. This document summarizes data processing and calibration changes that affect SIM L3 data and is not a complete list of changes affecting lower-level data products. Details of SIM L3 temporal and spectral data coverage can be found in Section 3. When referring to L3 data product columns (variables), references are in ALL_CAPS.

SIM L3 data is released on 12-hour and 24-hour cadences. The DOIs for V12 are:

- 12-hour: https://doi.org/10.5067/TSIS/SIM/DATA323
- 24-hour: https://doi.org/10.5067/TSIS/SIM/DATA324

TSIS-1 SIM V12 L3 data appears in three locations in the specified formats:

1. the LASP LISIRD website (ASCII, CSV, and NetCDF)
    - 12-hour: https://lasp.colorado.edu/lisird/data/tsis_ssi_12hr
    - 24-hour: https://lasp.colorado.edu/lisird/data/tsis_ssi_24hr
2. the LASP TSIS website (ASCII, IDL SAV file, and NetCDF)
    - https://lasp.colorado.edu/home/tsis/data
3. the NASA DAAC (ASCII)
    - https://disc.gsfc.nasa.gov/datasets

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1) Summary of TSIS-1 SIM V12 Activities and Changes From V11

V12 is an ‘off-cycle’ release[1] due to anomalies with the SIM Digital Signal Processor (DSP) and Electrical Substitution Radiometers (ESR). As described in Section 7.2, the SIM DSP stopped responding to ground commands on 03 Sept. 2023. DSP command and control was restored on 21 Oct. 2023. However, the post-anomaly checkout showed issues with the ESRs in certain configurations. As a result of the DSP anomaly, the Channel C scans scheduled for October 2023 were not performed[2]. Therefore, the degradation correction updates in V12 do not include updated Channel C data since the last observations in April 2023.

V11 was also an ‘off-cycle’ release that was required to mitigate the effects of increased degradation rates due to variable solar activity in solar cycle 25 (SC25). The V12 release provides improved degradation correction models designed to more accurately account for variable degradation rates.

Changes since the V11 TSIS-1 SIM data release include:

- Updated degradation correction models
- Improved diffraction corrections
- Added filtering for anomalous ESR data after the DSP and ESR anomalies
- Updated irradiance uncertainty calculations
- Added IRRADIANCE_TRUE_EARTH variable to L3 data products

[1]‘Off-cycle’ indicates that a data release was not triggered by the automatic re-calibration that occurs after each set of semi-annual Channel C scans.

[2]Channel C scans are scheduled when the Earth is ∼1 AU from the Sun, which occurs in early April and early October.

2) Details of TSIS-1 SIM V12 Changes

2.1 Updated Degradation Correction Models

The V12 updates to the degradation correction models are in response to the increased Channel A degradation rate, due to increased solar activity, that was originally noticed in August 2023 (see the V11v2 release notes). TSIS-1 SIM V10, and previous data releases, utilized extrapolated Channel A degradation models after the most recent Channel C scans. This practice was halted in V11 after January 20, 2023, as the existing degradation models could not account for the additional Channel A degradation due to increased solar activity in Solar Cycle 25 (SC25). The improved degradation models in V12 can accurately track the increased degradation due to SC25 solar activity and no extrapolation is employed for Channel A modeling. As discussed below, extrapolation of degradation models is still employed on Channels B and C.

Since no Channel C observations were taken in October 2023, as a result of the Digital Signal Processor (DSP) anomaly (see Section 7.2), the V12 degradation models using only Channel C data are necessarily extrapolated from the date of the last Channel C observations (April 3–5, 2023). All data leading up to the DSP anomaly have been used to create the V12 degradation models — anomalous ESR data taken after the anomaly are not included in the V12 models (see Section 7.2).

