

The 2008 Minimum Solar Spectral Irradiance from The ISS SOLAR Spectrometers Measurements

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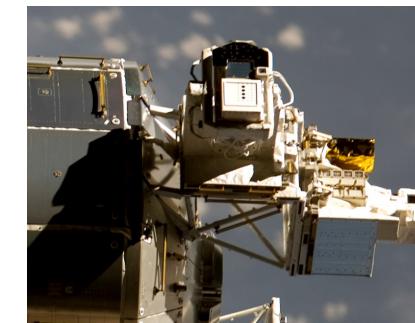
With contributions: N. Krivova (MPI), J. Harder, T. Woods, M. Snow (LASP), J. Fontenla (LASP), T. Sukhodolov⁴

SOLSPEC: A triple spectrometer having a spectral range: 170-3000 nm using double holographic gratings. The spectral range 170-3000 nm is measured in 11 minutes.

UV spectrometer: 170-380 nm, spectral width: 1 nm, sampling 0.4 nm

VIS spectrometer: 300-980 nm, spectral width: 1 nm, sampling 1.0 nm

IR spectrometer: 800-3000 nm, spectral width 9 nm, sampling 4 nm

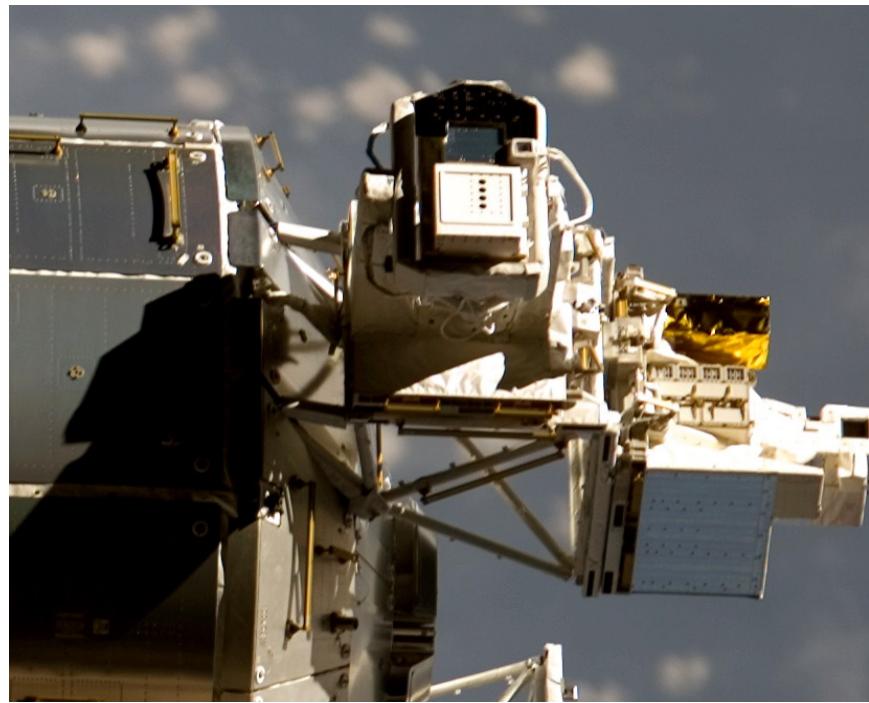


SolACES: A 4 grazing incidence grating spectrometers and two three-ionization chambers with exchangeable band pass filters to determine absolute fluxes from 17 to 150 nm.

SolACES has several gas reservoirs allowing to absorb the incident solar photons as a function of pressure, which determines the characteristics of the spectrometers.



S126E008245



Launched on 7 February 2008

SOLAR on COLUMBUS Laboratory

DATA AND MODELS USED IN THE PRESENT STUDIES

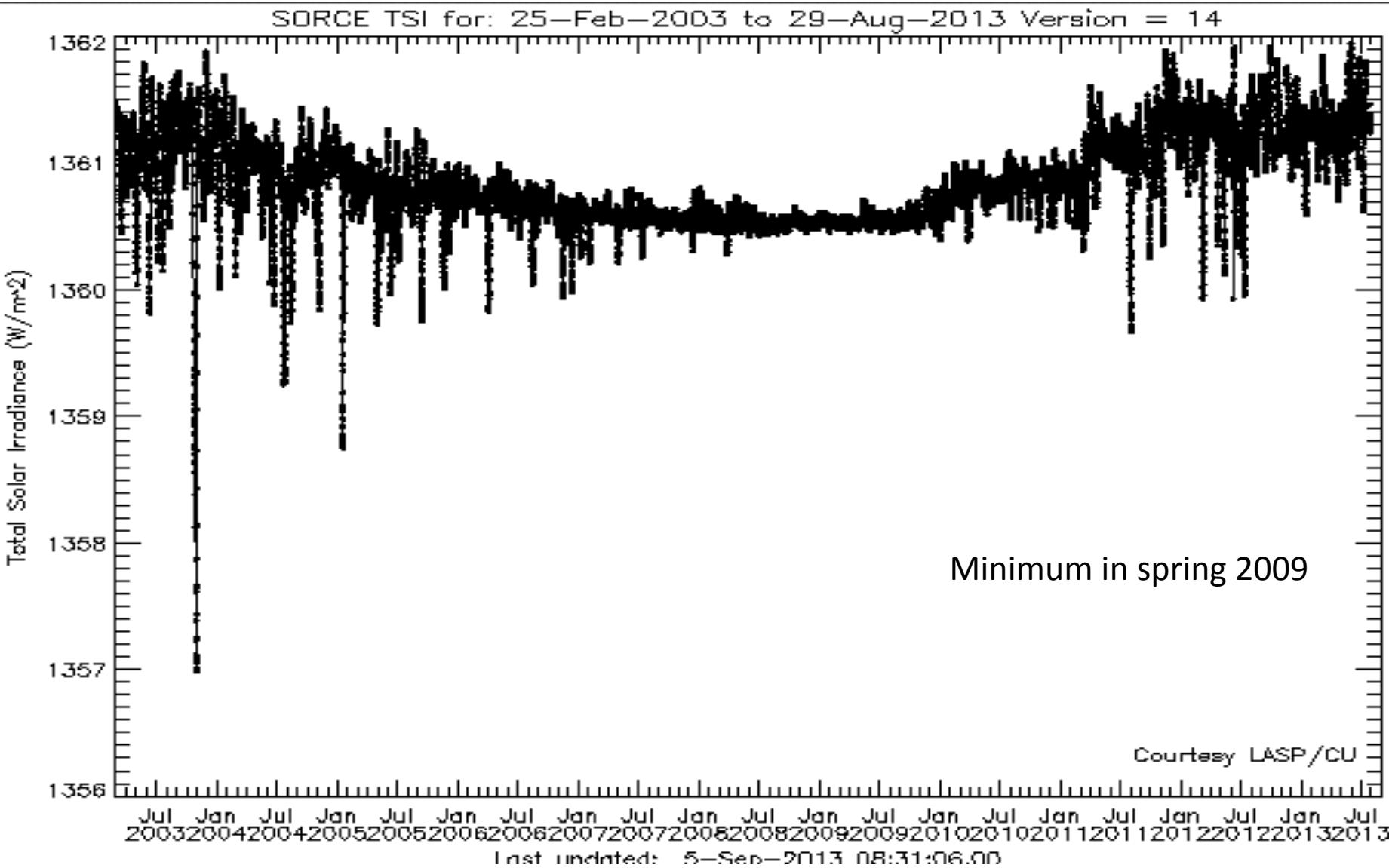
Instruments:

- SolACES and SOLSPEC onboard the ISS.
- SOLSTICE onboard SORCE to fill the gap between 150 and 170 nm.
- EVE / SDO for the preparation of the SDO launch (14-4-2008).
- Existing spectra:
 - ATLAS 3 (Thuillier et al., 2004). SSI at the transition cycle 22 to 23
 - Whole Heliospheric Interval (WHI, Woods et al., 2009) dated of 14 February 2008.
 - SCIAMACHY (Weber, private communication, 2013)
- Theoretical Models:
 - COSI (Shapiro et al., 2010) and SRPM (Fontenla et al., 2011)
- SSI reconstruction models:
 - SATIRE (Yeo et al., 2014) and NRLSSI (Lean et al., 2011)

IMPORTANCE OF THE SOLAR MINIMUM OF 2008

- Solar Spectral Irradiance (SSI) minimum may be used as the baseline of SSI reconstructions.
- Furthermore, it is used for running climate models in low solar activity periods such as the Dalton minimum.
- By comparing successive SSI minima, the long term trend of the solar activity can be studied. Nevertheless, the accuracy of the data used in this comparison is the key point.
- The different solar proxies at solar minimum (SSI, TSI, cosmogenic concentration, ...) have an accuracy time dependent given their link with the solar activity (e. g. SSN and cosmogenic concentration). Furthermore, they are essential to the solar physicists to investigate the cause of the minimum, in particular the recent 2008 minimum, lower than the two others (cycles 21 to 22 and 22 to 23).

