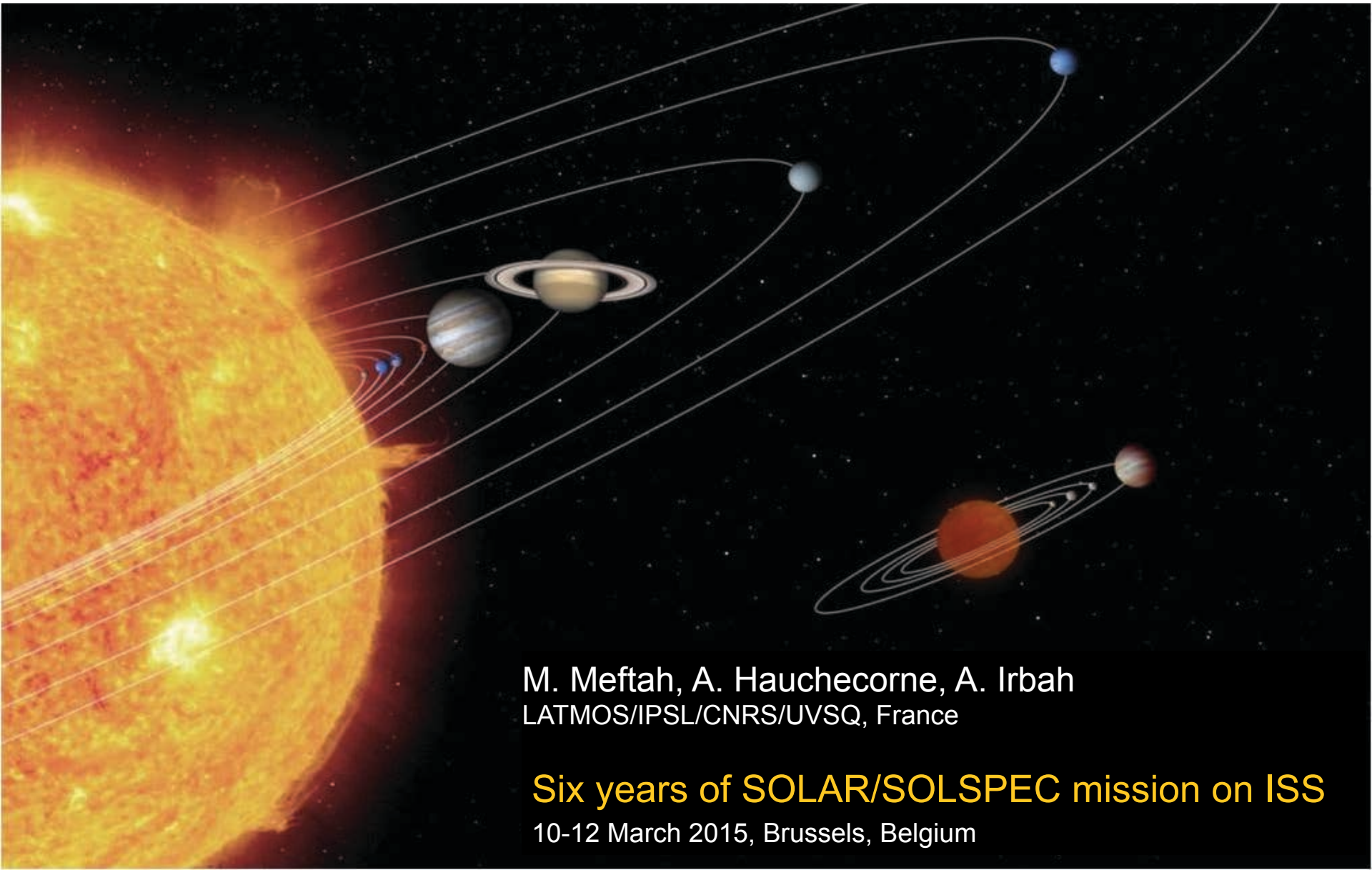


# On solar radius measurements during the rising phase of solar cycle 24



M. Meftah, A. Hauchecorne, A. Irbah  
LATMOS/IPSL/CNRS/UVSQ, France

**Six years of SOLAR/SOLSPEC mission on ISS**  
10-12 March 2015, Brussels, Belgium

# On solar radius measurements during the rising phase of solar cycle 24

## Presentation outline

- The PICARD mission and the scientific objectives
- The PICARD/SODISM space instrument
- PICARD SOL, our ground-based facility
- Scientific results
- Conclusion

# 1 – The PICARD mission and the scientific objectives (1/5)

PICARD is a scientific mission dedicated to the study of the Sun.

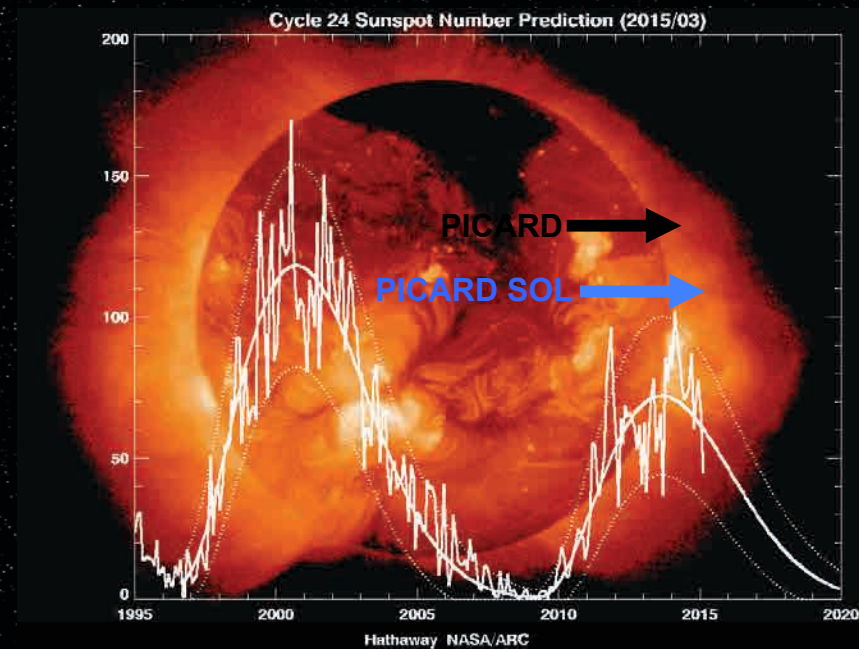
The name of the mission comes from Jean Picard (1620-1682), a pioneer of precise modern astrometry, who observed the sunspots, and measured their rotation velocity and the solar diameter.

The Picard mission expands observations of the global parameters of the Sun in the hope of linking the variability of its total and spectral irradiance to its geometric shape.

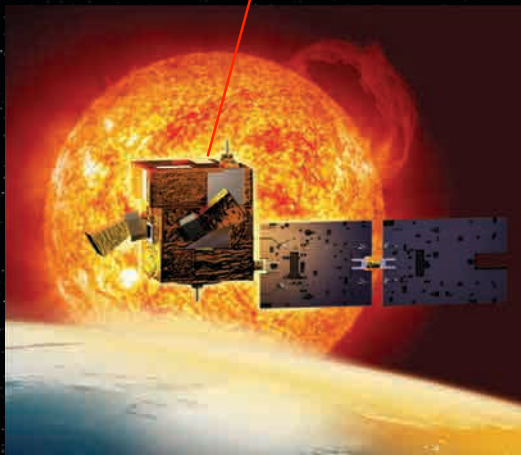
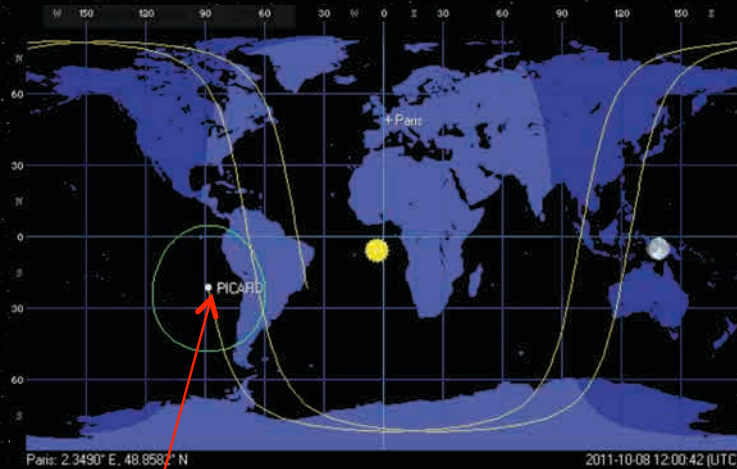
**PICARD observations are made during the ascending phase and the plateau of solar cycle 24.**



Jean Picard  
(1620-1682)



# 1 – The PICARD mission and the scientific objectives (2/5)



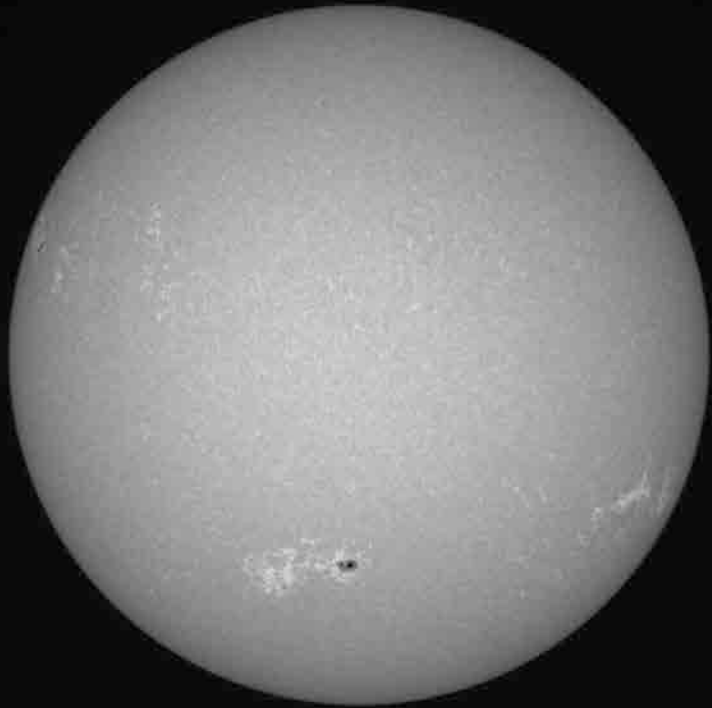
**PICARD** is a space mission, which was successfully launched on 15 June 2010 into a Sun synchronous dawn-dusk orbit (735 km, Inclination: 98.29°).



**PICARD SOL** is the ground component of the PICARD mission and is operational since March 2011 (Calern, France) – OCA and LATMOS (CNRS).

# 1 – The PICARD mission and the scientific objectives (3/5)

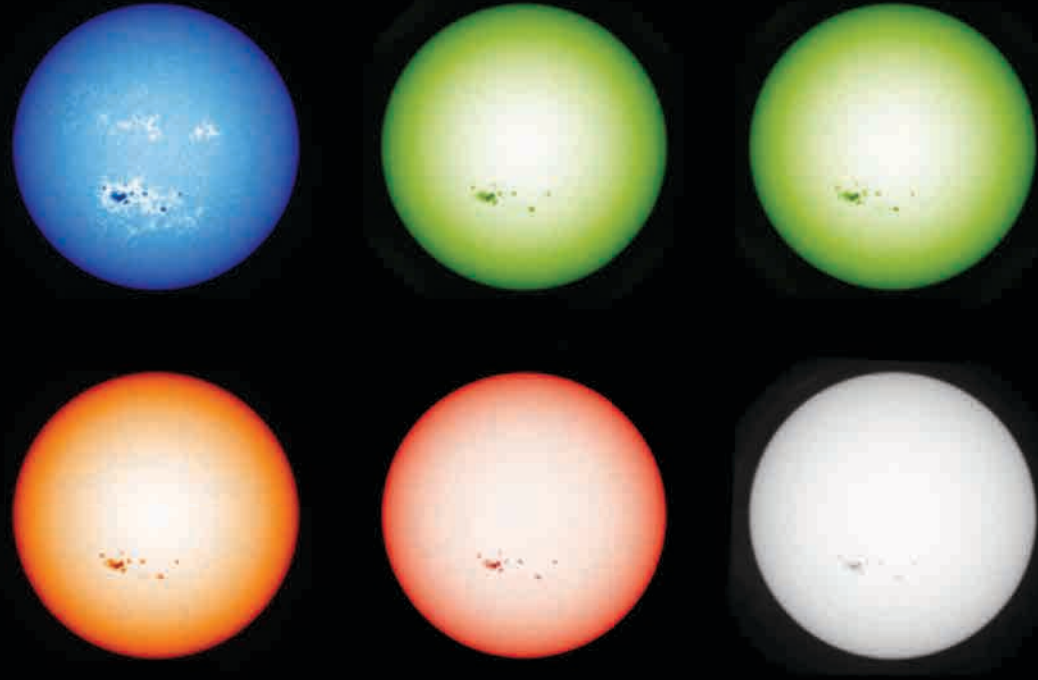
## PICARD



~ 1,300,000 images acquired

PICARD has recorded more than one million solar images from June 2010 to April 2014.