V12 includes the following degradation correction changes from V11:

1. **λ <408 nm:**
   - Channel B degradation models now use exponential fits across the full mission. The exponential models were found to more accurately represent the observed degradation rates while being less susceptible to noise (compared to the piece-wise[3] linear corrections that were previously used early in the mission and after the last Channel C scans).
2. **408 nm < λ < 740 nm:**
   - Channel A degradation models now use a polynomial fit until the April 2023 Channel C scans, after which a piece-wise linear correction is used. The polynomial fit better captures the increasing, solar-induced, degradation rates seen in this wavelength region (see the V11v2 release notes for further details).
3. **740 nm < λ < 800 nm:**
   - Channel A and B ESRs are now used in the degradation models, replacing the Channel B VIS detector. This change reduces the amplitude of the annual signal seen from 740–800 nm.
4. **1620 nm < λ < 1845 nm:**
   - Channel A ESR degradation model now uses a linear model rather than an exponential, as the linear model more accurately represents the observed degradation rate across the entire mission.

2.2 Improved Diffraction Corrections

The TSIS-1 SIM model used to correct optical diffraction has been updated to use the true apparent solar size at a given observation time. Previously, the model used the apparent solar size at the 1 astronomical unit (AU) distance and therefore was not accurately capturing the diffraction losses as the apparent solar size changed throughout the year. This change corrects annual signal oscillations observed in previous data releases for wavelengths greater than $\geq$ 900 nm by up to $\sim$50%. Examples of the reduced annual signal, for L2 irradiances before degradation correction, at 1400 and 1800 nm are shown in Figure 1.

2.3 Added Filtering for Anomalous ESR Data

As discussed in detail in Section 7.2, SIM ESR data began showing anomalous irradiances in certain wavelength ranges in certain configurations after the September 2023 DSP anomaly. As a result, the anomalous irradiances from these configurations are not used in the production of the V12 L3 data. ESR irradiance data from 1620–2300 nm are not published from October 2023 to January 2024, and 1620–1800 nm is not published from January 2024 to the present. Table 1 gives the approximate time periods and wavelength

[3] 'Piece-wise' linear corrections are calculated by linearly interpolating the ratio of an uncorrected channel measurement to a corrected one. This correction type is unaffected by degradation rate changes since there is no fit or assumption of a degradation model. However, they are more susceptible to short-term noise.

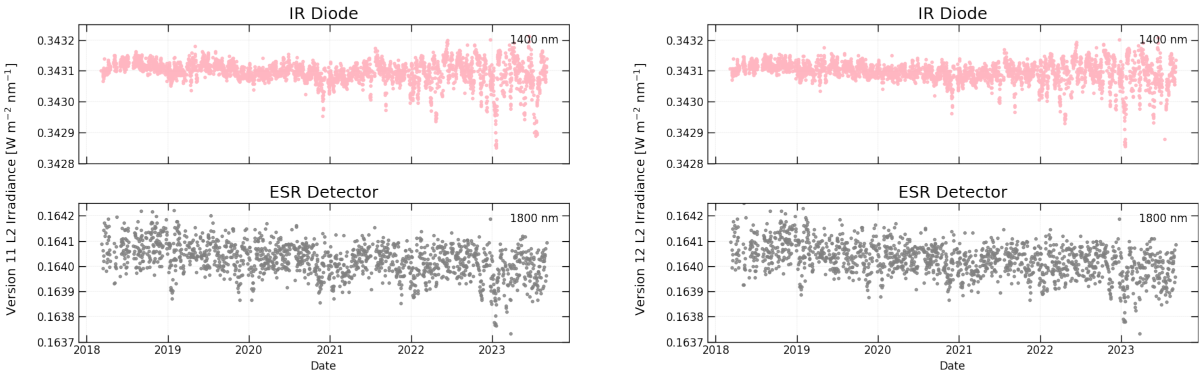

Figure 1: SIM L2 solar irradiances, uncorrected for degradation, at 1400 nm (top) and 1800 nm (bottom) for V11 (left) and V12 (right). The reduction in the annual signal is due to the improved V12 diffraction correction models that account for the changing solar size throughout the year.

regions of anomalous Channel A ESR data (see Figure 2). Additionally, there is a ∼500 parts-per-million (PPM) deficit in the V12 1800-2400 nm integrated ESR irradiance, as discussed in Section 7.2. The analysis is ongoing to investigate corrections for the ESR temporal and wavelength gaps for inclusion in V13.