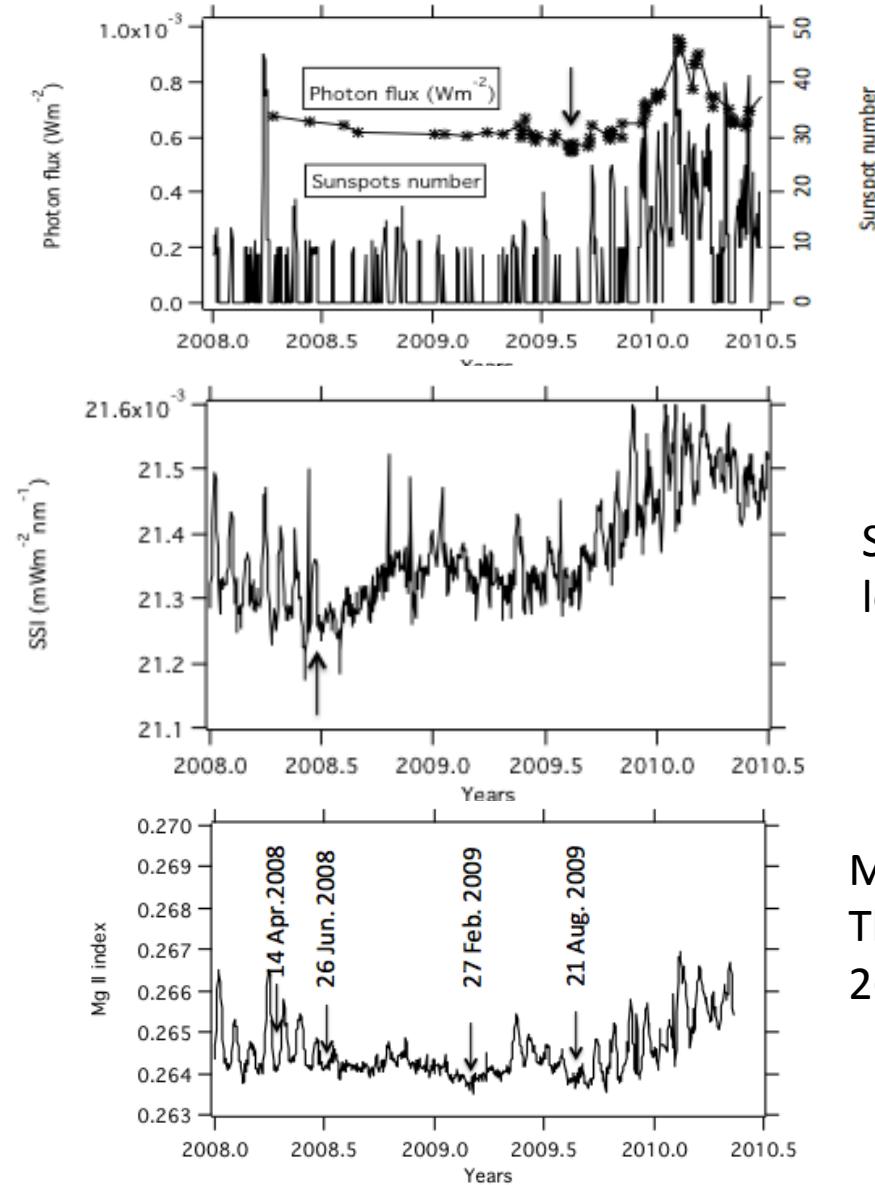
WHERE IS THE SOLAR MINIMUM ACTIVITY?



White et al (2011) found three different times for minimum of TSI, F10.7 and Mg II index

4

TIME FOR SOLAR SPECTRAL IRRADIANCE MINIMUM?



SolACES photon flux (Wm^{-2}) integrated from 16 to 29 nm and sunspots number during the solar minimum period between Solar Cycles 23 and 24 (Nikutowski *et al.*, 2011). The arrow shows the minimum EUV SSI that occurred on 21 august

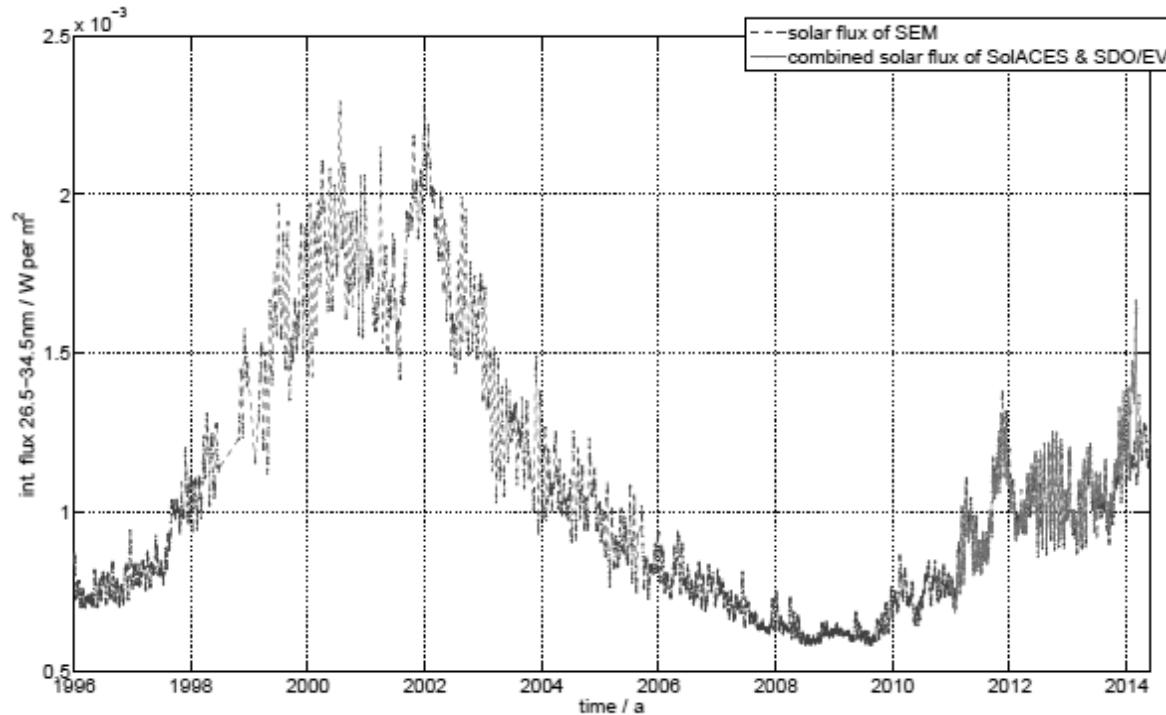
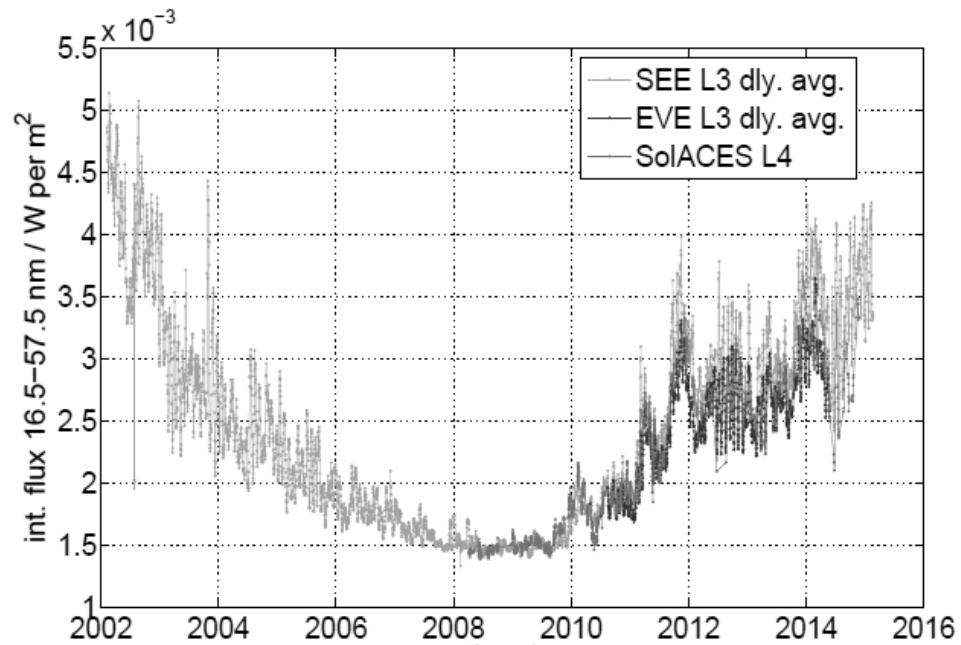
SORCE-SIM data at 210 nm show a minimum located around 26 June 2008.

Mg II index variation as a function of time. The arrows point to the values on 14 April 2008, 26 June 2008, 27 February 2009 and 21 August 2009.

EUV/UV minima occurring at different times were first noted by Hinteriger (1977).

EUV TIME SERIES

Schmidtke et al., 2015



SSI at the 2008 minimum

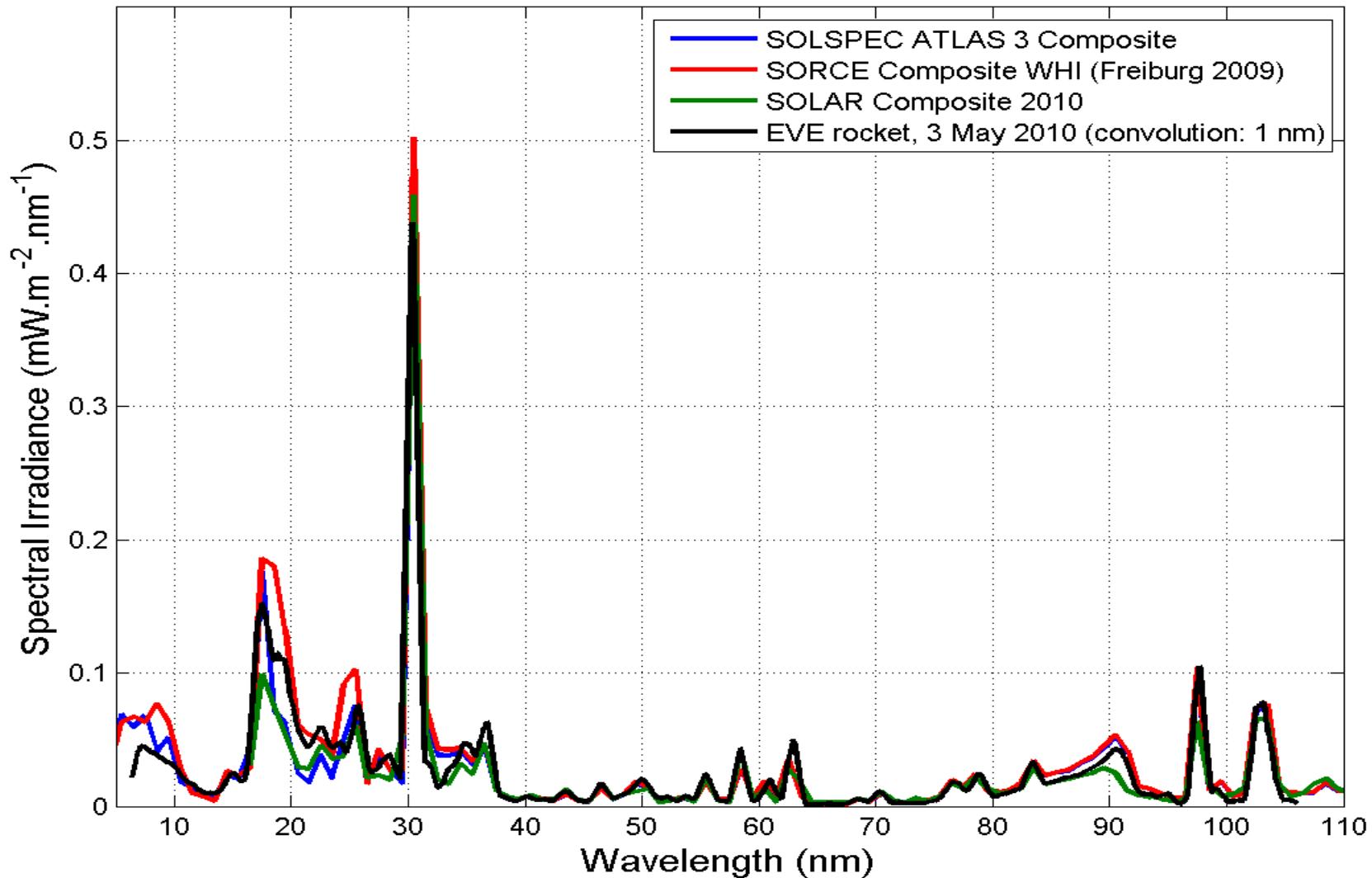
- The minimum is not occurring at the same time for all wavelengths.
- The EUV minimum occurs after the UV minimum.
- It is the smallest since 1978.
- By combining the data sets at their lowest value, we generated the absolute minimum SSI

