Recent Solar Spectral Irradiance Observations

M. Meftah[1], G. Cessateur[2], W. Schmutz[3], D. Bolsée[2], A. Shapiro[4], N. Pereira[2], A. Hauchecorne[1], L. Damé[1], A. Irbah[1], S. Bekki[1]

(1) CNRS-LATMOS, France
(2) BIRA-IASB, Belgium
(3) PMOD/WRC, Switzerland
(4) MPS, Germany

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Presentation outline

- Introduction
- SOLSPEC onboard the ISS
- The PREMOS photometer onboard PICARD
- The SES sensor onboard PICARD
- Conclusions

1 – Introduction

The solar spectrum is a key input for different disciplines.

- **Solar Physics**: the solar spectrum characterizes the outer layers of the Sun (photosphere, chromosphere, and corona). Furthermore, by comparison with theoretical reconstruction, an accurately measured solar spectrum allows to validate the temperature, the composition, and the densities of the solar atmosphere.

- **Atmospheric Physics**: the solar photons act on the Earth atmosphere by photo-dissociation, ionization, absorption, and scattering.

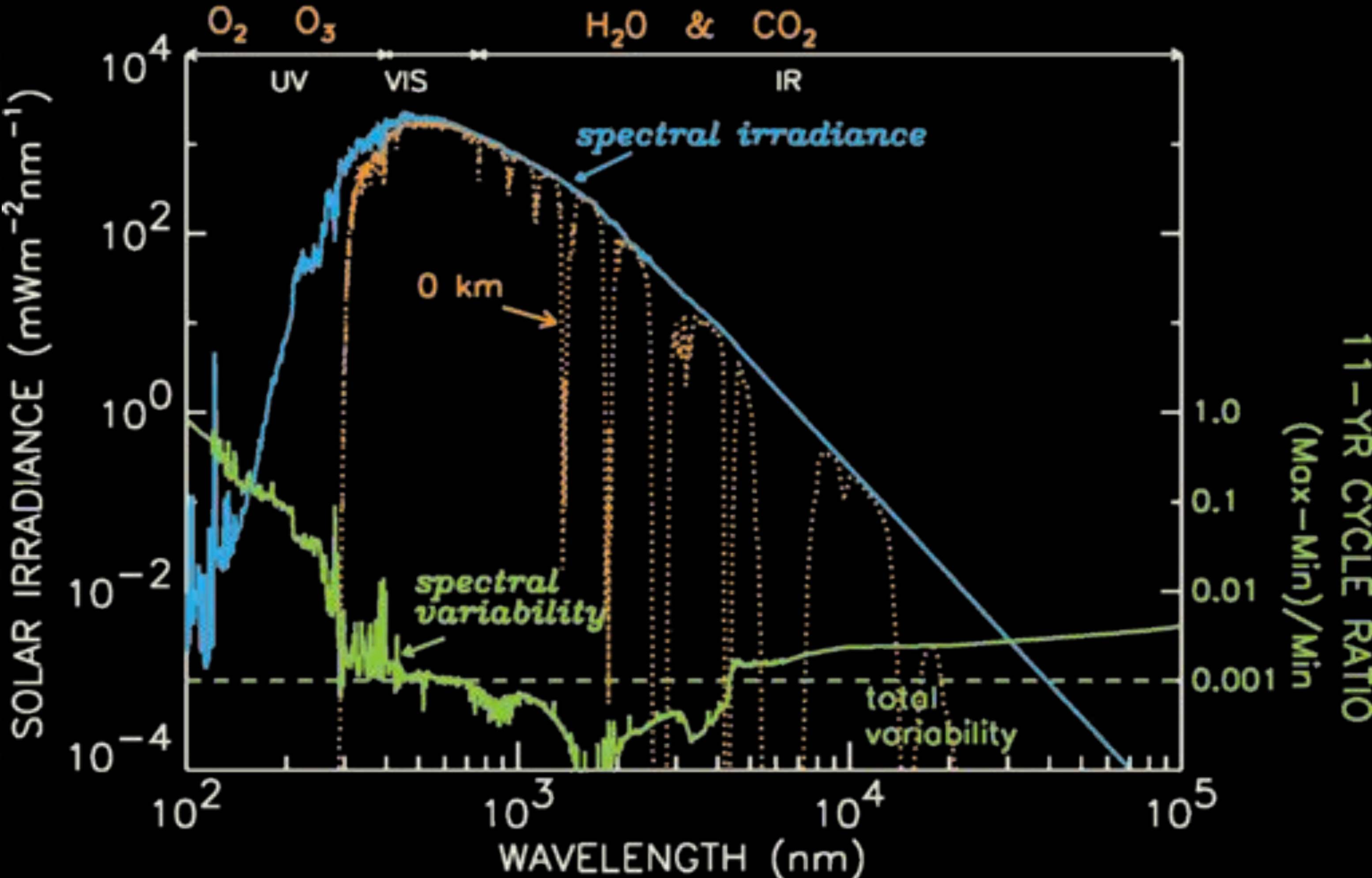
- **Climate Physics**: processes involving changes driven by the Sun on atmospheric parameters are today accepted as possible actors in rapid climate changes. Climate models request solar spectra corresponding to different solar activity regimes. The available information is based on reconstructions and models. However, they are not yet at the required level of accuracy for different levels of solar activity.

- Engineering, etc.

The fundamental issues for solar spectra measurements are:

- **Accuracy (absolute SSI determination) and its variability with solar activity,**
- **And long-term stability.**

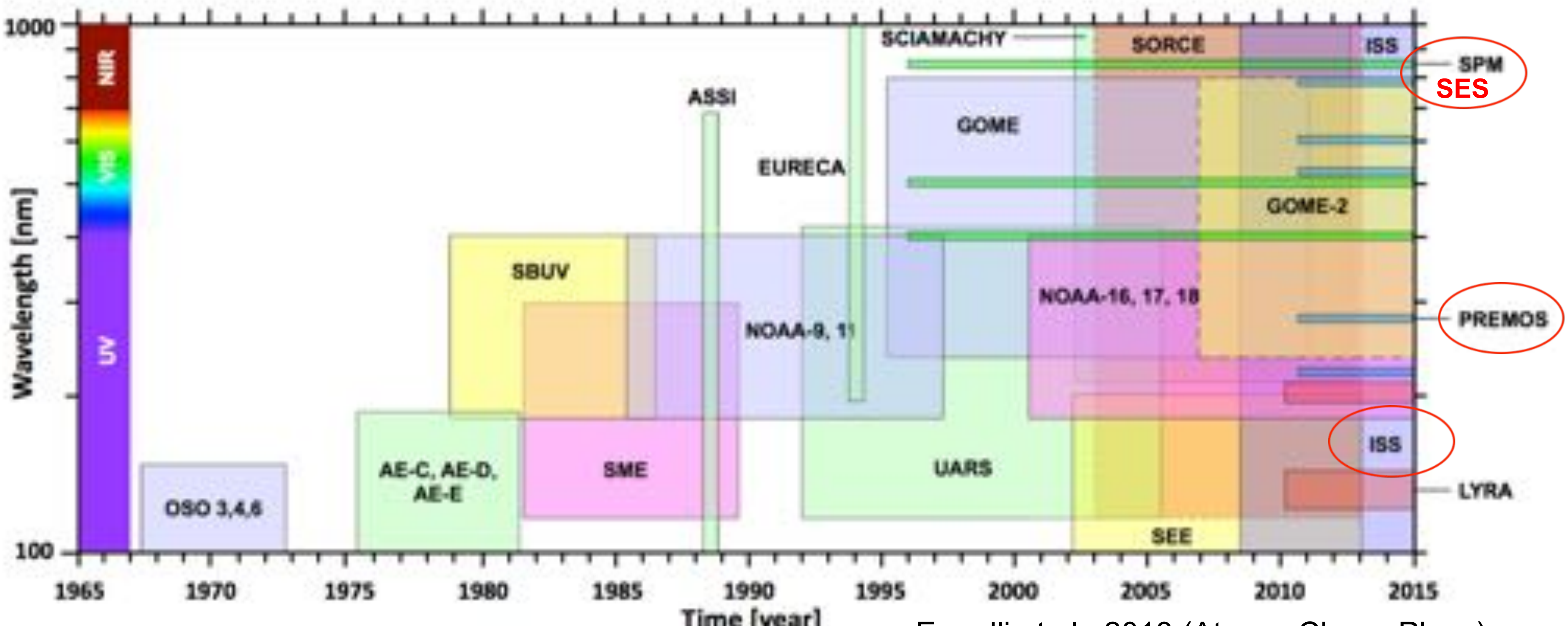
1 – Introduction



There is a need for a thorough understanding of how the Sun affects climate.
Thus, SSI variability (in particular the UV) during a solar cycle is of primary importance.

1 – Introduction

Overview of the main satellite missions that have made SSI observations at wavelengths higher than 100 nm.



Ermolli et al., 2013 (Atmos. Chem. Phys.)

I will present here recent SSI observations from the Ultra-Violet (UV) to the Near-Infrared (NIR), performed by European instruments such as the **SOLSPEC** spectrometer onboard the International Space Station (ISS), **PREMOS** and **SES** radiometers onboard PICARD.

1 – Introduction

Given the extent of the required spectral domain to be covered (EUV to IR), none alone instrument can achieve such requirement.

The data necessarily will be obtained from different instruments, preferably operated at the same time and onboard the same platform.

There is also semi-empirical models that provide reconstructions of SSI spanning the entire period of satellite observation at daily cadence:

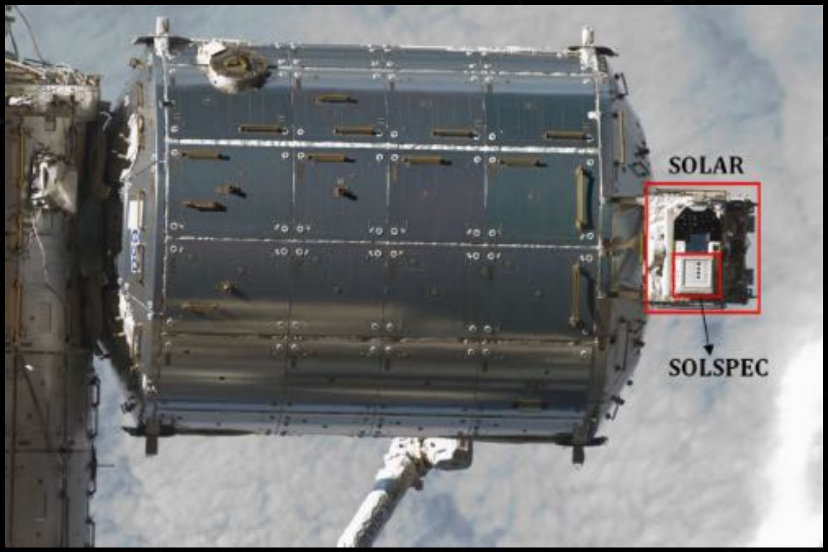
- Spectral And Total Irradiance REconstruction for the Satellite era (SATIRE-S, Yeo et al., 2014),
- COde for Solar Irradiance (COSI, Shapiro et al., 2010),
- Solar Radiation Physical Modelling (SRPM, Fontenla and Harder, 2005; Fontenla et al., 2011),
- Naval Research Laboratory Solar Spectral Irradiance (NRLSSI, Lean, 2000),
- And models developed in the Osservatorio Astronomico di Roma (OAR, Ermolli et al., 2013).

1 – Introduction

Our contribution aims at presenting the final SSI product for three instruments (SOSLPEC, PREMOS, and the SES), corrected for non solar features as well as for degradation, which could be used for space climate purposes. Our work is in progress.

These SSI observations will be compared to other observational data sets (SOLSTICE and SIM instruments onboard SORCE, etc.).

The SSI observations will be directly compared to modeling data (SATIRE-S, COSI, etc.)



SOLSPEC (IASB & LATMOS) mounted on external COLUMBUS platform. Credit: NASA.