Table 1: Approximate time and spectral range of anomalous ESR data

Time Range	**Wavelength Range (nm)**
October 2023 – January 2024	1620 – 2300
January 2024 – present	1620 – 1800

2.4 Updated Irradiance Uncertainty Calculations

Calculations of all SIM L3 irradiance uncertainties, except INSTRUMENT_UNCERTAINTY, have been updated to use the Standard Error of the Mean (SEM) of the L2 irradiances. Previous versions calculated uncertainties using averages. This change reduces the reported spectral irradiance uncertainties for wavelengths between 200 and 1620 nm by $1/\sqrt{n}$; where n is the number of exposures per data period, which nominally ranges from 1 to 4 per 24-hour period.

2.5 Added the IRRADIANCE_TRUE_EARTH Variable to SIM L3 Data Products

The TSIS-1 SIM L3 data products have been updated to include the spectral irradiance measurements reported at the true Earth-to-Sun distance at the observation time (IRRADIANCE_TRUE_EARTH). This irradiance data is now available in addition to the previously reported spectral irradiance measurements normalized to the mean solar distance of 1AU (IRRADIANCE_1AU). Note that all irradiances are reported for zero relative line-of-sight velocity with respect to the Sun. The IRRADIANCE_1AU measurements indicate emitted solar radiation variability (useful for solar studies), while IRRADIANCE_TRUE_EARTH reports the solar energy input to the Earth's atmosphere (useful for Earth climate studies).

The procedure used to derive IRRADIANCE_TRUE_EARTH is identical to that used by TSIS-1 TIM to derive TSI_TRUE_EARTH, with the Doppler and distance corrections being applied individually to each measurement based upon the mean time during the individual observation. However, unlike the TSIS-1 TIM reporting, we do not repeat our irradiance uncertainty estimates in the L3 data products. Instead, the user is instructed to convert the SIM irradiance uncertainties (σs) as shown in Equation 1.

$$\sigma(\mathbf{IRRADIANCE\_TRUE\_EARTH}) = \sigma(\mathbf{IRRADIANCE\_1AU}) * \frac{IRRADIANCE\_TRUE\_EARTH}{IRRADIANCE\_1AU} \tag{1}$$

3) TSIS-1 SIM V12 Temporal and Spectral Coverage

Table 2 gives the available time and spectral range for TSIS-1 SIM L3 data. Nominally, L3 irradiances have a latency of ∼25 days to allow for processing and the application of instrument degradation corrections. Data latency is driven by the cadence of Channel B observations, which are used in the degradation correction model. This delay may be extended due to delays in receiving telemetry and scheduling constraints such as ISS operations or periods of high beta angles.

Table 2: Time and spectral range of the dataset

Time Range	Wavelength Range (nm)
March 14, 2018 – October 1, 2023	200 – 2400
October 1, 2023 – January, 2024	200 – 1620, 2300 – 2400
January, 2024 – present	200 – 1620, 1800 – 2400

Temporal gaps are common in the TSIS-1 SIM data record due to ISS operational activities (e.g., orbit boost), anomalies (e.g., power outages), and obstructions at extreme beta angles. ISS obstructions can result in partial or complete loss of SIM spectra for a given day. Early in the mission, spectral gaps also occurred due to instrument planning and operations errors. Figure 2 shows the V12 L3 TSIS-1 SIM 24-hour data acquisition record as of the publication date of this document. Nominal data are shown in green, data quality flag (QUALITY=0), red points show missing data (QUALITY=1), and blue points show data backfilled from the previous day (QUALITY=2). Backfilling is never done when temporal gaps exceed 1 day. Pink data were acquired during the High-rate Fine Sun Sensor-B (HFSS-B(OFF)) pointing period (QUALITY=512, see Section 6), and purple data are both backfilled and during the HFSS-B(OFF) period (QUALITY=514). Data during the HFSS-B(OFF) pointing period have a wavelength-dependent spectral correction applied, maintaining their usability as quality SSI observations, but carrying a slightly higher uncertainty as captured in the ADDITIONAL_UNCERTAINTY column (see Section 5 and Section 7.1).