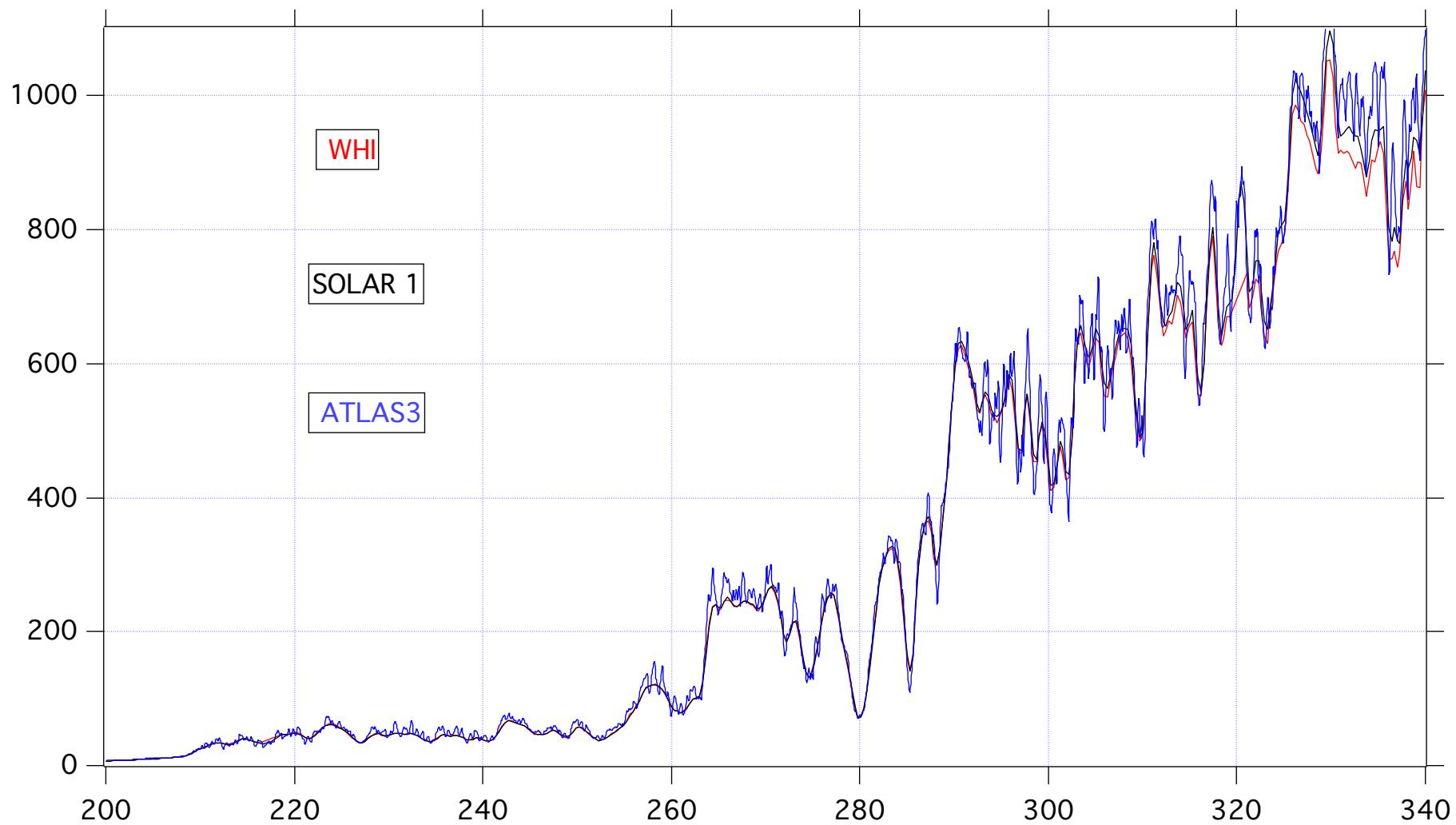
	ATLAS 3	WHI	SOLSPEC	SOLSTICE	SOLACES	EVE
Date	10 Nov. 1994	10, 16 Apr.	5, 8 Apr. 2, 4, 5, May 2008	5 Apr. 2008	21 Aug. 2009	14 Apr. 2008
SSN	18	<2>	<3>	0.	0.	7
F10.7	80.	<68.9>	<68>	71.3	67.	68.9
Mg II index	0.26747	<0.26416>	<0.26433>	0.26465	0.26375	0.26416

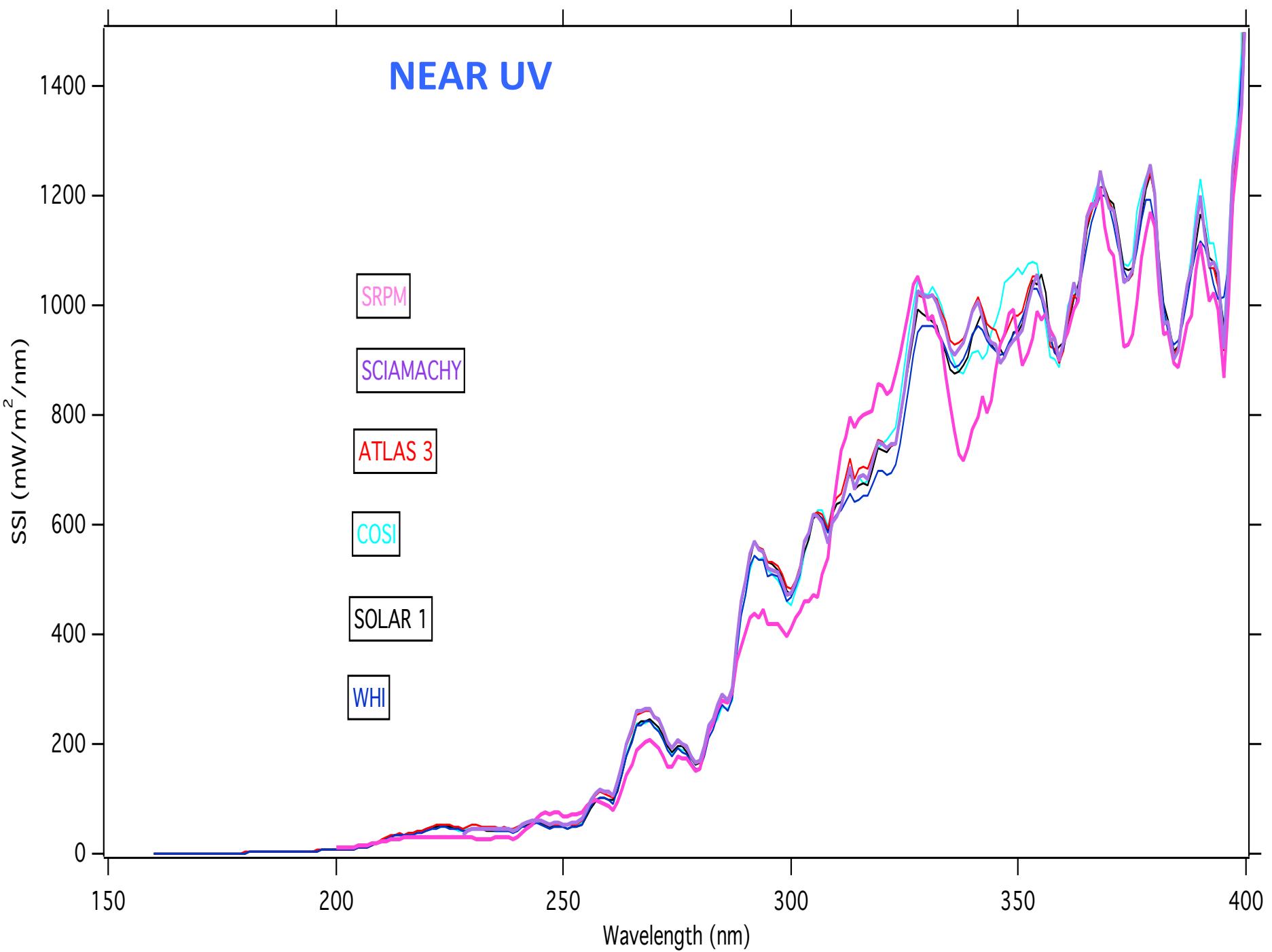
	SSN	F10.7	Mg II
ATLAS 3	18	80.0	0.26747
SOLAR 1	2.4	68.8	0.26421