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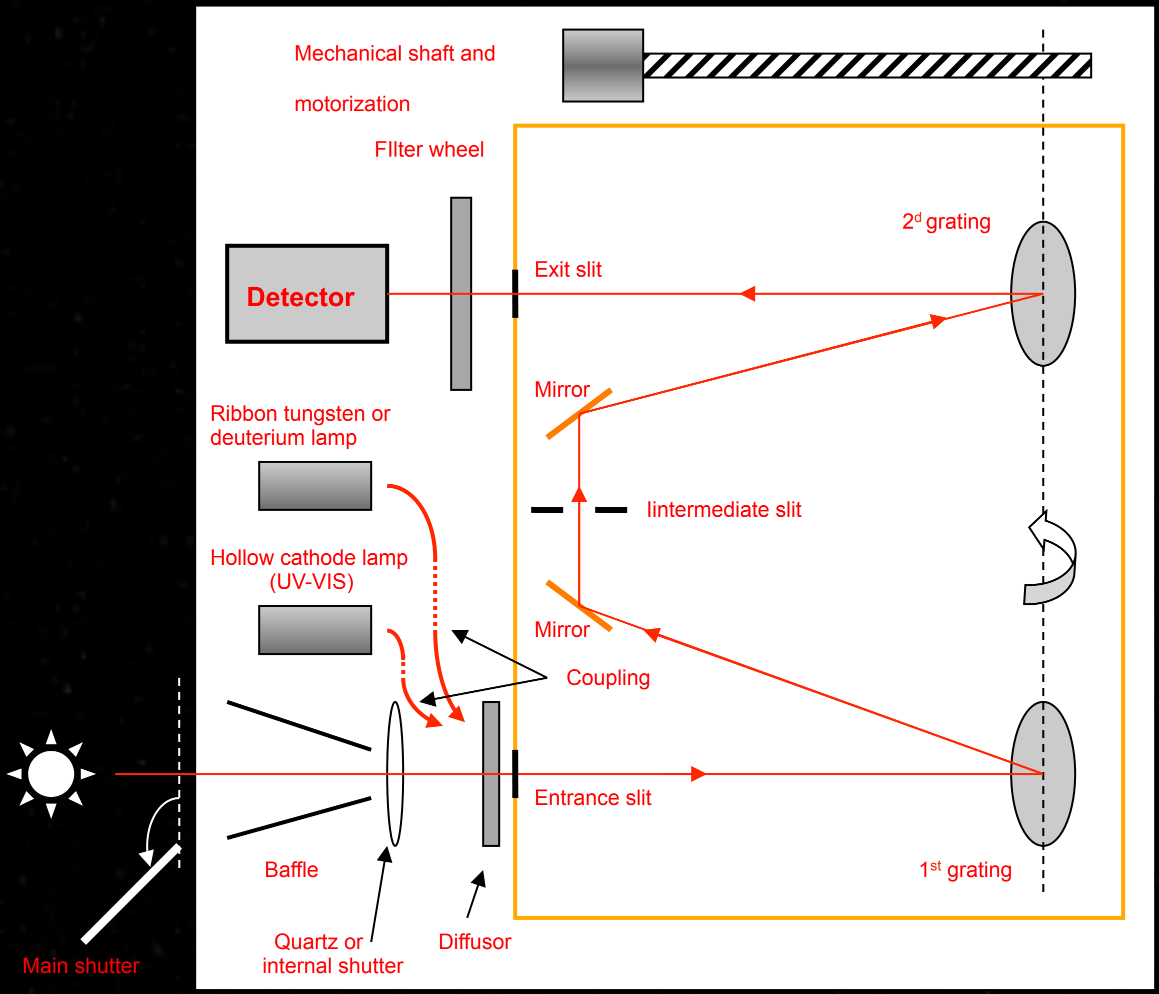
2 – SOLSPEC onboard ISS

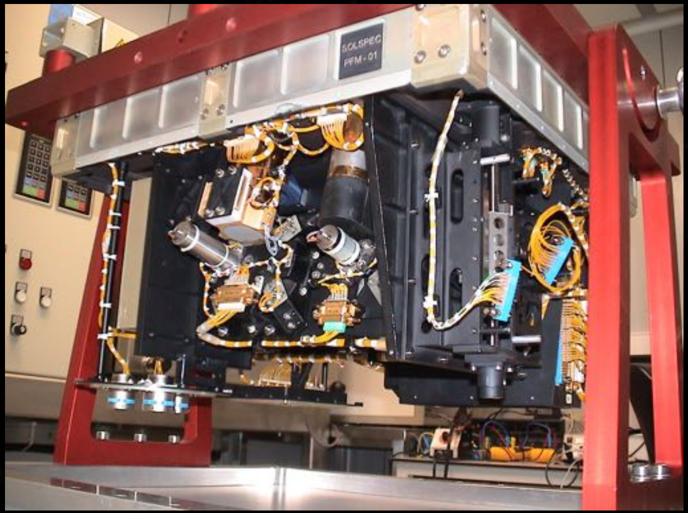
SOLSPEC is an absolute calibrated spectro-radiometer measuring the Solar Spectral Irradiance (SSI) from space.



Opto-mechanical configuration of one channel of the SOLAR/ SOLSPEC instrument for the SOLAR mission.

Credit: NASA.

2 – SOLSPEC onboard ISS



SOLSPEC status:

→ Around 8 years of measurements.

→ More than 1500 solar measurements (nominal, special UV, MgII & flat field).

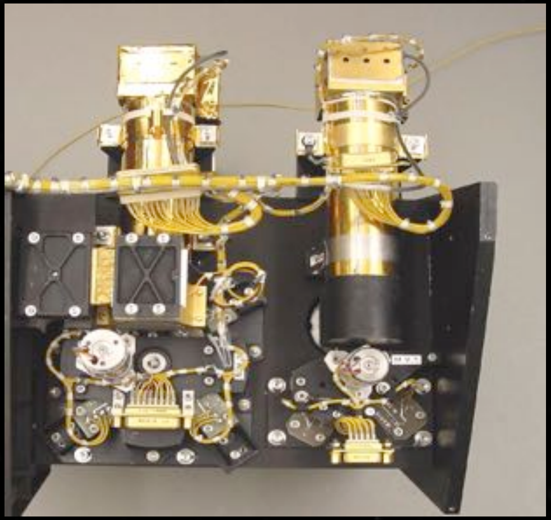
→ More than 3000 internal lamps measurements.

Main scientific objectives:

→ Measurement of a reference spectrum,
→ And the detection of SSI during Solar Cycle 24.

Space effetcs:

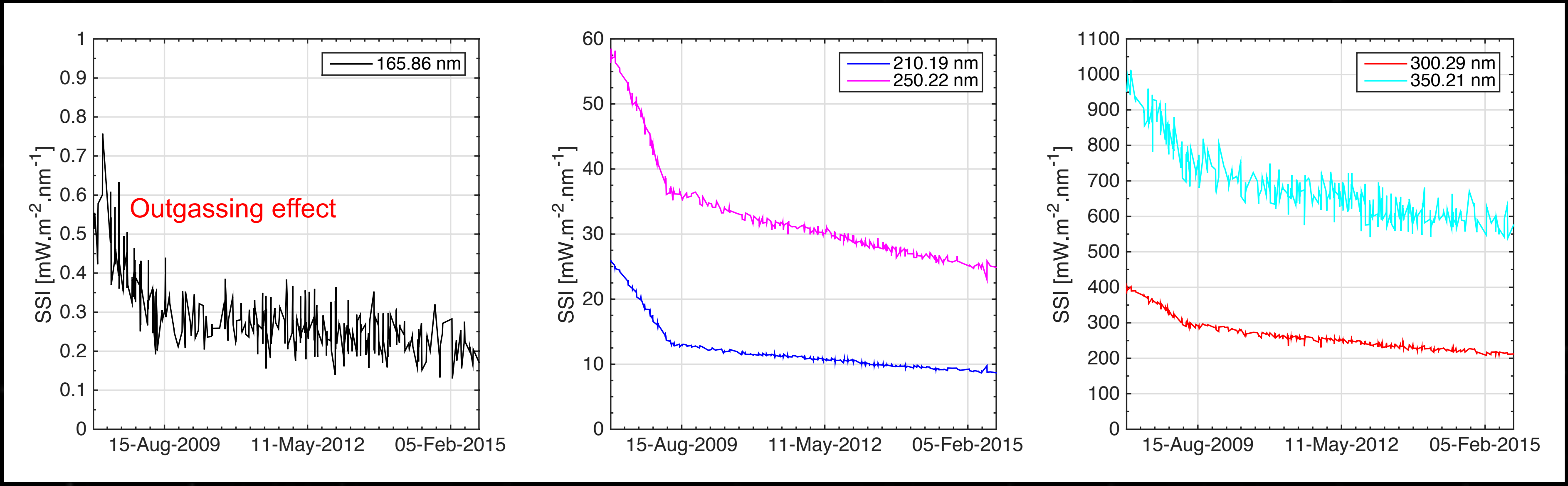
→ Due to the harsh space environment SOLSPEC is subject to degradation (in particular in the UV channel), both optically and thermally (indirect effect).



UV, VIS & IR detectors

2 – SOLSPEC onboard ISS

SOLSPEC is a robust instrument, everything being operational after 8 years of mission (except D2 lamps). Monitoring of all opto-mechanical and electronic parameters. However, during the first year of the mission, we saw a decrease of 50% around 200nm. For all wavelength in the UV band, we observe a degradation.



- UV channel and general strategy:

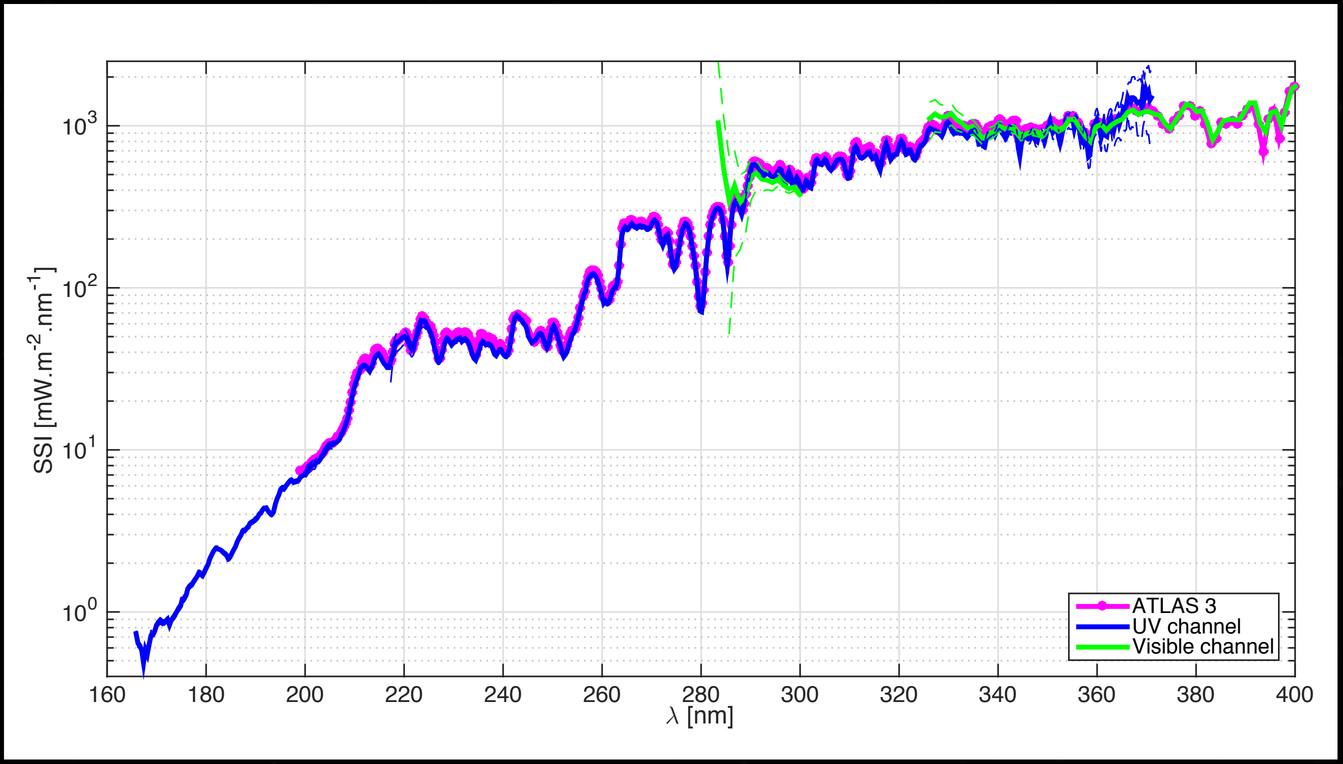
• UV Solar spectrum during the minimum of Solar Cycle 24 (beginning of the mission).

- And now:

• Determination of the aging correction (channel responsivity).
• Determination of the thermal correction (photomultiplier temperature effect).
• Analysis of the orbital effects on the measurements.
• Space calibration for understanding the behavior of SOLSPEC in space.

2 – SOLSPEC onboard ISS

- SOLSPEC solar spectrum (160-400 nm) – 2008 (solar minimum)
  - Good agreement with ATLAS 3 (less than 5% difference).
  - Deviations up to 10% between series of measurements (SOLSPEC, SORCE, SATIRE-S) can be observed because the uncertainty of SSI measurements from space in the UV are still high.

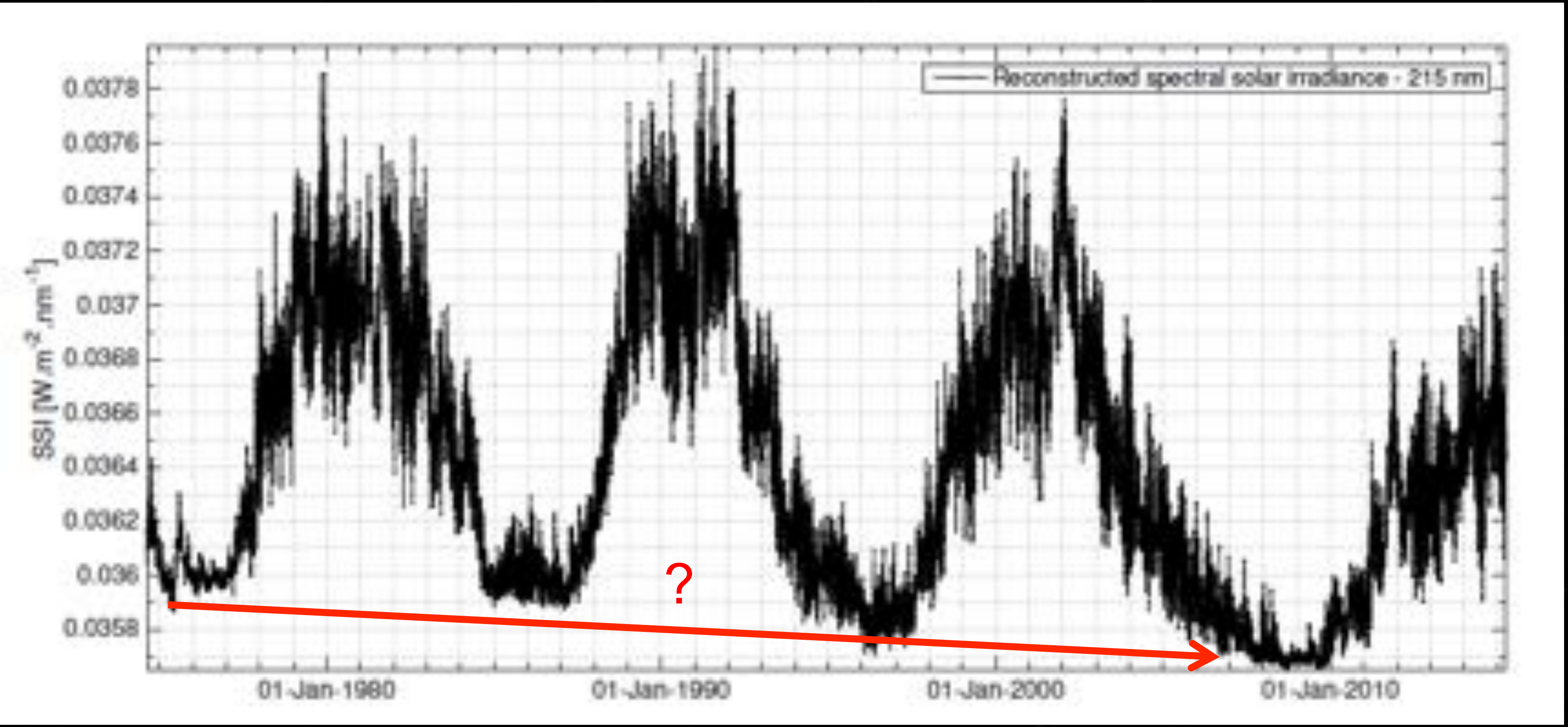


- Work in progress
  - Retrieval of the SSI UV variability during the solar cycle 24.
  - Comparison with PREMOS UV variability, SORCE, and all models (SATIRE-S, COSI, etc.).