## PICARD SOL



~ 100,000 images acquired

PICARD SOL operates nominally since 2011.

# 1 – The PICARD mission and the scientific objectives (4/5)

## - 1) Solar Astrometry

Measure the diameter of the Sun (absolute value) and its variations over time.

## - 2) Photometry

Measure the variations of the solar spectral irradiance over time.

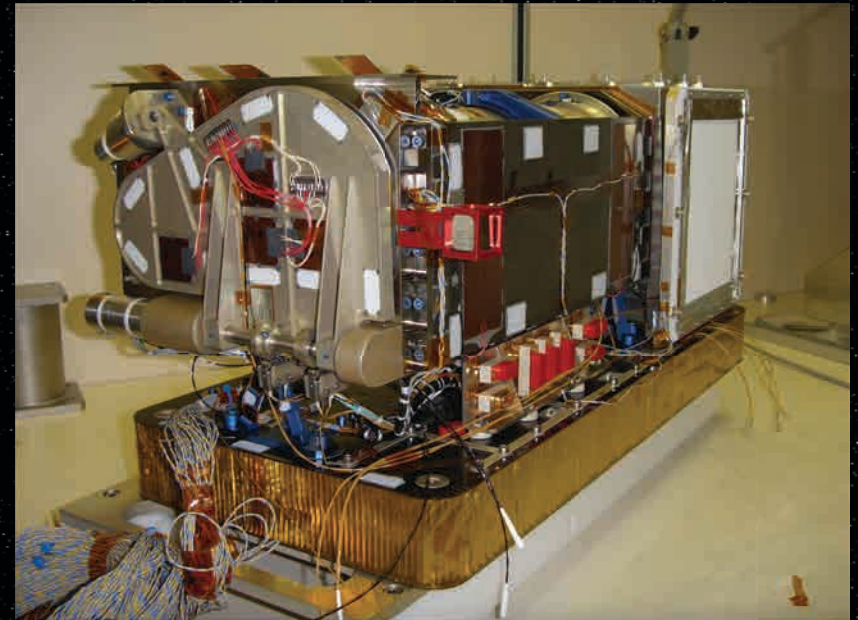
→ Analysis of spectral irradiance observed by PICARD/SODISM and link with SOLAR/SOLSPEC.

→ Crucial for our understanding of solar variability and its impact on Earth climate.



SOLAR/SOLSPEC

PICARD/SODISM



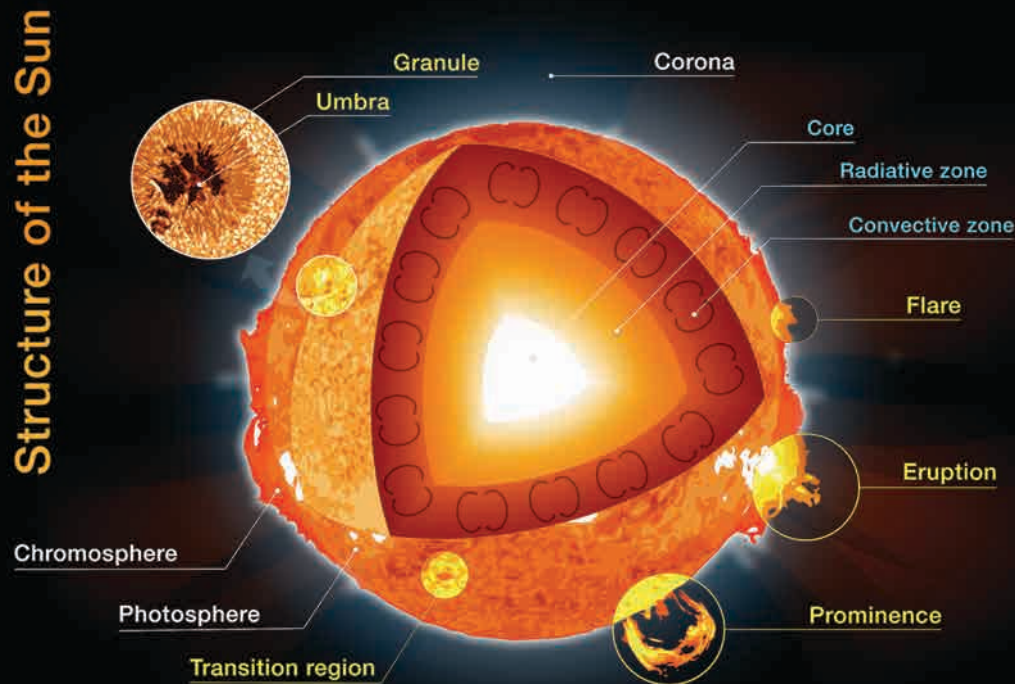
# 1 – The PICARD mission and the scientific objectives (5/5)

## Variability of the solar radius and magnetic field

Why it varies ? What is the impact on the variability of the spectral irradiance ?

## Time variation of the solar radius

- Influence of inner magnetic field ?
- Other influences ?
- Order of magnitudes: measurable or not ?



1) The first step is to determine the evolution of the solar radius during the rising phase of solar cycle 24.

2) Next, we will determine the evolution of the spectral solar irradiance over time.

## Presentation outline

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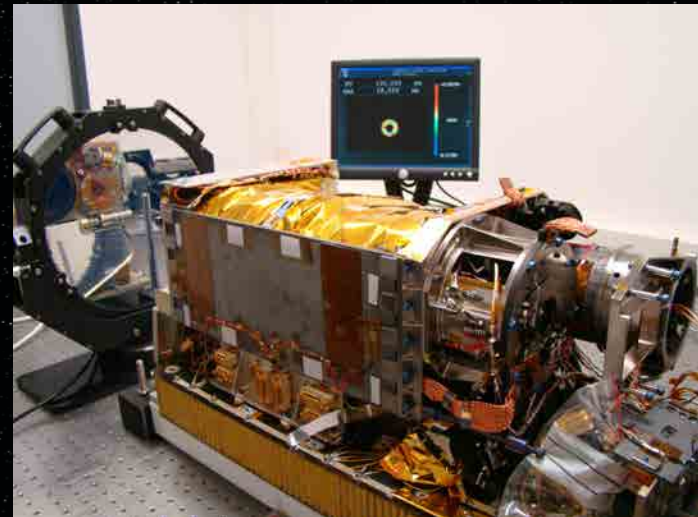
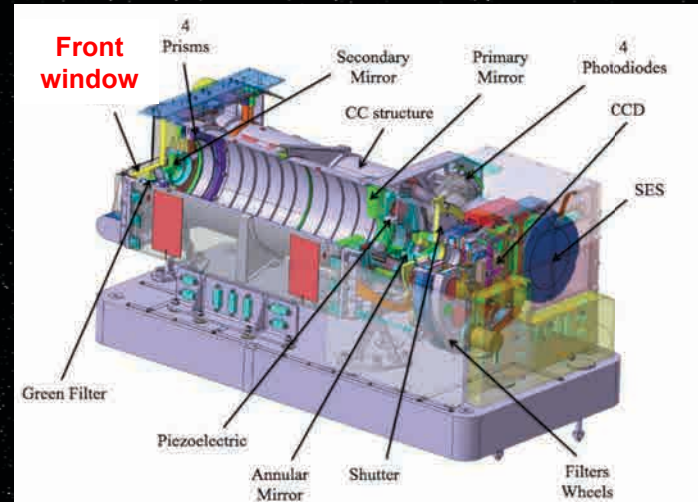


## 2 – The PICARD/SODISM space instrument (1/3)

**SODISM** is an 11-cm Ritchey-Chretien imaging telescope developed at CNRS by LATMOS (ex. Service d'Aéronomie, France) associated with a 2Kx2K Charge-Coupled Device (CCD), taking solar images at five wavelengths.

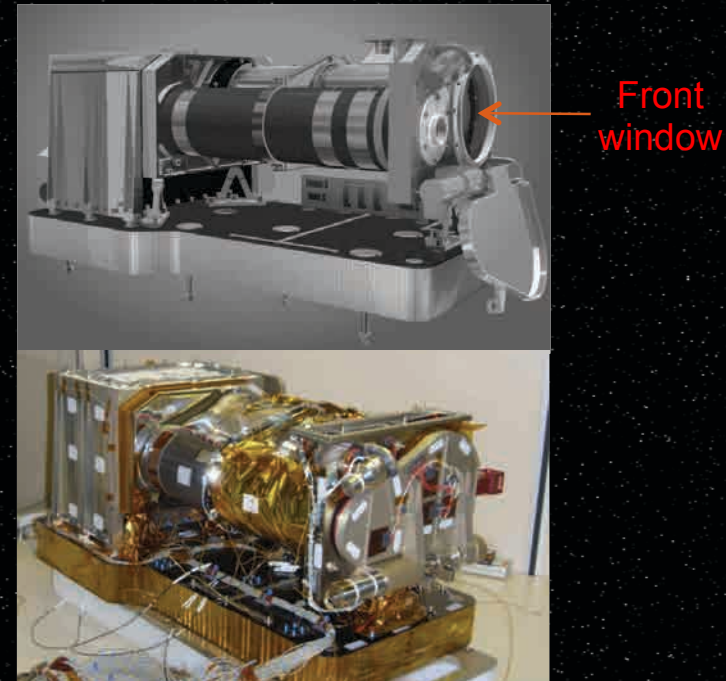
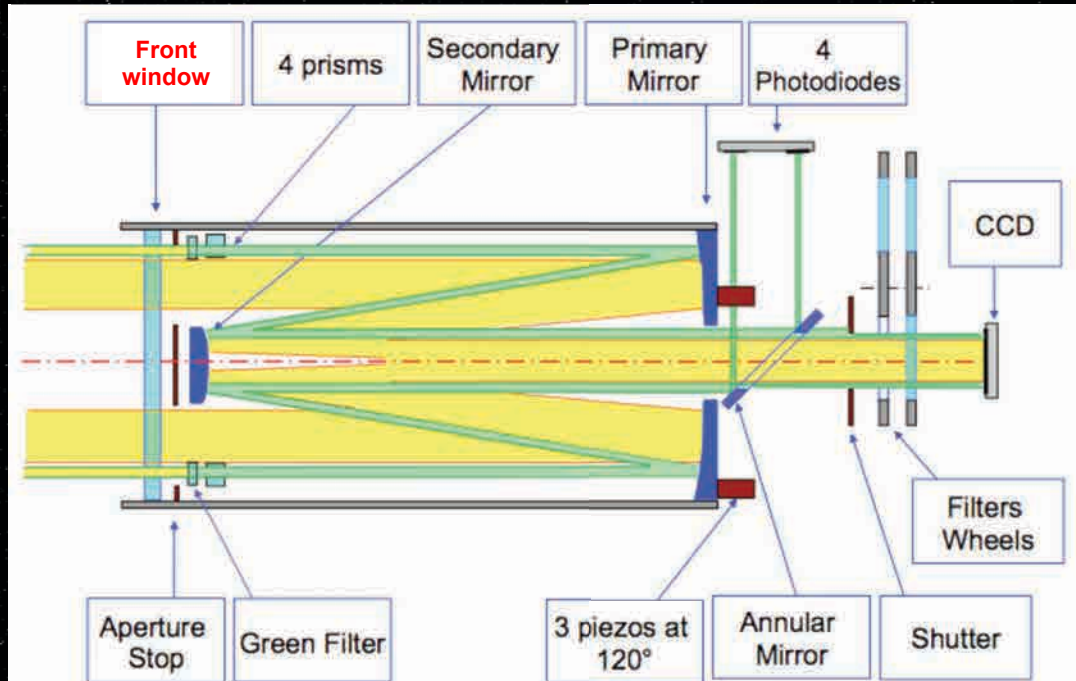
### SODISM main characteristics:

- Telescope type: Ritchey Chretien
- Focal length: 2626 mm
- Field of view: 35 arc-minutes
- Angular resolution: 1.06 arc-sec.
- Dimensions: 300x308x370 mm<sup>3</sup>
- Mass: 26.4 kg
- Power: 30.6 W
- Data flow: 2.2 Gbits per day
- One image per minute