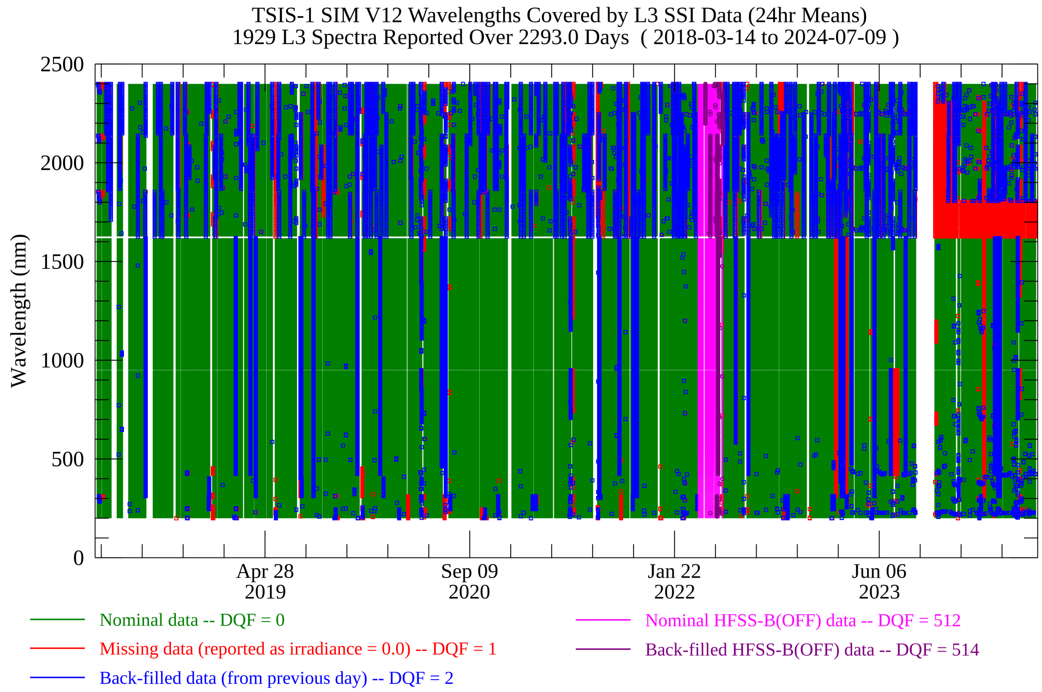

Figure 2: V12 TSIS-1 L3 SIM data acquisition record. As 09 July 2024, data are available 87% of days since the beginning of nominal operations on 14 March 2018. Note the missing L3 ESR data (1620–2300 nm, or 1620–1800 nm) after 21 Oct. 2023 due to the DSP and ESR anomalies as discussed in Section 7.2.

4) Comparison of TSIS-1 SIM V12 Integrated SSI to TSIS-1 TIM V04 TSI

Figure 3 compares the Total Solar Irradiance (TSI) measurements from the V04 data release of TSIS-1 TIM[4] with a TSI estimate (spectrally-integrated SSI, iSSI) derived from the V12 TSIS-1 SIM L3 data release. The SIM iSSI was generated by integrating the daily L3 spectrum from 200–2400 nm and adding an offset to account for wavelength regions not measured by SIM. Only complete SIM L3 spectra, with no missing or backfilled values, were used in Figure 3, therefore it is not currently possible in this figure to compare SIM iSSI to TIM TSI after the DSP anomaly of October 2023.

