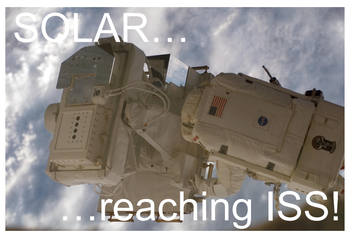
SOLAR/SOLSPEC



Launch in **2008**

Solar Spectral Irradiance Variability in the Ultraviolet over Cycle 24 with SOLAR/SOLSPEC 9 Years of Data from the ISS

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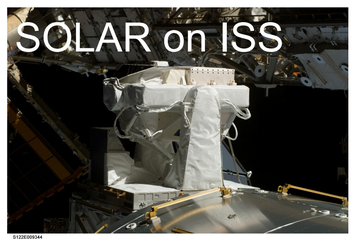
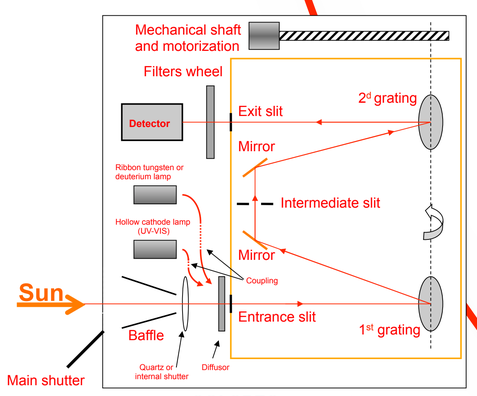


1 - Introduction/Objectives

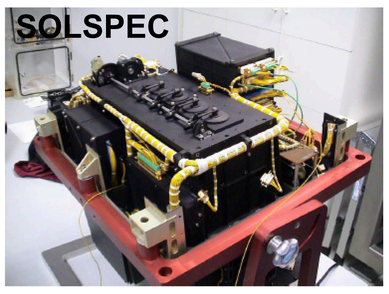
Accurate measurements of solar spectral irradiance (SSI) and its temporal variation are of primary interest to better understand solar mechanisms and the links between solar variability and Earth's atmosphere and climate. We present recent ultraviolet (UV) SSI observations performed by the SOLAR/SOLSPEC spectrometer on board the International Space Station. SOLAR/SOLSPEC observations cover the essential of the solar cycle 24, from April 5, 2008 to February 15, 2017.We provide an evolution of the solar spectral irradiance during Cycle 24 using the SOLAR/SOLSPEC data thanks to revised engineering corrections, improved calibrations, and advanced procedures to account for thermal and aging corrections of the instrument. The SOLAR/SOLSPEC observations are compared with other measurements (SORCE/SOLSTICE, SORCE/SIM) and models (SATIRE-S, NRLSSI). Importance of results justify a new mission (e.g. SoSWEET-SOUP) with enhanced SSI measurements (the SOLSIM newly designed SSI instrument).

2 - The SOLAR/SOLSPEC Instrument

SOLAR/SOLSPEC is a space qualified spectroradiometer measuring the Solar Spectral Irradiance (SSI) from 166 nm to 3088 nm. This instrument, developed under a fruitful LATMOS/BIRA-IASB collaboration, is part of the Solar Monitoring Observatory (SOLAR) payload, externally mounted on the Columbus module of the International Space Station.



SOLSPEC concept (one double monochrometer shown; 2 gratings rotating simultaneously)



SOLSPEC consists of three separated double-monochrometers that use concave holographic gratings (Jobin-Yvon) to cover "UV" (165-371 nm), "VIS" (285-908 nm), and "IR" (646-3088 nm) spectral ranges. Detectors are Electro-Mechanical Research photo-multiplier (PM) in the UV and VIS spectral ranges, and a Hamamatsu P2682 IR cell cooled at -21.8+/-0.05°C in the IR.