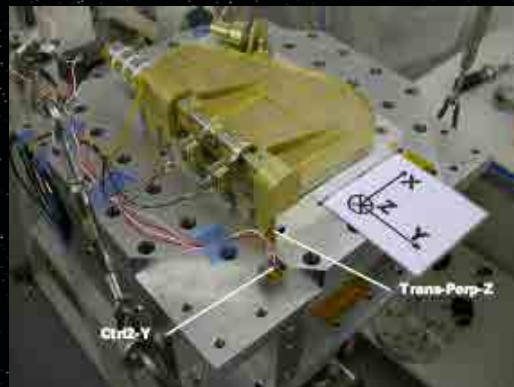
## 2 – The PICARD/SODISM space instrument (2/3)

### SODISM optical path and interferential filters characteristics

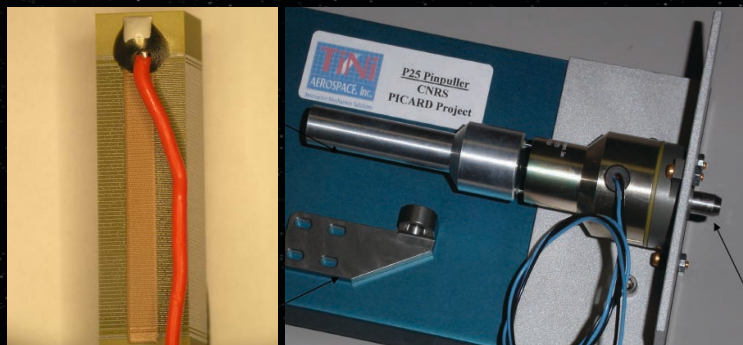
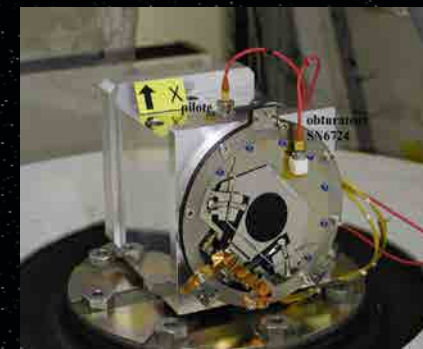


Wavelength $\lambda$ in nm	Bandwidth $\Delta\lambda$ in nm	Function
215.0	7	Sun activity, O <sub>3</sub> , measurement, diameter
393.37	0.7	Active regions observation
535.7	0.5	Oscillations (helioseismology)
535.7	0.5	Diameter, oscillations (helioseismology)
607.1	0.7	Diameter
782.2	1.6	Diameter

## 2 – The PICARD/SODISM space instrument (3/3)



**SODISM**, an imaging telescope with a lot of mechanisms and many technology



## Presentation outline

- The PICARD mission and the scientific objectives
- The PICARD/SODISM space instrument
- **PICARD SOL, our ground-based facility**
- Scientific results
- Conclusion

# 3 – PICARD SOL, our ground-based facility (1/1)



Solar diameter telescope (SODISM-2)



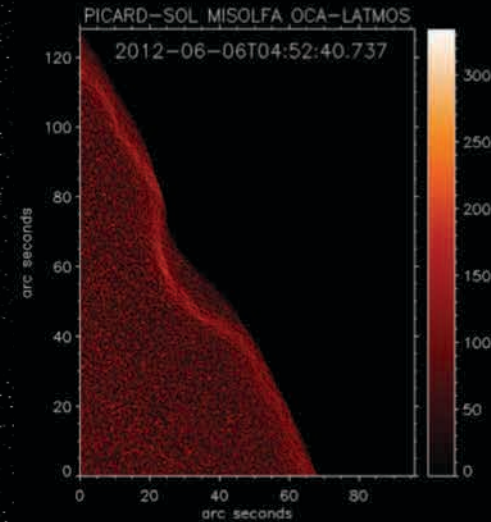
Turbulence monitor



Photometer



Pyranometer



During the 2012 transit of Venus

## Presentation outline

- The PICARD mission and the scientific objectives
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- PICARD SOL, our ground-based facility
- **Scientific results**
- Conclusion

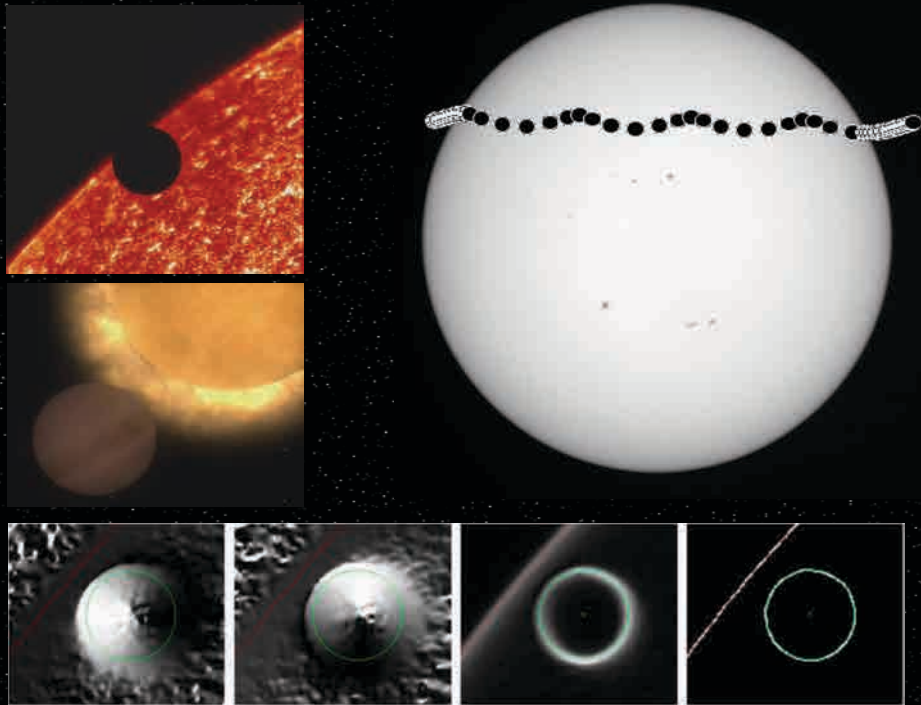
## **1-a) Solar Astrometry**

Measure the diameter of the Sun (absolute value)

With PICARD/SODISM space instrument

## 4 – Scientific results

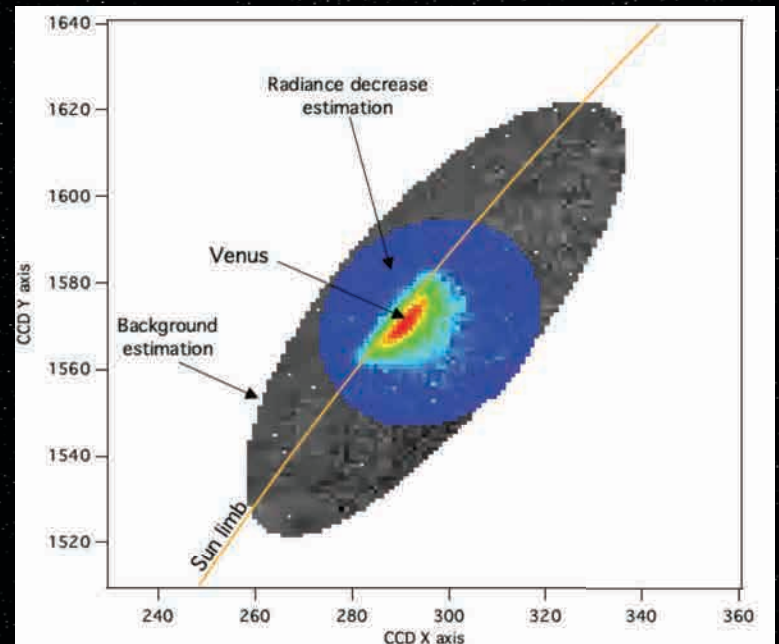
Solar radius determination is one of the oldest problems in astrophysics. The **transit of Venus on June 2012** provided a unique opportunity to determine the absolute radius of the Sun using solar imagers. The transit was observed from space by the PICARD spacecraft.



Meftah, Hauchecorne, Irbah et al., Sol. Physics, 2014

**959.86 +/- 0.20 arc-seconds**

**Method: location of the inflection point**



Hauchecorne, Meftah, Irbah et al., APJ, 2014

**959.85 +/- 0.19 arc-seconds**

**Method: estimation of the decrease in the intensity (independent of the psf)**

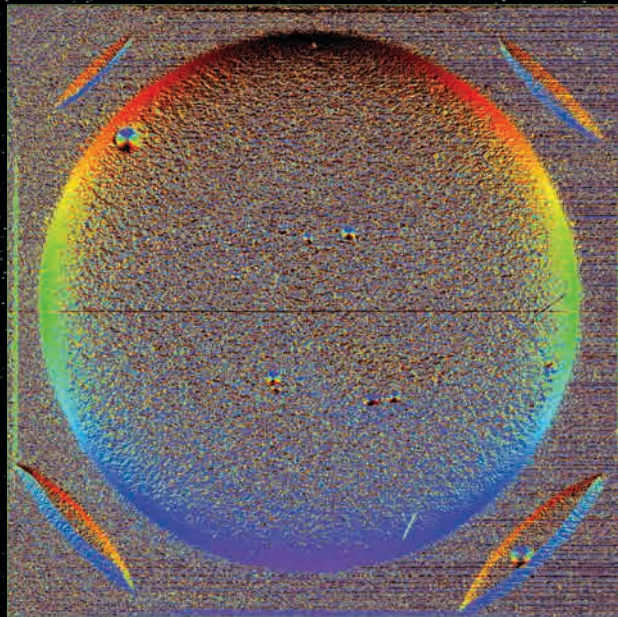


## 4 – Scientific results

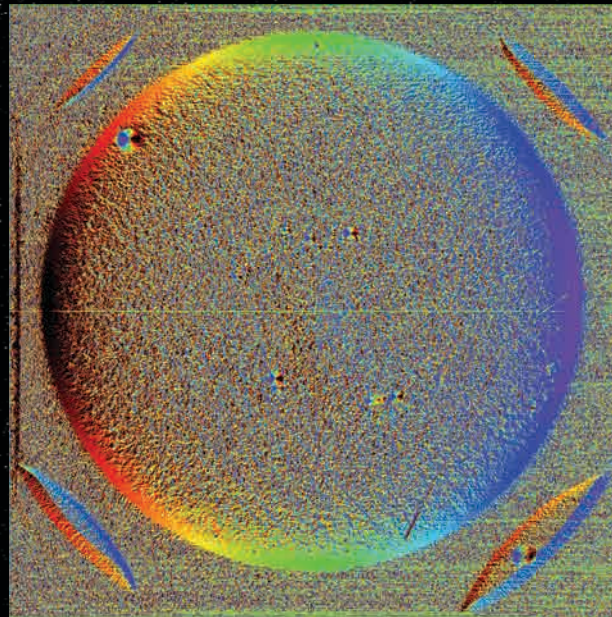
### Method for determining the radius of Venus and the Sun (IPP method)

- Noise removal (median filter to remove outlier pixels then a Gaussian blur is applied to smooth the edges in the image).
- Extracting contours (using a Sobel filter and the Canny method)

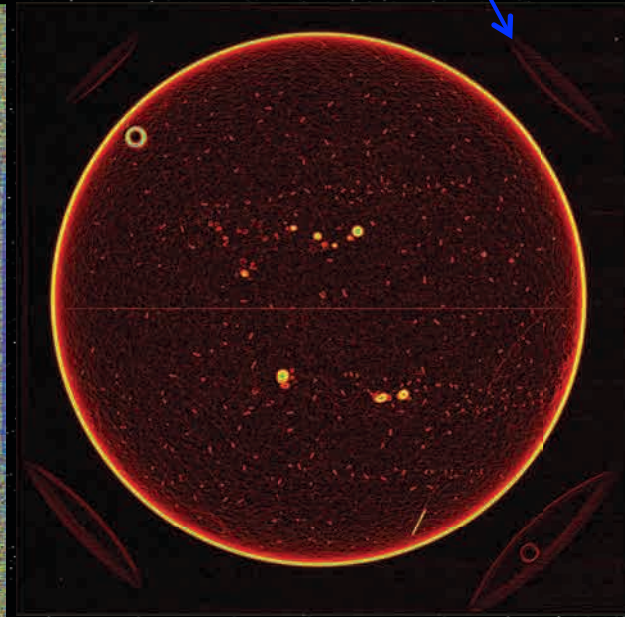
Auxiliary images  
obtained from  
prisms