Figure 3 highlights the quality of the long-term SIM corrections by comparing the V12 iSSI against the TSIS-1 TIM TSI V04, which has a reported stability correction uncertainty of ∼10 PPM (Parts-Per-Million)/year. This plot should not be used to evaluate the TSIS-1 SIM absolute calibrations, as the offset (+52.1486 W m^{-2}) was chosen to match TIM as closely as possible over the mission. However, this value is close to the theoretically expected value of ∼4% of the TSI that falls outside of the SIM instrument's spectral range.

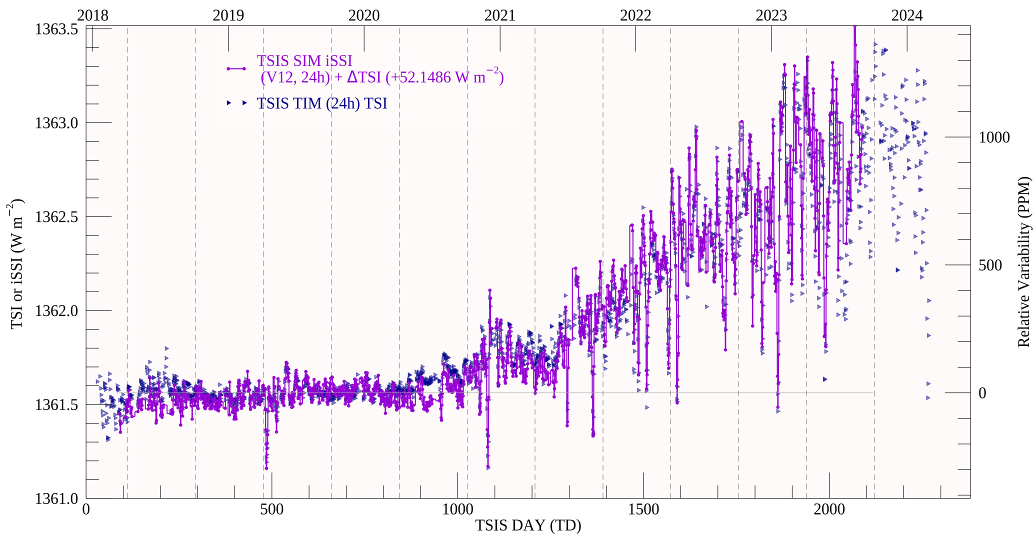

Figure 3: Comparison of V04 data release of TSIS-1 TIM (blue) Total Solar Irradiance (TSI) to the spectrally-integrated Solar Spectral Irradiance (iSSI) from the V12 data release of TSIS-1 SIM (purple). An offset of +52.1486 W m^{-2} has been added to the iSSI to account for wavelength regions not measured by SIM. Vertical lines indicate the planned semi-annual Channel C scan dates.

[4] See https://lasp.colorado.edu/home/tsis/data/tsi-data/

5) Definition of Uncertainties

Four types of uncertainties are reported in the TSIS-1 SIM L3 data release, these are:

INSTRUMENT_UNCERTAINTY (W m^{-2} nm^{-1}) is a pre-launch measure of instrument spectral irradiance uncertainty with contributions from component, and unit-level, instrument laboratory characterizations, and calibrations with the final end-to-end full spectrum validation of the measured irradiances against a NIST-traceable cryogenic radiometer performed in LASP's Spectral Radiometer Facility. Reported uncertainties represent an upper limit to the irradiance accuracy for each wavelength.

MEASUREMENT_PRECISION (W m^{-2} nm^{-1}) is a wavelength-dependent measure of the on-orbit variance in the scan-to-scan repeatability of the observed spectral irradiances during solar minimum. With the change to reporting the SEM instead of the average, MEASUREMENT_PRECISION is time and wavelength-dependent in TSIS-1 SIM L3 data releases starting with V12.

