SOLSPEC MEASUREMENT OF THE SOLAR ABSOLUTE SPECTRAL IRRADIANCE FROM 165 to 2900 nm ON BOARD THE INTERNATIONAL SPACE STATION

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SOLAR on COLUMBUS Laboratory
Launched on 7 Feb. 2008
SOLSPEC

Triple double grating spectrometer using D2, W, HC lamps. Range: 170 - 3000 nm. Calibrated with the PTB blackbody. SOLSPEC was built in cooperation between France, Belgium and Germany.

SOL-ACES

SOL-ACES (G) is a-4 grazing incidence grating spectrometers plus two three-ionization chambers with exchangeable band pass filters to determine absolute fluxes from 17 to 140 nm.

SOVIM

Four absolute radiometers (PMO6 (Ch) and DIARAD (B) as on board SoHO, and two sunphotometers.
METHODS OF CALIBRATION

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<th>Missions</th>
<th>Absolute calibration</th>
<th>On-board control</th>
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<td>SIM</td>
<td>SORCE</td>
<td>Characterization</td>
<td>2 twin instruments</td>
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<tr>
<td>SOLSTICE</td>
<td>SORCE</td>
<td>Surf$^1$ and D$_2$ lamps</td>
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<td>SEE</td>
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<td>Absolute detectors</td>
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<td>SOLAR-ISS</td>
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<td>SOLSPEC</td>
<td>SOLAR-ISS</td>
<td>PTB Blackbody</td>
<td>D2,W, HC lamps</td>
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<tr>
<td>EVE</td>
<td>SDO</td>
<td>Surf$^1$</td>
<td>Led (flatfield)</td>
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</table>

The different techniques ensure to minimize the systematic uncertainties. Agreement between data sets gathered by instruments based on different concepts also ensure that measurements are achieved in the absolute scale.

SURF: Synchrotron Ultraviolet Radiation Facility. 1= NIST; 2= PTB
Principle of the SOLSPEC spectrometer (1/2)

- 3 double-monochromators (UV, VIS, IR) allow to cover the range 165-3080 nm

- The six gratings simultaneously rotate

- References on board:
  - One hollow cathode lamp (HCL) providing lines from Argon, Zn and Cu to measure the slit function and the dispersion law.
  - Four tungsten ribbon lamps for the VIS and IR spectrometers calibration
  - Two deuterium lamps for the UV spectrometers calibration

- Entrance slits are covered by diffusors

- Quartz plates and a hole are carried by a wheel. The plates can be placed in front of the entrance diffusors to ensure their protection.

- A sensor measures the Sun position/platform axis.
Optical Schematics

Detector

Quartz* Plates Wheel

Diffusor

Filters wheel

Input slit

Output slit

Intermediate slit

Mirror

Main shutter

Spectrometer

* There are 2 movable quartz plates (Q1, Q2) per spectrometer
Principle of the SOLSPEC spectrometer (2/2)

Detectors: PMT in UV and visible domains, PbS cell in IR. Vis and IR detectors are cooled.

Signals: Counting for PMT’s, synchronous detection in IR (16 bits, 3 gains)

PMT’s data acquisition works with two modes
   - at fixed integration time
   - at fixed counts (fixed precision)

Spectral characteristics:

Total spectral range: 165-3080 nm

UV spectrometer: 165-380 nm, spectral width: 1 nm, sampling 0.1 nm

VIS spectrometer: 300-980 nm, spectral width: 1 nm, sampling 0.25 nm

IR spectrometer: 800-3080 nm, spectral width 9 nm, sampling 1 nm
## INSTRUMENT CALIBRATION

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<th>Ground</th>
<th>Orbit</th>
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<tr>
<td>Absolute photometry</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Relative photometry</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Linearity</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Slit Function</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Dispersion law</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Scattered light</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Flatfield</td>
<td>x*</td>
<td>X</td>
</tr>
<tr>
<td>Second order contribution</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

* More precise in space
CALIBRATION MEASUREMENTS ONLY ACHIEVABLE ON GROUND

- Absolute photometric response

- Linearity
The Sun will not generate a signal greater than $10^5$. 
ABSOLUTE CALIBRATION AT PTB

We use the Blackbody at PTB (Braunschweig, Germany) NIST FEL lamps and a D2 lamp (V0132 calibrated by PTB below 250 nm

Temperature is recorded by three radiometers: at rear of BB for control (red, PTB), In front (blue, PTB), in front (black, SOLSPEC).