Horizontal gradient



Vertical gradient

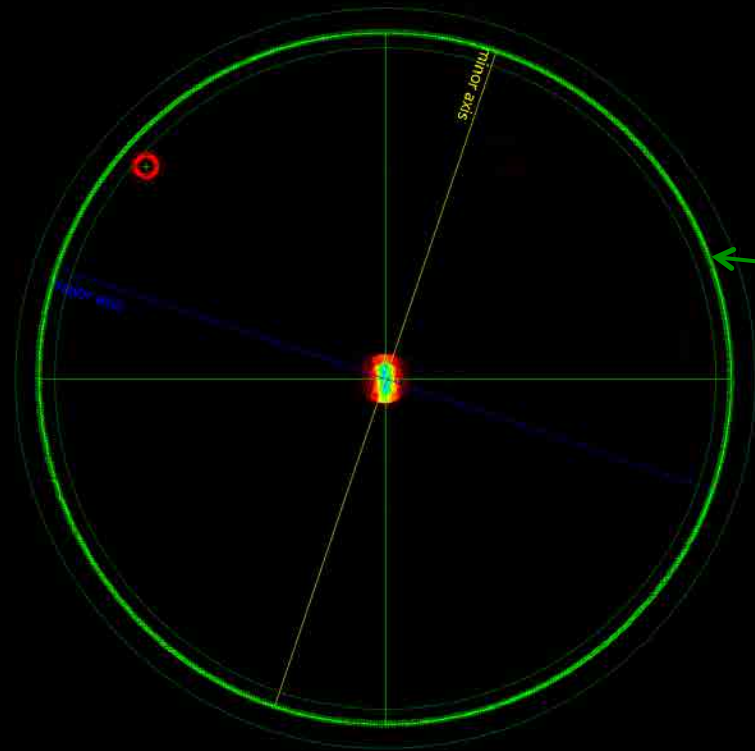


Norm of the gradient

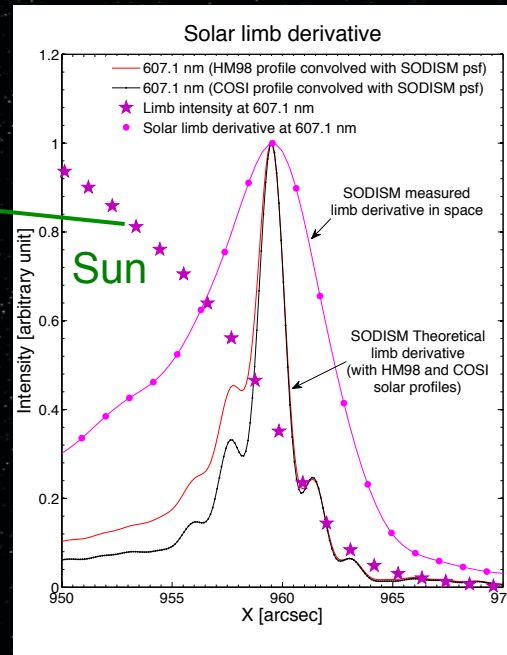
# 4 – Scientific results

## Method for determining the radius of Venus and the Sun (IPP method)

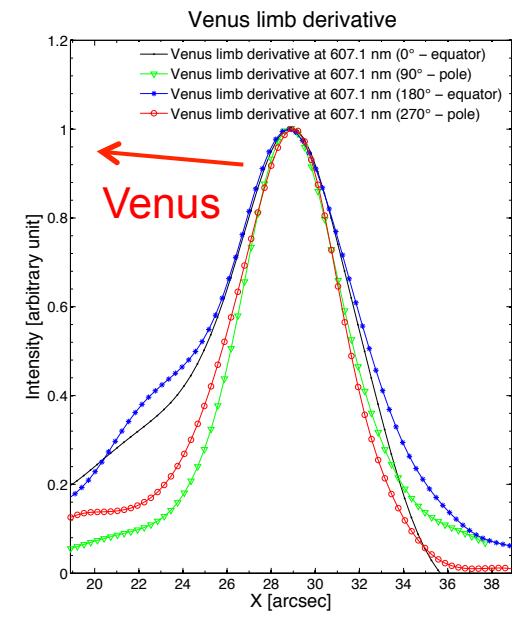
- Center detection using the Hough method
- Extracting the inflexion-point position (IPP)
- Characterizing the best fit (circle, ellipse, etc.)
- Determination of Venus radius and Sun radius



Venus and Sun "Hough" map

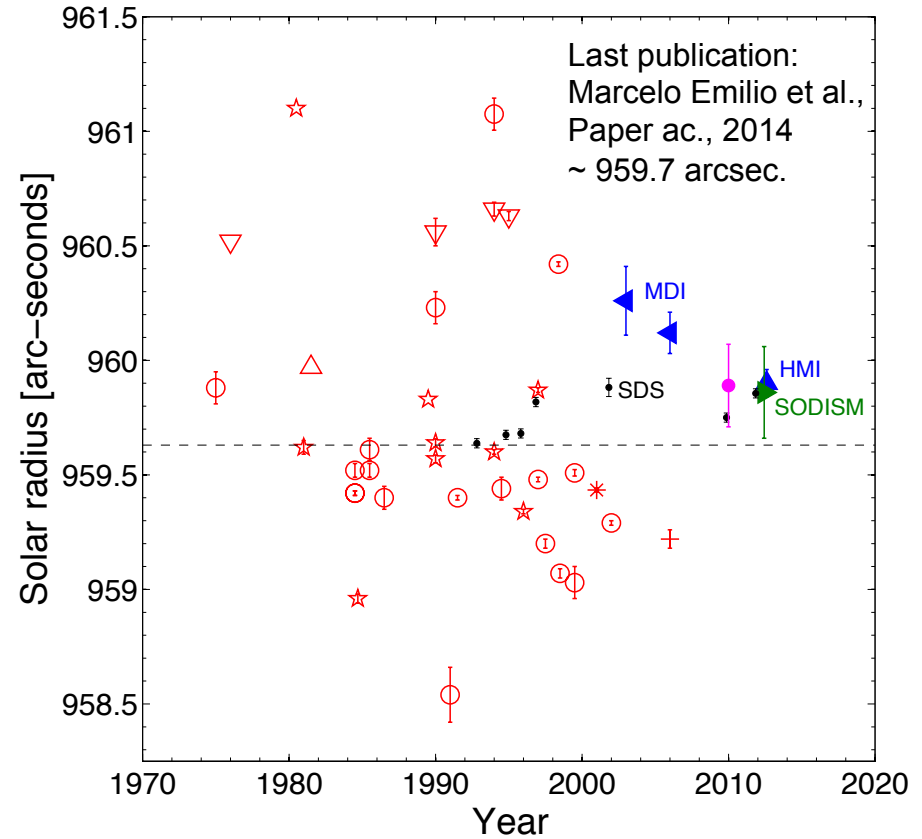
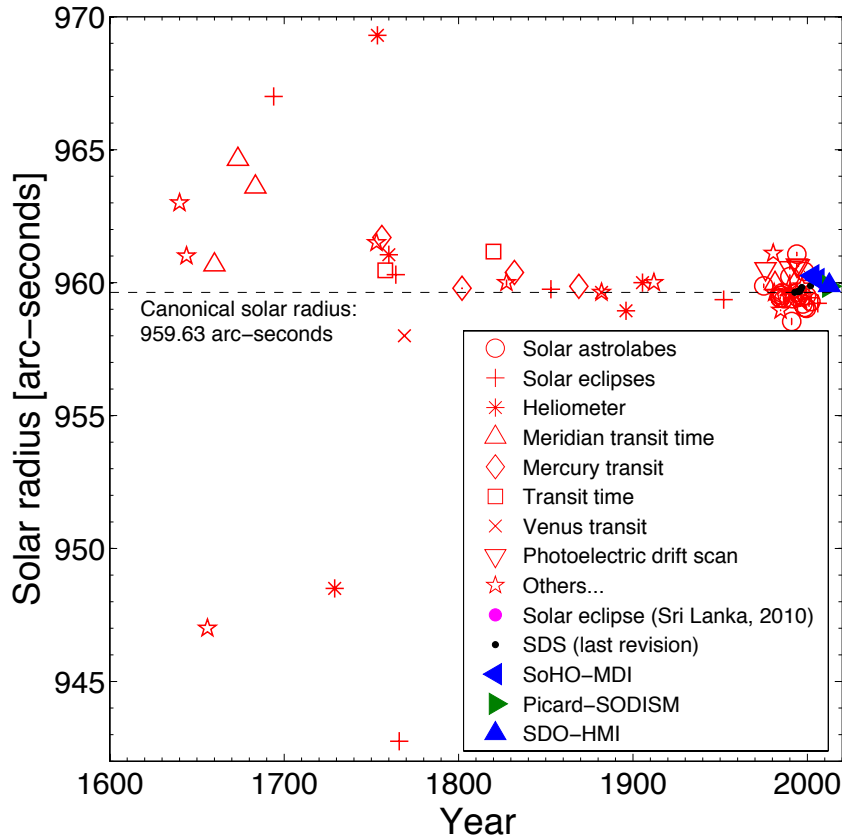


Extracting the inflexion-point position



# 4 – Scientific results

**R = 696,156 ± 145 km (PICARD)**



The work of the physicist is to establish a rigorous uncertainty budget.

## 1-b) Solar Astrometry

Measure the solar diameter variations over time

A) With PICARD ground-based facility

&

B) With PICARD/SODISM space instrument

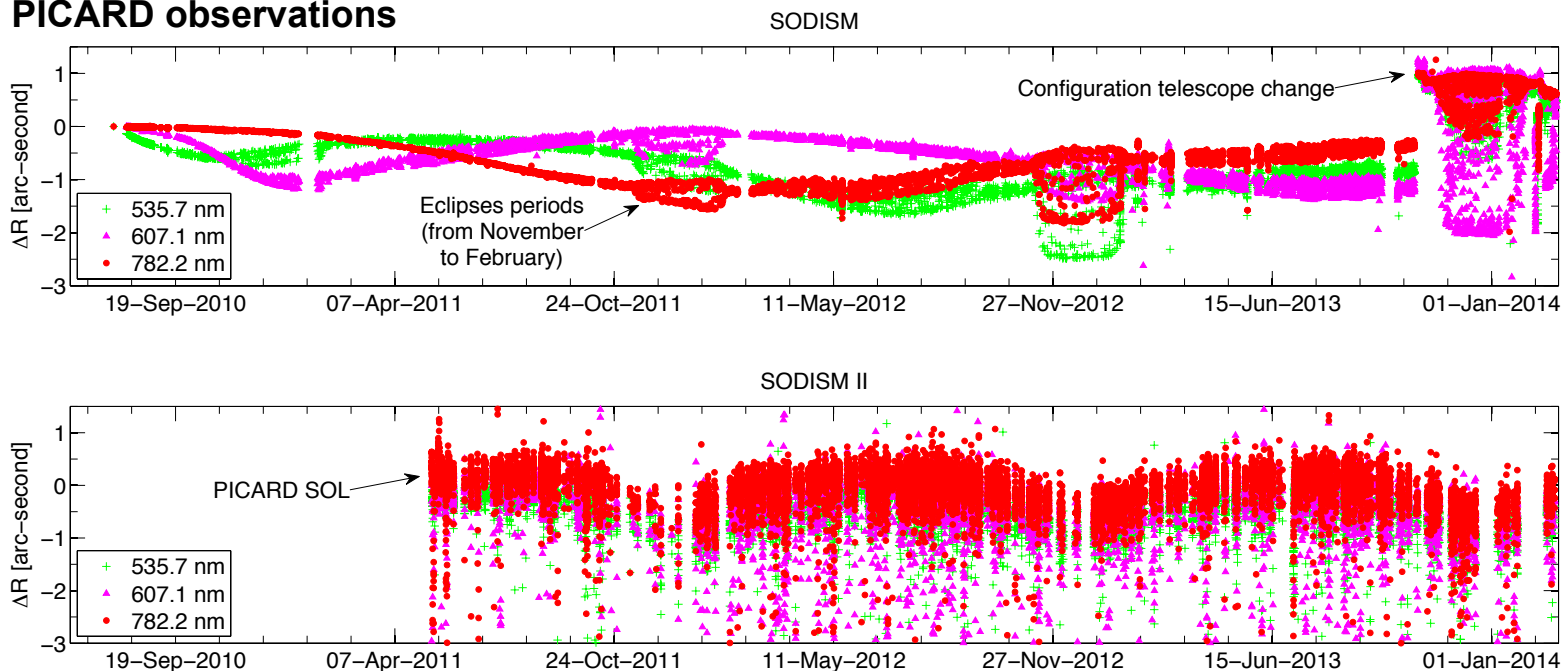
## 4 – Scientific results

Measurements of the solar radius are of great interest within the scope of the debate on the role of the Sun in climate change.

