Third Year Progress Report 1, *Developing a Climate Data Record for Total and Spectral Solar Irradiance*
NOAA Award Number NA09NES4400016
National Environmental Satellite Data and Information Service Program Office (NESDISPO)
Reporting Period: 08/01/2011 - 01/31/2012
Principal Investigator: Peter Pilewskie, Laboratory for Atmospheric and Space Physics, University of Colorado

During this reporting period a great deal of work was completed on the TSIS ATBD and on independent re-processing of SORCE Solar Irradiance Monitor (SIM) data. Co-Investigator Dr. Judith Lean submitted her progress in an independent report; those tasks are not listed herein.

1. TSIS ATBD

The TSIS Algorithm Theoretical Basis Document (ATBD) is primarily a description (though not the sole reference) of the Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM), and the algorithms used to convert the measured instrument power into total and spectral irradiance for all data levels for the TSIS mission. However, it will also play a role as a Climate-ATBD by providing a well-documented calibration history of the measurements that can be used for comparison and evaluation of the TSIS instruments to their future analogs. The document will be archived, maintained, and made publicly available at the NOAA Climatic Data Center. Such an approach will ensure the transparency of the data production.

To date, this is a unique approach for an instrument or mission ATBD, and the implementation of these dual goals will likely require periodic amendments to the document over the course of the TSIS mission. For instance, an amendment may be required when monitoring of the degradation of the SIM prism due to solar exposure require updated calibration coefficients for the acquired data set. The TSIS ATBD will help ensure good data stewardship, or management, of the TSIS contributions to the long-term data records in total and spectral solar irradiance. However, the process by which the long-term data records from various instruments across a number of missions are combined in a single composite is outside of the scope of the TSIS ATBD.

The algorithms (and data processing) for converting measured instrument signal to irradiance will follow a “Measurement Equation Approach,” an example of which is shown in Figure 1 for the SIM instrument. Every term on the right hand side of the equality in Figure 1 such as measured power, aperture area, absorptance of the ESR cavity, transmission of the prism, instrument slit function, and diffraction (including the wavelength dependency and temporal variations) must be measured, calibrated or characterized to accomplish this conversion. By following this approach, the TSIS ATBD will provide the logical flow for this process.

$$\mathcal{E}_\lambda(\lambda_s) = \frac{\mathcal{P}_{\mathrm{ESR}}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s)\, d\lambda}$$

ESR detected power

aperture

ESR Absorptance

prism transmission

slit diffraction

instrument function

Figure 1: Measurement Equation for the SIM instrument.

The planned content for the TSIS ATBD consists of 9 sections, listed and described in Table 1. A progress status is indicated by colored dots: green, yellow, and red referring to a status of "complete", "in progress", or "no progress, yet". We are on target for a late 2012 delivery of the document for review by an independent panel.

Table 1: Section outline and brief descriptions for the TSIS ATBD. Colored dots represent status of the ATBD. Green = "Complete", Yellow = "In Progress", Red = "No progress, yet".

Section Title	Description	Status
1. Introduction	a. Document Scope b. List of Supporting Documents	
2. Overview and Background Information	a. The Role of the Sun b. Mission Goals and Objectives c. Instrument Heritage, including Design Changes for TSIS SIM d. Requirements for future measurements of solar irradiance	
3. Instrument Design	Detailed enough to understand the algorithms, calibration, and validation sections. Descriptions will be provided for the following components (plus many others): a. ESRs b. apertures c. shutters d. prism and prism drive e. instrument slit function f. photodiode detectors g. standard resistance and volt h. Instrument Operation Modes	

4. Algorithm Description	Descriptions will follow a "Measurement Equation Approach" stepping through the conversion from measured instrument signal to irradiance (see text).	
5. Calibration and Characterization	Separated by instrument and Pre-Flight or In-Flight calibrations: a. Calibration Facilities: TSI Radiometry Facility, NIST SIRCUS, and LASP SIMRF b. Changes in cavity absorptance c. prism degradation d. changes in photodiode radiant responsivity e. servo loop gain changes f. monitoring of thermal background (dark measurements) g. pointing sensitivity (field of view maps)	
6. Degradation Correction and Uncertainty Estimates	a. TIM analysis based on Duty-Cycle b. SIM analysis based on Duty-Cycle	
7. Validation	a. Confidence in Measurements b. Comparison with other solar measurements c. Validation against models of solar irradiance d. Quality Control	
8. Data Product Requirements and Description	a. TSIS data level definitions b. Temporal Averaging c. Binning into desired Spectral Resolution	
9. Production of Science Data	a. Data Management b. Data Processing c. Data Structure d. Data Flow e. Data Storage Considerations f. Configuration Management	

2. SIM RE-PROCESSING

An independent evaluation of the relative degradation of the SORCE SIM instrument is underway.

Experimental Premise:

1. We assume that the irradiance measured by SIM A, I_A, as a function of SORCE mission day, t, is proportional to the degradation in the SIM A instrument and that this degradation is dependent upon the solar exposure time, .

2. Likewise, we assume the irradiance measured by SIM B, I_B, is proportional to the degradation in the SIM B instrument that occurs from time of solar exposure on SIM B,
   .
3. By analyzing the ratio of I_A to I_B, we can remove the solar variability from the measured signal. We have assumed that the Sun does not vary between near-coincident SIM A and SIM B measurements taken at time, t:

Equation 1: The ratio of SIM A/B irradiance is proportional to the ratio of the instrument degradation.

Data Set:

1. We have seven "golden" days where ESR scans over the full measurement range were obtained for both instruments within 24 hours of each other. These dates are SORCE mission days 453, 491, 673,852, 1034, 1223, and 1419. All of these days occur before the first on-board computer reset, at which point instrument characteristics were felt to have changed due to changes in temperature and modified calibration tables for the SIM instrument were subsequently uploaded.
2. For the golden days, we compute irradiance from the measured ESR power. (There is a known response between the reported data number 'DN' value and the power (Watts) of the instruments). These irradiances are free from all degradation corrections, computed solely from the ratio of measured ESR power to the product of a) entrance slit area, b) instrument slit function, and c) prism transmission, thereby converting DN to spectral irradiance ($Wm^{-2}nm^{-1}$). We also perform a 1 AU distance correction to remove the seasonal cycle from the measurements.
3. To remove sensitivity to possible wavelength shifts, we bin the irradiances for each instrument into bins ranging from 4nm (at ultraviolet wavelengths) to 50 nm (at infrared wavelengths).
4. The results are degradation-free irradiances measured by SIM A and SIM B at 83 wavelength bins for 7 days. These measurements comprise the I_A and I_B variables in Equation 1.

Determining Solar Exposure:

Data Set:

1. The cumulative exposure on the SIM A and SIM B instruments is extracted from instrument telemetry recorded in the SORCE database. These values comprise the and variables in Equation 1 and are illustrated (red lines) in Figure 2 for SIM A (left plot) and SIM B (right plot). The exposure is accounted separately according to the position of the hard radiation trap.

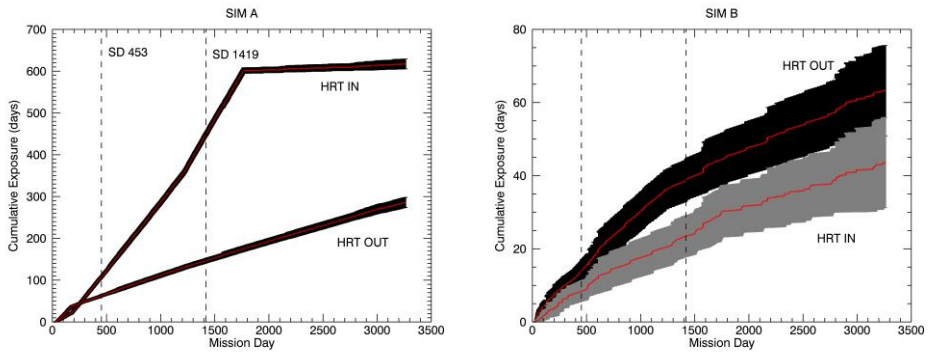

Figure 2: Cumulative exposure (days) of the SIM A/B instruments as a function of SORCE mission day. The region between the vertical dashed lines represents the experimental time period. The shaded region is the uncertainty in the cumulative exposure due to time periods where shutter position ("open" or "closed" is unknown). The fractional exposure of SIM B with respect to SIM A ranges from ~22 – 27% over the experimental time period.

2. There are uncertainties in the solar exposure times, which are predominantly due to uncertainties in the shutter position ("open" or "closed"), uncertainties in the position of the hard radiation trap ("in" or "out"), and uncertainties in spacecraft pointing knowledge via the fine sun sensor telemetry. These uncertain conditions result from "lost" (ex. corrupted packet, or overwritten at ground station) science packets, instrument housekeeping packets, and spacecraft housekeeping packets, respectively. This detailed accounting of 'gaps' in the solar exposure record are shown in Figure 3 for the SIM A, where the red line accounts for lost instrument housekeeping packets ('GAP HRT'), the black line accounts for uncertainty in shutter position ('GAP SCI'), and the dark blue line accounts for the uncertainty in instrument pointing ('GAP SC'). Other lines on the plot are telemetry variables being 'bookkept' as part of the determination of solar exposure.

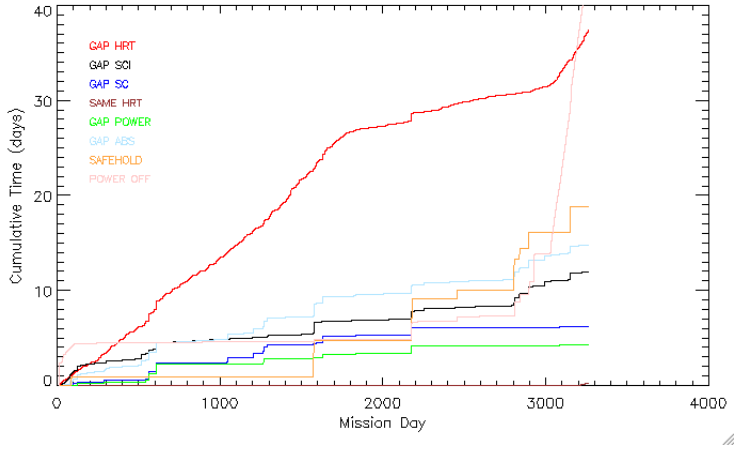

Figure 3: Cumulative time (days) of gaps in the SIM A measurement record (red, black, and blue curves) due to lost or corrupted housekeeping or science telemetry packets (see text). The vast majority of gaps in instrument housekeeping can be resolved via the SORCE planning database, leaving the gaps in science packet (and hence knowledge of shutter position) as the dominant uncertainty in determining solar exposure.