2 – SOLSPEC onboard ISS

SSI time series (SATIRE-S reconstruction) at 215nm that highlights a modulation of the 11-year solar cycle with a 5% amplitude.

A decrease of SSI is observed at each solar minima since 1976.



Interest to extend the measurements and to develop new instruments.

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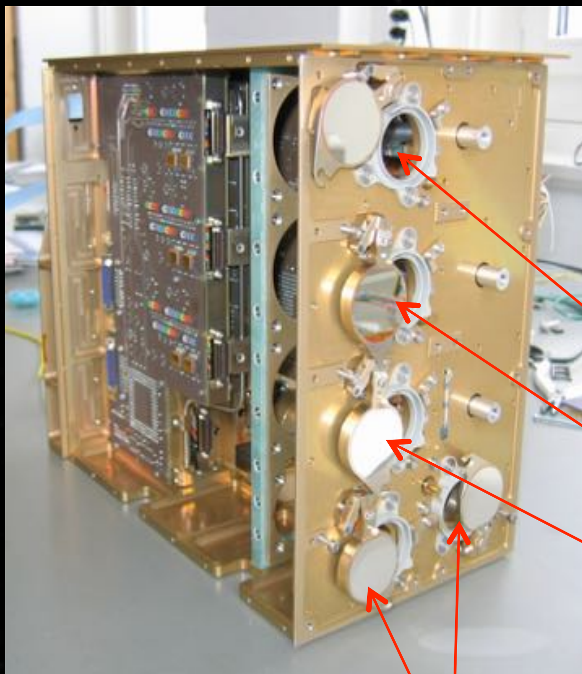
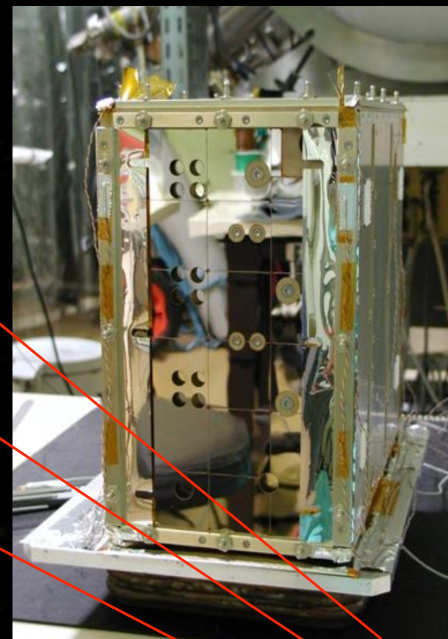
3 – The PREMOS photometer onboard PICARD

PREMOS consists of an absolute radiometer (TSI measurements) and photometers to measure SSI.

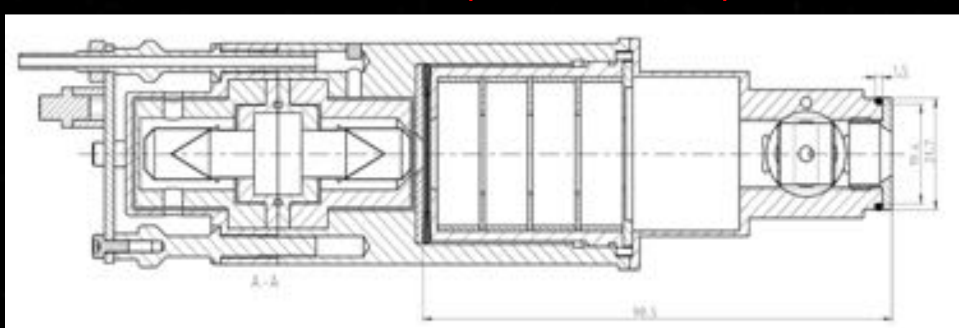
5 spectral channels at 215, 268, 535, 607, and 782 nm.

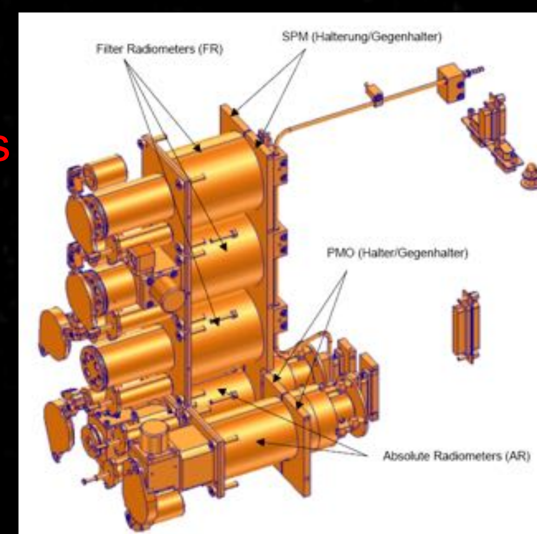




Radiometers (Head A & B)

Photometers
- Head A
- Head B
- Head C

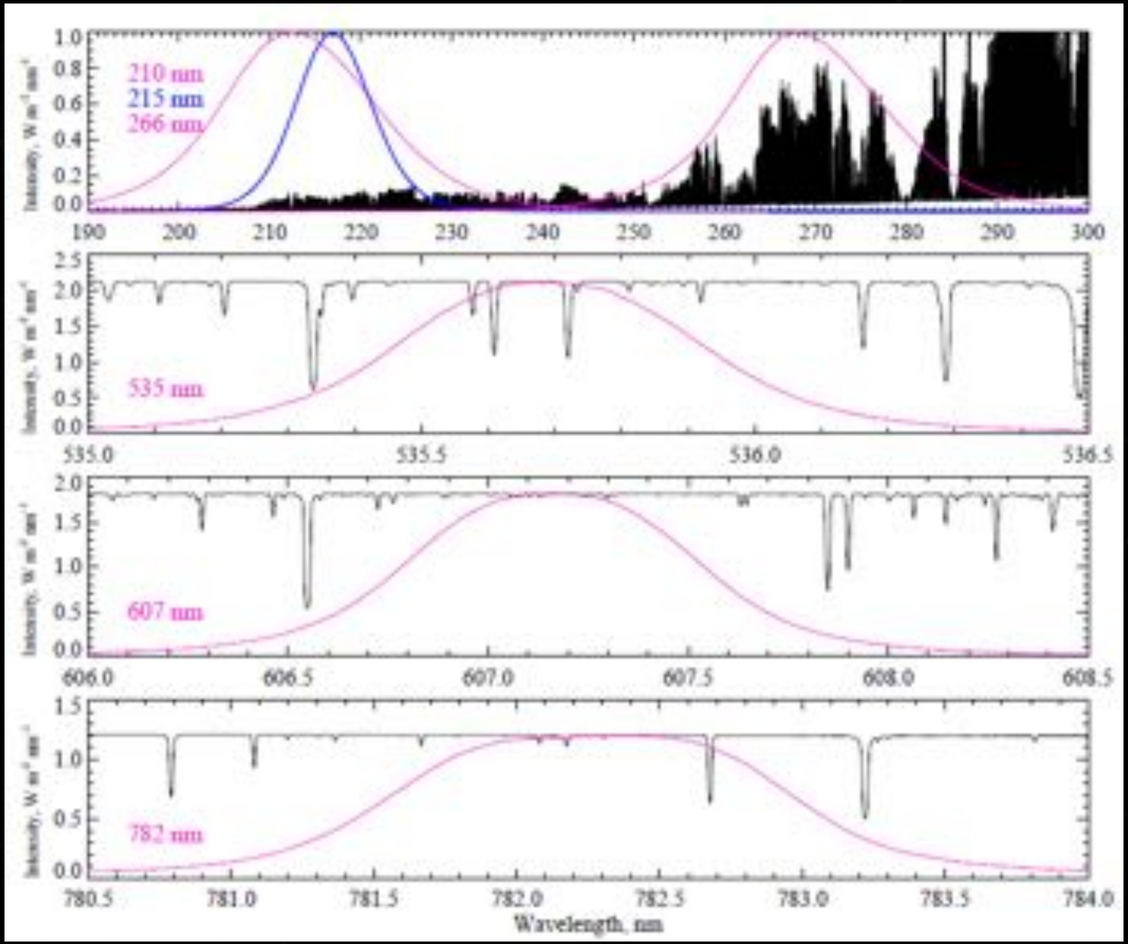




3 – The PREMOS photometer onboard PICARD

SSI variability observations at 5 wavelengths (215, 268, 535, 607, 782 nm)

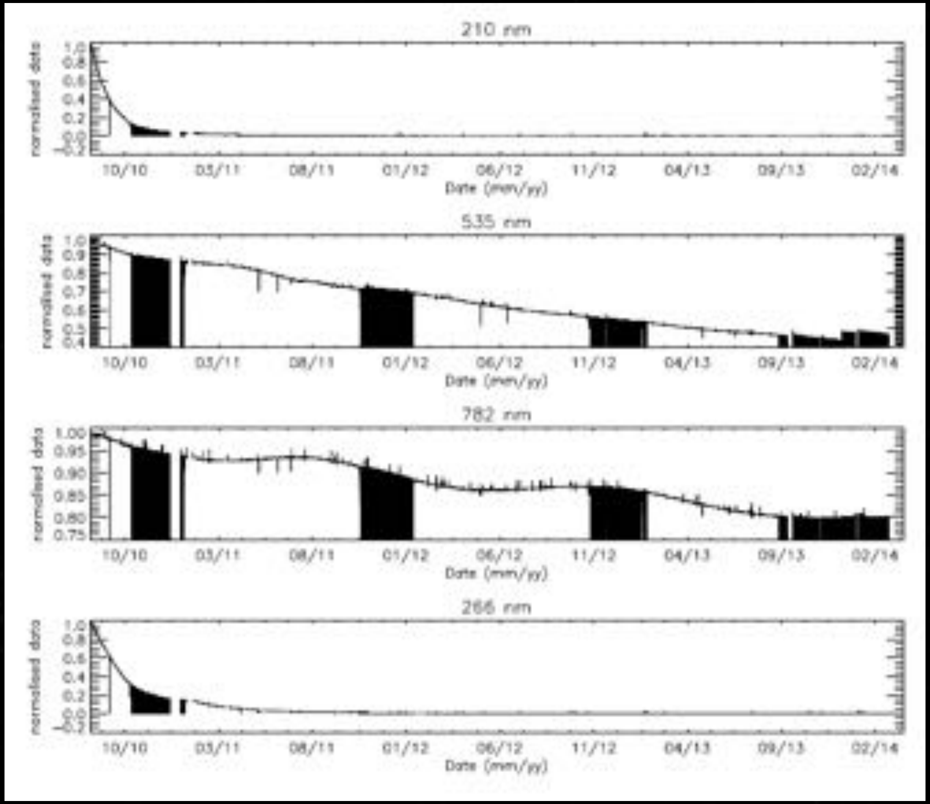
PREMOS/PICARD



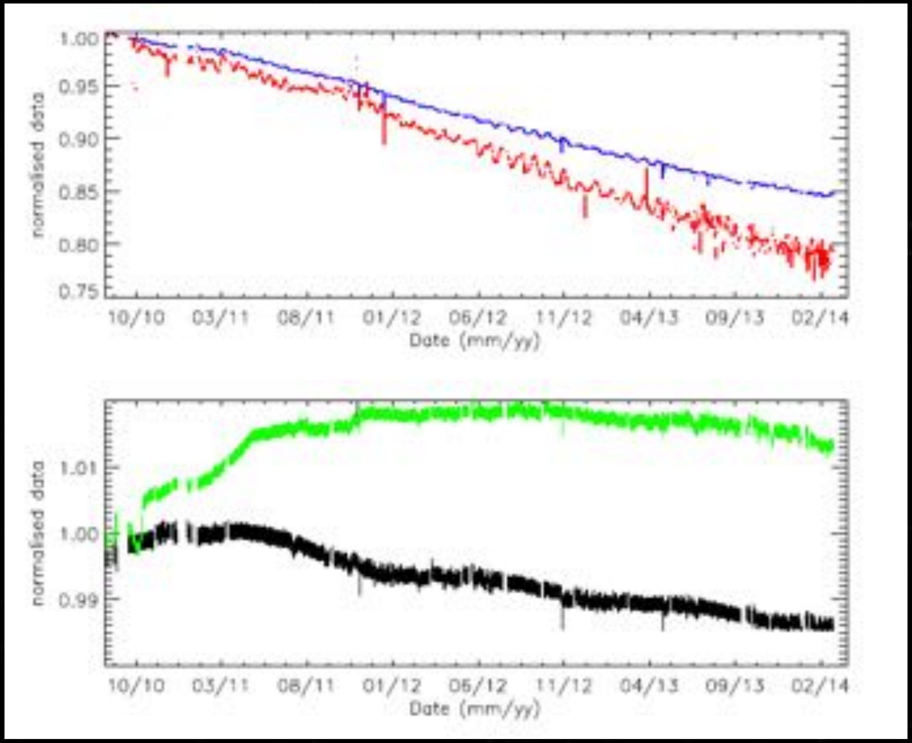
- ✓ September 2010 – April 2014
- ✓ Strong degradation…
- ✓ High cadence data
- ✓ Rotational modulation