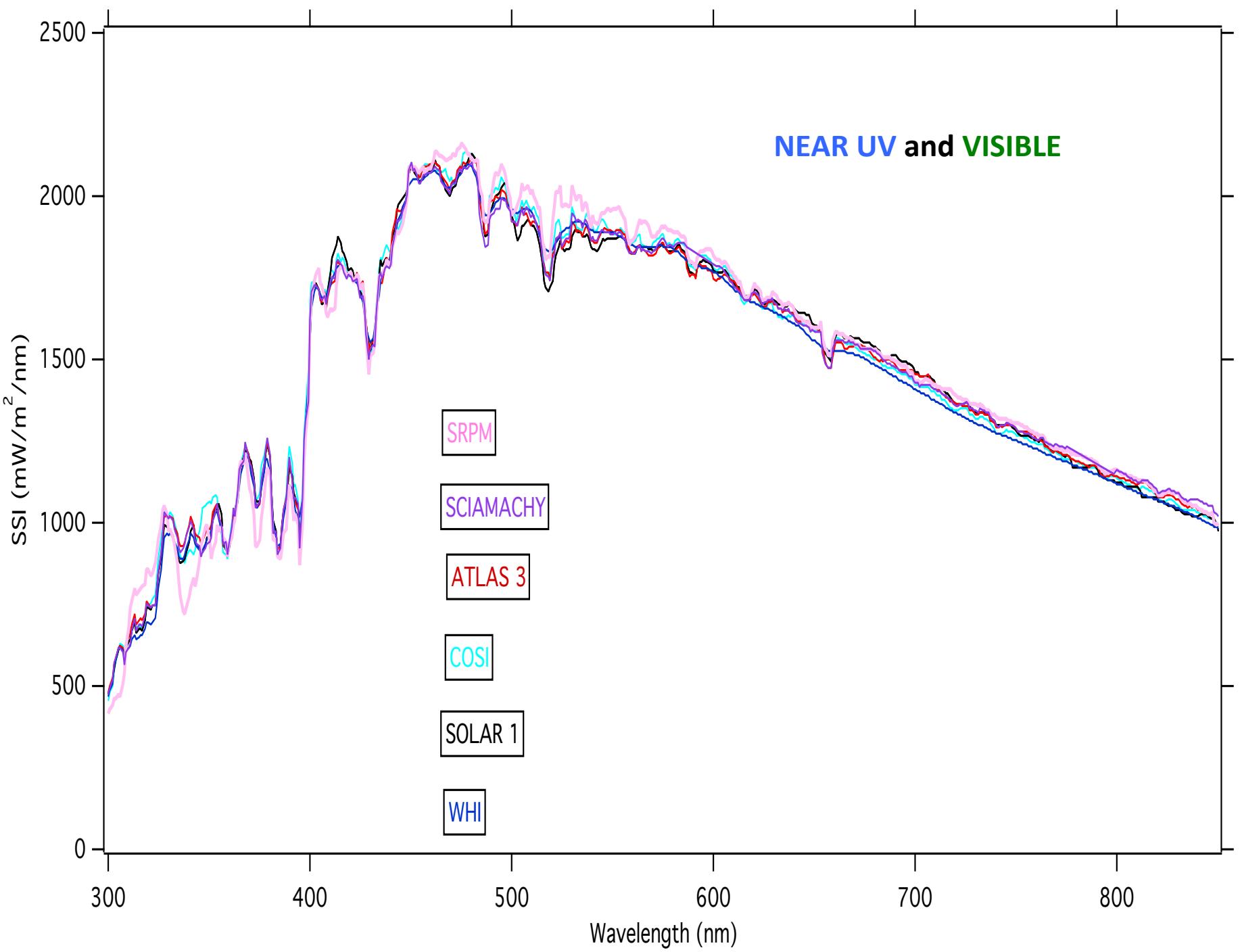
EUV DOMAIN

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









COMPARISON BETWEEN WHI, COSI and SOLAR 1 SPECTRA

$\Delta\lambda$ (nm)	Lines/continuum	WHI/SOL	COSI/SOL
17–120	See below	0.95	
28–35	He II, Fe XVI	0.75	
55–65	He I, OVI	1.26	
96–100	C III, Ly γ , NIII	1.28	
101–105	Ly β , OVI, CIII	0.87	
121–122	Ly α	1.38	
166–180	continuum	0.97	0.97
120–200	continuum,O II,C II, Si IV,C IV,Si II	1.00	0.95
180–220	continuum, Si II, Al edge	0.95	0.97
170–207	continuum, Si II, Al edge	0.98	1.00

Two reasons to explain the ratios far from unity:

- Photometric difference
- Difference in spectrometers psf shape and centering in which EUV emission lines are located.
This effect decreases as a function of the contribution of the continuum with respect to the emission or absorption lines,, i. e. at larger wavelength.

COMPARISON BETWEEN WHI, COSI, SOLAR 1, SOLAR 2, ATLAS 3, SRPM

$\Delta\lambda$ (nm)	SRPM/SOL	COSI/SOL	A3/SOL	WHI/SOL	WHI/A3	WHI/COSI	SRPM/COSI
210--350	0.96	1.01	1.03	0.98	0.95	0.96	0.95
350--500	0.99	1.00	1.00	0.99	0.99	0.98	0.98
350--850	1.01	1.00	1.00	0.99	0.99	0.99	1.01
220--260	0.95	1.00	1.09	0.98	0.90	0.99	0.95
260--300	0.85	0.97	1.02	0.97	0.94	0.99	0.87
300--340	1.01	1.02	1.03	0.98	0.95	0.96	0.99
340--370	0.96	1.02	1.00	0.99	0.98	0.97	0.95
350--425	0.97	1.00	0.99	0.99	0.99	0.98	0.96
425--500	1.00	1.00	1.00	0.99	0.99	0.99	1.00
500--575	1.05	1.02	1.01	1.02	1.01	1.00	1.02
575--650	1.01	0.99	0.99	0.99	0.99	0.99	1.01
650--725	1.00	0.98	0.99	0.97	0.98	0.99	1.02
725--800	1.02	0.99	1.00	0.98	0.98	0.99	1.02

$\Delta\lambda$ (μm)	COSI/A3	WHI/A3	SOL1/A3	SOL2/A3	SCIA/A3	COSI/SOL2
210-2400	0.992	0.993	0.997	0.984		
1000-2000	0.997	1.003	0.996	0.950		
1000-1761	0.983	1.005	0.999	0.958	0.980	
1000-2400	0.976	1.004	0.997	0.949		
1936-2042	0.947	0.992	0.992	0.909	0.939	
2260-2384	0.965	1.011	1.000	0.949	0.965	
2400-2900						1.042

SOLSPEC-ISS IR SPECTRUM

First analysis of the SSI-SOLSPEC-ISS data yielded a spectrum which is about 7% around 1700 nm than ATLAS 3.

Extended investigations were made, and now, explanation has been found.

Consequently, we built two composites:

SOLAR 2 uses SolACES (16-149.5 nm), SOLSTICE (150-170 nm) and SOLSPEC-ISS (170-2900 nm).

SOLAR 1 is identical to SOLAR 2 except in the range 1100 to 2400 nm where ATLAS 3 IR SSI is used.

We use:

Measurements:

ATLAS 3 (Thuillier et al., 2004)

Whole Heliospheric Interval (WHI, Woods et al., 2009) dated of 14 Feb. 2008

SCIAMACHY2004 (Pagaran et al., 2010)

SCIAMACHY2002 (Weber, private communication, 2013)

SOLAR 2 = SOLSTICE + SolACES + SOLSPEC both onboard the ISS

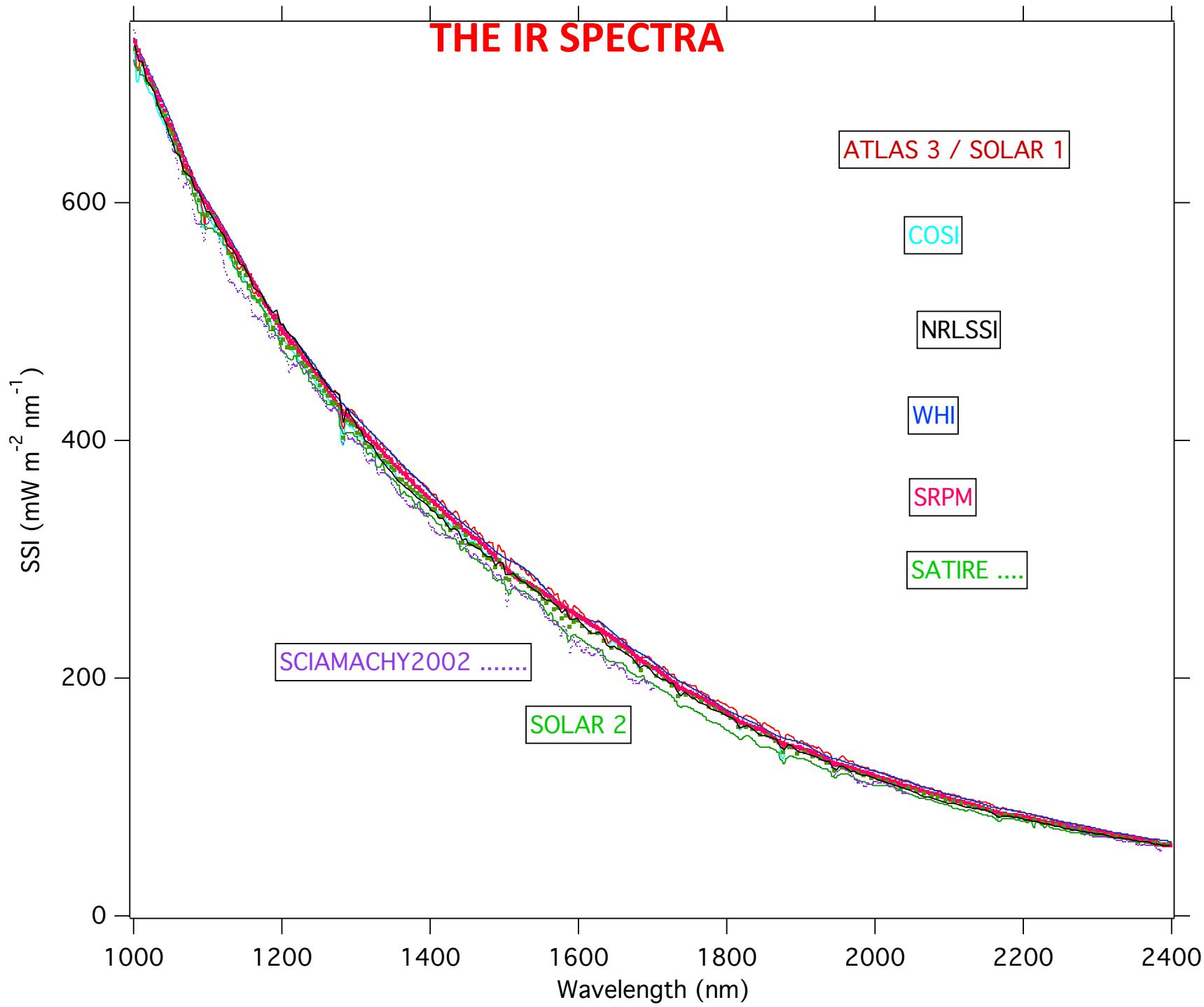
SOLAR 1 = SOLSTICE + SolACES + SOLSPEC + ATLAS 3 (1100-2400 nm)