Possible temporal variations of the solar radius are important as an indicator of internal energy storage and as a mechanism for changes in the TSI.

Space observations are a priori most favorable, however, space entails a harsh environment. On ground, the instruments are affected by atmosphere.

### PICARD observations



B) PICARD/  
SODISM space  
instrument

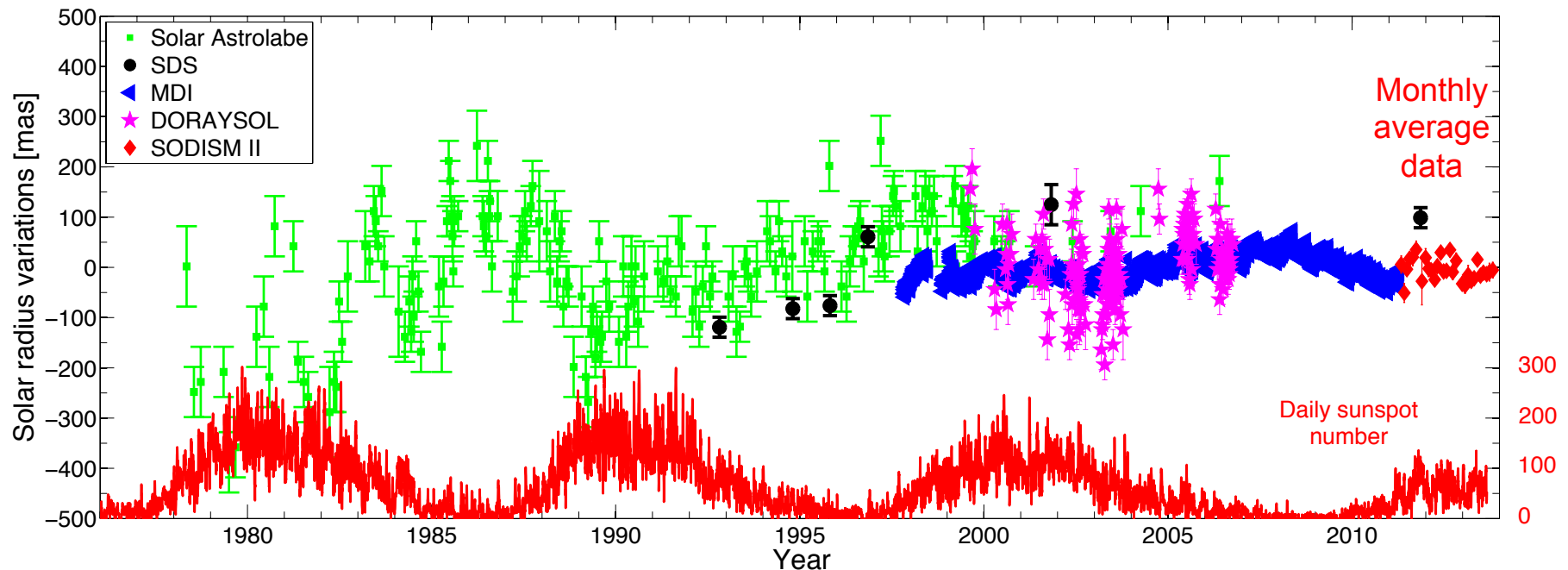
A) PICARD  
ground-based  
facility

# 4 – Scientific results

## A) PICARD ground-based facility solar radius variations

Our ground results (PICARD SOL) were corrected for the effects of refraction and turbulence by numerical methods.

→ *Solar radius variations  $\Delta R_{\odot} < 50 \text{ mas}$*

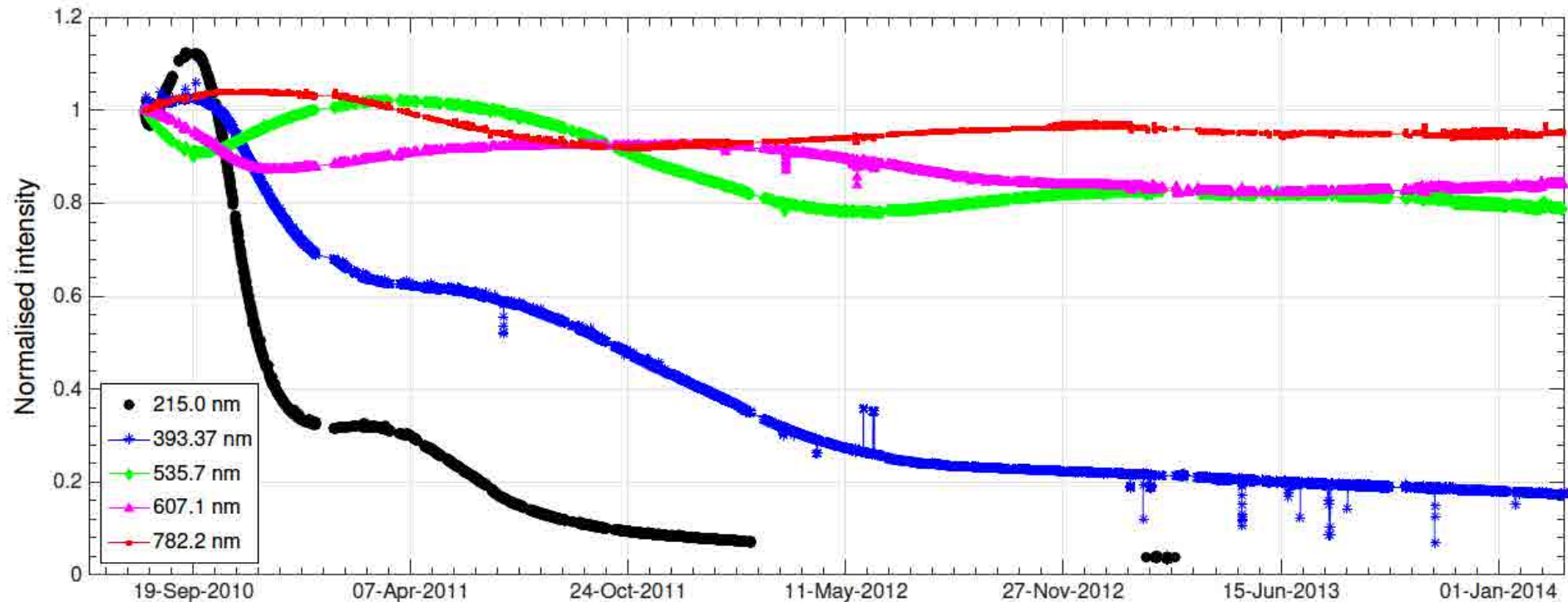


## 4 – Scientific results

### B) PICARD SODISM space instrument solar radius variations

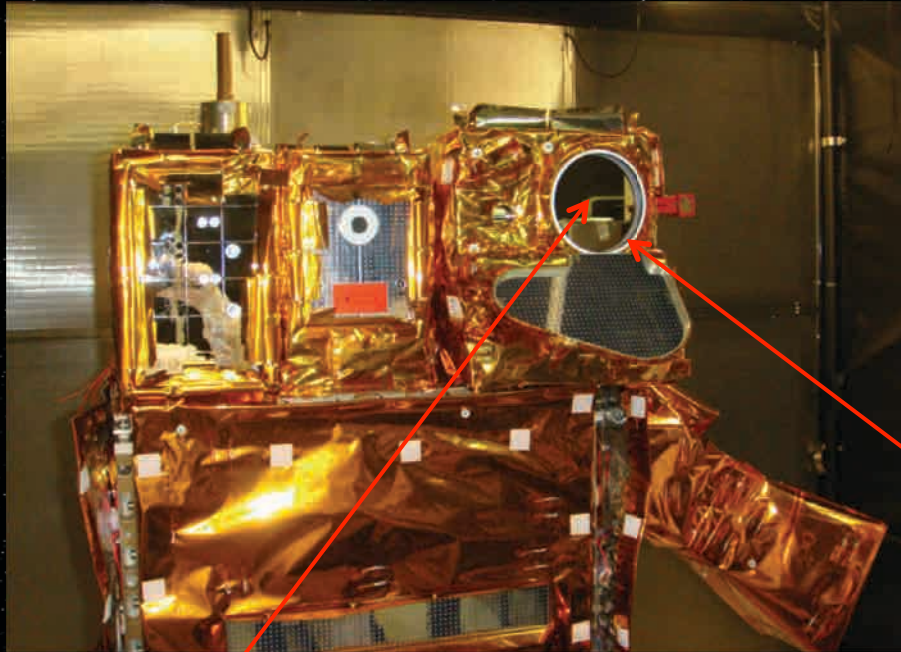
Several physical phenomena can lead to severe degradation of the optical performance of **our space results** (PICARD). In the case of SODISM, these effects entail solarization and polymerization of molecular contamination.

--- Normalized time series of integrated intensity during the PICARD space mission  
→ High degradation in the UV



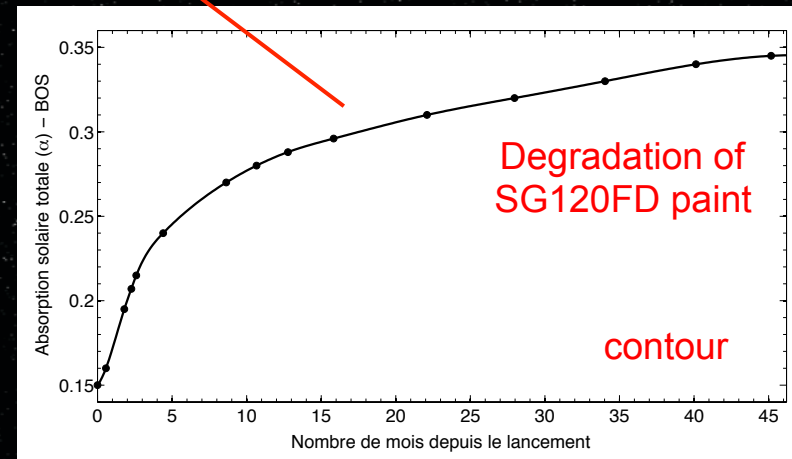
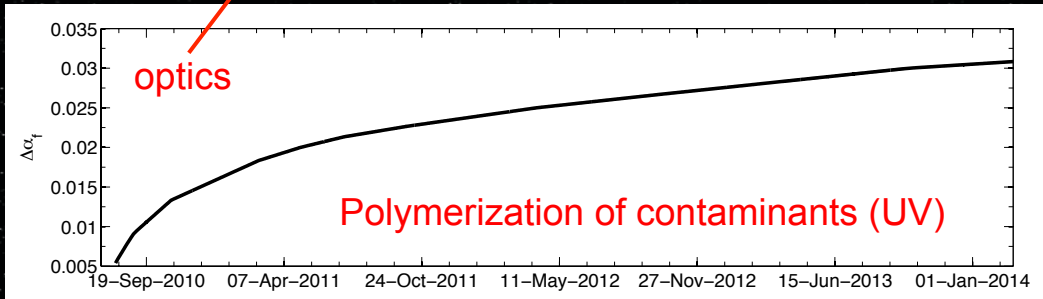
# 4 – Scientific results

## B) PICARD SODISM space instrument solar radius variations



Two different solar absorption evolutions (optics, contour)