MEASUREMENT_STABILITY (W m^{-2} nm^{-1}) is a relative metric of the on-orbit degradation correction uncertainties. It has contributions from uncertainties due to the post-processing of data (including instrument degradation correction) and differences between the observed irradiances of the three separate SIM channels. Measurement stability is given as 0.0 at wavelengths $>$ 1845 nm, where the degradation corrections are currently not calculated, and for all data that arrives after the last bi-annual Channel C calibration scans. The bi-annual Channel C scans trigger a new data release version, so generally, there will be at least six months of measurement stability values that are 0.0 until they are determined during the creation of the next data release.

ADDITIONAL_UNCERTAINTY (W m^{-2} nm^{-1}) is a composite irradiance uncertainty pertaining to anomalous periods and the associated corrections in the data record, as indicated by the QUALITY data column. This uncertainty is applied to data where, due to atypical circumstances, the data have a higher uncertainty than nominal measurements.

5.1 Notes on Uncertainties

- Beginning with the V08 release, MEASUREMENT_PRECISION is no longer a term in the MEASUREMENT_STABILITY uncertainty.
- As of V12, the only type of ADDITIONAL_UNCERTAINTY is related to the HFSS-B(OFF) pointing anomaly in March through May 2022 (QUALITY=512). Channel- and wavelength-specific spectral corrections were needed during this period, introducing additional irradiance uncertainty.
- V10 extended the prism degradation corrections longward of 1050 nm to 1845 nm. MEASUREMENT_STABILITY uncertainties in this bandpass now include degradation uncertainty estimates.
- Prior to V12, ADDITIONAL_UNCERTAINTY, MEASUREMENT_PRECISION, and MEASUREMENT_STABILITY were averaged if more than one exposure was available during the data period (12 or 24-hour). These values are now reported as Standard Error of the Mean (SEM) values. See § 2.4.

For deriving TSIS-1 SIM absolute irradiance uncertainties, it is recommended that V12 users add in quadrature all four uncertainty values. For a relative irradiance uncertainty, reflecting the uncertainty in the irradiances between two time periods, use MEASUREMENT_PRECISION, MEASUREMENT_STABILITY, and ADDITIONAL_UNCERTAINTY added in quadrature.

6) Data Quality Flags

Each TSIS-1 SIM L3 spectral irradiance measurement includes an associated bit-wise integer data quality flag (DQF) in the QUALITY data product column. A QUALITY value of 0 indicates nominal data that has no associated DQFs. If a spectral irradiance measurement has multiple DQF flags set, the values of each flag are summed to create the final QUALITY value. For example, a QUALITY value of 514 indicates backfilled data that was obtained during the HFSS-B(OFF) pointing anomaly. A table of all TSIS-1 SIM L3 DQFs is shown in Table 3.

Table 3: TSIS-1 SIM L3 data quality flags (DQFs). Note that a QUALITY value of 0 (zero) indicates that no DQF is associated with a particular spectral irradiance measurement and that data should be considered nominal.

Flag Value	**Flag Name**	**Description**
1	MISSING_VALUE_FLAG	Indicates missing data items.
2	FILL_VALUE_FLAG	Indicates data items that have been backfilled from previous measurements within one day.
512	BAD_HFSSB_POINTING	Indicates irradiance measurements for which a wavelength-dependent correction was applied to account for the HFSS-B(OFF) pointing anomaly that affected data obtained from 19 March to 19 May 2022. See Section 7.1 for more information.

7) Notable Events

7.1 Spectral Corrections and Uncertainties During HFSS-B(OFF) Pointing

As discussed in detail in the V08 and V09 L3 release notes[5], during two months from 19 March – 19 May 2022, TSIS-1 SIM observations were offset in pointing by ∼1 arcmin due to surface contamination of the HFSS-B (High-rate Fine Sun Sensor-B). In this document, this is referred to as the HFSS-B(OFF) pointing period. On 19 May 2022, pointing was switched to the redundant sun sensor, HFSS-A, unaffected by surface contamination.