3 – The PREMOS photometer onboard PICARD

Degradation problems on PREMOS



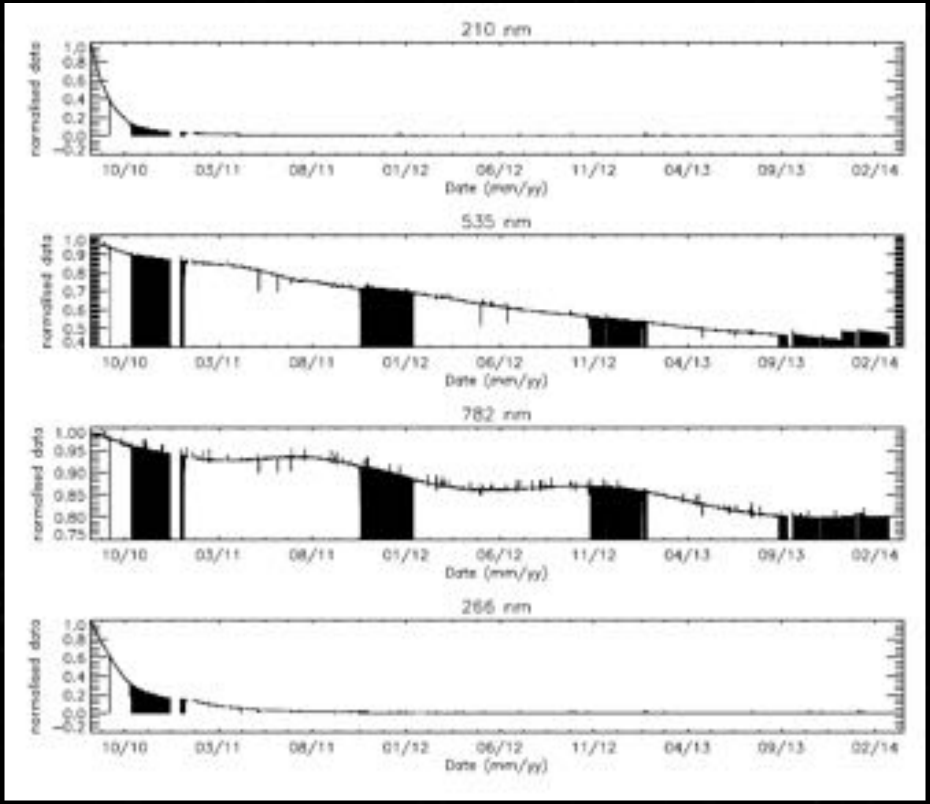
- ✓ Head C
  - ➢ 210 and 266 nm: 20 and 14 %
  - ➢ 535 nm: ~ -1.1%
  - ➢ 782 nm: ~ +1.5 %



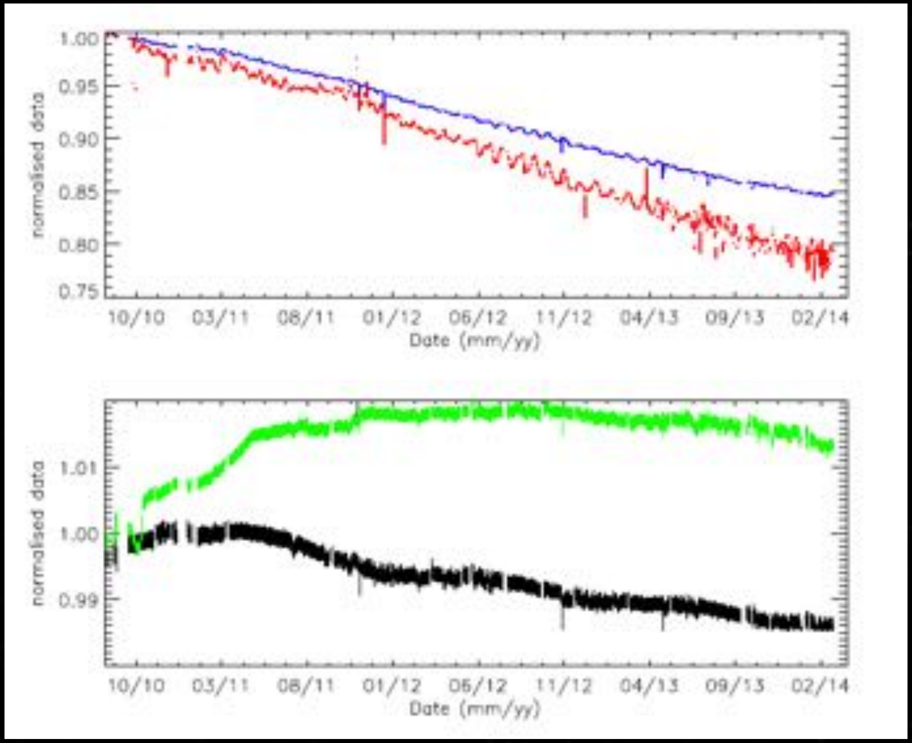
- ✓ Head A
  - ➢ 210 and 266 nm: more than 99%
  - ➢ 535 nm: ~ 50%
  - ➢ 782 nm: ~ 20 %

3 – The PREMOS photometer onboard PICARD

Degradation problems on PREMOS



- ✓ Head C (Once per day)
  - ➢ 210 and 266 nm: 20 and 14 %
  - ➢ 535 nm: ~ -1.1%
  - ➢ 782 nm: ~ +1.5 %

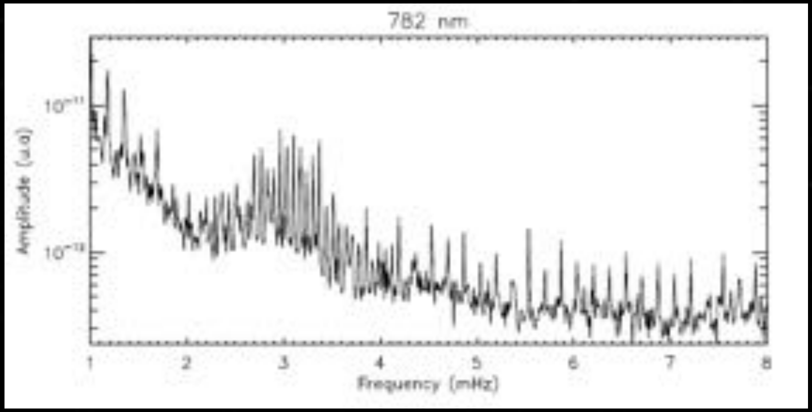


- ✓ Head A (High Cadence)
  - ➢ 210 and 266 nm: more than 99%
  - ➢ 535 nm: ~ 50%
  - ➢ 782 nm: ~ 20 %

3 – The PREMOS photometer onboard PICARD

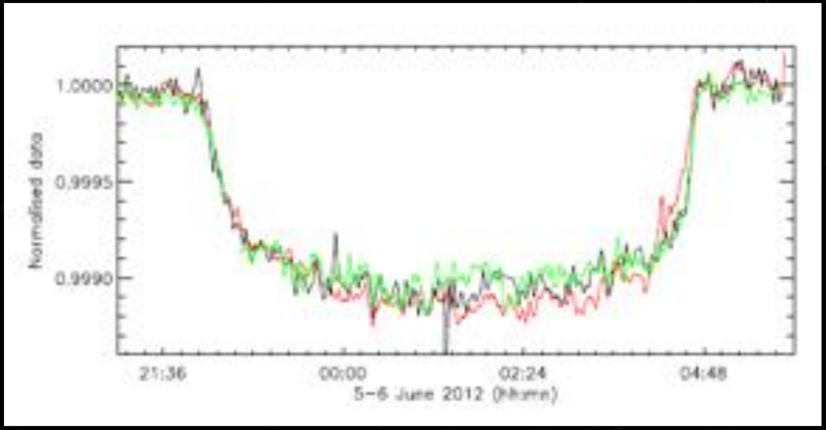
What can we do with Head A ?

- ✓ Helioseismology



- ✓ Flare detection? No flare signature has been found, either directly or using statistical methods…

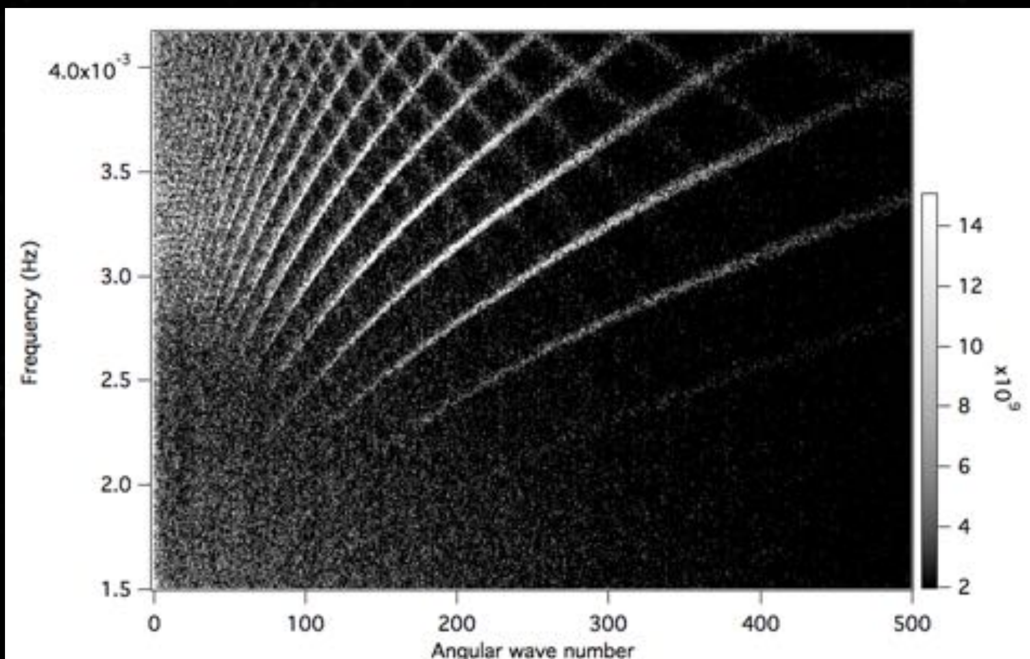
- ✓ Venus transit



3 – The PREMOS photometer onboard PICARD

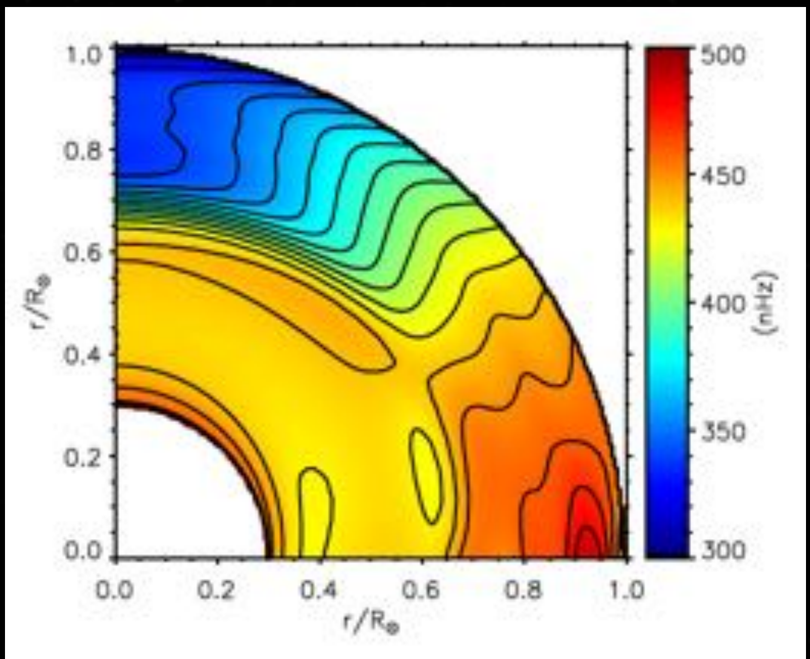
Helioseismology – link with the SODISM telescope onboard PICARD

- The p modes are detected in SODISM limb images.
- The steep gradient of the tachocline (transition region between the radiative interior and the differentially rotating outer convective zone) at the base of the convection zone (located at a radius of at most 0.70 times the Solar radius) is clearly seen.
- …



l-v diagram computed from three days of SODISM solar observations at 535 nm (limb images in April 2011).