→ There is a very strong contamination of the satellite





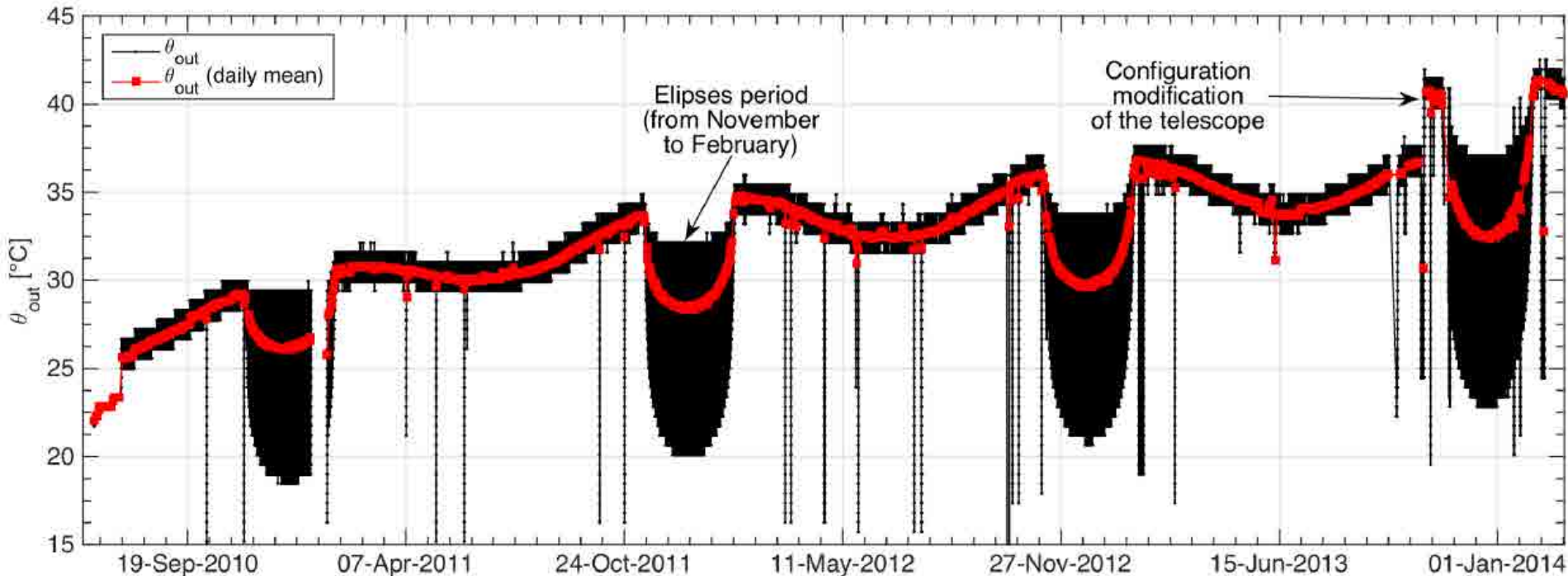
# 4 – Scientific results

## B) PICARD SODISM space instrument measurements

--- Normalized time series evolution (contamination)

--- Important temperature change of SODISM front window and direct impact on solar radius measurements

→ How to correct the data?



# 4 – Scientific results



## B) PICARD SODISM space instrument measurements

We developed a simulator to try to correct the “signal” (thermo-optical effect).

- Solar Spectrum (Atlas 3)
- Solar flux (SOVAP, PREMOS, TIM, etc.)
- IR and albedo flux (BOS)

Front window temperatures as function of housekeeping data

SODISM intensities

Wave-front and  
Zernike polynomials

$$T = T_{\infty} + \frac{Flux}{\epsilon_{out} \times \sigma \times \bar{T}} + C_1 \times J_0(i \times r \times C) + C_2 \times Y_0(i \times r \times C)$$

Front window index vs. temperature

$$W_0 = \sum_{k=1}^{36} Z_k = f\left(\lambda, \frac{\partial n}{\partial T}, \Delta T(\alpha_f), \dots\right)$$

$$\frac{\partial n}{\partial T} = A_0 + A_1 \times \exp\left(\frac{-\lambda}{B_1}\right) + A_2 \times \exp\left(\frac{-\lambda}{B_2}\right)$$

$$E = \exp(2i \times \pi \times W_0) \quad \text{Complex Wave-front}$$

$$M_{False}(t) = FI_{SODISM}(t) * M_{True}(t)$$

$$PSF_{SODISM} = (FFT2(E))^2 \quad \text{PSF}$$

Many instruments have  
this problem.

Bi-dimensional fast  
Fourier transformer

$$LDF_{SODISM} = \left(\sum PSF_{SODISM}\right) * (LDF)$$

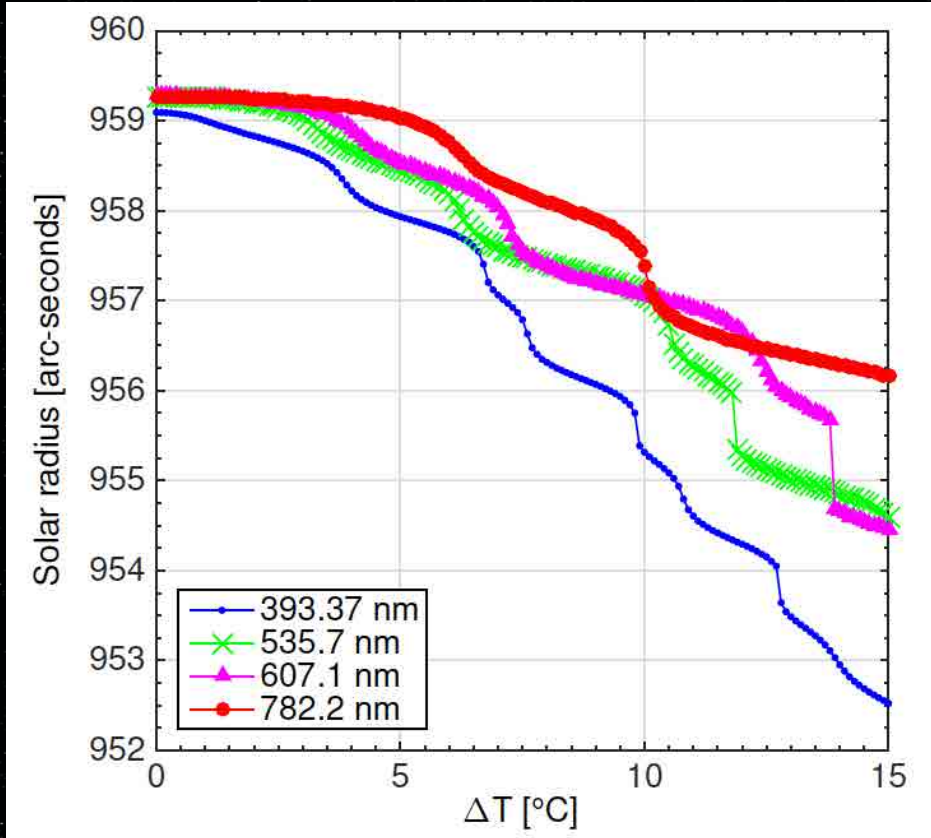
Limb darkening function  $\rightarrow$   $LDF_{SODISM}$

Convolution

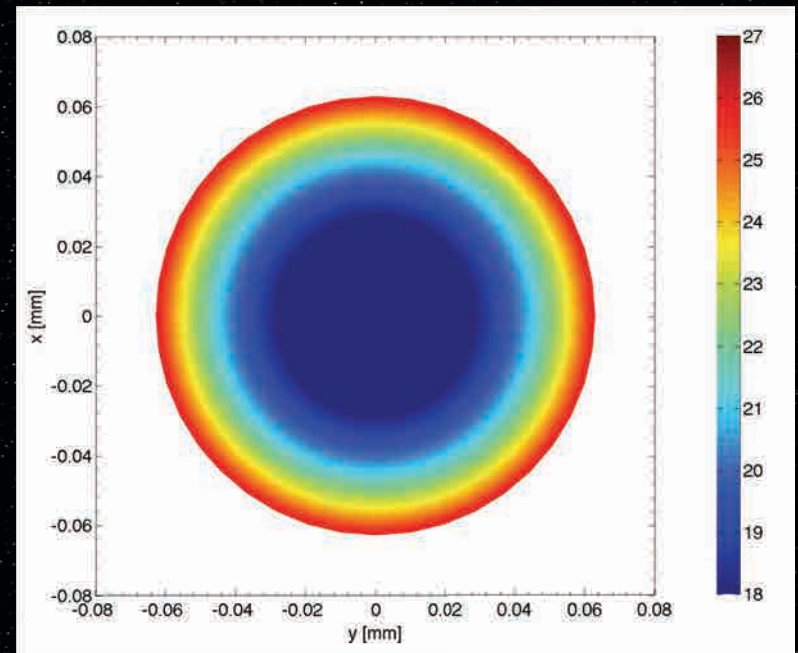
## 4 – Scientific results

### B) PICARD SODISM space instrument measurements

#### Relation between solar radius and temperature gradient



Evolution of the solar radius (determined by the inflection point method) as a function of a temperature gradient for different wavelengths.



Temperature gradient on SODISM front window

## 4 – Scientific results

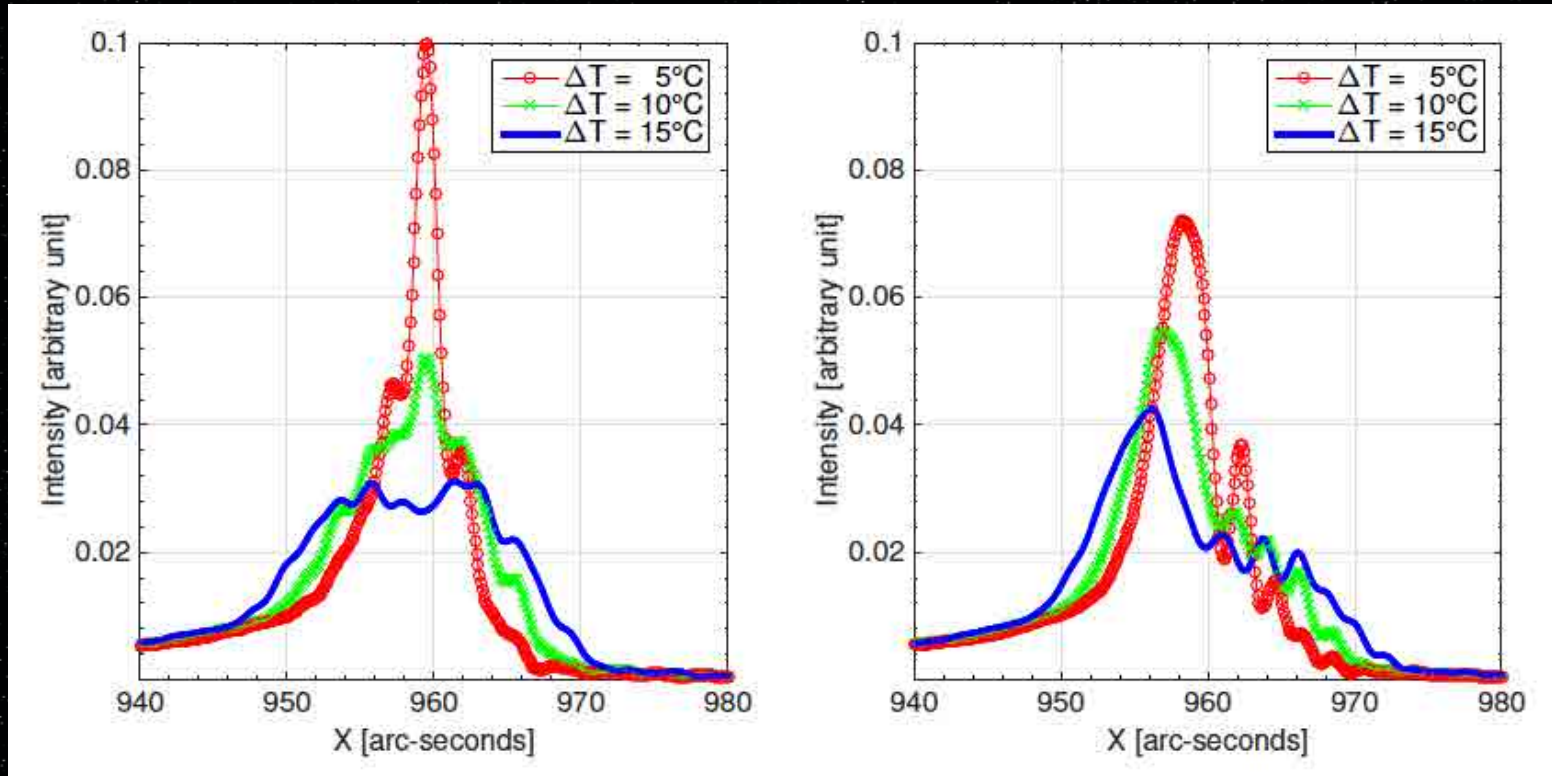
### B) PICARD SODISM space instrument measurements

The space environment (UV effects, contamination, thermal cycling, etc.) combined with initial defects in telescope calibration (astigmatism, position of the focal plane, etc.) can degrade considerably the measurements taken by our instrument.