PTB ensures an absolute temperature at 0.44 K accuracy.
SOLSPEC responsibility using BB: in red. As the BB is not usable below 200 nm, a D2 lamp was used (blue) calibrated by PTB in vaccum. This lamp and SOLSPEC were set in a vaccum chamber. Given the dimension of the chamber, the distance Instrument/lamp was very short → scattered light. After taking into account this effect, an agreement was found in the overlapping region.
We used PTB BB and FEL NIST lamps. They provide consistent results. The discontinuities shown above are due to the filter change as a function of wavelength (second order and density filters).
The discontinuities are due to the filters (second order and density). Special care was taken about the water vapor on the optical path (shown in red).
IR1, IR2, IR3 are the three outputs of different gains. Discontinuities are due to filters change.
UNCERTAINTIES TAKING PART IN THE MEASUREMENTS

A: Ground calibration
   A1 alignment instrument/source
   A2 optical path
   A3 distance instrument/source
   A4 Source intensity
   A5 Source stability in time

B: In orbit
   B1: Depointing

C: In orbit and on ground
   C1: Counting
   C2: Detectors linearity
   C3: Dark current
   C4: Wavelength scale
   C5: Slit function
   C6: Scattered light
   C7: Temperature effect (detector, …)
   C8: HV stability

Then, uncertainties are geometrically combined.
Dominant uncertainties are: ground calibration and counting in orbit.
HOLLOW CATHODE LAMP

Role:

- Measures in orbit the slit function
- Measures in orbit the dispersion law
- Used as reference source
LINES PROVIDED BY THE HOLLOW CATHODE LAMP
Spectrometers Slit Functions in UV, VIS, IR
SLIT FUNCTION

With an isolated line

When two lines are adjacent in the slit function

R13 - (visible)
Ar I 763.51 nm

R1 - (UV)
Zn I 213.86 nm
INSTRUMENT DISPERSION LAW

The line wavelength associated to the corresponding step number allows to derive the dispersion law. It is consistent with the theoretical law.
The s/n ratio remains acceptable.
BEHAVIOR SPECTRAL CHARACTERISTICS IN SPACE AS A FUNCTION OF TIME

SOLSPEC - Lampe HCL - Résultats en orbite
Raie Cu I 249.22 nm - FWHM (nm)

Cu I 249.22 nm (plage R5)

SOLSPEC - Lampe HCL - Résultats en orbite
Raie Ar I 738.40 nm - FWHM (nm)

Ar I 738.40 nm (plage R12)
THE LINE INTENSITY COVARIANCE

Line 249 nm (red)
Line 738 nm (black)
FLATFIELD MEASUREMENTS IN ORBIT
SECOND ORDER EFFECT

SOLSPEC - Canal UV - Etude de l'ordre 2
Comparaison entre l'ordre 1 et la contamination d'ordre 2 pour une mesure solaire

Canal UV, mesure solaire en orbite
Each spectrometer is equipped by two quartz plates. They are set on a wheel together with a hole. They allow to protect the entrance diffusors from the hard radiation.

Operations:

- Solar measurements are daily made with Q1
- Once per month, Q2 is exposed to measure the transmission ratio Q1/Q2
- Q1 transmission is also measured by measuring the ratio Q1/hole.
BEHAVIOR OF QUARTZ PLATES IN ORBIT

SOLSPEC - Quartz plate #1 Ageing
(Q1/No_Q)

Visible

IR

Wavelength (nm)
Q1 is the most frequently used quartz plate.
BEHAVIOR OF D2 LAMP IN ORBIT

200nm

220nm

250nm
D2 LAMPS POWER SUPPLY

It failed. Then, no D2 can be activated.

How to solve this problem?

We use the following facts:

- the aging in visible and IR is very small and furthermore it is controlled by use of the two tungsten ribbon lamps,
- the covariance of the lines hollow cathode lamp allows to monitor the line intensity in UV.

This procedure has been validated for the period where the D2 were still working.
IR: LIMIT OF DETECTION

SOLSPEC - Mesure solaire en orbite (ISS, 16 novembre 2009)
Impact de l'ordre 2 en fin de spectre

En rouge : contribution apparente de l'ordre 2
CONCLUSIONS

NIST lamps and BB from PTB are providing consistent results for the instrument responsivity determination.