Meftah et al, 2013 (Solar Physics)



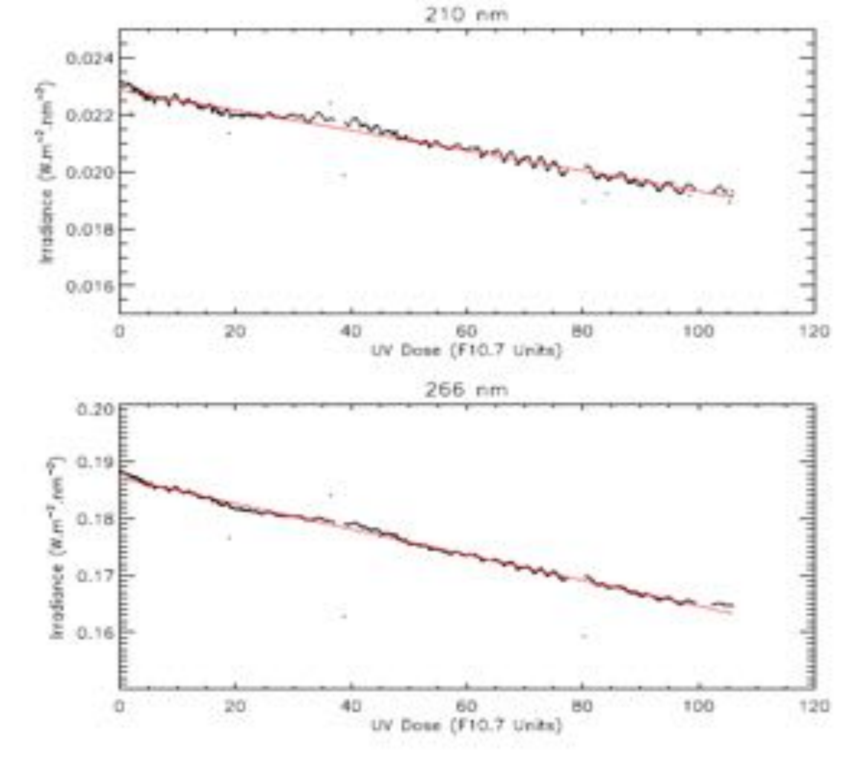
Symmetric part of the internal solar rotation rate with respect to the equator (with SODISM intensity images over the period from April to November 2011).

Corbard et al, 2013

3 – The PREMOS photometer onboard PICARD

What can we do with Head C ?

- ✓ UV channels :degradation correction using a UV dose function. We do not consider the exposure time, but the amount of UV received by the system A T_{UV} + B

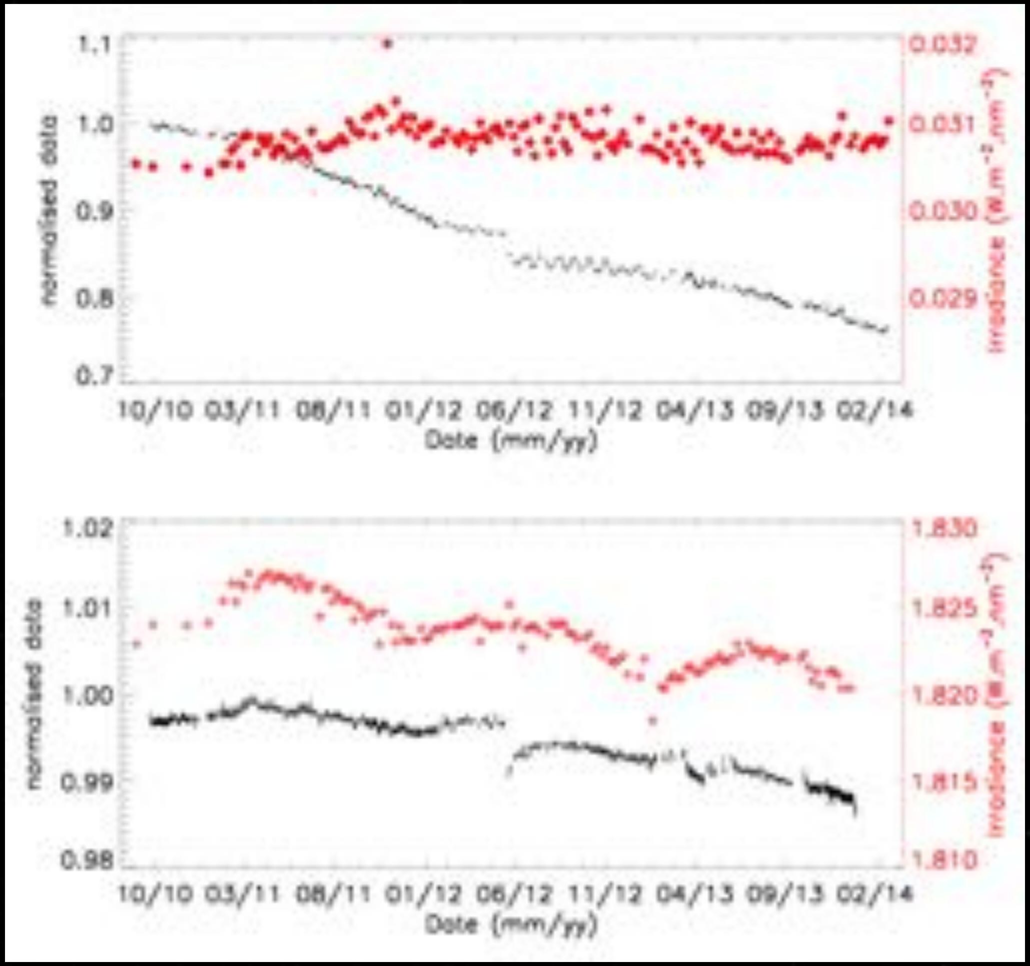


- ✓ F10.7, Mg II or Lyman α as UV proxies
- ✓ Linear or quadratic regression

- ✓ Visible and near-IR channels ? Degradation oscillations are difficult to correct without any further information. Comparison with SODISM and LYRA in progress. 27- day modulation only available so far.

3 – The PREMOS photometer onboard PICARD

Head B



- 215 nm
25% for channel 1
no degradation for channel 3 (once a week)
Possibility here to correct directly the irradiance at 215 nm

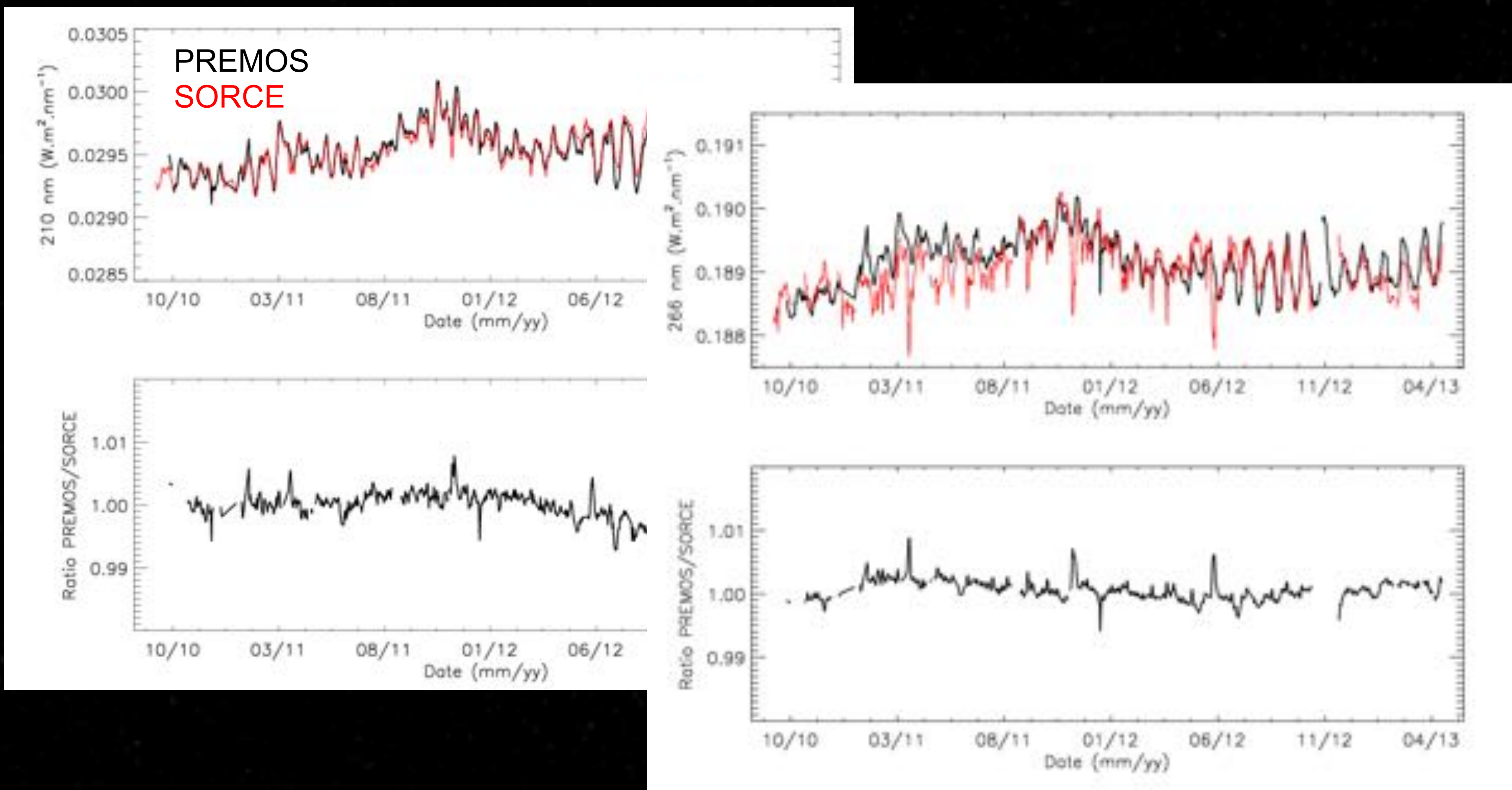
- 607nm
1% for channel 2
0.3 % for channel 4 (once a week)
Oscillations patterns for 607 nm no yet understood. Only the 27-day solar modulation.

3 – The PREMOS photometer onboard PICARD

Validation of the PREMOS data

- ✓ Solar variability in the UV

Comparison with SORCE/SOLSTICE data sets (level 3, version 15)



3 – The PREMOS photometer onboard PICARD

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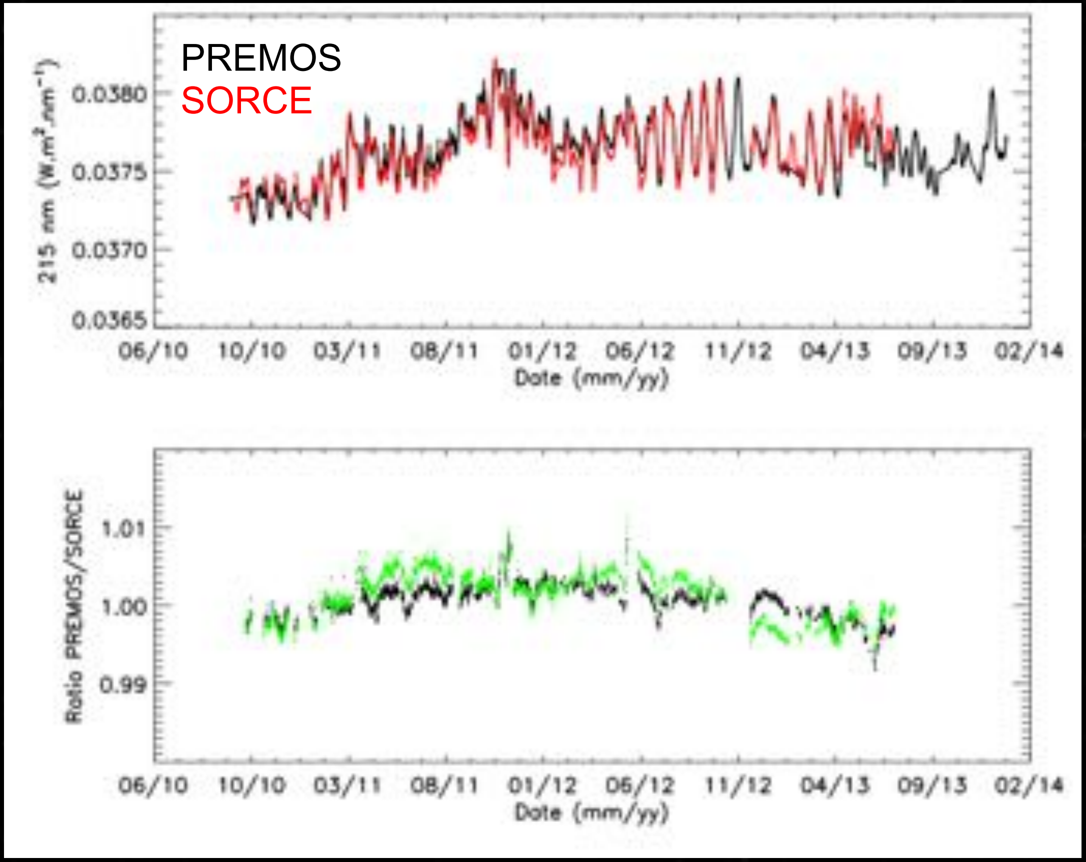


	210 nm	215 nm	266 nm
PREMOS vs SORCE	0.83 (0.69)	0.85 (0.72)	0.67 (0.42)