Solar models :

- COSI
- HM98
- Neckel2005

SODISM PSF  
is predominant

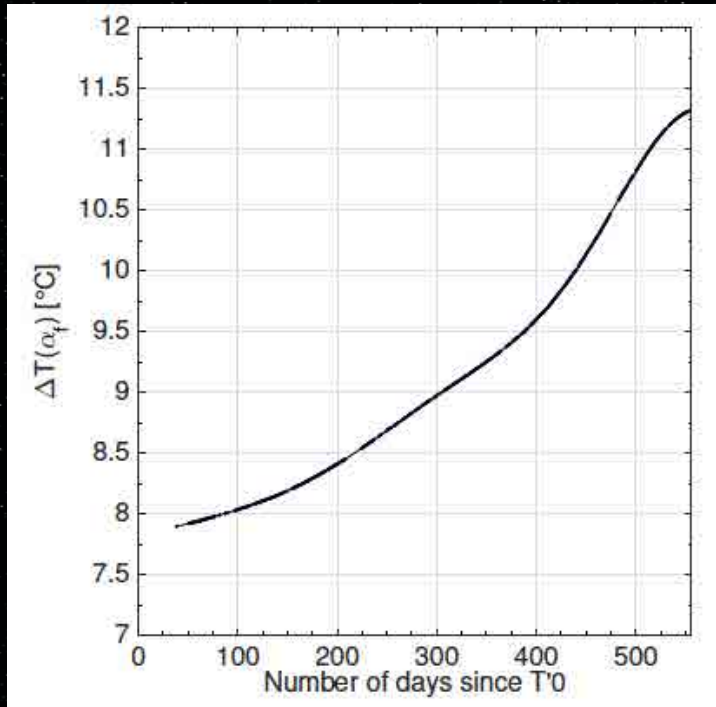


Evolution of the solar limb first derivative (simulation) for different angular sectors of the image. Consistent with what we observe.

# 4 – Scientific results

## B) PICARD SODISM space instrument measurements

### Temperature gradient evolution and uncertainty budget of the model



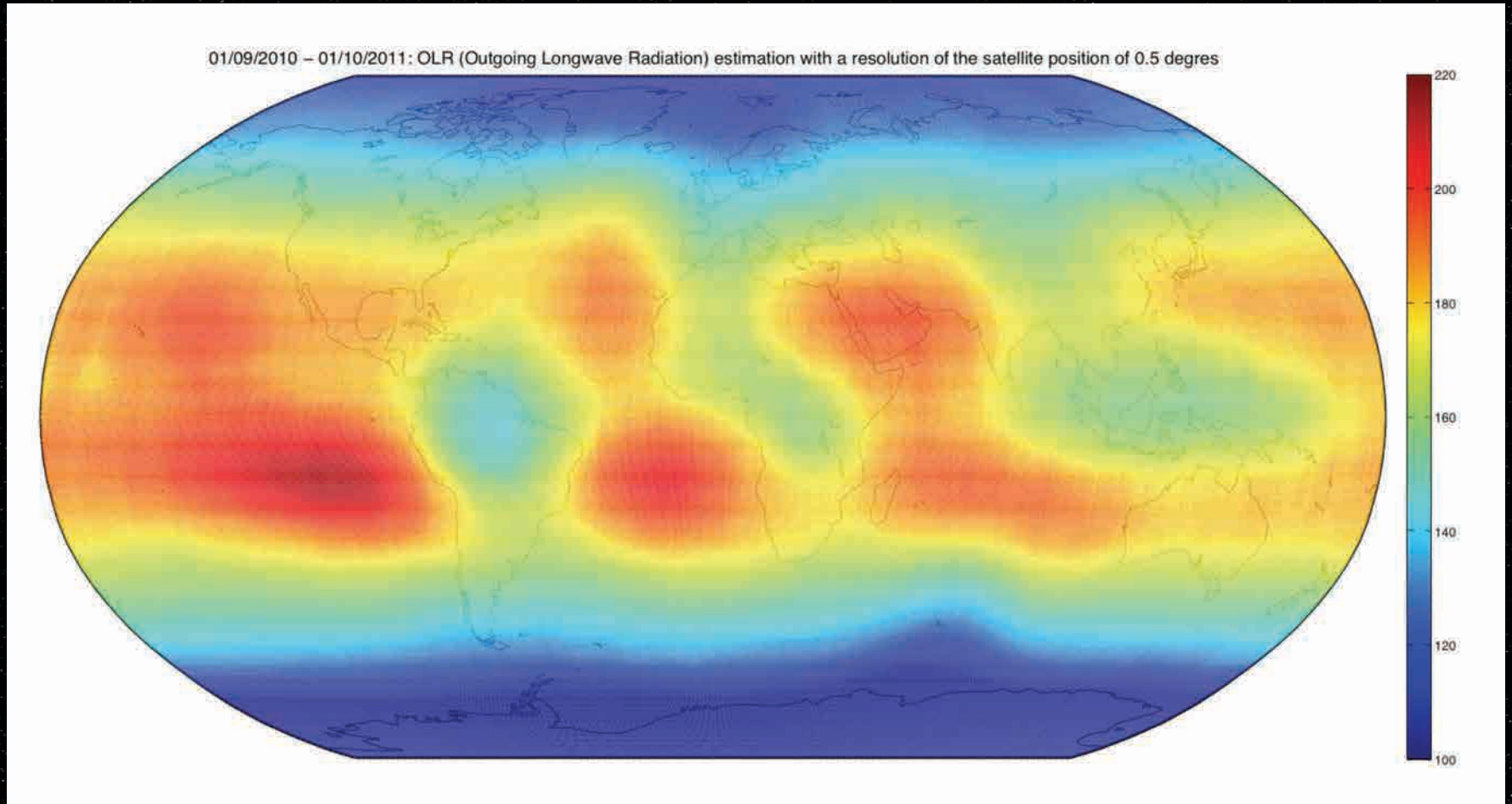
Evolution of the front window temperature gradient.

Uncertainty sources	Typical values	Uncertainty	Error on ΔT [°C]	Uncertainty type
$\alpha_f^{(a)}$	0.14	±0.001	±0.10	Test (S) & aging (R)
$\varepsilon_{out}^{(b)}$	0.81	±0.01	±0.30	Test (S)
$\Lambda^{(b)}$	1.38 W.m <sup>-1</sup> .K <sup>-1</sup>	±0.04 W.m <sup>-1</sup> .K <sup>-1</sup>	±0.31	Test (S)
$\theta_{out}^{(a)}$	22 °C	±0.10	±0.03	Calibration & measurement (S)
$\varphi_S^{(c)}$	1,362 W.m <sup>-2</sup>	±2.4 W.m <sup>-2</sup>	±0.02	Measurement (S)
$\varphi_{IR}^{(c)}$	238 W.m <sup>-2</sup>	±6.0 W.m <sup>-2</sup>	±0.02	Literature (S & R)
$\varphi_A^{(c)}$	~20 W.m <sup>-2</sup>	±9.0 W.m <sup>-2</sup>	±0.02	Literature (S & R)

### Uncertainty budget.

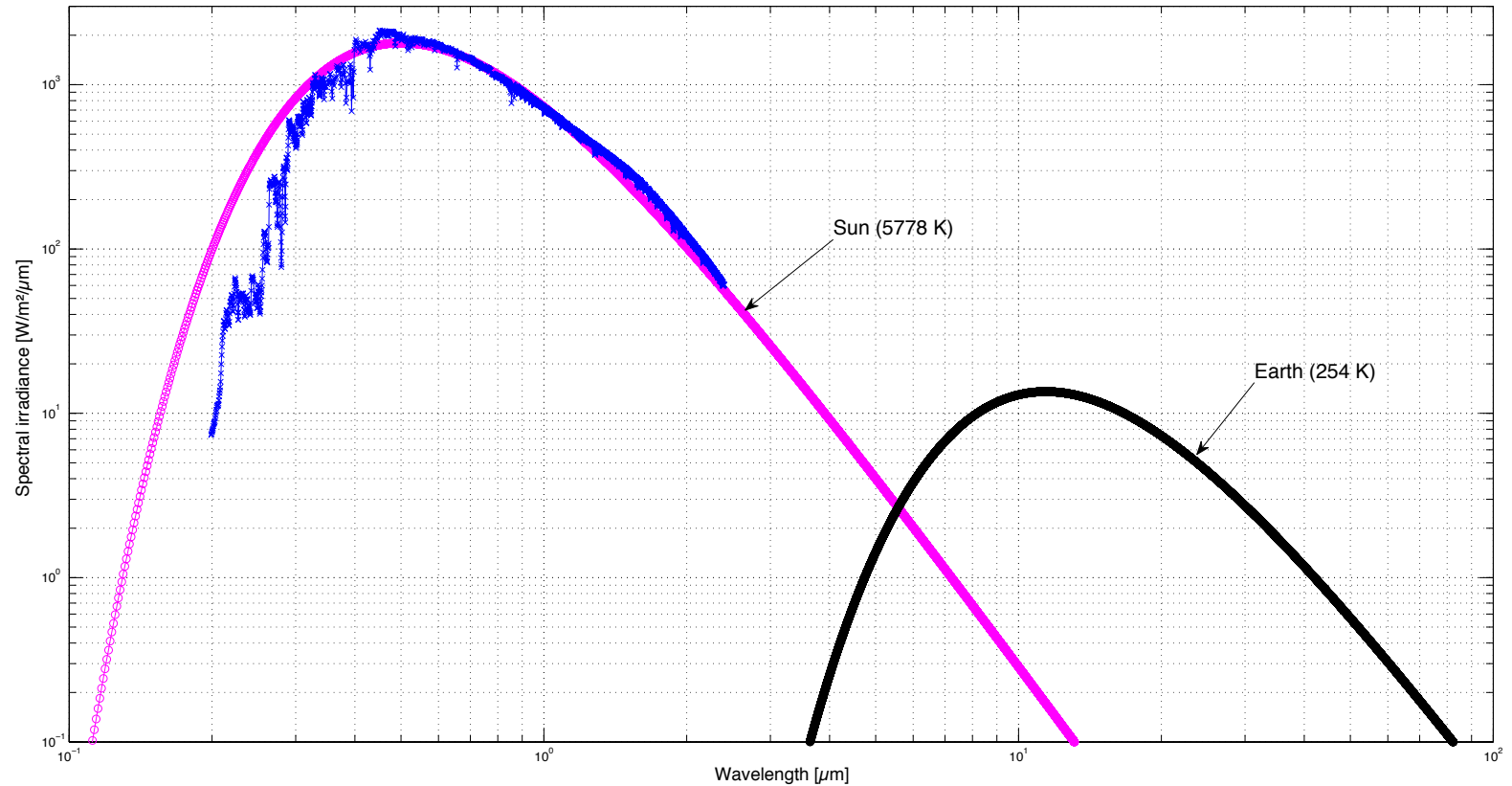
- Spectral reflection and transmission measurements were performed with a spectrophotometer (Agilent Cary 5000 UV-NIS-NIR). The estimated tolerances are expected to be less than +/-1%.
- Near-normal IR reflectance measurements were performed in accordance with ASTM E408 (with an IR Reflectometer model DB100). The estimated tolerances are expected to be less than +/-1.5%.
- etc...

## 4 – Scientific results



IR flux used in the model (obtained with PICARD data).

## 4 – Scientific results



Solar spectrum used in the model (obtained with PICARD data).