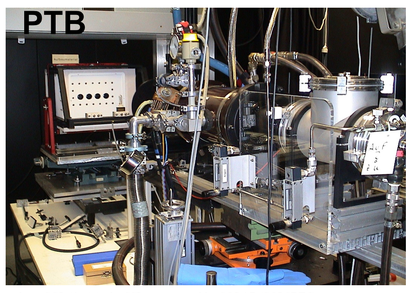
3 - Absolute Calibration

Radiometric characterization conducted at the BIRA-IASB for:

- determination of the non-linearity of the detectors;
- accurate wavelength calibration of the spectrometers;
- angular response of the entrance optics;
- selection of the internal filters (rejection of the second order of diffraction).

Absolute calibration was carried at the PTB (Physikalisch-Technische Bundesanstalt, Germany) using blackbody and deuterium lamps (standards of spectral irradiance).

Blackbody BB 3200pg (PTB)



SSI equations and models for the UV and Visible channels

$$SSI_S(\lambda,t) = \left(S_n(\lambda,t) - \frac{<DC(t)>}{\tau(t)}\right) \times R(\lambda,t) \times \left(\frac{z(t)}{1\,au}\right)^2$$

$$SSI_R(\lambda,t) = SSI_S(\lambda,t) \times \frac{1}{1-\frac{\alpha_T(\lambda,t)}{100}\times(T_P - T_S(t))} \times \frac{1}{Deg(\lambda,t)} \times \frac{1}{I_E(\lambda,t)}$$

where $SSI_S(\lambda,t)$ is the SSI as measured by SOLAR/SOLSPEC at a given wavelength (λ) and for a given time (t). $S_n(\lambda,t)$ (in counts s^{-1}) is the linearized signal provided by the detector (solar blind photomultiplier). The two spectral ranges ('UV' and 'VIS') are linear within their whole dynamical range (until 20 000 counts s^{-1}). $<DC(t)>$ (in counts) is the mean dark current of the detector taken before and after a solar spectrum measurement during the integration time ($\tau(t)$ in s). $R(\lambda,t)$ (in mW m^{-2} nm^{-1} counts^{-1} s) represents the absolute responsivity of the instrument. $z(t)$ (in km) is the distance between SOLAR/SOLSPEC and the Sun. The astronomical unit ($1\,au$) is equal to 149 597 870.700 km.

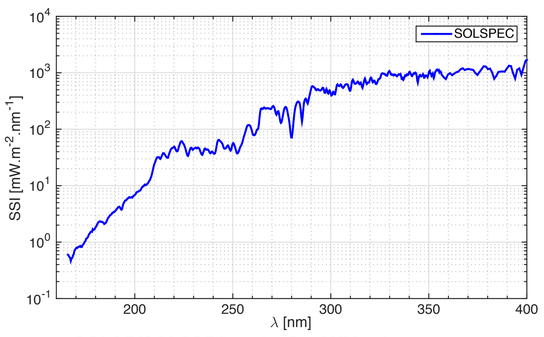
where $\alpha_T(\lambda,t)$ is the temperature coefficient of the UV PM (% °C^{-1}). T_P represents the temperature reference of the UV PM during ground calibration (23.3°C). $T_S(t)$ (in °C) represents the temperature of the UV PM in space. $Deg(\lambda,t)$ characterizes the degradation of the instrument (dimensionless factor where $Deg(\lambda,t) \leq 1$). The SOLAR/SOLSPEC internal optics and the quartz

Standard uncertainties are calculated using the Law of Propagation of Uncertainty (LPU). For the UV, at 1 σ, values are in agreement with the calculated ones: **<2%** for the **200–340 nm** band and **<4%** for the **180–350 nm** band.