3. Uncertainties in the position of the hard radiation trap (red curve) can be resolved by consulting the SORCE planning database. We also assume (based on the precise pointing of the SORCE satellite) that uncertainties in pointing, based on lost telemetry information for the fine sun sensor in spacecraft housekeeping packets (blue curve), are small. This leaves the lack of knowledge in shutter position (black curve) as the dominant uncertainty in determining the solar exposure. This black curve is plotted as a error reported in Figure 2a, and similarly for SIM B (not shown).

Functional Form of the Degradation

1. As an initial approximation, we assume the instrument degradation has the following functional form: .
2. While the exposure time is different for each instrument, we assume that α is the same.
3. We assume that the ratio of the instrument degradations must be proportional to the ratio of the measured irradiances per Equation 1.
4. Using a fitting routine, we converge on an α that best replicates the measured ratio data.
5. We repeat the analysis for each of the 83 wavelength bins to compute $\alpha(\lambda)$.
6. The results are preliminary and future analysis will be performed to verify the experiment approach and implementation, the choice of the functional form of the degradation, and the degrees of best fit of the decay parameter.

Third Year Progress Report 2, *Developing a Climate Data Record for Total and Spectral Solar Irradiance*
NOAA Award Number NA09NES4400016
National Environmental Satellite Data and Information Service Program Office (NESDISPO)
Reporting Period: 02/01/2012 - 07/31/2012
Principal Investigator: Peter Pilewskie, Laboratory for Atmospheric and Space Physics, University of Colorado

During this reporting period two primary tasks were accomplished and detailed below: new degradation corrections studies for the Solar Radiation and Climate Experiment (SORCE) Spectral Irradiance Monitor (SIM); status update for the JPSS Total and Spectral Solar Irradiance Sensor (TSIS) Algorithm Theoretical Basis Document (ATBD).

1. INVESTIGATION OF RELATIVE DEGRADATION OF SORCE SIM INSTRUMENT

An independent evaluation of the relative degradation of the SORCE SIM instrument is underway. Since the last update, efforts have focused on refining the uncertainties in the SORCE SIM solar exposure time, and in investigating impact on instrument degradation from solar exposure time compared to that based on the photon flux (i.e. the photon flux striking the prism is not constant with time and will be dependent upon solar variability and the distance between the spacecraft and the Sun).

Experimental Premise:

1. We assume that the irradiance measured by SIM A, I_A, as a function of SORCE mission day, t, is proportional to the degradation in the SIM A instrument and that this degradation is dependent upon the solar exposure on the instrument, t_e^A.
2. Likewise, we assume the irradiance measured by SIM B, I_B, is proportional to the degradation in the SIM B instrument that occurs from amount of solar exposure on SIM B, t_e^B.
3. By analyzing the ratio of I_A to I_B, we can remove the solar variability from the measured signal. We have assumed that the sun does not vary between near-coincident SIM A and SIM B measurements taken at time, t.

$$\frac{I_A}{I_B} \propto \frac{\left(\frac{sun_t}{d(t_e^A)}\right)}{\left(\frac{sun_t}{d(t_e^B)}\right)}$$

$$\frac{I_A}{I_B} \propto \frac{d(t_e^B)}{d(t_e^A)}$$

Equation 1: The ratio of SIM A/B irradiance is proportional to the ratio of the instrument degradation.

Data Set:

1. We have seven “golden” days where ESR scans over the full measurement range were obtained for both instruments within 24 hours of each other. These dates are SORCE mission days 453,

491, 673, 852, 1034, 1223, and 1419. All of these days occur before the first on-board computer reset, at which point instrument characteristics were felt to have changed due to changes in temperature and modified calibration tables for the SIM instrument were subsequently uploaded.

2. For the golden days, we compute irradiance from the measured ESR power. (There is a known response between the reported data number 'DN' value and the power (Watts) of the instruments). These irradiances are free from all degradation corrections, computed solely from the ratio of measured ESR power to the product of a) entrance slit area, b) instrument slit function, and c) prism transmission, thereby converting DN to spectral irradiance ($Wm^{-2}nm^{-1}$). We also perform a 1 AU distance correction to remove the seasonal cycle from the measurements.
3. To remove sensitivity to wavelength shifts, we bin the irradiances for each instrument into bins ranging from 4nm (at ultraviolet wavelengths) to 50 nm (at infrared wavelengths).
4. Resulting are degradation-free irradiances measured by SIM A and SIM B at 83 wavelength bins for 7 days. These measurements comprise the I_A and I_B variables in Equation 1.

Determining Solar Exposure:

Data Set:

The cumulative exposure on the SIM A and SIM B instruments is extracted from instrument telemetry recorded in the SORCE telemetry database, and, in the instance of missing telemetry data (i.e. from lost or overwritten data packets, corrupt data packets, no transmission of data, or human error), from knowledge of planned spacecraft and instrument activities in the SORCE planning database. These values comprise the t_e^A and t_e^B variables in Equation 1. The exposure is accounted separately according to the position of the hard radiation trap ('out' or 'in'), and spacecraft pointing criteria ('10 arc' minutes around Sun center, or full field of view).

There are uncertainties in the solar exposure. The position of the shutter, which modulates sunlight entering the prism cavity, is recorded in the science telemetry packet. Spacecraft pointing knowledge via the fine sun sensor is recorded in the spacecraft housekeeping packet. The position of the hard radiation trap, a fused silica glass window (i.e. same material as the prism) that acts as a light filter to absorb radiation at UV wavelengths and reduce prism degradation, is recorded in the instrument housekeeping packet. Analysis suggests the dominant source of uncertainty in solar exposure is due to uncertainty in shutter position. Figure 1 shows a flow diagram documenting the various pathways by which the solar exposure and its uncertainty are calculated for this analysis.

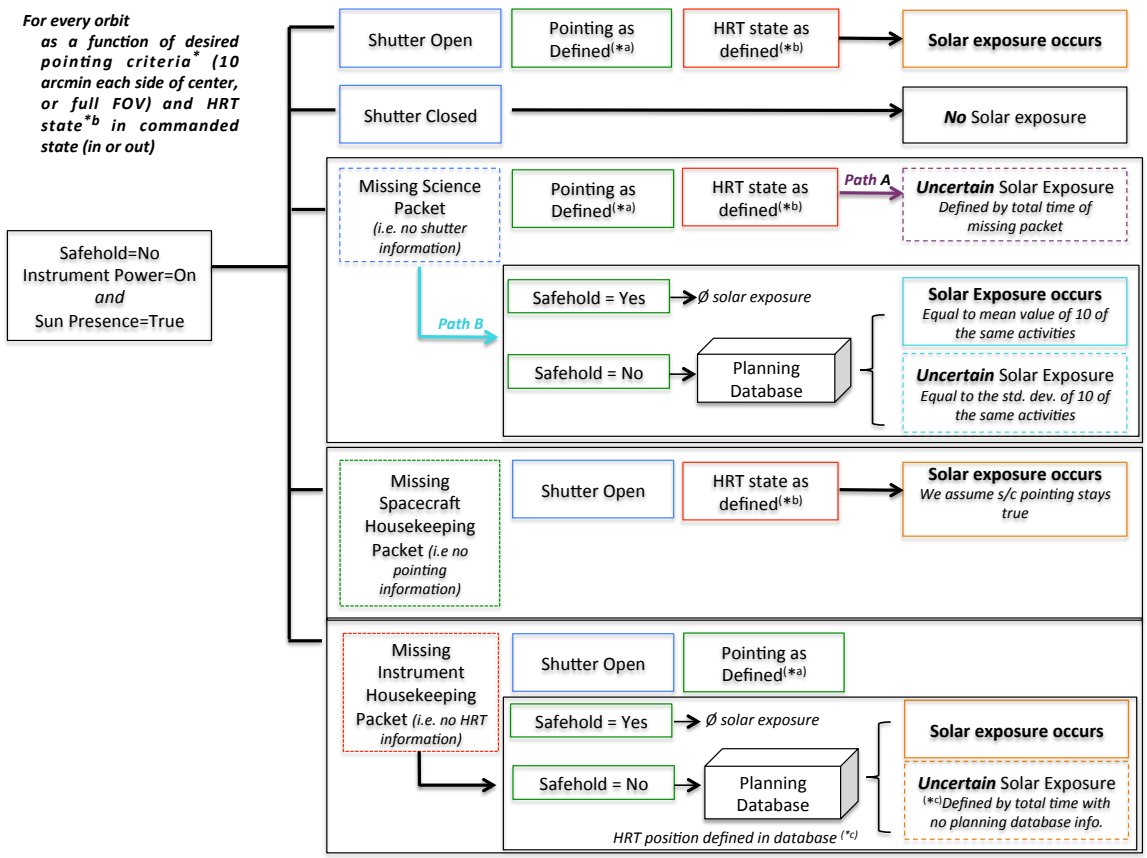

Figure 1: Flow diagram used in this analysis to compute solar exposure and uncertainty in solar exposure for the SORCE SIM channels. For every orbit, and for the desired s/c pointing criteria and position of the hard radiation trap, recorded telemetry is used to determine if the instrument was powered on, operating nominally, and viewing the Sun. Solar exposure is the accumulated time (seconds) for which these conditions are met. No solar exposure occurs when the instrument shutter is closed. For this analysis, we have assumed that the s/c pointing stays true even if pointing information is lacking in the telemetry database. For these conditions, solar exposure is calculated nominally as described above. In the vast majority of cases with no HRT telemetry, the position of the HRT can be determined from the planning database, and the solar exposure is calculated nominally as described above. The uncertainty in solar exposure due to lack of knowledge of HRT position is defined by the total time with no HRT planning database information (a cumulative time of 0.008 and 0.05 days, respectively for SIM A and SIM B over the first 3263 days that SORCE has operated). The largest uncertainties come from lack of knowledge in shutter position. An *upper limit* in this uncertainty is defined by the total time of the missing science packets ('Path A'). This is an overestimate of the uncertainty, as the instrument shutter would not be open and letting sunlight onto the prism the entire time. We apply a statistical analysis to better quantify the uncertainty in solar exposure due to missing science packets. For ten of the same science activities, of the same version number, the mean and standard deviation of the solar exposure is determined, and define the refined solar exposure and uncertainty. The choice of ten activities is arbitrary, and since determined to be too large; the statistical analysis resolves only 4% and 0% of the uncertainty respectively in SIM A and SIM B defined in 'Path B'. Since the current analysis *does not account for the accumulated time where the statistical analysis gave a null result*, 'Path B' is a biased low limit in the solar exposure. Future analysis will involve methods to better quantify the uncertainty in solar exposure due to lack of knowledge in shutter position.