Theoretical models: COSI (Shapiro et al., 2011)

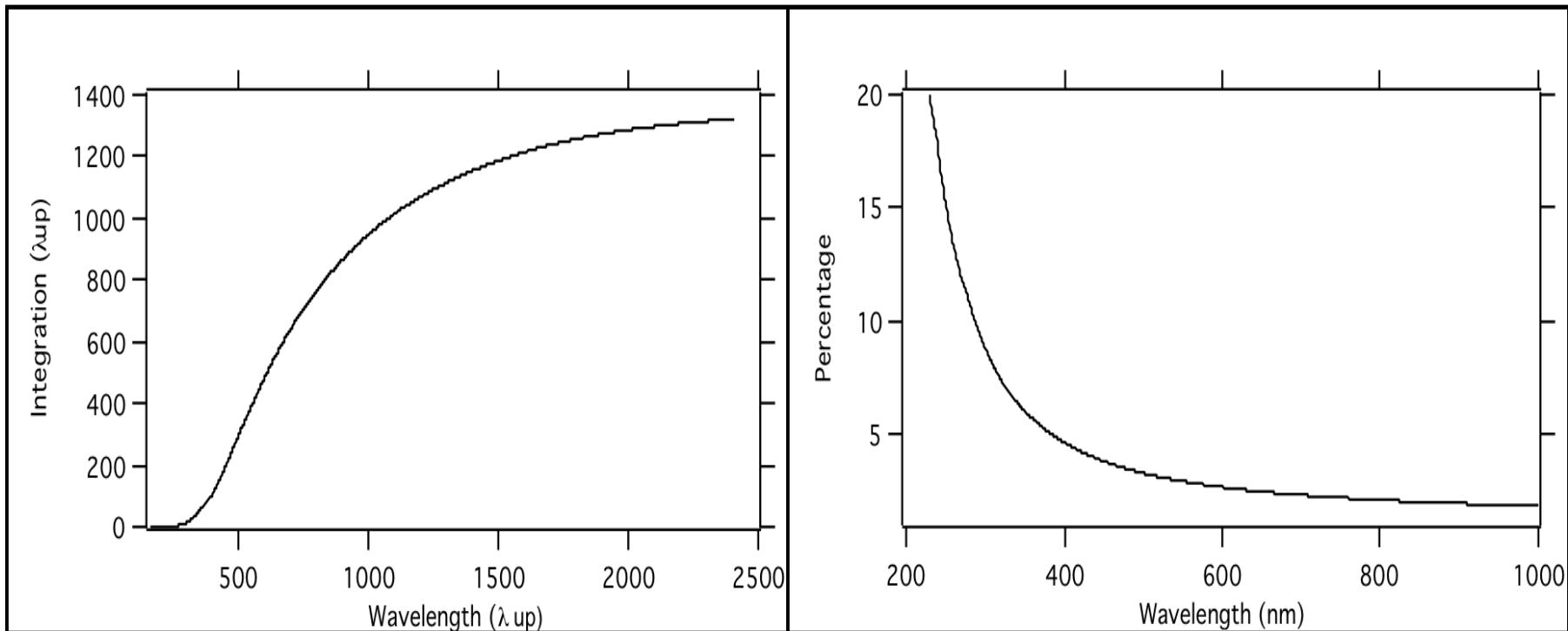
SRPM (Fontenla et al., 2011)

Semi-empirical models: NRLSSI (Lean et al., 2011), SATIRE (Yeoh et al., 2014)

THE IR SPECTRA



DEFICIT SOLAR 2/ATLAS 3 in the interval 1000-2400 nm: 19 W/m²



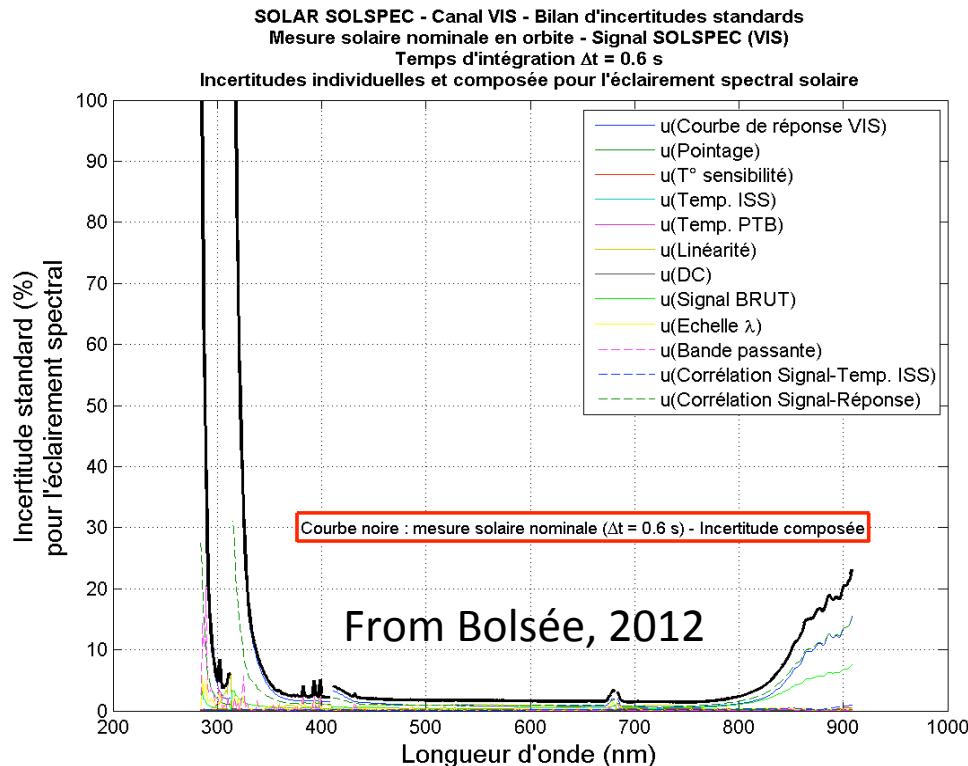
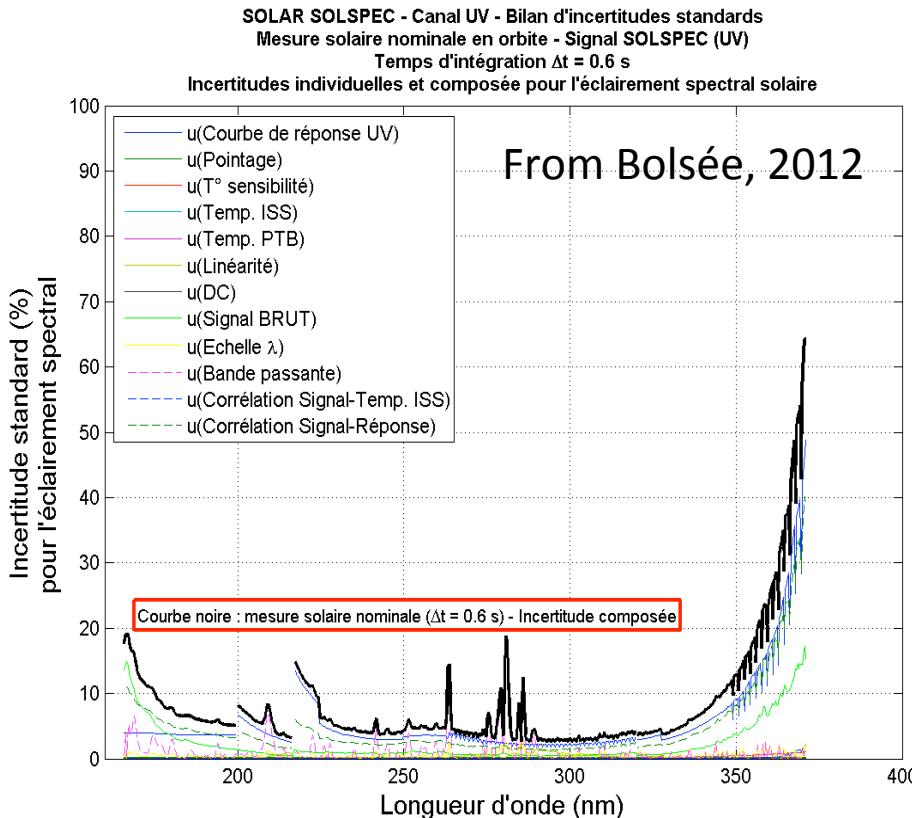
The left panel shows the variation of the integrated **WHI** spectrum as a function of λ_{up} . The right panel shows the percentage of **systematic** overestimation of SSI to represent 19W/m² as a function of λ_{up} .

The right panel shows that with 2% constant uncertainty, the corresponding domain extends to 1000 nm. However, a systematic 2% uncertainty is unlikely given the distribution of contributing uncertainties as a function of wavelength.

With 5% uncertainty, the corresponding domain extends to 400 nm.