4 - SSI in the UV

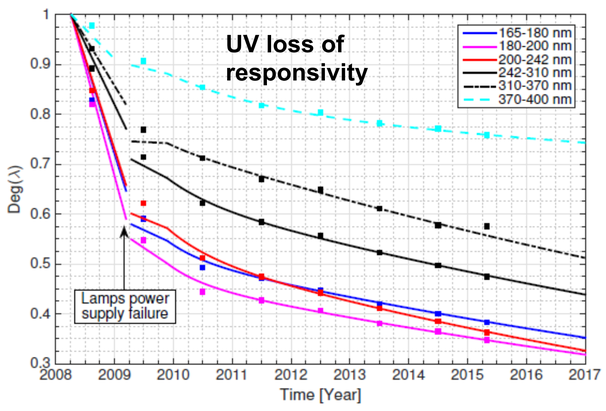
Reference 'Quiet Sun' UV Spectrum

First objective of the SOLAR/SOLSPEC data is to provide SSI in the UV for the 2008 period (beginning of the SOLAR mission, no degradation and Solar Minimum) and to compare it with other instruments (important for modelling issues).



SOLAR/SOLSPEC 'quiet Sun' UV solar spectrum

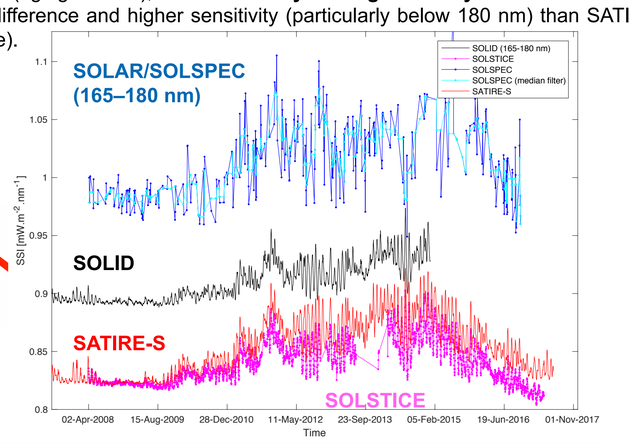
Degradation/Aging Correction



Using the signal of internal lamps as relative standards and engineering and measured mechanical and optical responses to thermal changes, we could monitor and determine the UV responsivity changes in function of time and wavelength, and corrected them. Note that degradation has three periods: fast contamination by lamps outgassing (up to failure of their power supply in 2009), consolidation time of few months and, since 2010, a very regular, linear and well modeled (and correctible) slow decrease. As expected (not shown), the degradation rate is lower for the VIS and IR spectrometers than in the UV spectrometer.

Measurement of SSI UV Variability

SOLSPEC was calibrated under vacuum for wavelengths below 200 nm. In space, after the correction of responsivity (aging effects), **SSI variability during solar cycle 24** is successfully retrieved and shows a significant difference and higher sensitivity (particularly below 180 nm) than SATIRE-S (and SORCE, since used as reference).



Δλ [nm]	SOLAR/SOLSPEC	SATIRE-S	SORCE/SOLSTICE
Lyman-α (comparison)	–	–	~28 %
165 – 180	~7.0 ± 2.0 % (1σ)	~6.7 %	~8.3 %
180 – 200	~6.9 ± 2.5 % (1σ)	~5.4 %	~8.2 %
200 – 242	~3.5 ± 1.7 % (1σ)	~2.1 %	~3.1 %

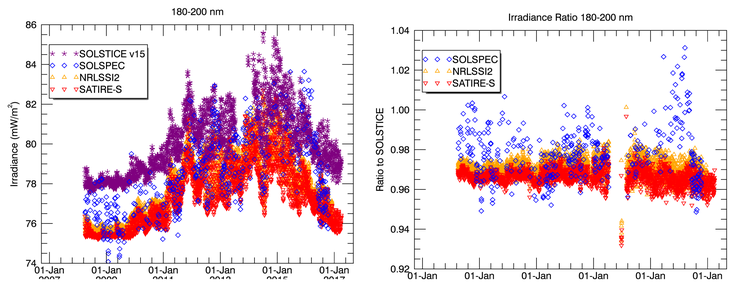
SOLAR/SOLSPEC Variability along the Solar Cycle 24
~7% 165-180 nm
~3.5% 200-242 nm