SOLSPEC and SOL-ACES are operating on a daily basis. Up to now, all days in a solar rotation cannot be observed given the position of the ISS solar panels.

This situation will be improved soon.

The instrument has lost the D2 power supply.

Given the use of the other available lamps, the monitoring the intensity scale can be made to take into account the aging effect in space.

Quasi no aging exists in the visible and IR. In UV, it is compensated by use of the aboard lamps (D2, then HCL).

On board, many types of calibration can be run (scattered light, quartz transmission, FF, wavelength scale, psf, …).

Main problem: lack of staff to produce time series.
SOLAR-ISS SSI RESULTS IN ORBIT
AND COMPARISONS WITH SORCE

G. Thuillier and G. Schmidtke

Below 140 nm, data were provided by SOL-ACES team.
COMPARISON SORCE SOLSPEC / ATLAS 3

SOLAR SOLSPEC - Canal UV
Eclairage spectral solaire associé à l'intercycle 23-24
Comparaison avec ATLAS 3 normalisé

SOLAR SOLSPEC - Canal UV - Comparaison entre :
ATLAS 3 normalisé - SORCE - SOLAR SOLSPEC
Convolution : 3 nm

Ratio : SOLAR SOLSPEC / ATLAS 3 normalisé
Ratio : SORCE / ATLAS 3 normalisé

Référence : ATLAS 3 normalisé au 1er juin 2008
COMPARISON SORCE SOLSPEC / ATLAS 3

**SOLAR SOLSPEC - Canal VIS**
Eclairage spectral solaire associé à l'intercycle 23-24
Comparaison avec ATLAS 3 convolu à 2 nm et SIM (SORCE)

![Graph 1](image1.png)

**SOLAR SOLSPEC - Canal VIS**
Comparaison entre ATLAS 3 et SOLAR SOLSPEC
Convolution : 5 nm

![Graph 2](image2.png)
## COMPARISON SORCE / SOLSPEC

<table>
<thead>
<tr>
<th>Ratios to ATLAS 3</th>
<th>166-180 (nm)</th>
<th>180-220 (nm)</th>
<th>220-260 (nm)</th>
<th>260-300 (nm)</th>
<th>300-340 (nm)</th>
<th>340-370 (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLSPEC</td>
<td>1.069 ± 0.047</td>
<td>0.974 ± 0.013</td>
<td>0.919 ± 0.023</td>
<td>0.968 ± 0.027</td>
<td>0.973 ± 0.019</td>
<td>0.965 ± 0.051</td>
</tr>
<tr>
<td>SORCE</td>
<td>0.914 ± 0.024</td>
<td>0.976 ± 0.034</td>
<td>0.906 ± 0.015</td>
<td>0.924 ± 0.008</td>
<td>0.945 ± 0.014</td>
<td>0.982 ± 0.015</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>350-425 (nm)</th>
<th>350-425 (nm)</th>
<th>425-500 (nm)</th>
<th>500-575 (nm)</th>
<th>575-650 (nm)</th>
<th>650-725 (nm)</th>
<th>725-800 (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLSPEC</td>
<td>1.005 ± 0.018</td>
<td>1.001 ± 0.009</td>
<td>0.991 ± 0.009</td>
<td>1.007 ± 0.005</td>
<td>1.010 ± 0.006</td>
<td>0.999 ± 0.005</td>
</tr>
</tbody>
</table>
A discrepancy exists centred at 1800 nm reaching 10%.
An exhaustive research has been carried out to find the origin of this difference.

The possible causes are:

- Distance source to entrance pupil,
- BB temperature,
- Absorption by H$_2$O during ground calibration
- Diaphragm diameter,
- Flatfield,
- Dark current,
- IR detection: detector linearity
- signal numerisation linearity
Using ZMAX, we have simulated a drift of the intermediary slit. The size and position of the light spot is a weak function of wavelength and may fall not perfectly on the slit for all wavelength.

As a first approximation, it is a cosine effect. We have numerically verified this effect.