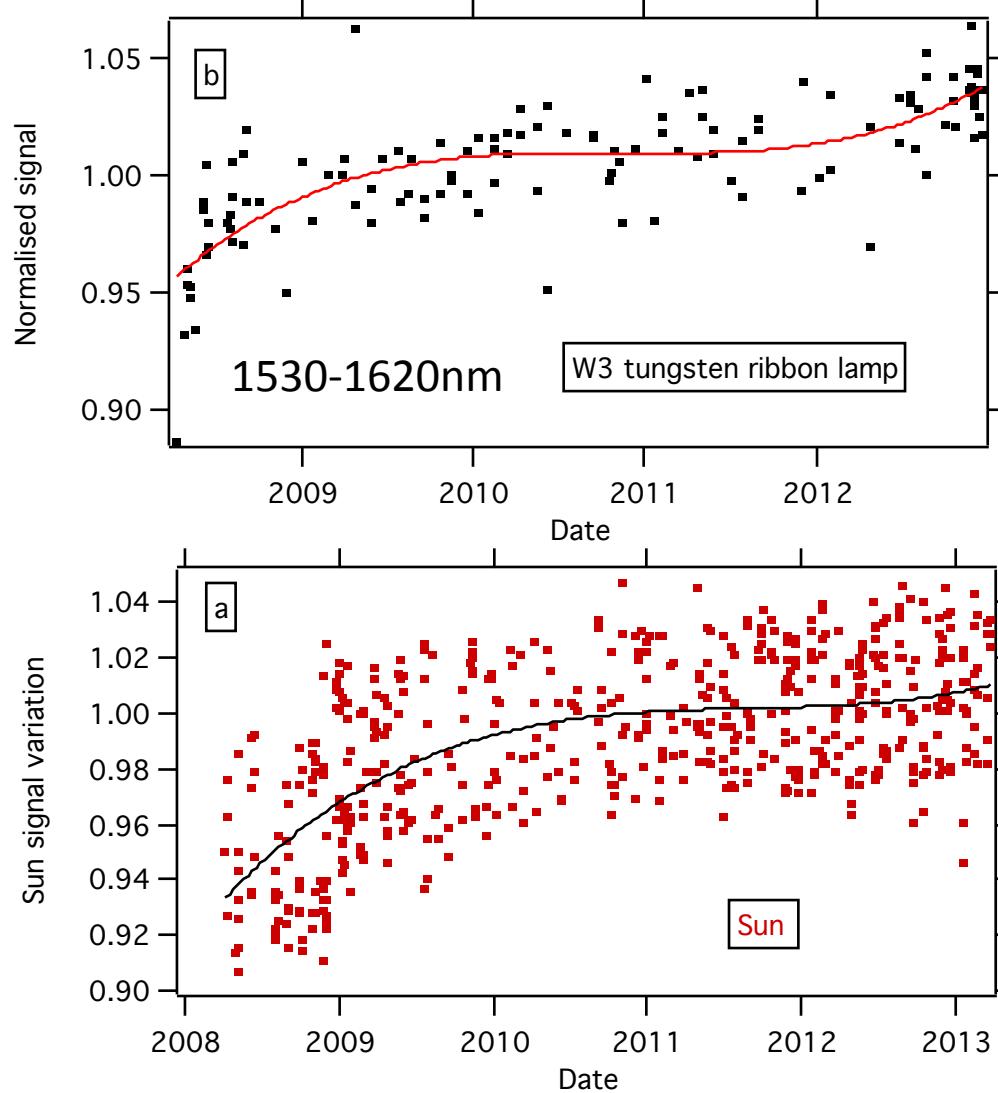
Such uncertainties are not compatible with the accuracy of the SIM-SORCE instrument absolute calibration.

UNCERTAINTIES : not an even function of wavelength



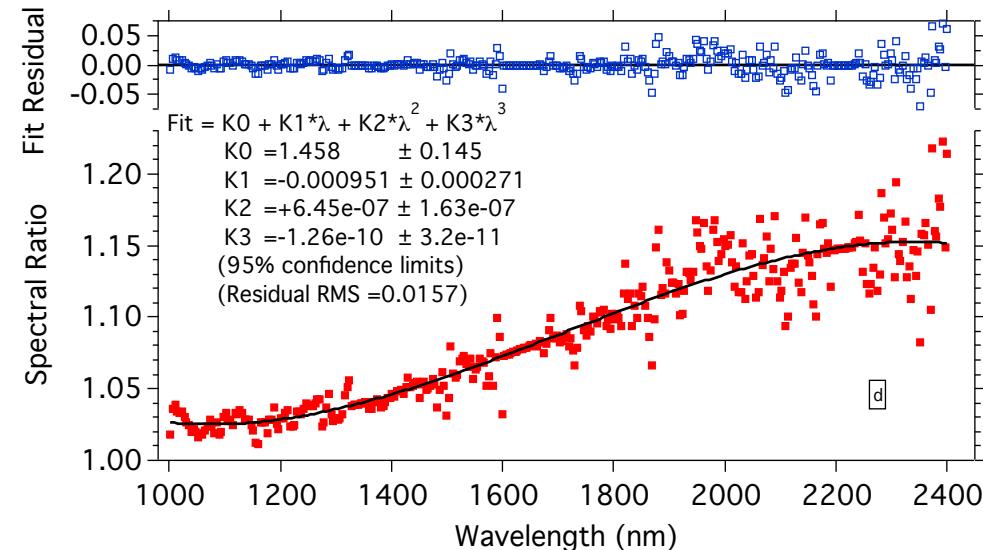
In the range of 200-350 nm, the background uncertainty is 4 %, with increase at 10 to 15 % around 220 nm, several peaks above 10 % at 265 nm, and 280 nm, and the significant uncertainty increase in the range 350-370 nm from 10 to 65%.
 For the visible spectrometer, at 350 nm, the uncertainty is 6% and decreases afterward. Between 800 and 900 nm, the uncertainty increases from 3 to 10 %.

IR SPECTROMETER RESPONSIVITY STABILIZATION WITH TIME

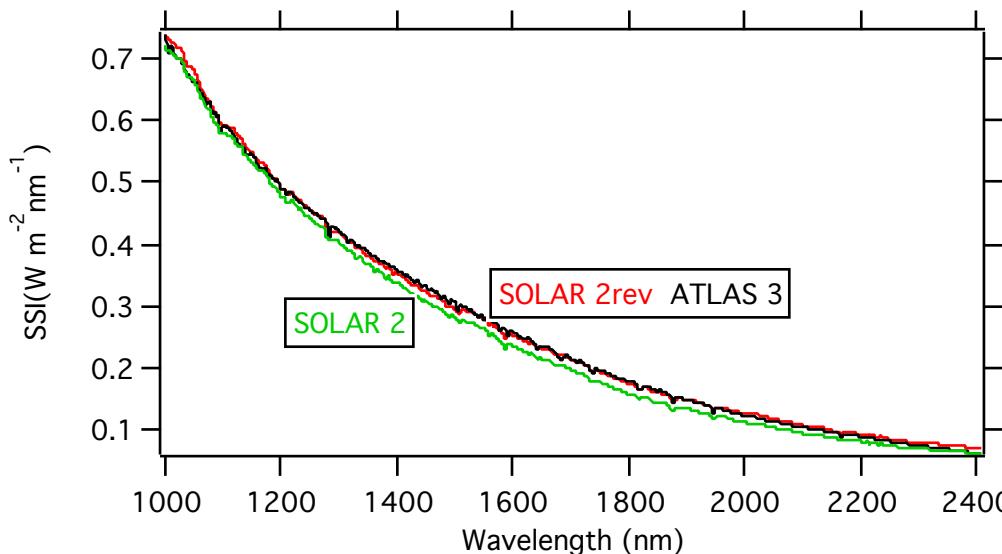


SOLAR 2 was measured at **first light**. The deficit of 7% at 1700 nm mainly originates from the IR spectrometer responsivity change with time (contamination on ground, at launch, by internal outgassing?). Is that ratio function of wavelength?

CORRECTION OF IR SOLAR 2: METHOD



The ratio of the 2010 mean spectrum to 2008 mean spectrum is displayed as a function of Wavelength. Around 1330, 1600 and 2200 nm, there is a spectrometer filter change, that generates variations in the ratio amplitude of about $\pm 5\%$, which is removed by using the polynomial fitting.