An on-orbit calibration campaign to derive channel- and wavelength-dependent spectral correction factors for Channels A & B during the HFSS-B(OFF) pointing period was undertaken in June 2022. To limit solar exposure, especially at off-1AU locations, Channel-C calibration scans were not included. This campaign consisted of two sets of calibration observations, taken two weeks apart. In each set of calibration observations, irradiance data were alternately acquired for each detector and channel combination using the contaminated HFSS-B(OFF) and the uncontaminated HFSS-A. To reduce the impact of a changing Sun, every effort was made to minimize the time between identical scans taken with different pointing (sun sensors).

These spectral pointing corrections, applied in V08 and later data releases, bring irradiance data during the HFSS-B(OFF) period in line with nominal measurements, albeit with slightly higher uncertainty. This added uncertainty reflects the uncertainty in the off-pointing corrections, given the solar variability in the observed irradiances during the special calibration experiments. These uncertainties are reported in the column labeled ADDITIONAL_UNCERTAINTY in all V12 L3 data products.

7.2 DSP and ESR Anomalies of September 2023

On 03 Sept. 2023, the SIM Digital Signal Processor (DSP) stopped responding to ground commands. DSP command and control was restored on 21 Oct. 2023. However, the post-anomaly checkout showed issues with the electric substitution radiometers (ESRs) in certain configurations.

Potential corrections to the affected ESR data are being investigated for inclusion in V13. ESR L3 data taken after 21 Oct. 2023 that do not currently meet the TSIS-1 SIM accuracy standards are not published in V12 (1620 nm$< \lambda <$1800 nm or 1620 nm$< \lambda <$2300 nm; see Table 1).

All ESR data shown in Table 1 have been flagged and are not published in V12. However, there is an uncorrected ∼500 parts-per-million deficit in the published V12 1800–2400 nm ESR integrated SSI (iSSI, see Figure 4). Potential corrections for the iSSI issue are also being investigated for inclusion in V13.

If possible, a spectral correction for the anomalous ESR data will be developed, and the existing data gaps removed. A correction will occur no earlier than the V13 data release (Fall/Winter 2024). The V12 ESR data gaps are visible after Oct 2023 in Figure 2, and do not allow the iSSI to be presented in Figure 3 after this date.

[5]TSIS-1 SIM Release note can be found at https://lasp.colorado.edu/tsis/data/ssi-data/sim-ssi-release-notes/.