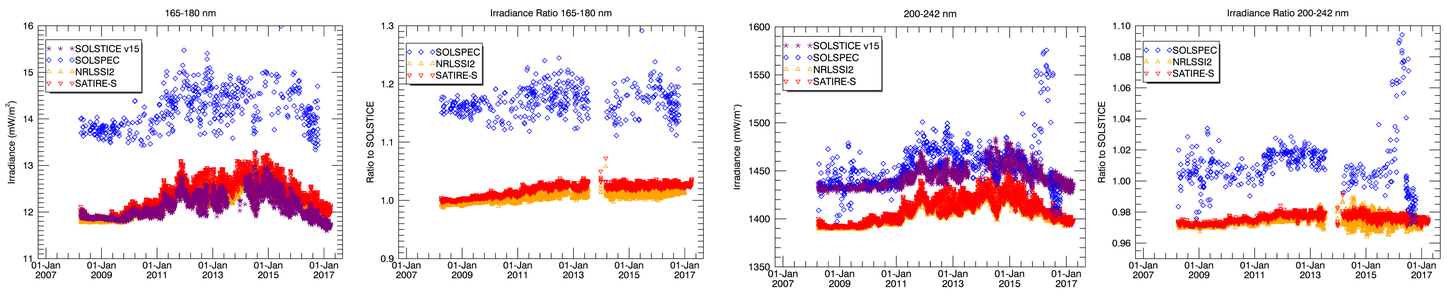
SOLSPEC SSI variability during solar cycle 24 (2008 – 2016) has amplitudes comparable to SORCE/SOLSTICE and SATIRE-S although some differences are noticeable in the far UV below 180 nm; a comparison SOLSPEC/SORCE in UV is of prime interest for an absolute calibration attempt of these measurements and confirmation of aging corrections.

SOLAR/SOLSPEC analysis, results and data are presented in Meftah, Bolsée, Damé, et al. (2016).

Comparisons of SSI UV Variability

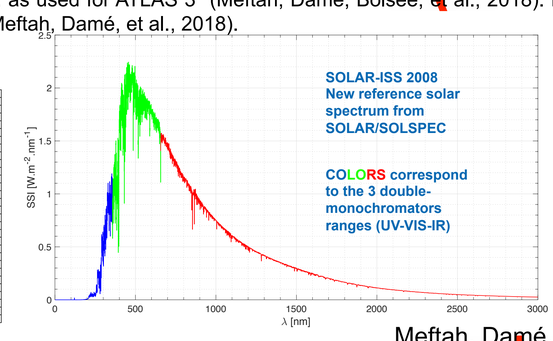
Retrieval of **SSI UV variability** @165-180, 180-200, 200-242 nm during Solar Cycle 24 and instructive comparisons with SOLSTICE and models (SATIRE-S and NRLSSI2).

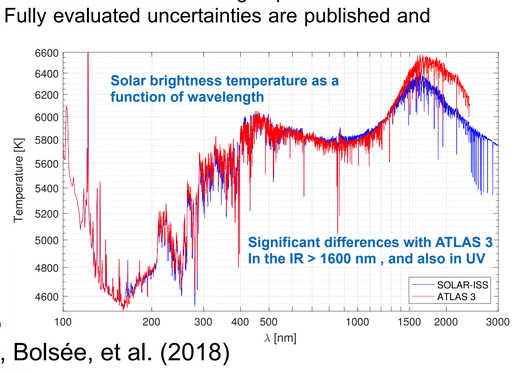




5 - SOLAR-ISS (new Reference Spectrum 165 - 3000 nm)