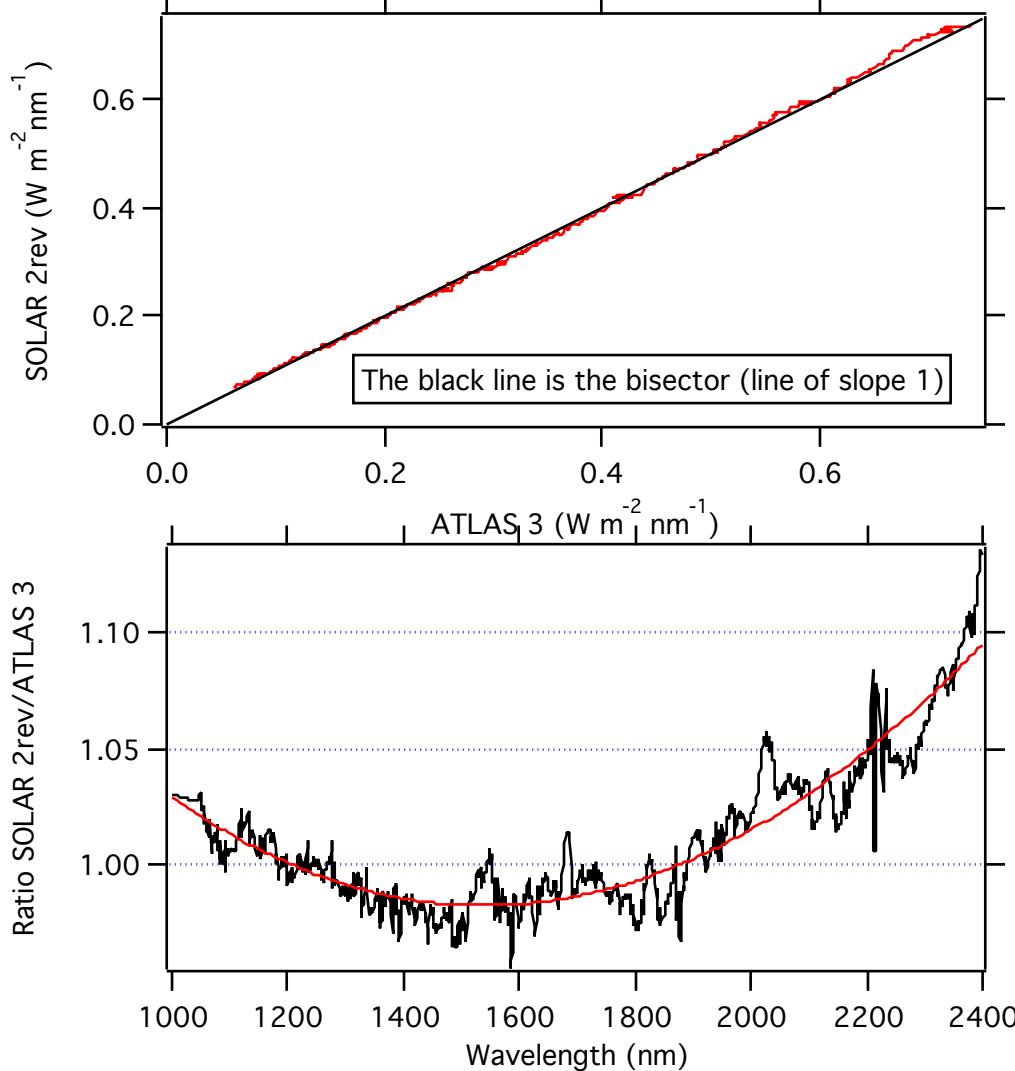


The trend 2010/2008 with wavelength depicted in the above Figure has been fitted by a 3rd order polynomial and applied to SOLAR 2.

The resulting spectrum is named SOLAR 2rev. It is shown with ATLAS 3 and SOLAR 2.

As the difference between SOLAR 2rev and ATLAS 3 is within the thickness of the lines, the next panel displays one versus the other.

CORRECTION OF SOLAR 2: RESULTS



λ (μm)	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.3	2.4
SOLAR 2rev/ATLAS 3 difference	3.	1.	1.	2.	1.	1.	2.	5.	9.
Uncertainty on 2010/2008 ratio	0.65	0.70	0.90	1.5	1.8	2.5	5.0	5.2	7.0
Uncertainty on SOLAR 2/ATLAS 3 ratio	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	7.0
Combined uncertainties (lines 2 and 3)	4.4	4.4	4.4	4.6	4.7	5.0	6.6	6.7	10.

IR SOLAR 2revised: TSI IMPLICATION

The IR spectrometer responsivity is increasing with time as shown.

It is also a slight function of wavelength as shown by the ratio of a spectrum in 2010 (instrument stabilized) to the spectrum at first ligh (SOLAR 2).

This correction is applied to the IR SOLSPEC measurements (SOLAR2) providing SOLARrev.

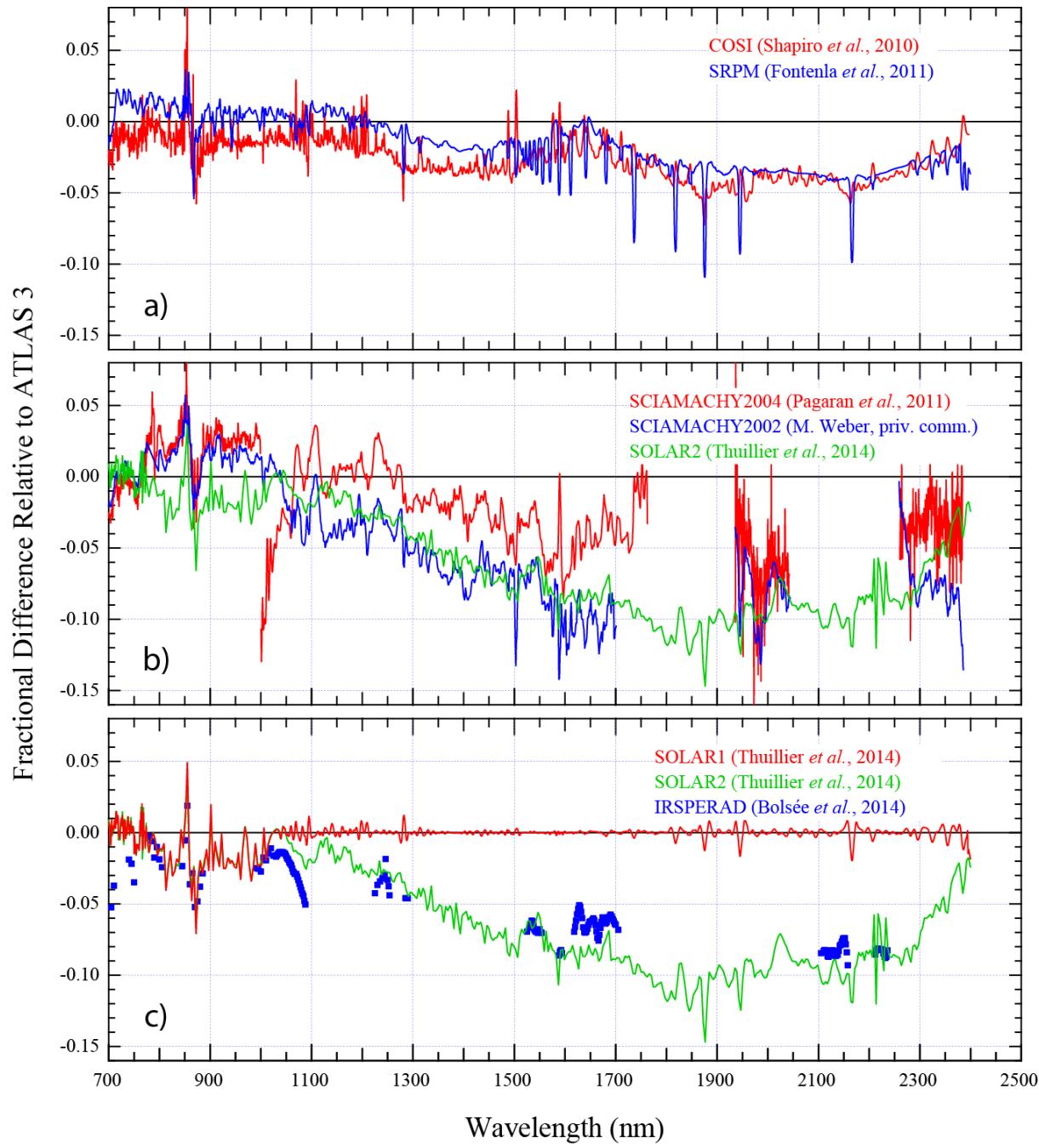
The power provided by these spectra obtained by integration between 1000 and 2400 nm, is displayed below:

Spectrum	Power between 1 and 2.4 μm	Difference/ To ATLAS 3	Comments
SOLAR 1	373.0 W m^{-2}	0.	ATLAS 3
SOLAR 2	354.2 W m^{-2}	19 W m^{-2}	SOLSPEC-ISS
SOLAR2rev	369.3	3.7 W m^{-2}	SOLAR 2 revised

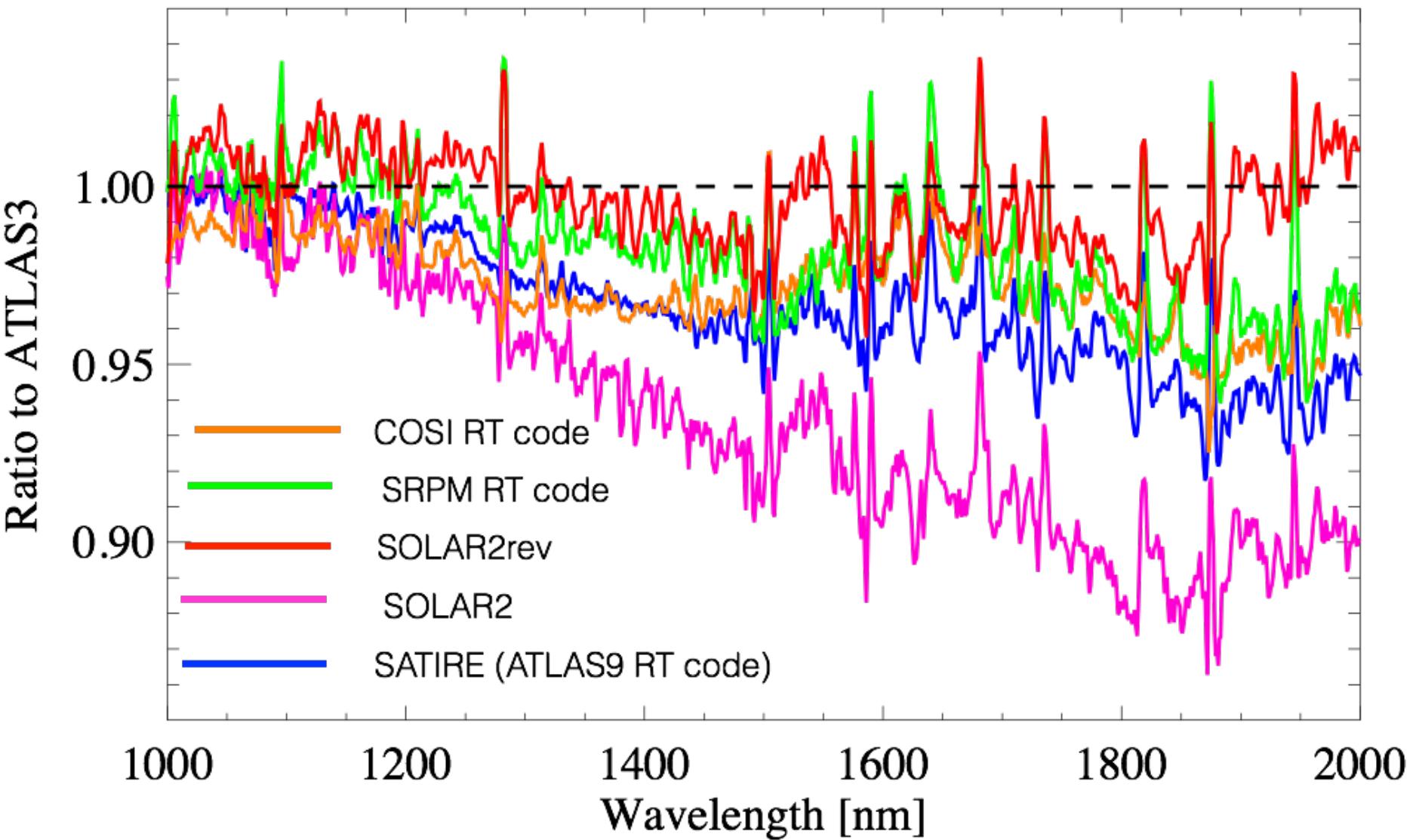
This correction allows to reduce the difference SOLAR 2 to ATLAS 3 to 1%.