The photon flux the prism surface is exposed to will be a function of solar exposure time (computed as outlined in Figure 1), variability in the Sun's output, and the distance between the spacecraft and the Sun. Degradation of the prism transmission due to this photon flux will also depend upon the wavelength-dependent energy of the photons and with the absorption properties of the organic material. We approximate the importance of this photon flux by considering only photons at the Lyman-alpha wavelength (121.6 nm), a wavelength located near the center of a range expected to be

most important in the degradation of space instrument optics, where solar variability is decreasing and absorption cross sections of typical organic materials are increasing towards longer wavelengths. We compare an accumulated photon flux 'dose' over the course of the SORCE mission with an accumulated solar exposure time. A time series of daily average Lyman-alpha photon flux measured by the SORCE SOLSTICE instrument is shown in Figure 2 (black line); we use the red curve which shows the Lyman-alpha photon flux after the removal of the 1 AU spacecraft-sun distance correction.

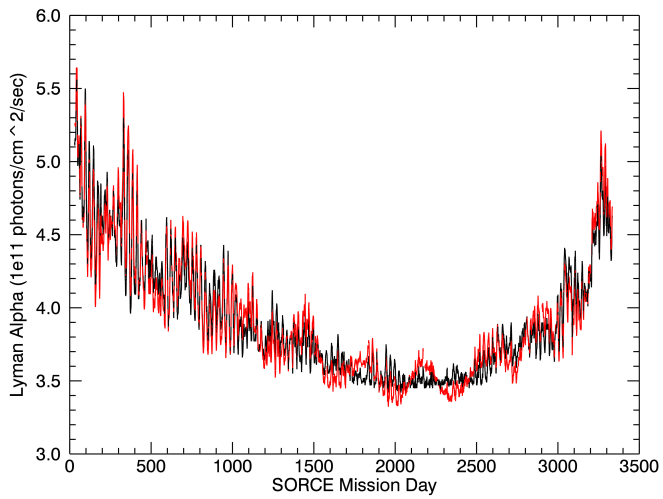

Figure 2: Time series of Lyman-alpha photon flux (1e11 photons /cm2/sec) obtained from SORCE SOLSTICE measurements with (black) and without (red) a 1-AU distance correction (black). We apply the red curve in our photon 'dose' analysis. SORCE mission day ~2000 corresponds to near solar minimum conditions (year 2008.5). SORCE mission day 0 was in early 2003, on the declining phase of solar cycle 23. The variability and magnitude of the Lyman alpha photon flux is nearly double at solar maximum than at solar minimum conditions.

We apply equation 2 to convert solar exposure in calendar time to a photon dose.

$$photon(per\ day) = SunExposure_{sec} * LymanAlphaPhotons_{\frac{photons}{\sec cm2}} * slit\ area_{cm2}$$

Equation 2: Daily photons striking the prism are determined through the product of solar exposure, Lyman alpha photon flux, and the area of the instrument entrance slit.

The results of the cumulative solar exposure and uncertainties (see Figure1) for each SIM channel, and the conversion to cumulative photon events over the course of the SORCE mission (see Equation 2) are shown in Figure 3 and Figure 4.

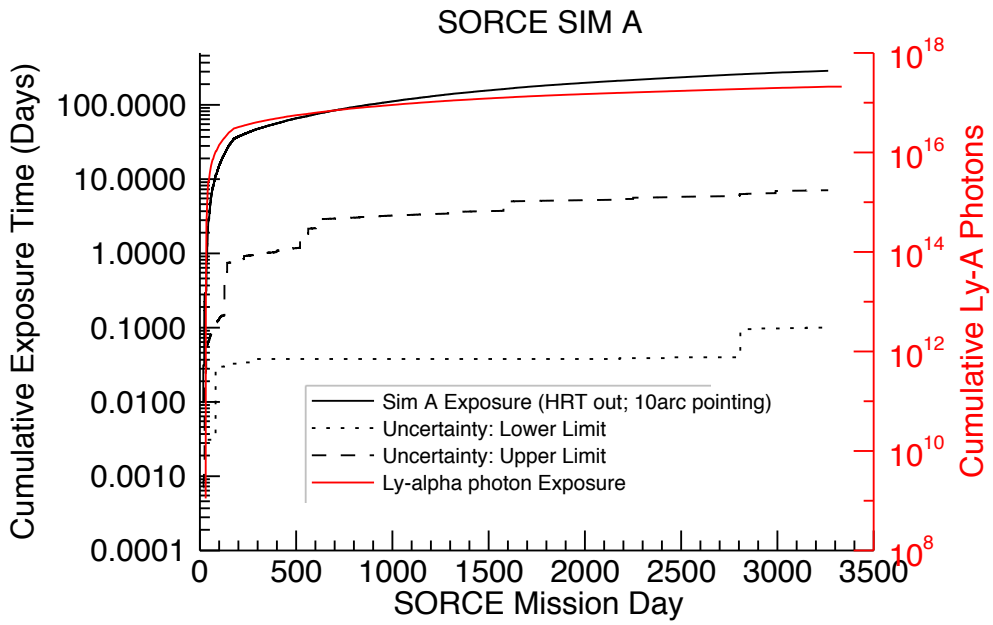

Figure 3: Cumulative solar exposure (solid black line) on SIM channel A. Upper (dashed line) and lower (dotted line) limits in exposure uncertainties are shown. A cumulative photon dose (red line; right axis) is computed from knowledge of the solar exposure per Equation 2.

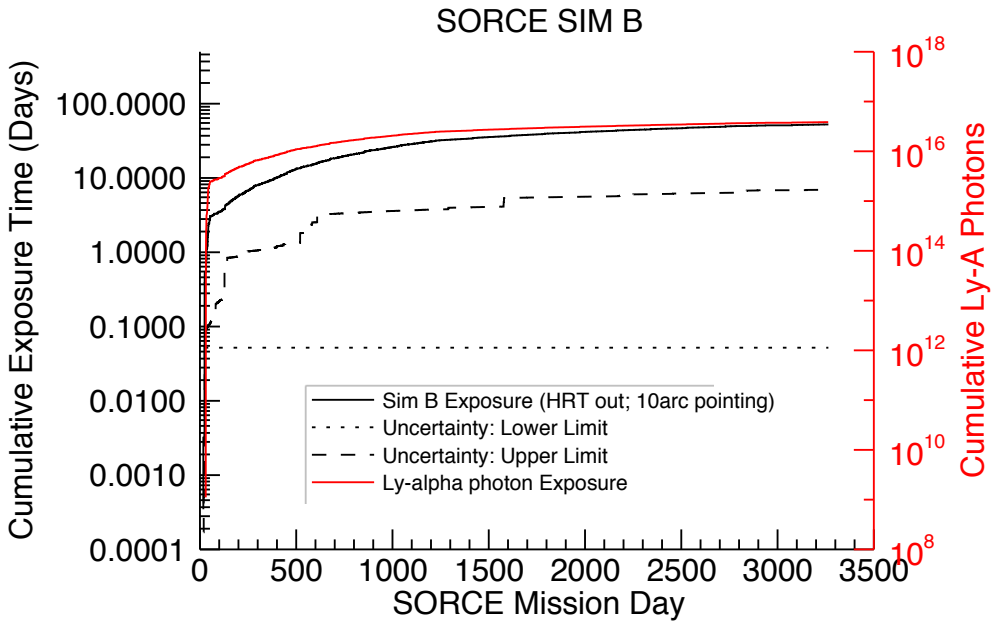

Figure 4: Cumulative solar exposure and photon dose on SIM channel B. Plot details are as described in Figure 3.

By applying a scaling factor, one can plot the cumulative solar exposure and photon dose on the same scale and determine the relative impact of photon dose. For both channels, we compute a scaling factor for the cumulative Lyman alpha photon dose such that the total dose by SORCE day 3209 is equivalent to the cumulative days of solar exposure on that same day. The results are shown in Figure 5. This information is simply a subset of that shown in Figure 3 and Figure 4, but without the log-scaling for easier visualization of differences. Due to the greater exposure of the SIM A channel, accounting for the Lyman alpha photon dose has a larger impact than for the B channel.

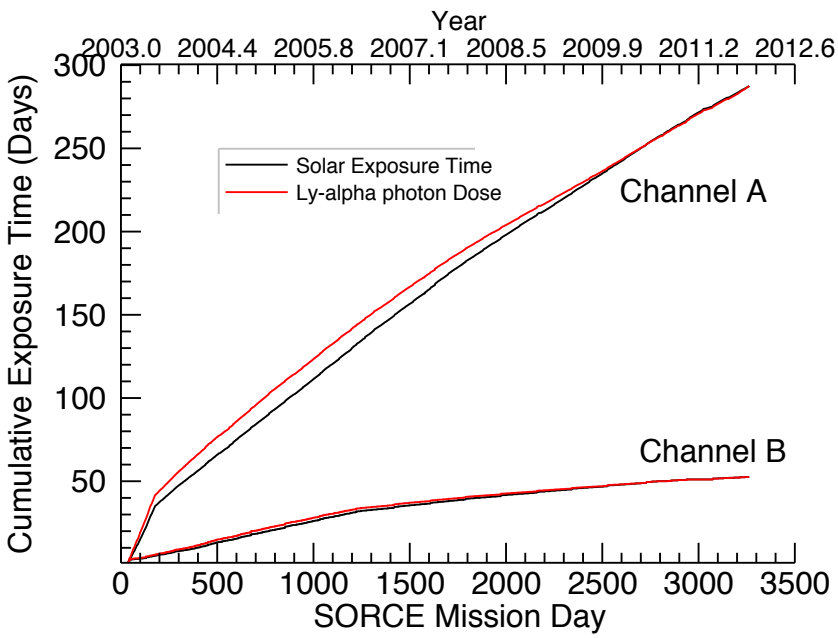

Figure 5: Comparison of the cumulative solar exposure (in days; black line) to cumulative photon dose (scaled to days; red line) for both SIM channels. Channel A is exposed approximately 287 days and channel B 52 days over the time period analyzed. Due to the greater calendar exposure time on the A channel, the photon dose impact is larger. The data is a subset of that shown in Figures 3 and 4, but on a linear scale. The scaling factor applied to the cumulative Lyman alpha dose forces the exposure 'photon days' to be equivalent to the cumulative exposure time at the final data point in the time period analyzed.