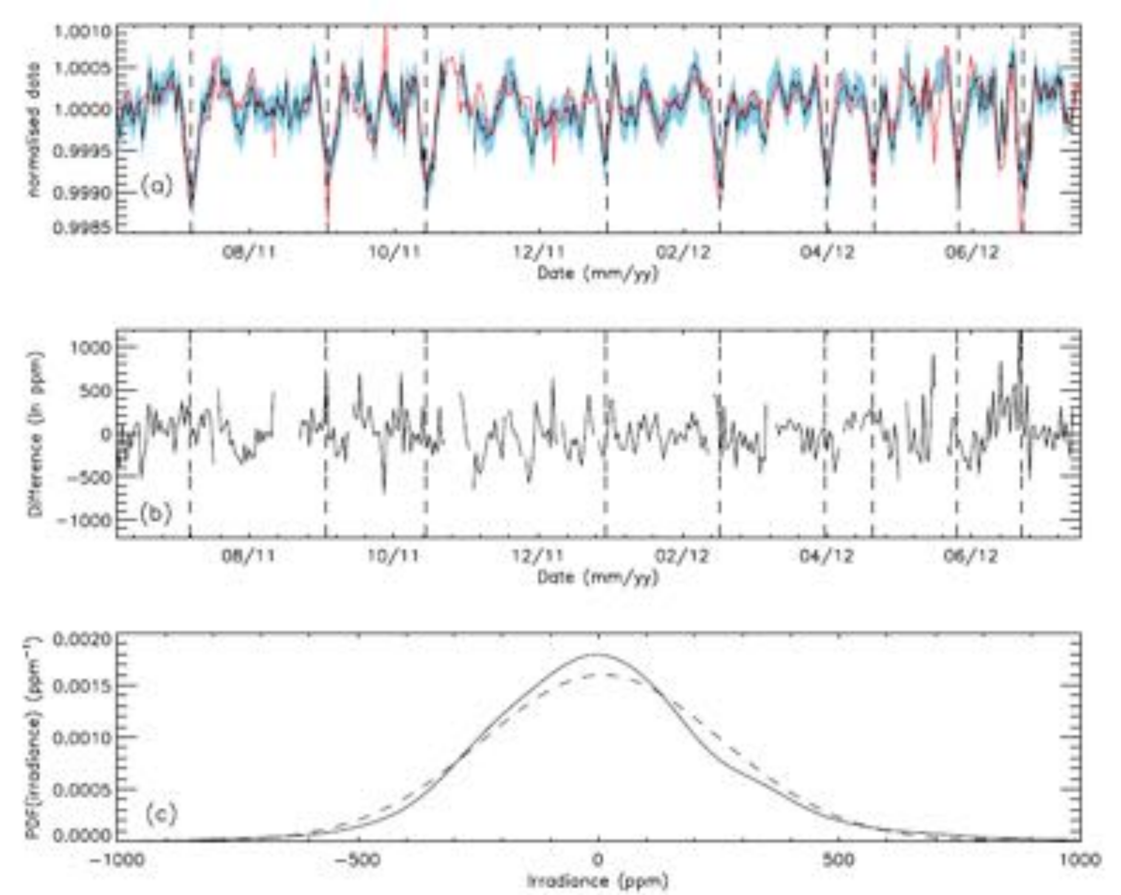
- ✓ Good correlation between PREMOS UV channels and SORCE/SOLSTICE data
- ✓ Excellent agreement for 215 nm. Degradation correction not model dependent !
- ✓ Possibility to use the 215 channel for filling the SORCE gap between July 2013 and Feb. 2014

3 – The PREMOS photometer onboard PICARD

Validation of the PREMOS data

- ✓ Solar variability in the visible and near-IR (27-day modulation)

Comparison with SORCE/SIM data sets (level 3, version 22)



- ✓ Sunspot passages in very good agreement
- ✓ Noise distribution not gaussian
- ✓ Noise estimation for PREMOS

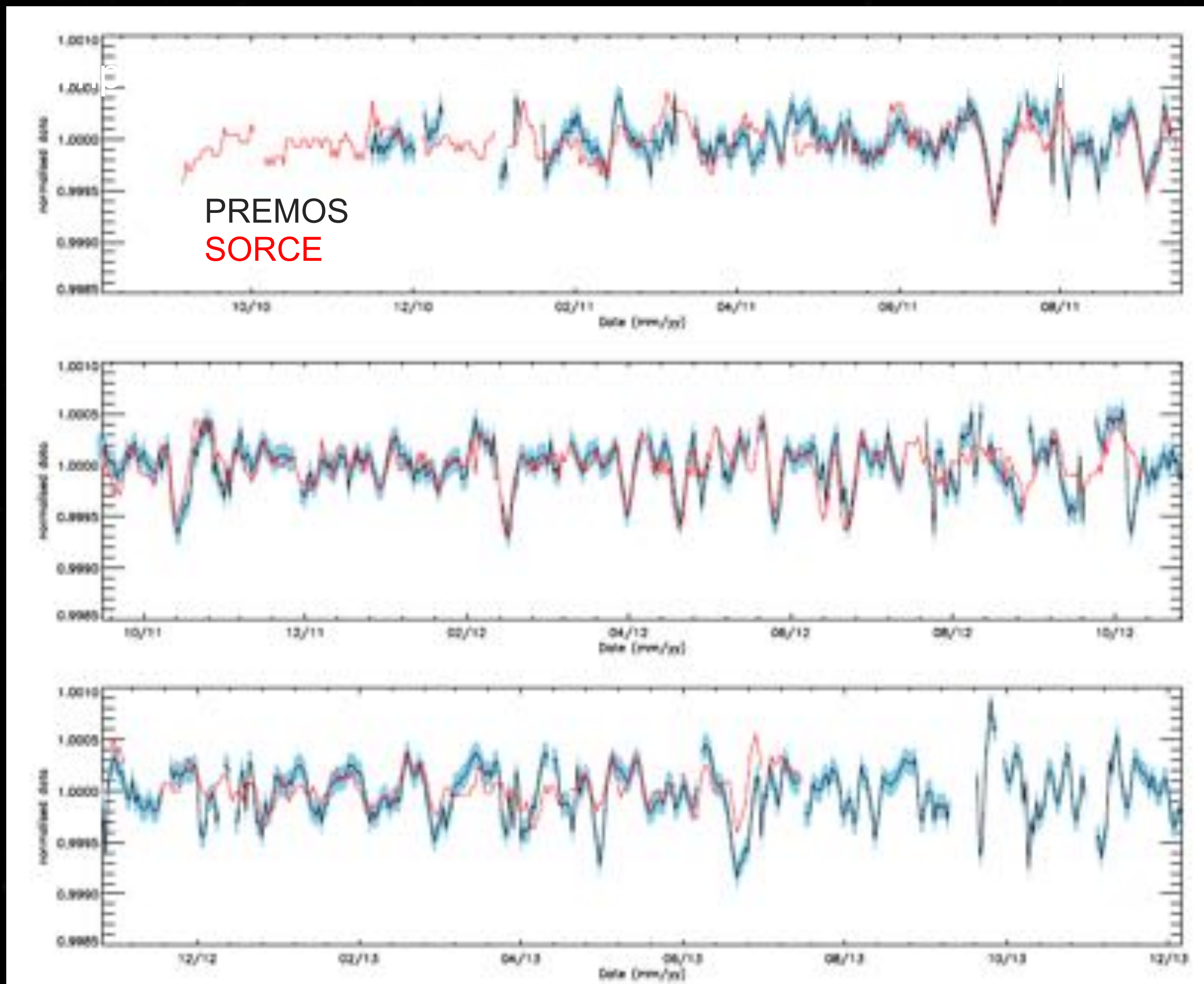
$$\sigma_{\text{PREMOS}} = \sqrt{\sigma^2_{\text{Total}} - \sigma^2_{\text{SIM}}}$$

	N	R (R^2)	σ (in ppm)
535 nm	740	0.63 (0.4)	205
607 nm	559	0.58 (0.34)	242
782 nm	717	0.61 (0.37)	120

3 – The PREMOS photometer onboard PICARD

Validation of the PREMOS data

- ✓ Solar variability in the visible and near-IR (27-day modulation)



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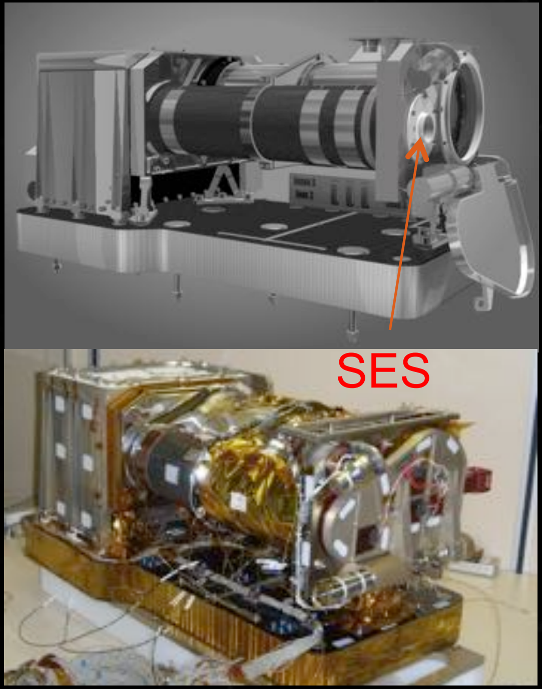
4 – The SES sensor onboard PICARD

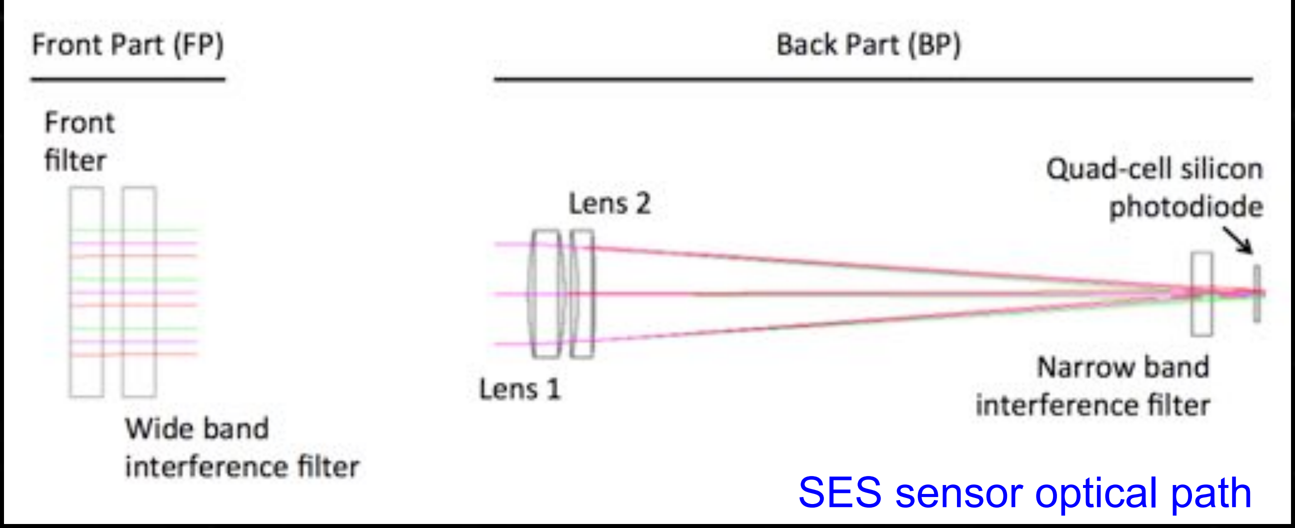
A Sun Ecartometry Sensor (SES) was developed to provide the stringent pointing requirements of the satellite. SES is a part of the SODISM telescope.

The SES sensor produced an image of the Sun at 782 +/-2.5 nm.

From the SES data, we obtained a new time series of the spectral irradiance at 782 nm from 2010 to 2014.

Artist's view of the Picard satellite and SES location that highlights the front part of the sensor with its front filter.

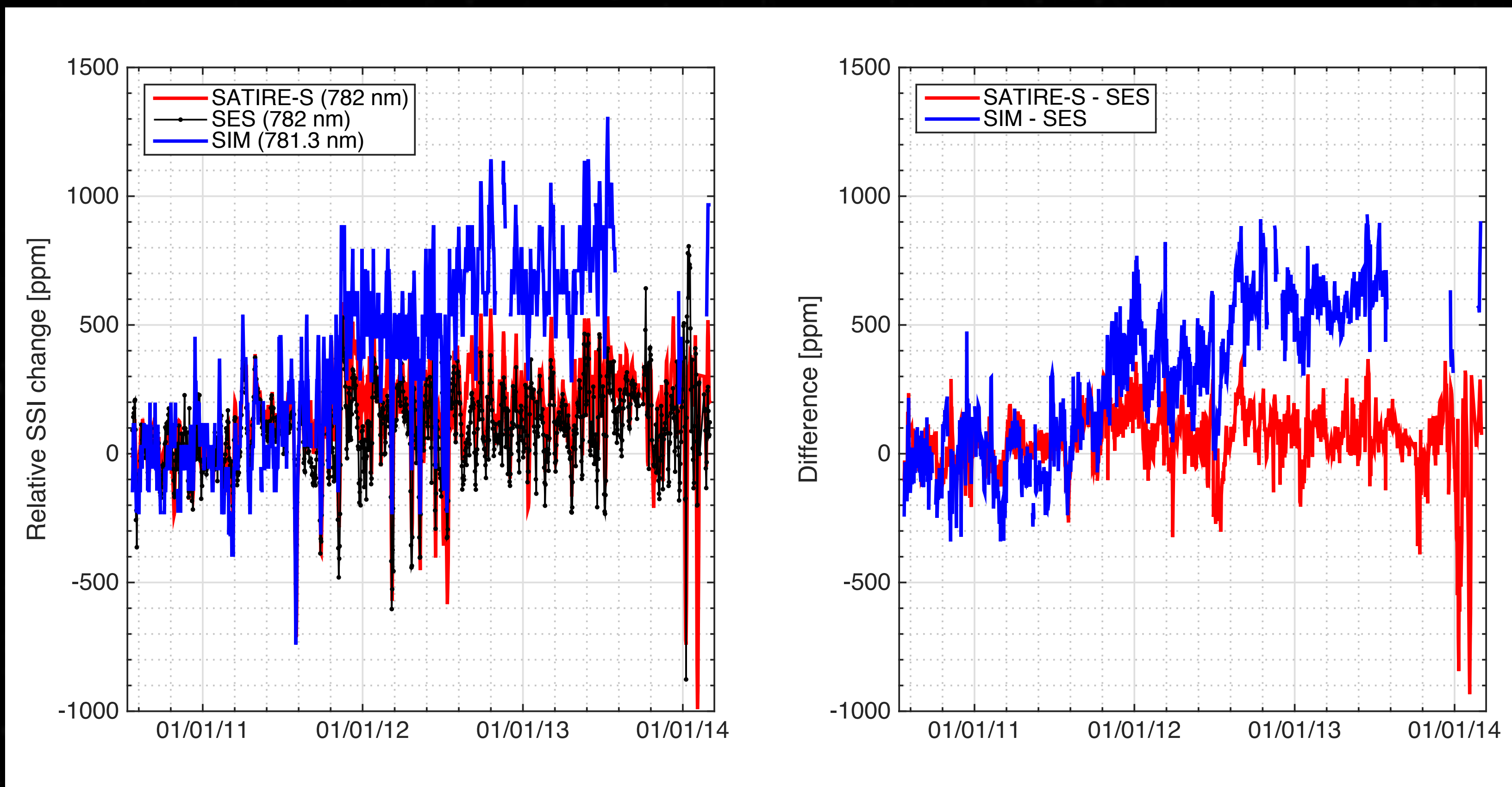




SES sensor optical path

4 – The SES sensor onboard PICARD

- Comparisons between SES data at 782 nm, SIM measurements at 781.3 nm, and SATIRE-S semi-empirical model at 782 nm.
- The SES trends diverge significantly from those shown by SORCE/SIM but are compatible with the SATIRE-S semi-empirical model.