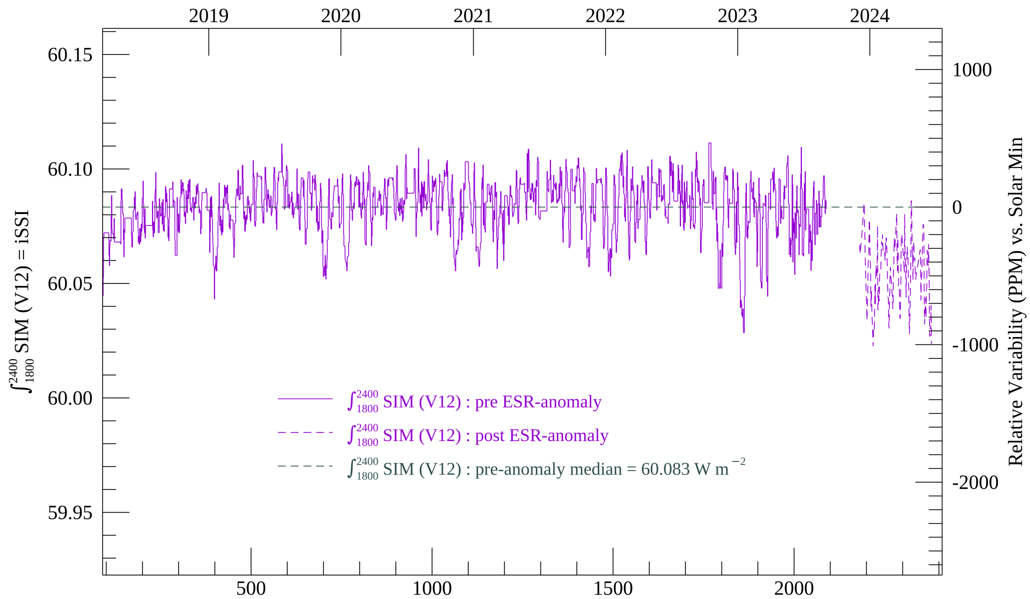

Figure 4: Comparison of V12 1800–2400 nm integrated SSI (iSSI) pre and post ESR-anomaly, showing a ∼500 parts-per-million (PPM) iSSI deficit. The right axis shows the PPM offset as compared to the Solar minimum iSSI of 60.083 W m^{-2} in the 1800–2400 nm bandpass. Corrections for this issue are planned for V13.

8) Additional Notes

- TSIS-1 SIM L3 V12 data products use average irradiances when more than one exposure is available for a given wavelength over the data product period (12 or 24-hour). Beginning with V12, on-orbit uncertainty values reflect this averaging by reporting the standard error of the mean (SEM) for MEASUREMENT_PRECISION, MEASUREMENT_STABILITY, and ADDITIONAL_UNCERTAINTY, whereas previous versions reported the average uncertainties.

- As a result of the SEM uncertainty change described above, the file format of the TSIS-1 SIM L3 NetCDF files was changed on August 22nd, 2024. The MEASUREMENT_PRECISION variable changed from wavelength-dependent to wavelength and time-dependent.

- SIM line spread function (LSF) details are available on the LASP TSIS-1 website: https://lasp.colorado.edu/home/tsis/data/ssi-data/.

- An IDL (Interactive Data Language) reader for the ASCII formatted data is available at: https://lasp.colorado.edu/data/tsis/file_readers/read_lasp_ascii_file.pro.

- Known V12 data issues that are under further investigation include:

  - Annual oscillations: There are annual oscillations in the SSI time series of some wavelengths, particularly longer than ∼700 nm. The annual oscillations for wavelengths longer than ∼900 nm have been reduced by up to ∼50% with the change described in Section 2.2 as of V12.

  - Residual temperature dependencies: The diode and ESR temperature corrections are less accurate during excursions from nominal operating temperatures. This is particularly true near the edges of the detector bandpasses.

- Previous TSIS-1 SIM L3 data releases are archived on CU-Scholar.
- Note for Python users using the NetCDF files:
  - The **xarray** package (2022.3.0) does not properly decode Julian dates (JD) into datetimes. Users should include the '**decode_times=False** in the **xarray.open_dataset** call to keep times in JD.
  - When using **NetCDF4.num2date** (1.5.8) or **cftime.num2date** (1.6.0) to convert the time column, users should provide the flag **has_zero_year=True** to properly convert JD to datetimes.

9) V12 Release Notes Revision History

Revision Version	Contributors	Version Notes
1.0	Michael Chambliss, Stéphane Béland, Keira Brooks, Luke Charbonneau, Odele Coddington, Courtney Peck, Steven Penton, and Erik Richard	Initial Release March 4th, 2024
2.0	Michael Chambliss, Stéphane Béland, Luke Charbonneau, Odele Coddington, Courtney Peck, Caitlin Poling, Steven Penton, and Erik Richard	Added Figure 4 to document a known irradiance deficit at the longest SIM wavelengths. July 17th, 2024
3.0	Michael Chambliss, Stéphane Béland, Luke Charbonneau, Odele Coddington, Courtney Peck, Caitlin Poling, Steven Penton, Matthew Maclay, Lizzie McMaster, and Erik Richard	Added discussion in § 2.4, § 5.1, and § 8 about on-orbit uncertainties being SEM instead of averages, and NetCDF file format change. August 22nd, 2024