The fractional exposure of the B channel with respect to the predominantly used A channel is determined through the ratios of 1) the solar exposure of B channel normalized by the solar exposure of A channel, or 2) the photon 'dose' experienced by the B channel normalized by the photon 'dose' of the A channel. Figure 6 shows that the B channel is exposed roughly 14-24% of the time that the A channel was exposed. Near start of mission, SIM B was exposed to a larger degree. There is a second 'kink' near SORCE mission day 1250, where planned operations changed and there was a reduction in the rate of sun exposure on the B channel. These preliminary results suggest the current degradation model applied to the SORCE SIM data (grey curve) may under correct for potential instrument degradation, when compared to this solar exposure analysis in calendar time (black curve) or photon dose (red curve).

Figure 7 shows the differences between the current exposure analysis and the ratio of the column values (B to A) that are applied currently.

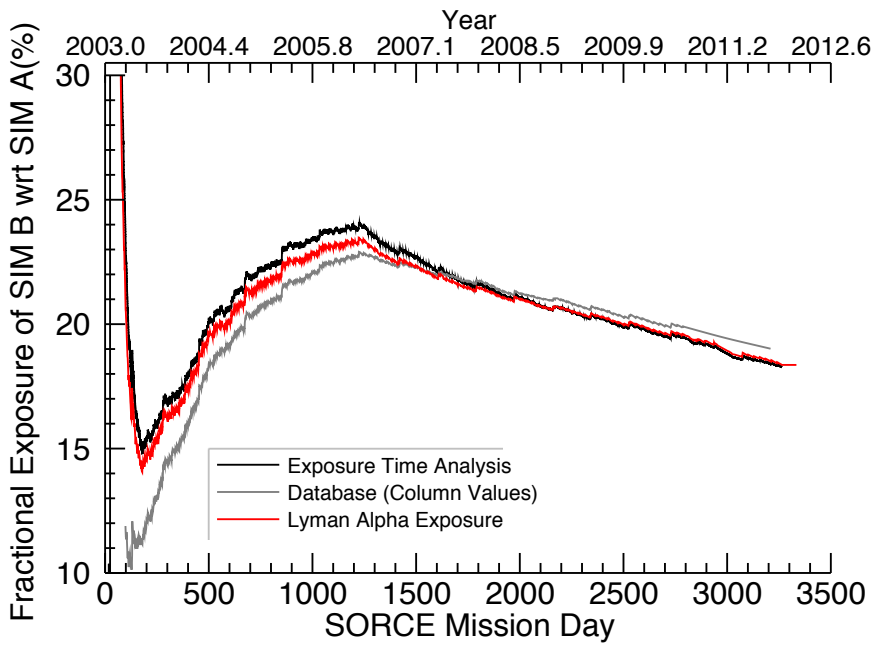

Figure 6: Fractional exposure of SORCE SIM B channel with respect to the A channel (in percent). Time-dependent differences exist whether a solar exposure time is considered (black line) or a Lyman alpha photon 'dose' is considered (red curve). Also shown in the ratio of the 'Column' values for B relative to A channel (grey curve) available in the SORCE database and as currently applied in the SORCE SIM degradation model.

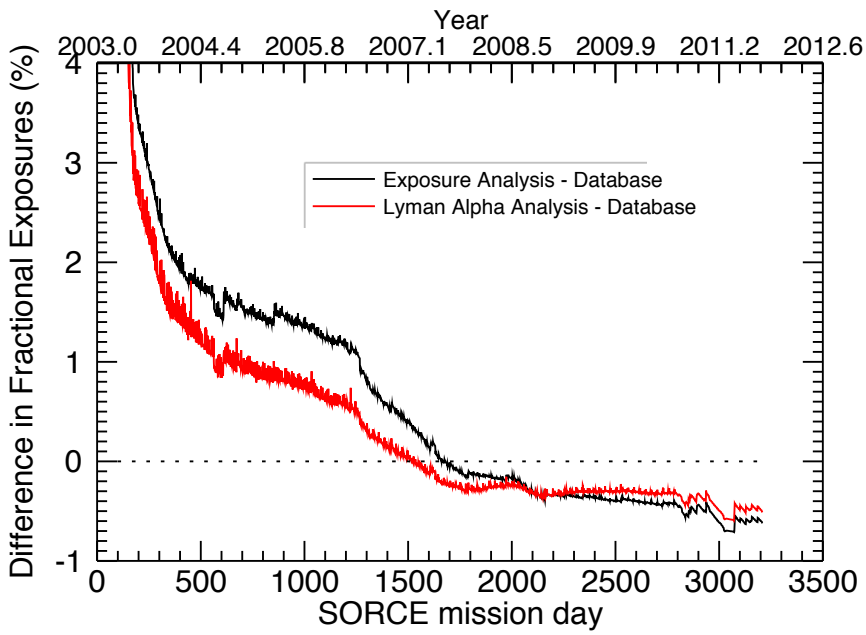

Figure 7: The difference (in percent) between the exposure analyses in this work to the ratio of the 'Column' values available in the SORCE database (as shown in Figure 6).

We compute the difference between the fractional exposure as a function of calendar time and the fractional exposure as a function of photon dose, to determine an upper bound on the impacts of photon flux on long term instrument exposure. What results is the difference between the black and red curves from Figure 6, and shown in Figure 8. These results suggest that, from roughly SORCE mission day 200 -1200, the fractional exposure in the channels due to photon flux was approximately 0.5% less than the computed fractional exposure in the channels due to the solar exposure time.

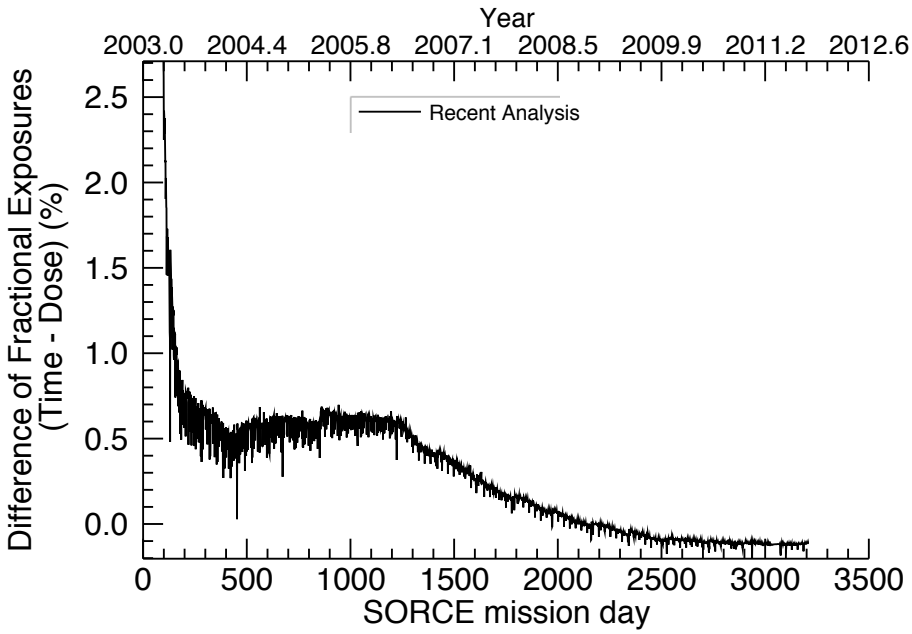

Figure 8: The impacts of photon dose obtained by the difference of fractional exposure based on calendar time (Figure 6; black curve) and the fractional exposure based on photon flux (Figure 6;red curve).

Functional Form of the Degradation

The following steps outline the approach for determining the wavelength dependence of the relative instrument degradation. The approach is contingent upon knowing the exposure time for each instrument, as outlined in the above sections.

1. As an initial approximation, we assume the instrument degradation has the following functional form: $d(t_e) = e^{-\alpha t_e}$.
2. While the exposure time is different for each instrument, we assume the α is the same.
3. We assume that the ratio of the instrument degradations must be proportional to the ratio of the measured irradiances per Equation 1.
4. Using a fitting routine, we converge on an α that best replicates the measured ratio data.
5. We repeat the analysis for each of the 39 wavelength bins (see Table 1) to compute α(λ) shown in Figure 9.
6. The results of Figure 9 are preliminary and future analysis will be performed to verify the experiment approach and implementation, the choice of the functional form of the degradation, and the degrees of best fit of the decay parameter. The results are also based on an older version of calculated solar exposure, that did not correct for some of the uncertainties discussed above.

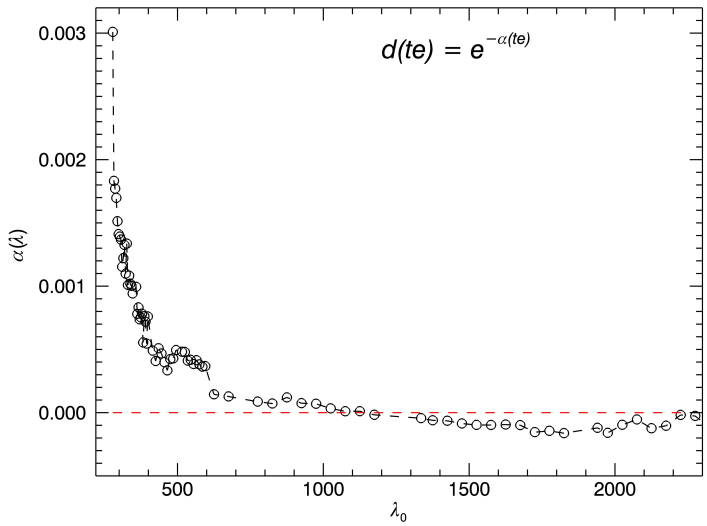

Figure 9: The wavelength dependence of the relative instrument degradation, assuming an exponential decay with solar exposure.

Differing Behavior in Binned SIM A/B irradiance versus cumulative solar exposure as a function of wavelength:

1. Analysis of the binned measured irradiance as a function cumulative solar exposure shows differing systematic offsets as a function of wavelength.
2. We have improved our binning analysis by choosing "smart" bins that avoid sharp absorption/emission features. The 39 bins are defined in Table 1. The following bins were removed from analysis (not shown) due to missing SIM B data on our canonical day, SD 453: Please see *simab_bin.pro* for binning analysis code and binning method comparisons in *reprocessing work.pptx*. (Older analysis binning done in *simab_interp.pro*)
3. The differences could be explained by determining the "dose" (i.e. events) of exposure, which we approximate by the cumulative Lyman alpha photon flux for shutter open and HRT out time periods.
4. If not, another possibility that could explain the changes in systematic offsets would unaccounted for wavelength shifts.
5. The following three plots show SIM A (black symbols) and SIM B (orange symbols) binned irradiance as a function of cumulative solar exposure for the 7 "golden days" listed above. Results are shown for three wavelength bins: 310.8 – 312.4 nm, 529-535 nm, and 1340-1400 nm.
6. SIM B was found to measure systematically high for the following wavelength bins (reported by midpoint) 532, 550, 590, 630, 675, 780.5, 875, 925, and 975 nm. SIM B was found to measure systematically low for the following wavelength bins (reported by midpoint) 1215, 1370, 1450, 1550, 1650, 1750, 1825, 1975, 2050 nm.