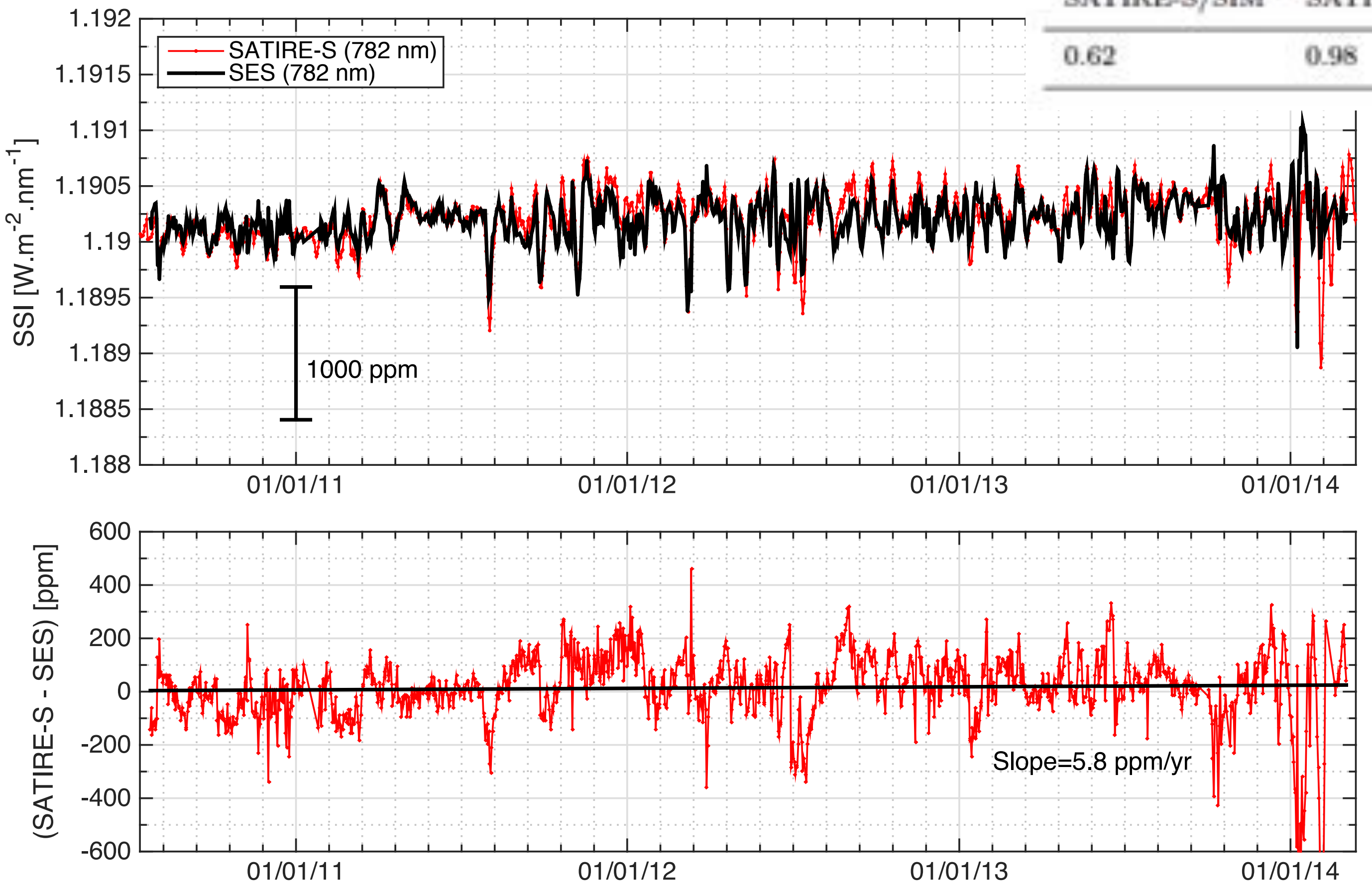


(left) Relative solar spectral irradiance change as observed by the SES sensor (black curve) and SIM (blue curve). The red curve corresponds to the solar spectral irradiance at 782 nm obtained with the SATIRE-S model.
(right) Differences between SATIRE-S, SIM, and SES results.

4 – The SES sensor onboard PICARD

Table 1. Pearson's linear correlation coefficient (R^2) between the SES sensor, SATIRE-S, SIM, and the TSI.

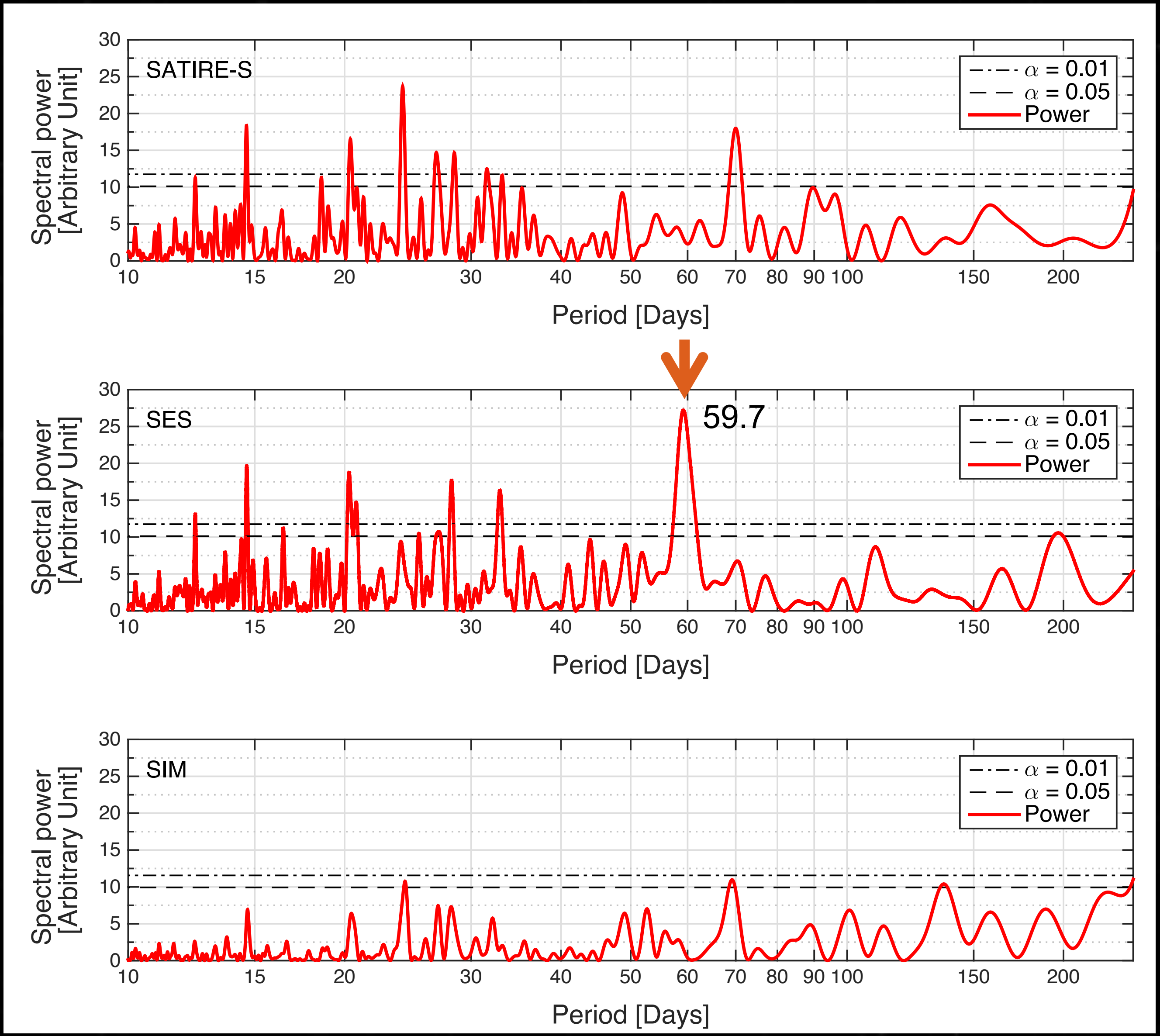
SES/SATIRE-S	SES/SIM	SES/TSI
0.75	0.52	0.74
SATIRE-S/SIM	**SATIRE-S/TSI**	**SIM/TSI**
0.62	0.98	0.70



Meftah et al., 2016 (Solar Phys.)

(top) SSI variability time series of the SES sensor at 782 nm and of the SATIRE-S model at 782 nm. (bottom) Differences between SATIRE-S and SES SSI variability at 782 nm. There may be a difference of up to 500 ppm in the solar spectral irradiance level between SES and SATIRE-S.

4 – The SES sensor onboard PICARD



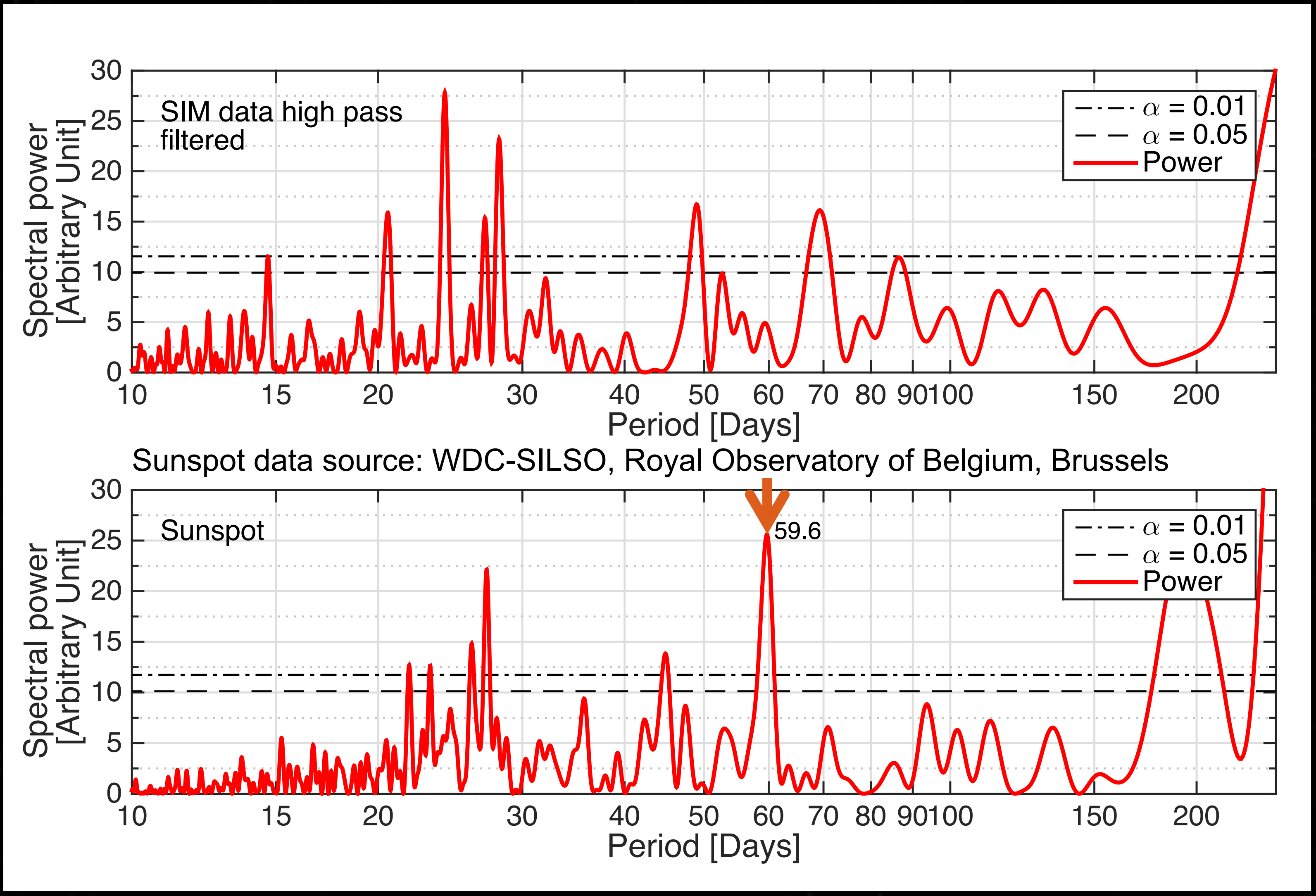
Lomb–Scargle periodogram of three time-series.