Other scenario:

W lamp prior and at first light
COMPARISON WITH ROCKET EVE (3 MAY 2010)

Composite Solar Spectra (May-June 2008) & EVE rocket, 3 May 2010 (convolution: 1 nm)

Spectral Irradiance (mW.m⁻².nm⁻¹)

Wavelength (nm)

10 20 30 40 50 60 70 80 90 100 110

10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷

SOLSPEC ATLAS 3 Composite
SORCE Composite WHI (Freiburg 2009)
SOLAR Composite 2010
EVE rocket, 3 May 2010 (convolution: 1 nm)
COMPOSITE SPECTRA COMPARISON (2/6)

Composite Solar Spectrum (May–June 2008)

- SOL-ACES
- SOLSPEC ATLAS 3 Composite
- SEE TimeD
- SORCE composite WHI (Freiburg 2009)
COMPOSITE SPECTRA COMPARISON (4/6)
DISTRIBUTION PER SPECTRAL INTERVALS (W/m$^2$): DOMAIN 200-2400 nm

<table>
<thead>
<tr>
<th>Range (µm)</th>
<th>ATLAS3 Wm$^{-2}$</th>
<th>SORCE Wm$^{-2}$</th>
<th>SOLSPEC Wm$^{-2}$</th>
<th>COSI Wm$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21-0.35</td>
<td>55.02</td>
<td>53.6</td>
<td>53.9</td>
<td>53.9</td>
</tr>
<tr>
<td>0.35-0.50</td>
<td>241.4</td>
<td>243.7</td>
<td>246.3</td>
<td>246.7</td>
</tr>
<tr>
<td>0.35-1.</td>
<td>888.9</td>
<td>893.3</td>
<td>900.9</td>
<td>901.9</td>
</tr>
<tr>
<td>1-2</td>
<td>332.8</td>
<td>338</td>
<td>337.3</td>
<td>329.9</td>
</tr>
<tr>
<td>0.21-2.4</td>
<td>1311.4</td>
<td>1320.2</td>
<td>1327.3</td>
<td>1285.7 (0.21-2.0)</td>
</tr>
</tbody>
</table>
### DISTRIBUTION PER SPECTRAL INTERVALS (mW/m²): Domain 17-200 nm

<table>
<thead>
<tr>
<th>Range (nm)</th>
<th>ATLAS3 mWm⁻²</th>
<th>SORCE mWm⁻²</th>
<th>SOLSPEC mWm⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>17-120</td>
<td>2.72</td>
<td>3.11</td>
<td>2.52</td>
</tr>
<tr>
<td>120-200</td>
<td>106.89</td>
<td>106.91</td>
<td>102.23</td>
</tr>
</tbody>
</table>
COMPARISON WITH MODELS

- Fontenla et al. (2004): agreement between model and derived temperature
- COSI (Shapiro et al., 2010)
ATLAS3 – COSI comparison. I. UV and visible
Disagreement at 1800-2300 nm will be addressed in the new release of the COSI data.
Above 2650 nm, the sun irradiance becomes weak as well as the instrument responsivity. Several spectra have to be used together.
Can we detect the minimum of SSI during the cycles 23-24 transition?
Minimum solar activity around June-July 2008

Red = WHI (SORCE plus several other instruments) spectrum (Woods et al., 2009)
Blue = ISS-SOLAR (SOLSPEC and SOL-ACES) spectrum (Thuillier et al., 2012)
Can we detect the minimum of SSI during the 23-24 cycles transition?

SSI: is June 2008 the solar minimum at the cycles 23-24 transition?
LOOKING FOR THE SOLAR MINIMUM at SSI

Black: 26 July 2008 (WHI),
SOL-ACES spectra:
Red: 27 February 2009
Blue: 21 Aug. 2009
The differences are wavelength dependent.
HWI is in red. Its reconstruction using ATLAS 3 and the Mg II coefficients is shown in blue.

Comparison between the 'WHI' spectrum and the spectrum retrieved for 1st June 2008 from ATLAS 3 MgII Index: 0.26419 - 5 nm convolution

Ratio of the HWI and its reconstruction
CONCLUSIONS

1) In general, there is a convergence of different instruments in terms of SSI absolute value and variability;

2) Looking in details, around 60 nm SOL-ACES (ISS) shows smaller SSI values than SEE (ISS);

3) The transition from cycle 23 to 24 as seen at the SSI is not uniform and in fact presents several quasi minima.

4) The agreement ATLAS 3/SOLSPEC-ISS is better using a correction based on the Mg II index at the time of the SOLSPEC-ISS measurements;

5) SIM (SORCE) measurements in UV shows a minimum occurring prior to the minimum in EUV.

6) The SSI can be reconstructed from a reference spectrum assuming its variability and referencing it to MgII index (e.g. SOLSTICE and SIM spectra).