Table 1: Wavelength ranges for the 39 "Smart" bins.

Bin #	Wavelength Range (nm)	Bin #	Wavelength Range (nm)
1	267-268.3	21	761-800
2	282-282.7	22	800-850
3	288-288.9	23	850-900
4	300.8-302.2	24	900-950
5	310.8-312.3	25	950-1000
6	330.5-332.5	26	1000-1100
7	339.7-341.2	27	1100-1200
8	359.5-362	28	1200-1230
9	366-370	29	1340-1400
10	372.5-374.5	30	1400-1500
11	377.8-380	31	1500-1600
12	417-424	32	1600-1700
13	435-438	33	1700-1800
14	450-460	34	1800-1850
15	460-470	35	1950-2000
16	529-535	36	2000-2100
17	540-560	37	2100-2200
18	580-600	38	2200-2300
19	620-640	39	2300-2350
20	650-700	-	-

2. TSIS ATBD

The TSIS Algorithm Theoretical Basis Document (ATBD) is primarily a description (though not the sole reference) of the TIM and SIM instruments and the algorithms used to convert the measured instrument power into total and spectral irradiance for all data levels for the TSIS mission. However, it will also play a role as a Climate-ATBD by providing a well-documented calibration history of the measurements that can be used for comparison and evaluation of the TSIS instruments to their future analogs. The document will be archived, maintained, and made publicly available at NOAA's Climate Data Center. Such an approach will improve the transparency of the data production.

To date, this is a unique approach for an instrument or mission ATBD, and the implementation of these dual goals will likely require periodic amendments to the document over the course of the TSIS mission. For instance, an amendment may be required when measurements monitoring the degradation of the SIM prism due to solar exposure result in updated calibration coefficients for the acquired data set. The TSIS ATBD will help insure good data stewardship, or management, of the TSIS contributions to the long-term data records in total and solar spectral irradiance. However, the process by which these long-term data records are "stitched together" into a composite record from various instruments across a number of missions is outside of the scope of the TSIS ATBD.

The algorithms (and data processing) for converting measured instrument signal to irradiance will follow a "Measurement Equation Approach", an example of which is shown in Figure 10 for the SIM instrument. Every term on the right hand side of the equality in Figure 1 such as measured power, aperture area, absorptance of the ESR cavity, transmission of the prism, instrument slit function, and diffraction (including the wavelength dependency and temporal variations) must be measured, calibrated or characterized to accomplish this conversion. By following this approach, the TSIS ATBD will provide the logical flow for this process.

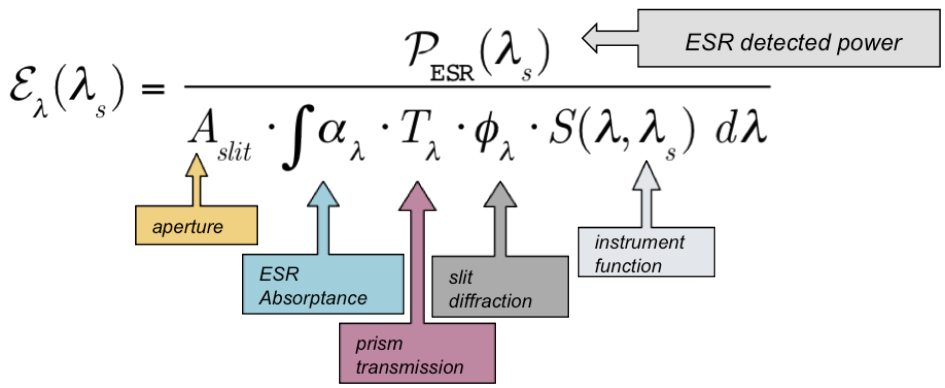

Figure 10: Measurement Equation for the SIM instrument.

The TSIS instruments are characterized as "absolute sensors" at the component, instrument, and spacecraft levels. The overall measurement uncertainty is a root sum square error of the individual uncertainties. These values will be tabulated as an "Error Budget" in the ATBD documentation.

The long-term stability requirement of the data, which provides the quality assurance, will be met through on-orbit degradation correction. Interchannel comparisons track exposure time dependent changes. The descriptions of the planned instrument activities and 'duty cycling' of the channels will be provided in the ATBD documentation.

The planned content for the TSIS ATBD consists of 9 sections as listed and briefly described in Table 2. A progress status is indicated by colored dots: green and yellow, referring to a status of "complete", or "in progress".

In the period since the last progress summary, several sections have been completed and distributed for internal review. These include the Introduction, Overview and Background Information, and the TIM-specific discussions in the Instrument Design, Algorithm Description, and Calibration and Characterization. Recently, the calibration and the characterization of the TSIS SIM instrument has been completed at LASP and the data is being analyzed. In the upcoming months, the SIM-specific material for the ATBD will be completed. The TSIS data processing team is currently ingesting instrument calibration and test data and preparing for the production of science data.

We are on target for a late 2012 delivery of the document to a review team.

Table 2: Section outline and brief descriptions for the TSIS ATBD. Colored dots represent status of the ATBD. Green = "Complete", Yellow = "In Progress". * = Out for internal review

Section Title	Description	Status
1. Introduction	a. Document Scope b. List of Supporting Documents	*
2. Overview and Background Information	a. The Role of the Sun b. Mission Goals and Objectives c. Instrument Heritage, including Design Changes for TSIS SIM d. Requirements for future measurements of solar irradiance	*
3. Instrument Design	Detailed enough to understand the algorithms, calibration, and validation sections. Descriptions will be provided for the following components (plus many others): a. ESRs b. apertures c. shutters d. prism and prism drive e. instrument slit function f. photodiode detectors g. standard resistance and volt h. Instrument Operation Modes	*
4. Algorithm Description	Descriptions will follow a "Measurement Equation Approach" stepping through the conversion from measured instrument signal to irradiance (see text).	
5. Calibration and Characterization	Separated by instrument and Pre-Flight or In-Flight calibrations: a. Calibration Facilities: TSI Radiometry Facility, NIST SIRCUS, and LASP SIMRF b. Changes in cavity absorptance c. prism degradation d. changes in photodiode radiant responsivity e. servo loop gain changes f. monitoring of thermal background (dark measurements) g. pointing sensitivity (field of view maps)	*
6. Degradation Correction and Uncertainty Estimates	a. TIM analysis based on Duty-Cycle b. SIM analysis based on Duty-Cycle	
7. Validation	a. Confidence in Measurements b. Comparison with other solar measurements c. Validation against models of solar irradiance d. Quality Control	
8. Data Product Requirements and Description	a. TSIS data level definitions b. Temporal Averaging c. Binning into desired Spectral Resolution	
9. Production of Science Data	a. Data Management b. Data Processing c. Data Structure d. Data Flow e. Data Storage Considerations f. Configuration Management	

Fourth Year Progress Report 2, *Developing a Climate Data Record for Total and Spectral Solar Irradiance*
NOAA Award Number NA09NES4400016
National Environmental Satellite Data and Information Service Program Office (NESDISPO)
Reporting Period: 02/01/2013 - 07/31/2013
Principal Investigator: Peter Pilewskie, Laboratory for Atmospheric and Space Physics, University of Colorado

The TSIS ATBD was completed during the final 6 months of this program. It will be submitted as part of the final report.

We presented a summary of our past 6 months progress (including updates on *Production Approach*; *Validation & Quality Assurance*; and *Users & Applications*) at the annual CDR Meeting in Asheville, 30 Jul. – 1 Aug., 2013. The talk also included plans for the transition phase of this project which were developed and finalized during the time of this reporting period; see *Milestones & Schedule for solar irradiance FCDR production* on chart 13 of the presentation.

CDR DEVELOPMENT PROJECT

Total and Spectral Solar Irradiance

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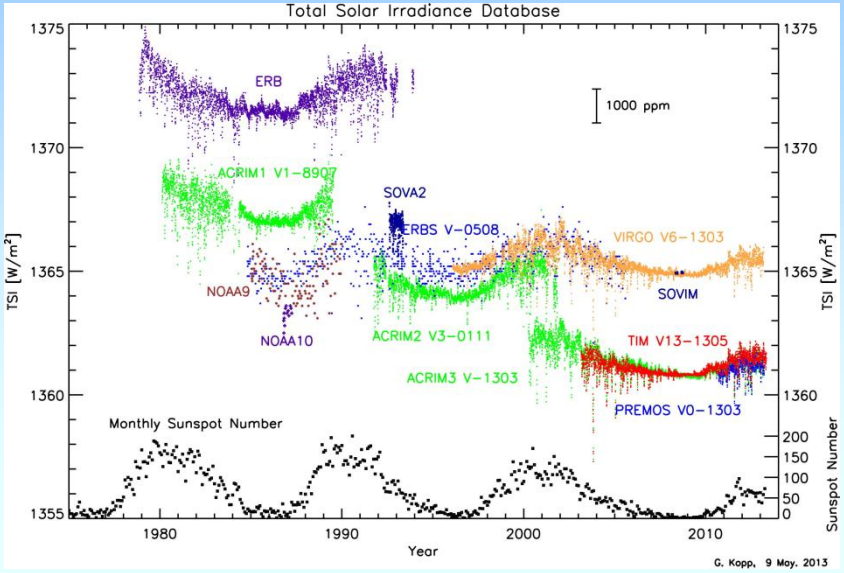
Outline

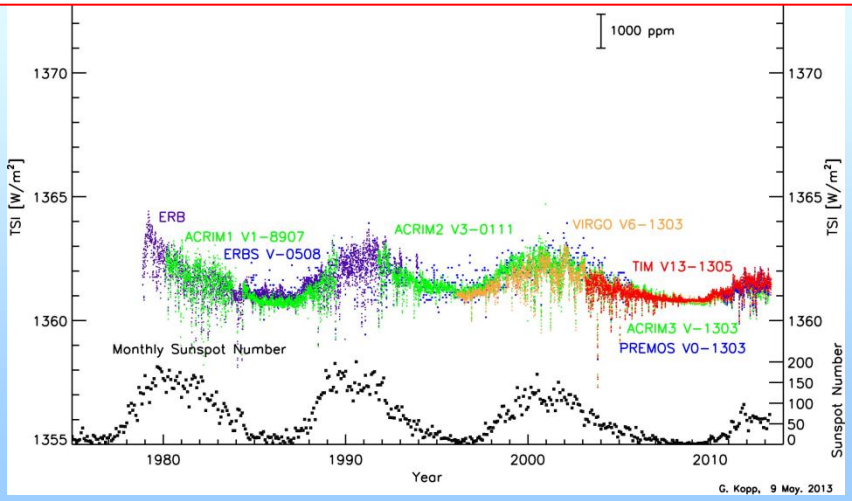
- Project Description
- Production and QA Approach
- Applications
- Schedule & Issues

Solar Irradiance CDR Development

- Solar Irradiance CDR Development Team
  - maintain several duties of the former NPOESS Operations and Algorithms Team (OAT)
  - Ensure the effective and technically robust utility of the solar irradiance CDRs
    - Collaborate with user community and other CDR Teams.
  - Ensure data stewardship of TSI and SSI through:
    - Develop the TSIS Algorithm Theoretical Basis Document.
    - CDR development from current and heritage satellite instruments.
    - Construct irradiance composites.
    - Develop related solar irradiance products and algorithms to be distributed to the broader community.
  - Enable the rapid and reliable generation of Solar Irradiance Climate Data Records following the launch of TSIS.