Similar solar periodicities between the SES sensor, SORCE, and SATIRE-S.

The slowly varying trend contributions in SIM increase the variance in the data and thus decrease the power spectral density (PSD) relative to the false-alarm probability.

4 – The SES sensor onboard PICARD

The Figure displays the Lomb–Scargle periodograms of the SIM data after they are high-pass filtered. SES and sunspot data show a periodicity around 59.5 days, which is also observed in SODISM solar radius data (Meftah et al., 2015 (ApJ)).

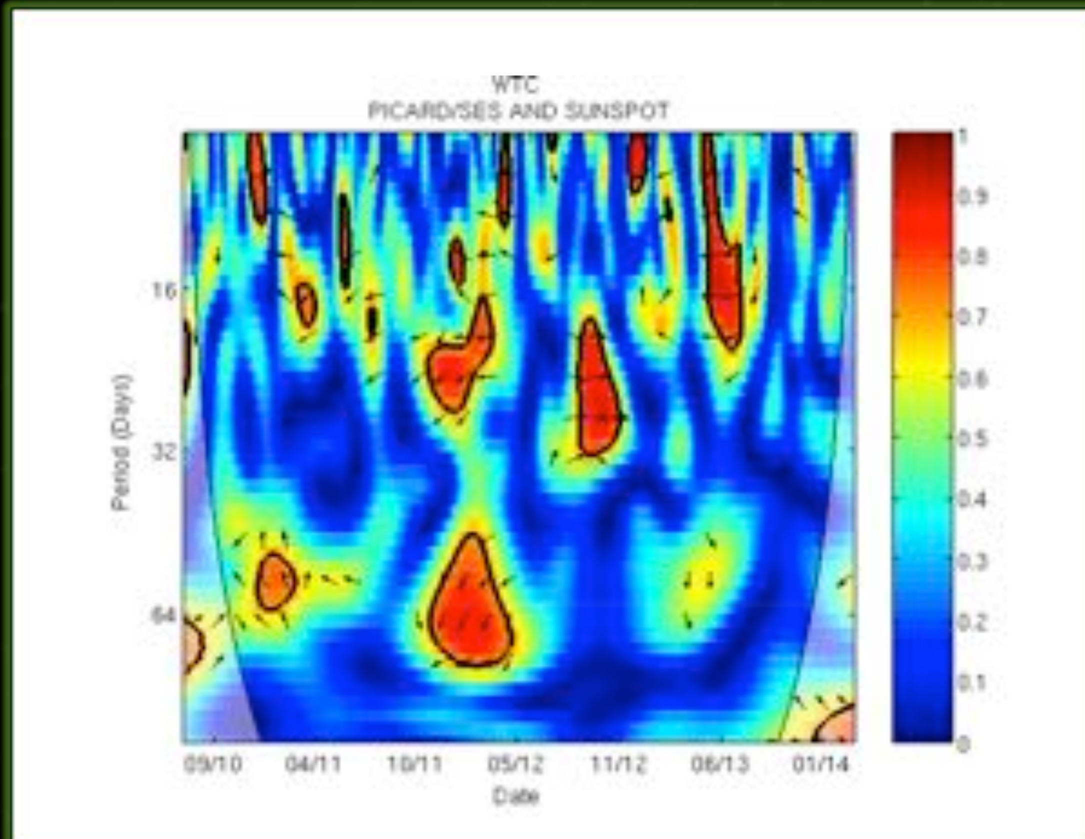


4 – The SES sensor onboard PICARD

The figure shows the wavelet transform coherence results between sunspot and SES data.

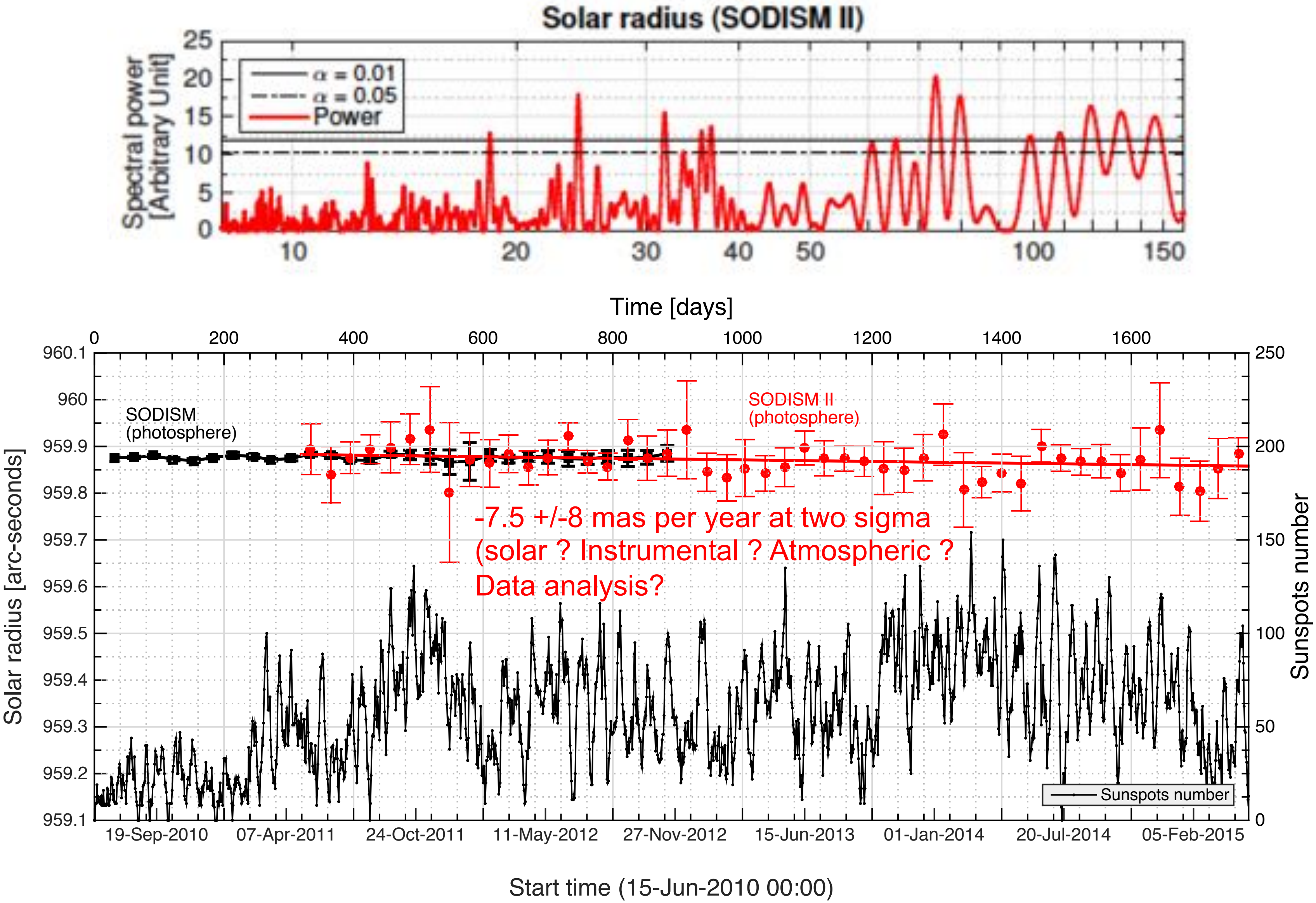
The most outstanding feature is an area of strong significant coherence centered around 59.5 days but extending vertically to about 45 and 80 days, and lasting for about seven months (from the end of 2011 to mid-2012). Smaller patches of strong coherence can also be found over the interval of the 16- to 35-days period, most likely related to the solar rotational period.

Wavelet Transform Coherence (WTC) between sunspot and SES. Solid contour lines represent the 95 %confidence level. Arrows represent the relative phase between sunspot and SES time series. The cone-of-influence is represented by the pale areas at the vertical edges of the figure.



4 – The SES sensor onboard PICARD

Impact of very small solar radius variations (<20 mas) on SSI models depending on periodicities?



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Conclusions

SOLSPEC

- UV solar spectrum (166 to 400 nm) during the minimum of Solar Cycle
- Work in progress about a solar spectrum between 166 and 3088 nm.
- Work in progress about SSI variability

PREMOS

- COSIR model: Irradiance variability is induced by the evolution of surface magnetism
- 5-th component model is enough to reproduce a very large fraction of the variability
- Comparison between the COSIR model and observations with SPM and PREMOS are in very good agreement !
- SORCE observations suffer from a high disturbance by instrumental noise. Good correlation however acceptable in the UV (< 250 nm) and in the range 500-800 nm
- COSIR synthetic variations are the better estimate for SSI variability when noise of the observations is as large as solar variations
- The COSIR Model should now be tested for long term trends

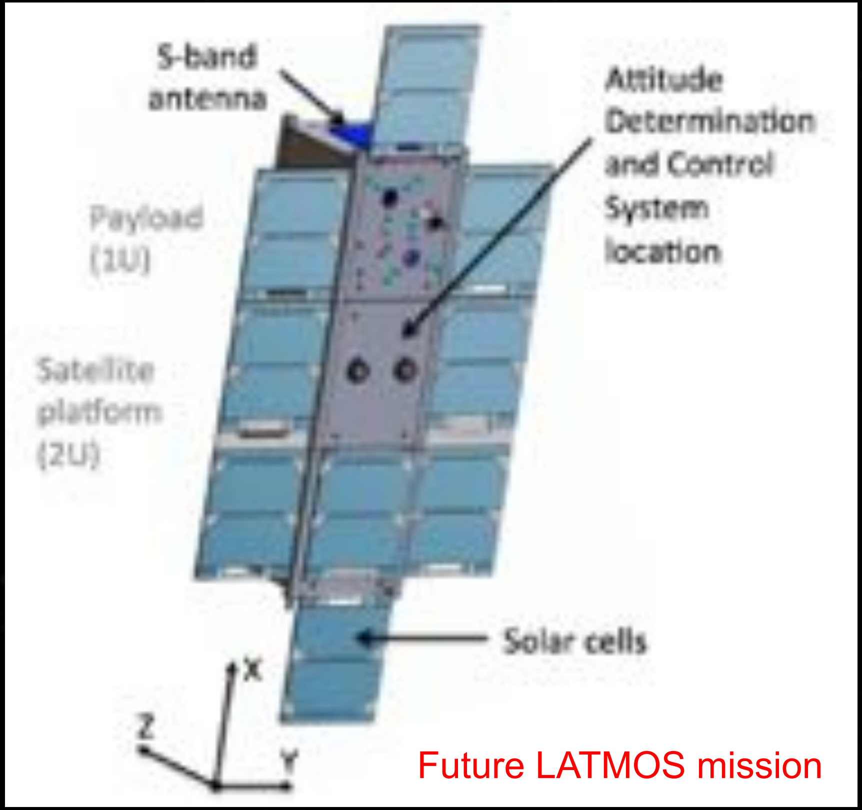
SES

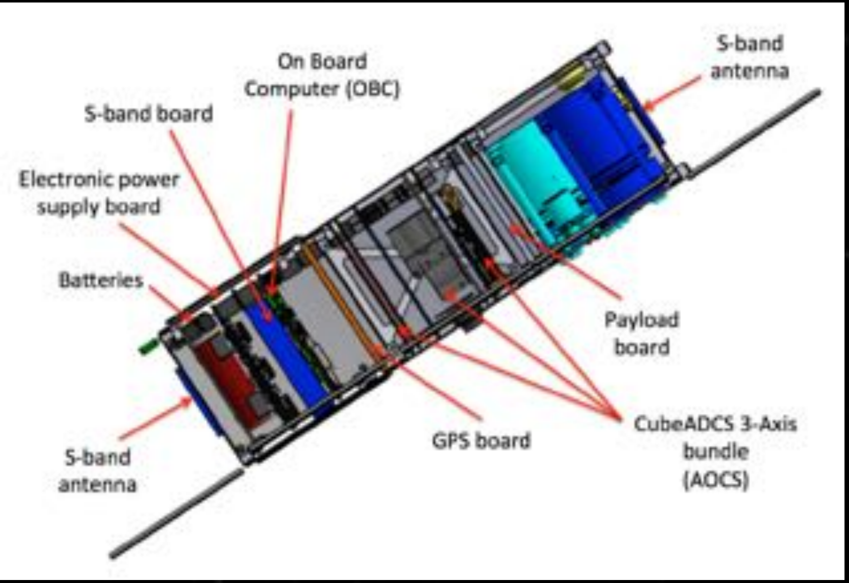
- The SES trends diverge significantly from those shown by SORCE/SIM but are compatible with the SATIRE-S semi-empirical model
- Similar solar periodicities between the SES, SORCE, and SATIRE-S were highlighted (14.6, 20.3, 28.3, and ~32 days)
- SES data show a significant solar periodicity at around 59.5 days, which is also observed in SODISM solar radius data and sunspot number data

Conclusions

It exists differences in these time series that highlight the importance of having a large number of measurements to improve the models.

Great interest to extend previous measurements (SSI and TSI).





Thank you for your attention