Such a difference is compatible with the uncertainty affecting these two spectra.

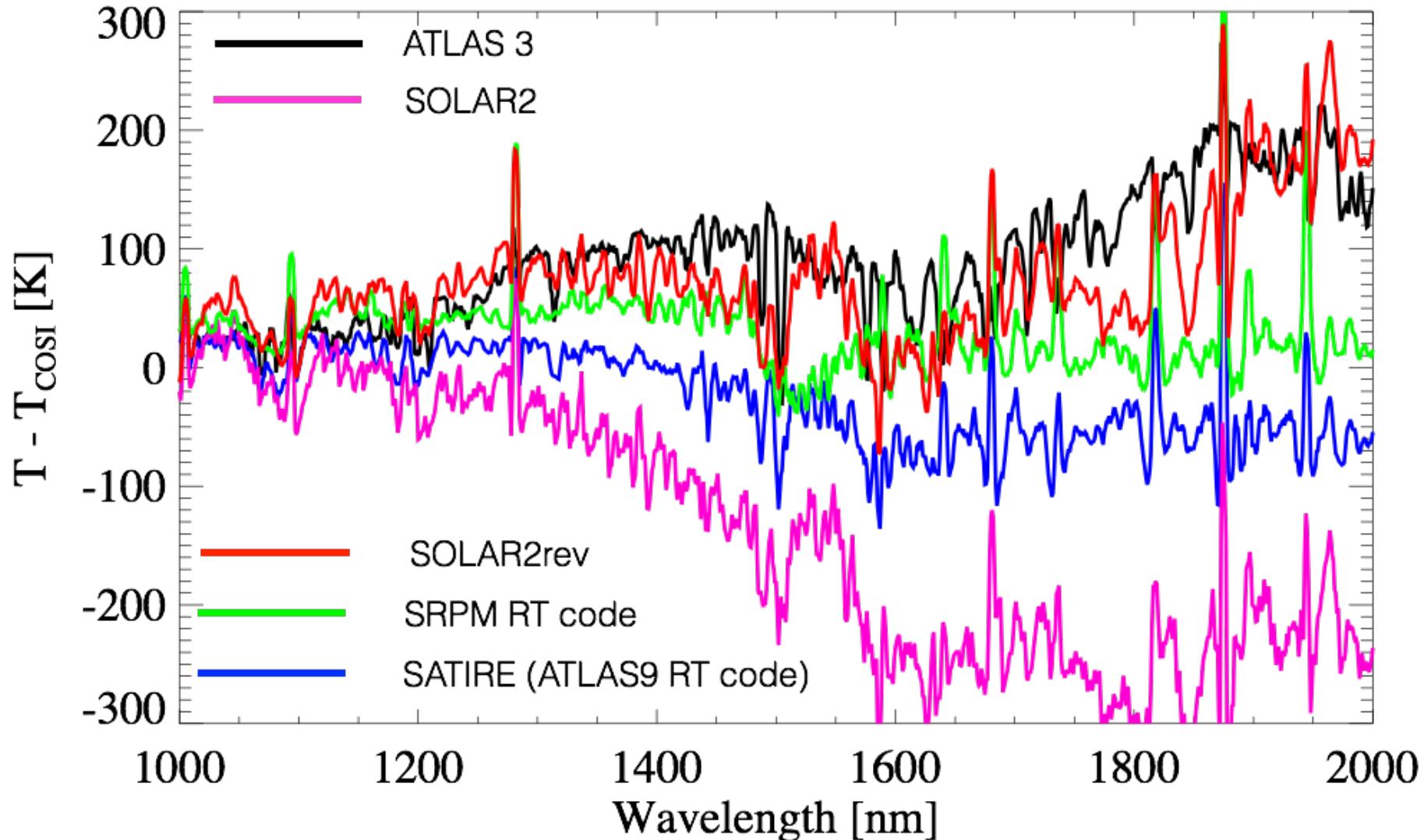
Consequently, SOLAR 2revised with the wavelength trend is in agreement with ATLAS 3.



IR SOLAR 2revised: SSI COMPARISON

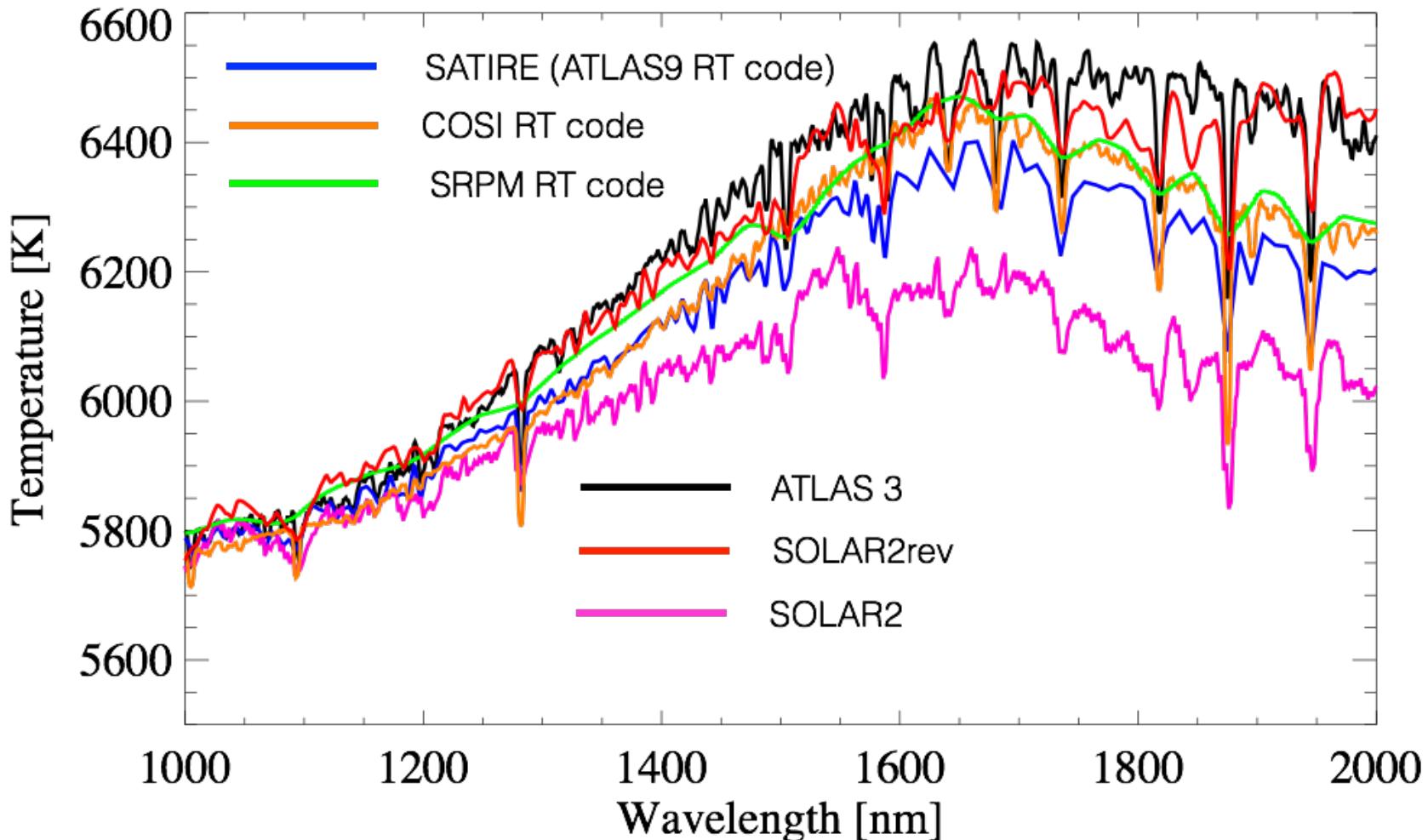


IR SOLAR 2revised: MODELING COMPARISON and PLAN



We expect an *increase* of IR intensity given by COSI after the effects of horizontal temperature inhomogeneities are taken into account (work in progress).

IR SOLAR 2revised: MODELING COMPARISON



According to SOLAR2 the temperature increase near 1600 nm is only about 300 K relative to the brightness temperature near 500 nm. Such a small increase (with respect to brightness temperature at 500 nm) would imply that the IR and visible photons emission are formed at nearly the same altitude in the photosphere, which is very unlikely from any kind of solar models.

CONCLUSIONS

1) The SOLAR 2 spectrum extending from 17 nm to 2400 nm has been obtained by the SOLSPEC and SolACES spectrometers both running on the ISS.

It is compatible with WHI and compatible with ATLAS 3 in the visible range. In UV, the SSI is lower than ATLAS 3 given the very low solar activity period during which it was measured.

2) The **IR** SSI SOLAR 2 is lower than ATLAS 3

The origin of the discrepancy in the IR domain between ATLAS 3 and SOLAR 2-ISS is due to a late stabilization of the IR spectrometer. Its origin remains unknown up to now.

SOLAR 2-ISS in the IR domain is incompatible

- with the TSI
- with the solar models in IR (Irradiance and brightness temperature)
- with the absolute calibration of both SIM-SORCE and SOLSPEC-ISS in the visible

3) SOLSPEC calibration coefficients are correct if applied when the IR spectrometer has reached its stability. The long time to recover this stability remains unexplained.

4) Using data when the stabilisation is achieved, IR SOLAR 2_{revised} becomes compatible with ATLAS 3, TSI and solar models (**SATIRE, NRLSSI, COSI, SRPM**), however incompatible with ground based measurements.

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