Calibration differences, chiefly internal instrument scatter are responsible for the instrument offsets. [*Kopp and Lean*, 2011]



Project Description

CDR(s) (Validated Outputs)	Period of Record	Spatial Resolution; Projection information	Time Step	Data format	Inputs	Uncertainty Estimates (in percent or error)	Collateral Products (unofficial and/or unvalidated)
Total Solar Irradiance	1978 – present	N/A	1 day	SORCE: ASCII and IDL save, and HDF5. Similar data formats are planned for TSIS. LASP will also produce in NetCDF4, and conform to CDRP data and metadata requirements.	Raw satellite sensor telemetry data; composites from individual sensor level 3 irradiance data. TSI: ERB, ACRIM-I,II,&III, ERBS, SOVA, VIRGO, PREMOS, and TIM, SORCE Mg II index product, NGDC sunspot data SSI: SIM, SOLSPEC, SCIAMACHY, SORCE Mg II index product, NGDC sunspot data	0.01-0.035%	N/A
Solar Spectral Irradiance	2002-present	N/A	1 day			0.2-1%	N/A

Production Approach: TSI/SSI

- Converting from Instrument signal to irradiance follows a "Measurement Equation Approach"

$$\mathcal{E}_\lambda(\lambda_s) = \frac{\mathcal{P}_{\mathrm{ESR}}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s)\, d\lambda}$$

ESR detected power

Aperture area

ESR Absorptance

prism transmission

slit diffraction

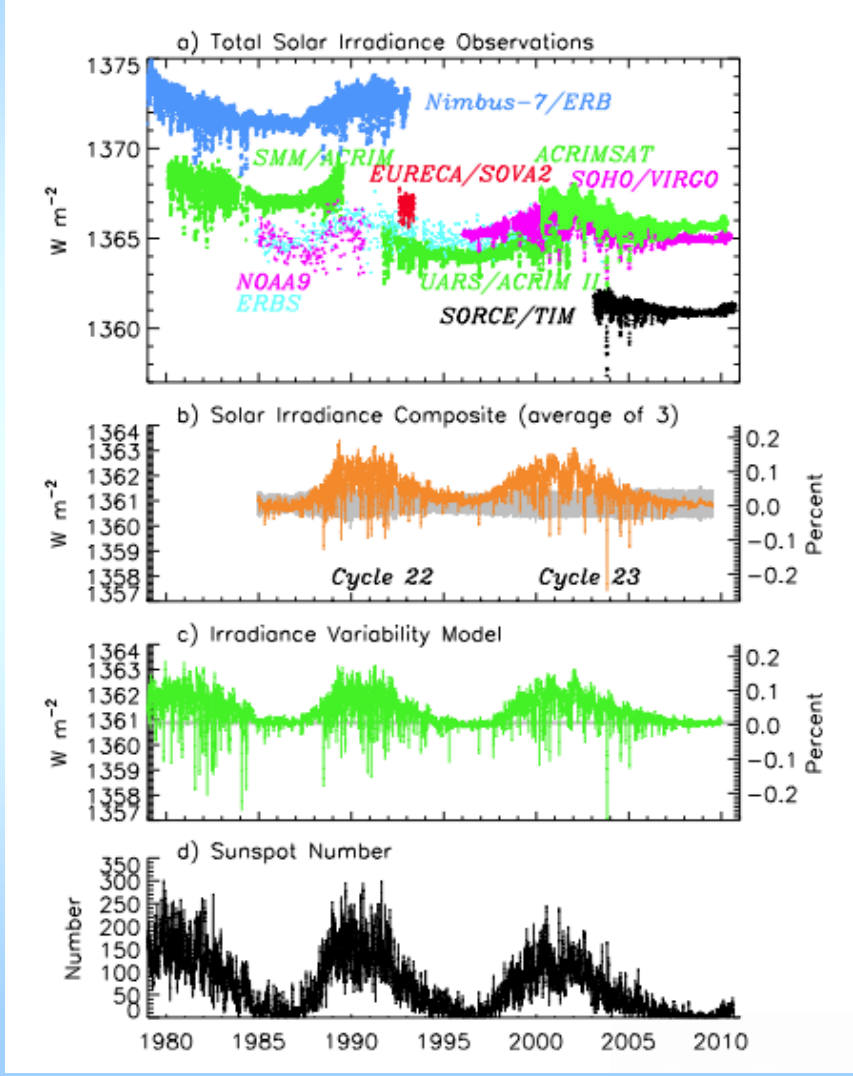
instrument function

Measurement equation for the SIM instrument

- Measurement and characterization/calibration of all terms on the right-hand-size of equation are performed
  - shutter waveform factor, entrance aperture/slit, bolometer absorption, equivalence ratio, loop gain, diffraction correction, prism transmission, exit slits, instrument function convolution, photodiode radiant responsivity…

Production Approach: TSI Composite CDR

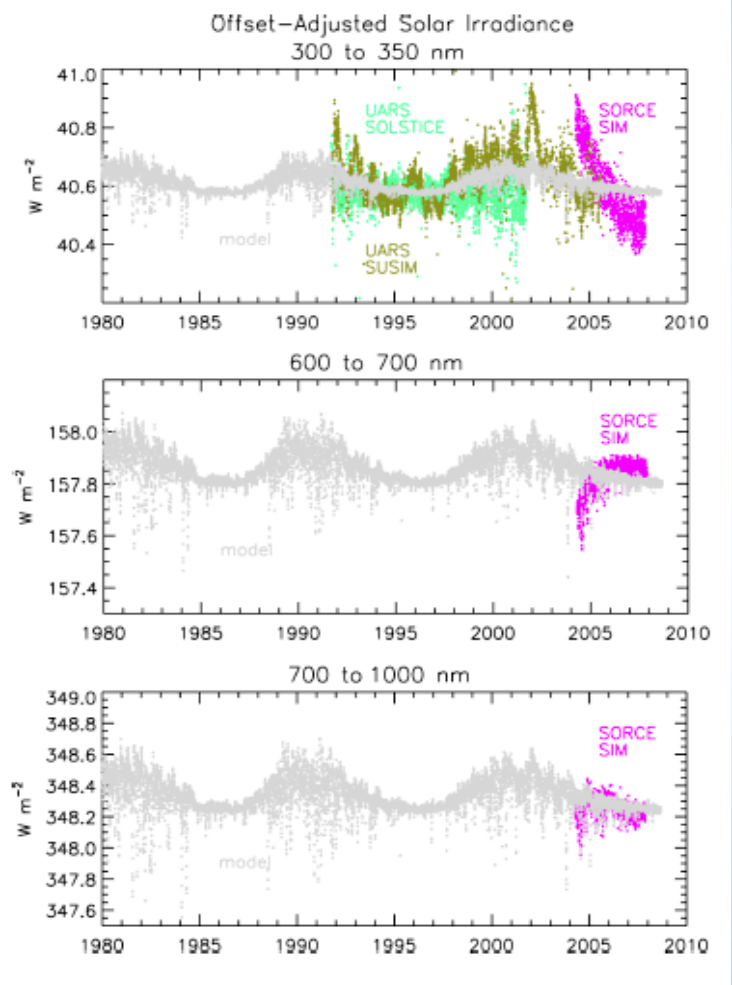
- An empirical model [*Lean et al.*, 2005] determines the net effect of opposing influences by sunspot darkening and faculae brightening to solar irradiance variability. Necessary steps include:
  - Align absolute scales of individual radiometers.
  - Input 1: Use daily SORCE Mg II index product (or other) as a proxy for facular signal.
  - Input 2: Daily projected sunspot area from NGDC sunspot record.
  - Relative proportions of sunspot & faculae are determined using a linear scaling with coefficients determined by multiple regression of the two inputs against current SORCE TIM observations to create daily TSI variability.



Kopp and Lean, 2011

Production Approach: SSI Model

- NRL SSI model uses same two inputs (daily sunspot area and Mg II index) as TSI irradiance model [*Lean et al.*, 2000; ; *Lean & Woods*, 2009; *Thullier et al.*, 2013 *submitted to Solar Physics*]. Additional or different steps include:
  - Scaling coefficients determined by multiple regression against UARS SOLSTICE observations for NRLSSI Version 1 (and from solar theory for irradiance > 400 nm) and from SORCE SIM & SOLSTICE for NRLSSI Version 2.
  - For SSI, the scaling coefficients are separate from those for TSI and provided for each 1 nm bin from 120-100000 nm.
  - SSI model is internally consistent with TSI (i.e. TSI is calculated daily, independent of SSI, and the integral of SSI verified to add to the TSI).