- **VIS**: measured SSI is mostly in accordance with SIM and ATLAS 3 results (based on first light spectrum 2008).
- **IR**: measurements extend to 3 µm (unique performance in space). SSI level between 1.6-2.4 µm as measured by SIM, ATLAS3 and SOLAR/SOLSPEC is still controversial although good in visible and IR with SCIAMACHY. Thanks to the thermal tests, we have higher accuracy information on the SOLAR/SOLSPEC spectrum (Meftah, Damé, Bolsée, et al., 2017). The new SOLAR reference spectrum is developed by combining our measurements with high spectral resolution information, as used for ATLAS 3 (Meftah, Damé, Bolsée, et al., 2018). Fully evaluated uncertainties are published and available (Meftah, Damé, et al., 2018).





Meftah, Damé, Bolsée, et al. (2018)

6 - Highlights and Conclusions

- Robust performances of the instrument in orbit for 9 years since 2008.
- High accurate characterization: determination of the measurement equation thanks to the exhaustive pre-flight radiometric characterization and absolute calibration work.
- In-flight improvement of the characterization (thermal tests) allowing to understand and correct degradation (aging) and data dispersion (IR & visible anomalies).

SOLAR/SOLSPEC 9 years of SSI measurements provide important contributions:

- **1) Retrieval of highly sensitive SSI UV variability during Solar Cycle 24.**
- **2) New UV (165–400 nm) and IR (660 to 3000 nm) reference solar spectra.**
- **3) New values for the level of SSI in the UV and IR, challenging older solar reference spectra.**
- **4) New complete solar reference spectrum SOLAR-ISS from 165 to 3000 nm for the 2008 Solar cycle 24 minimum.**

7 - Future Steps for SSI

1 - Detailed SSI UV determination during Cycle 24, using SOLAR/SOLSPEC data from April 2008 to February 2017 (work in progress!).

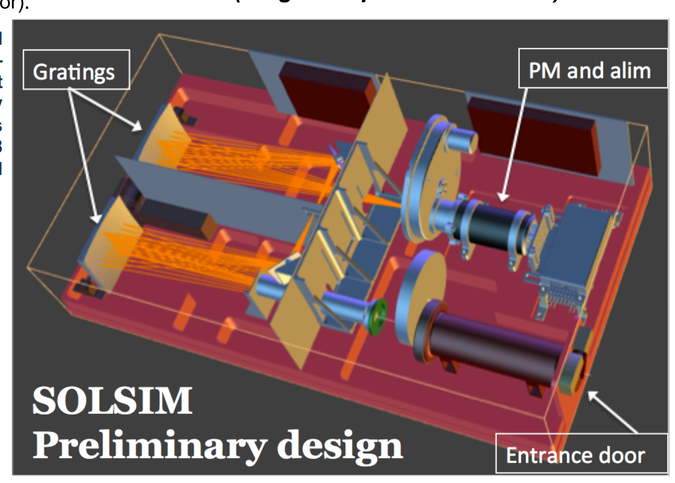
2 - Improvement of our quantitative understanding of the effects of solar irradiance variability on the atmosphere and climate (ANR program proposed).

3 – Design a new/improved **SSI space instrument** based on the long experience acquired in design, production, integration and qualification with the SOLSPEC instrument: **SOLSIM** (SOLar Spectral Irradiance Monitor).

...2017

The SOLAR Facility on the ISS was decommissioned February 15 after almost 9 years of observations (longest experiment on ISS!)

Preliminary opto/mechanical design of the SOLSIM UV-SSI instrument. SOLSIM has only one optimized UV double-monochromator covering 160 – 340 nm) with an almost constant spectral resolution of 0.65 nm. Deuterium lamps are replaced by UV diodes for calibration to avoid outgassing and thermal issues experienced with SOLAR/SOLSPEC. Weight of instrument is only 8 kg and dimensions limited to 450x140x250 mm³, adapted to small satellites platforms possibilities.



Acknowledgments

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