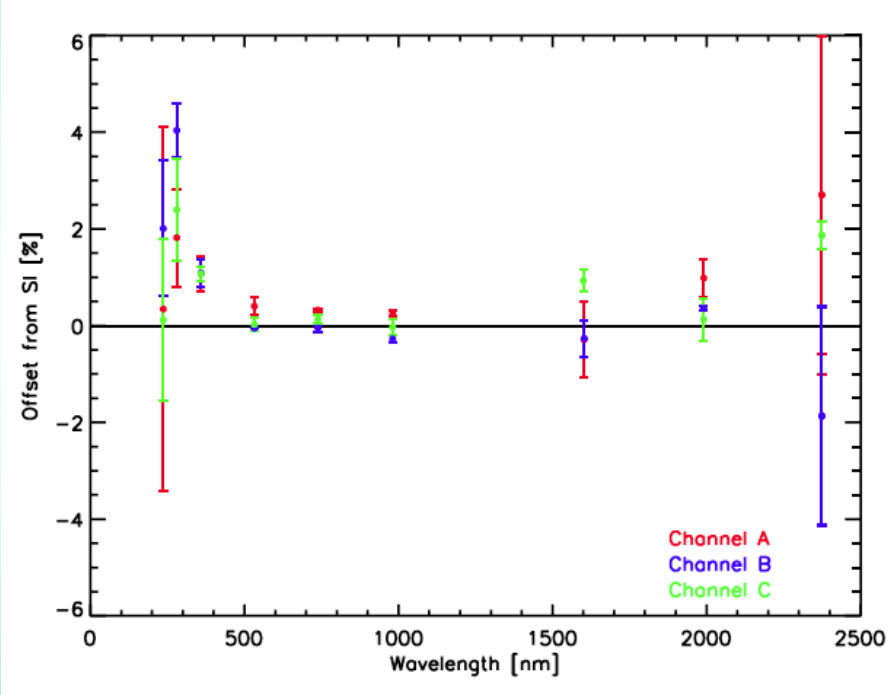


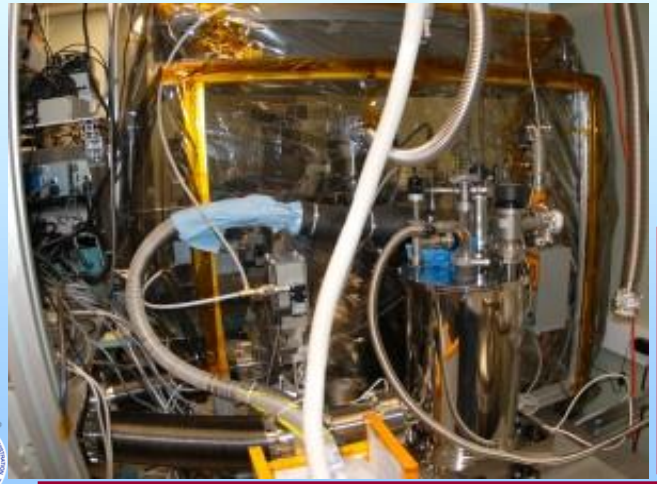
Comparisons of measured SSI to model output derived by scaling sunspot blocking and proxies of facular variability [*Lean and Woods, 2009*].

Validation & Quality Assurance: TSIS TSI & SSI

1. Calibration & Characterization
   - The TSIS instruments are "absolute sensors".
   - Overall measurement uncertainty is a root sum square error of the individual uncertainties.
   - End-to-end validation.

TSIS SIM to Cryogenic Radiometer Comparison: Preliminary Results

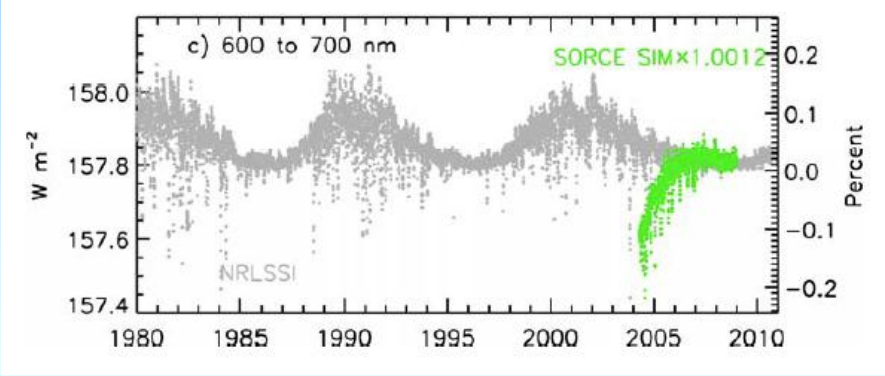




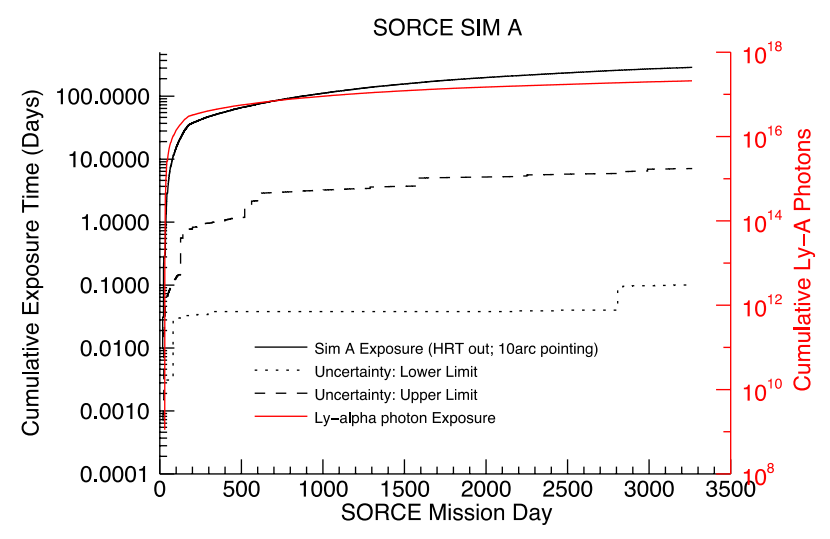
The TSI Radiometer Facility (TRF) and Spectral Radiometer Facility (SRF) at LASP tie irradiance comparisons to a NIST L-1reference cryogenic radiometer at power levels typical of the Sun and under flight-like vacuum conditions.

Validation & Quality Assurance: TSIS TSI & SSI

2. On-orbit degradation correction.
3. Comparisons with other data sets and models of solar irradiance
4. New research focus areas involve investigation of solar exposure and degradation of SORCE SIM.
   - Comprehensive accounting of solar exposure time and potential differences between solar exposure time and photon "dose".
   - Bayesian-like methodologies for propagating measurement and exposure uncertainties, and allowing for the possibility of "recovery" in degradation.



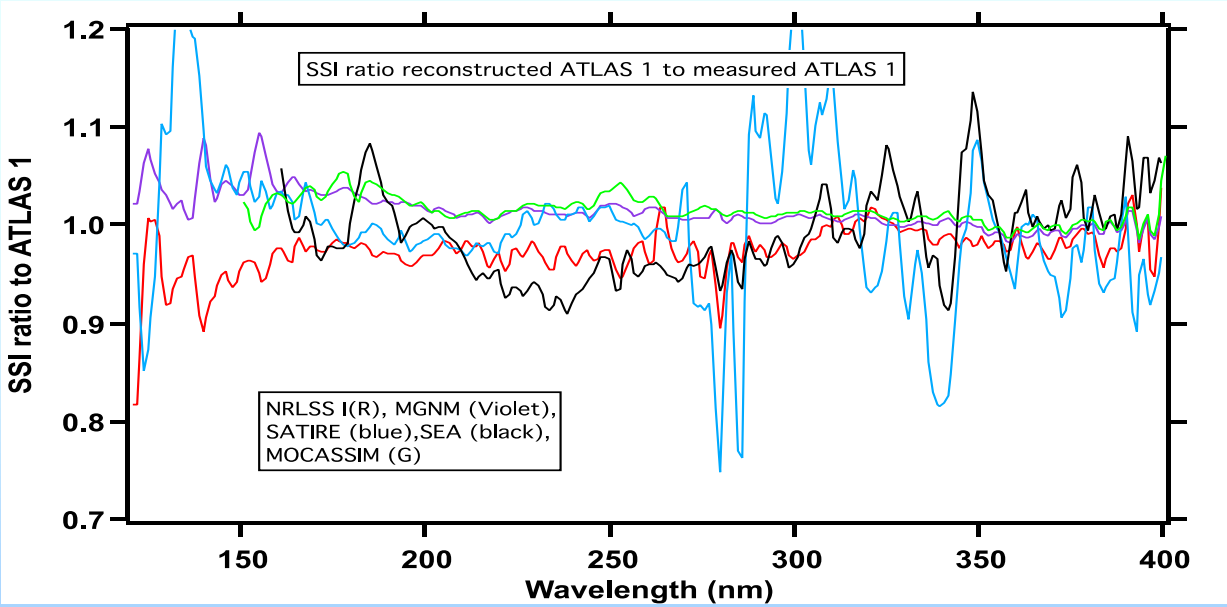
SORCE SIM data shows out-of-phase behavior at different wavelengths and 3-5x greater variability in the UV compared to models. [Lean and DeLand, 2012].



Converting from Solar Exposure Time to Photon "Dose"

Validation & Quality Assurance: Models of SSI

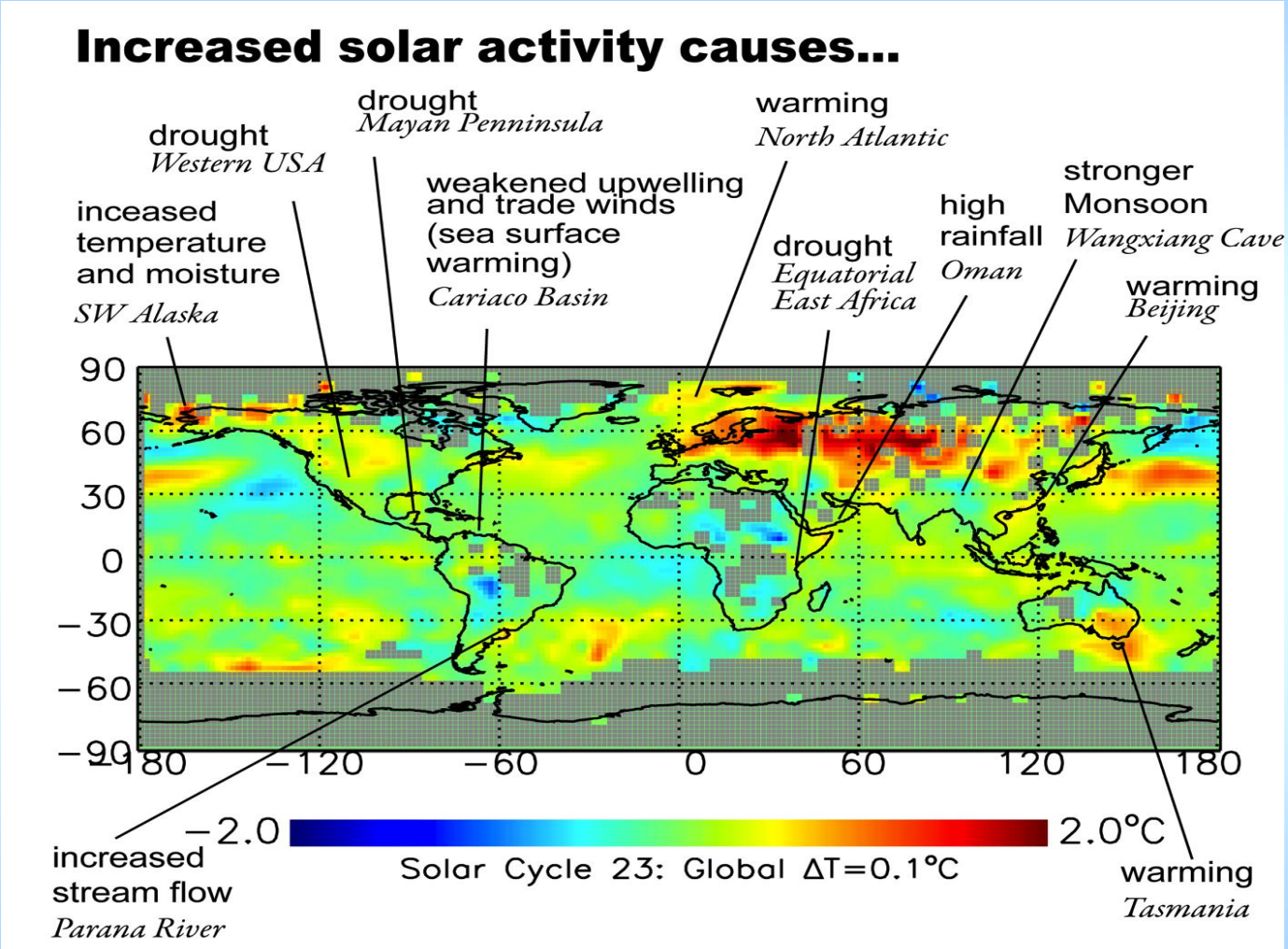
- Comparisons of modeled SSI variability with revised/reanalyzed SORCE SIM data.
- Systematic comparison among models and observations of SSI variability.



Comparison of SSI models to measurements: Ratio of the ATLAS 1 reconstructions by models to the original ATLAS 1 [*Thullier et al.*, 2013 *submitted*].

Users & Applications

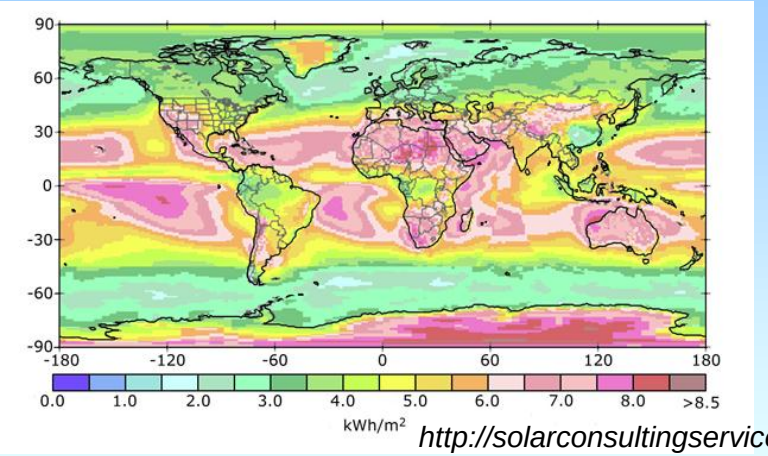
Global Summary of various relationships between solar activity and climate



Map is derived from analysis of the current surface temperature record, taking into account ENSO, volcanic influences, anthropogenic influences, and solar variability (as in [*Lean, 2010*]).

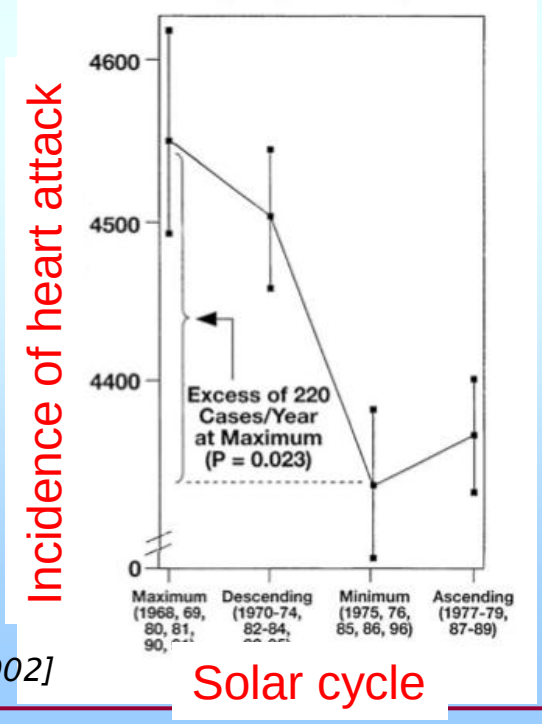
Users & Applications

- CDR development teams for energy budget (CERES/ERB), ozone, and temperature remote sensing
- Modelers of global climate, stratospheric processes, and stratospheric climate
  - require solar spectral irradiance as top-of-atmosphere boundary condition (i.e. not sufficient to use just TSI)
- Renewable Solar energy community
  - solar irradiance variability is used to test and improve PV cell technology and guide large solar energy projects (to supply electricity to utility companies).
- Heliobiology
  - Do conditions on the Sun and in Earth's magnetosphere affect human health?



http://solarconsultingservices.com

Daily-average direct normal irradiance (*DNI*): the solar "resource" available from the Sun to a collection device.



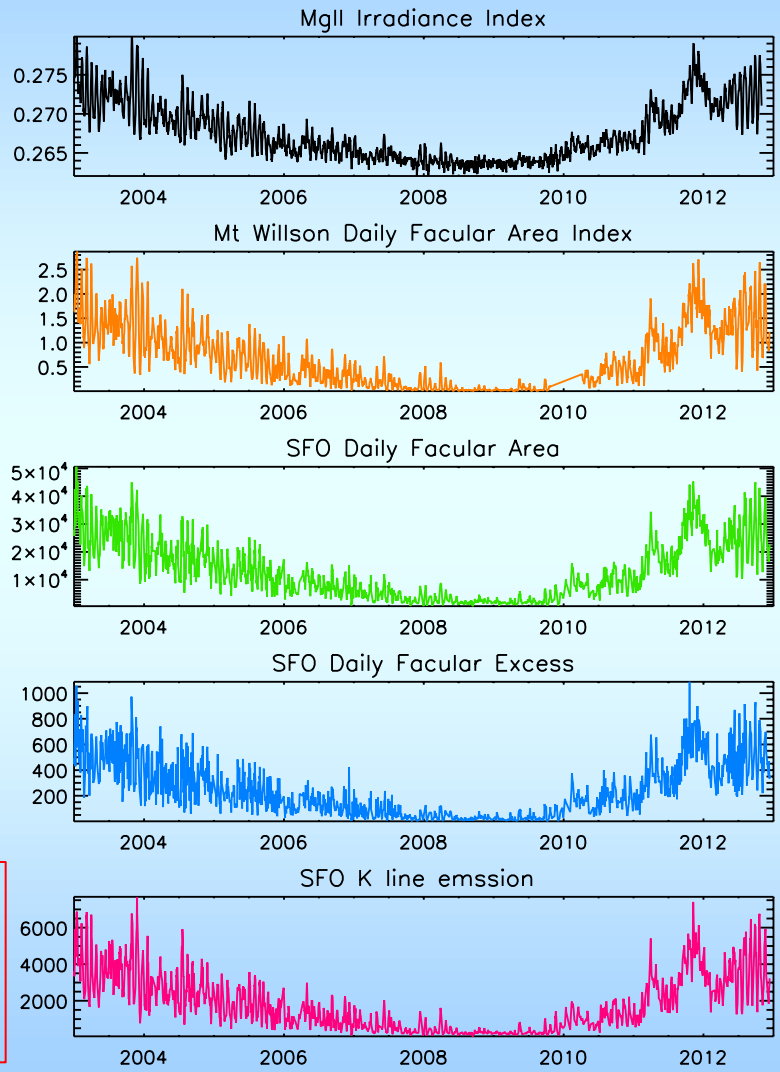
[Cornélisson et al., 2002]

Schedule & Issues

- Accomplishments over last year:
  - TSIS ATBD near completion.
    - Key sections to complete include the SIM calibration/characterization and SIM error budget table.
  - Comprehensive accounting of solar exposure & photon dose (and uncertainties).
  - Methodology in development for a Bayesian-like study of instrument degradation.
  - Scaling coefficients developed (NRLSSI V1) and in development (NRLSSI V2).
- Milestones & Schedule for solar irradiance FCDR production.
  - Implementation plan: within 45 days of award.
  - Documentation:
    - Data Flow Diagram and Maturity Matrix: within 90 days of award
    - Climate-ATBD: within 6 months of award
  - Data (to conform to CDRP data and metadata requirements):
    - Procedures for obtaining & reducing sunspot and facular indices (i.e. source code, coefficients, input time series from 1978 to current time): within 270 days of award
    - CDR data set: within 300 days of award
  - Quality Assurance:
    - Report: within 300 days of award
    - QA results: with each data set delivery (procedures for validating sunspot & facular indices)
  - CDR maintenance (time series data set updates):
    - Extending forward from end of previously delivered data set
    - Within 7-10 days of updates of the NGDC sunspot data
    - Will address errors, discrepancies, or limitations
  - Stewardship Support
    - LASP to provide access to CDR via a publically-accessible website within 2 weeks of new productions, will track quarterly data downloads, and a mechanism for users to report issues.

Schedule & Issues

- Risks or concerns
  - SSI and TSI composite record CDR requires *daily* NGDC sunspot record and Mg II index product (or other facular proxy product).
    - NOAA/NASA also make measurements of Mg II index (in case of loss of SORCE spacecraft).
  - There is a need to formally validate and quality-check these indices.
    - Currently, comprehensive but informal validation of sunspot area and Mg II index with 4-5 other time series.



Comparison of 5 different time series used as proxy indicators of facular brightening in solar irradiance models. [*Kopp and Lean Study B report*, recently submitted to NOAA].