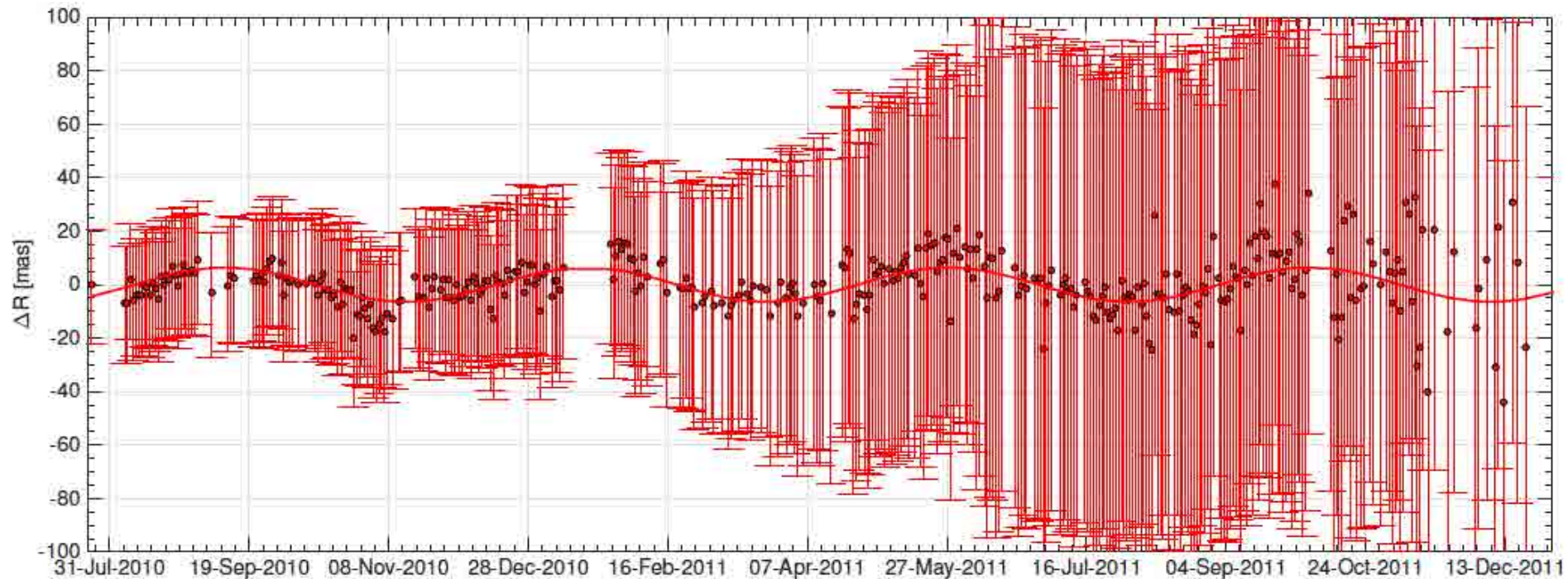
## 4 – Scientific results

### B) PICARD SODISM space instrument measurements

Our space results (PICARD) were corrected for the temperature effects and contamination.

→  $\Delta R_{\odot} < 20 \text{ mas}$  variations during the rising phase

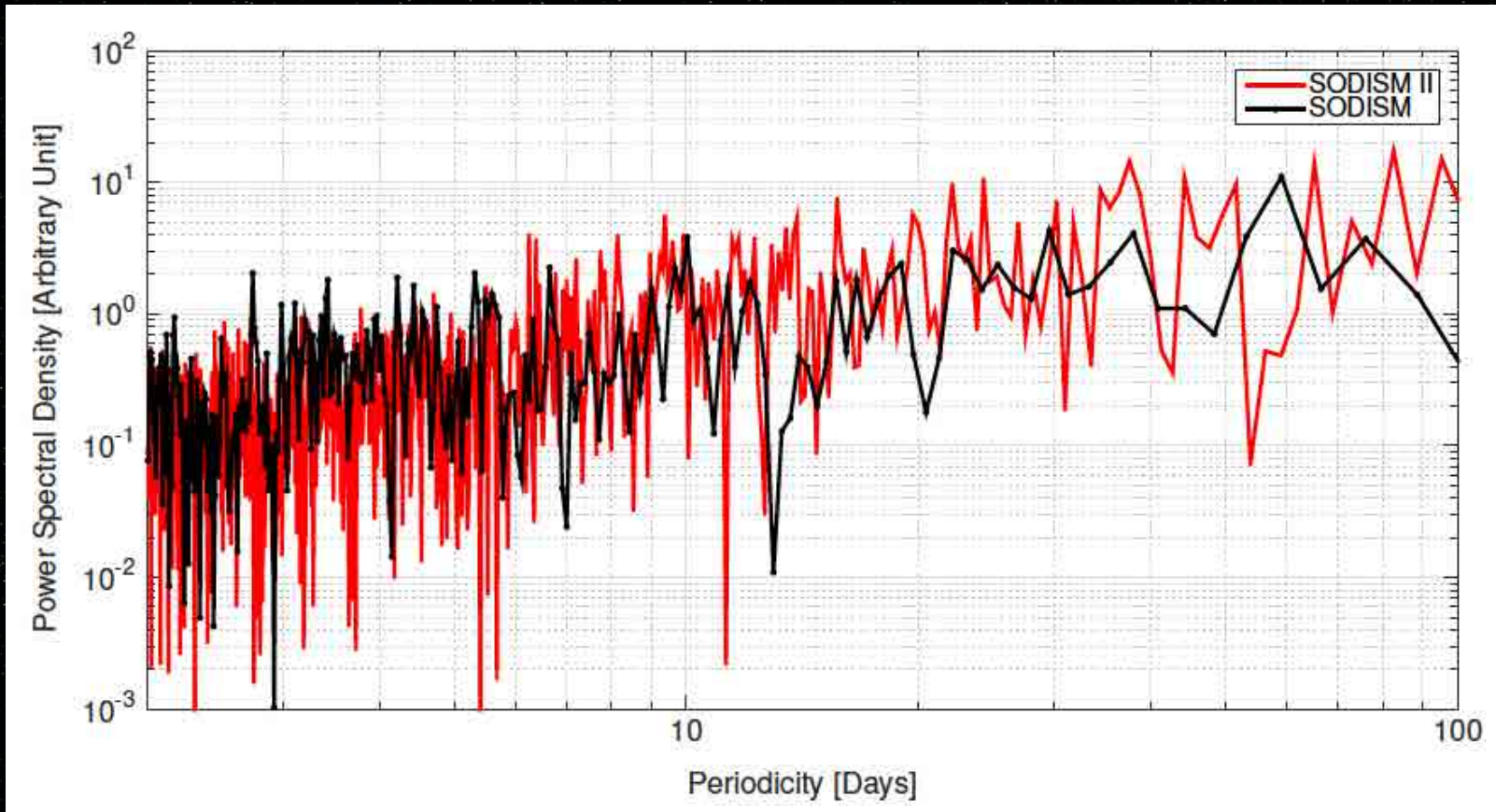
We find a small variation of the solar radius from space measurements with a typical periodicity (6.5 mas variation in the solar radius with a periodicity of 129.51 days → same with ground-based).





## 4 – Scientific results

### B) PICARD SODISM space instrument measurements

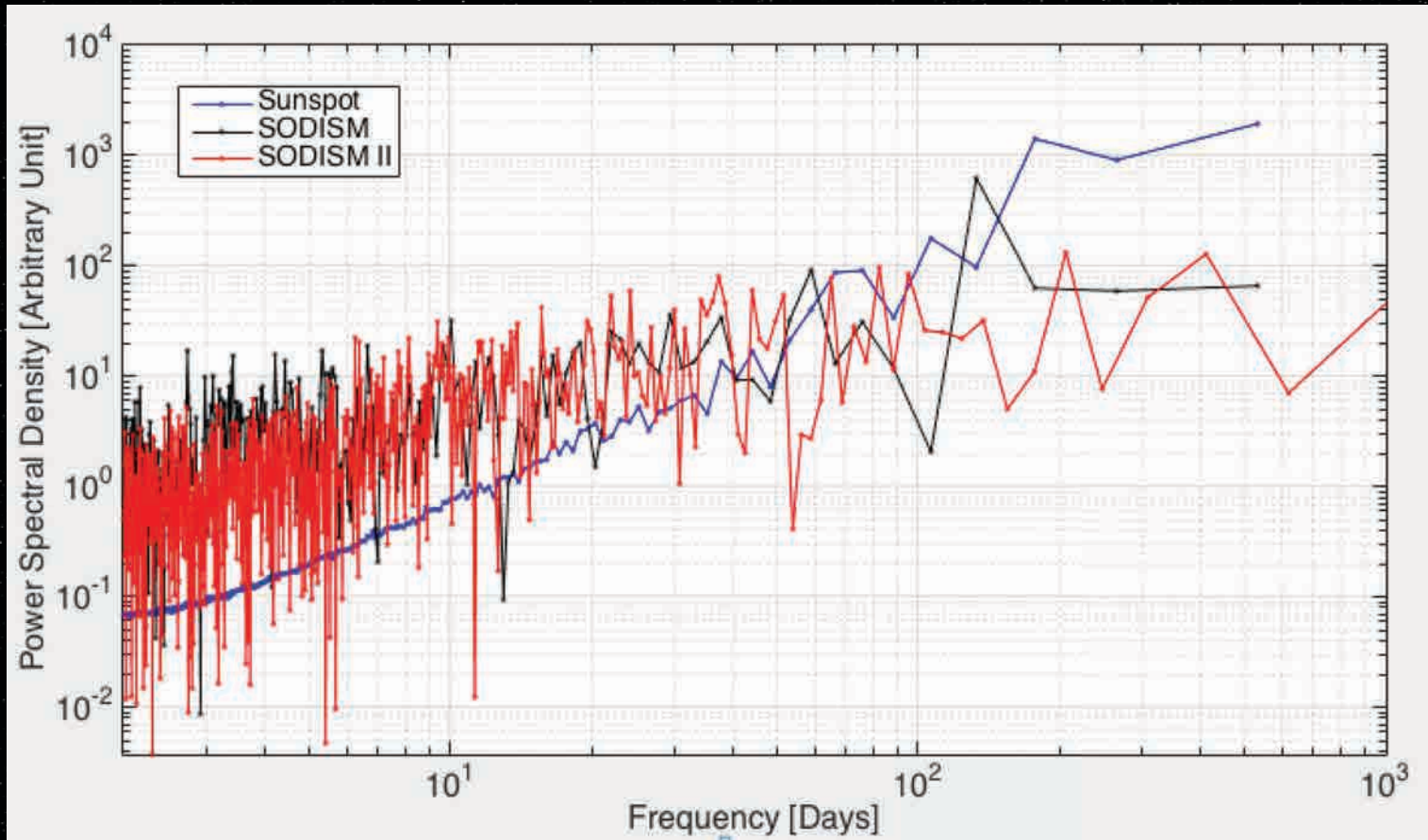


Spectral  
analysis

Periodicity analysis of the solar radius from few days to one hundred days.

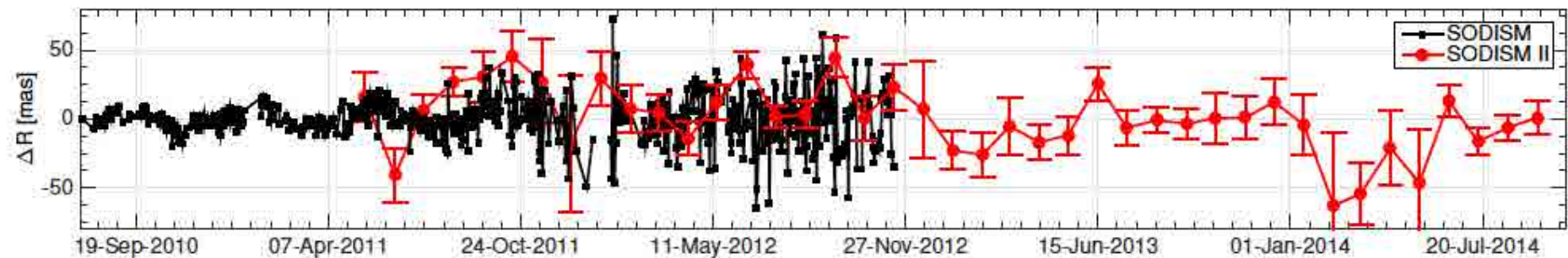
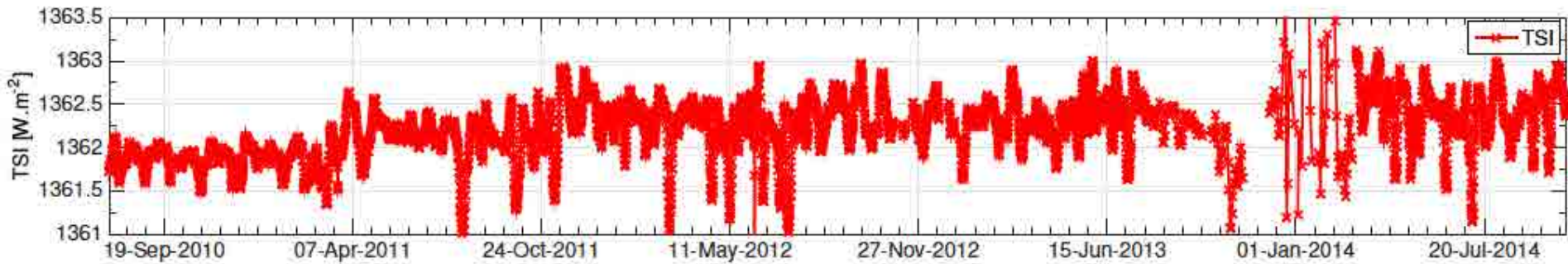
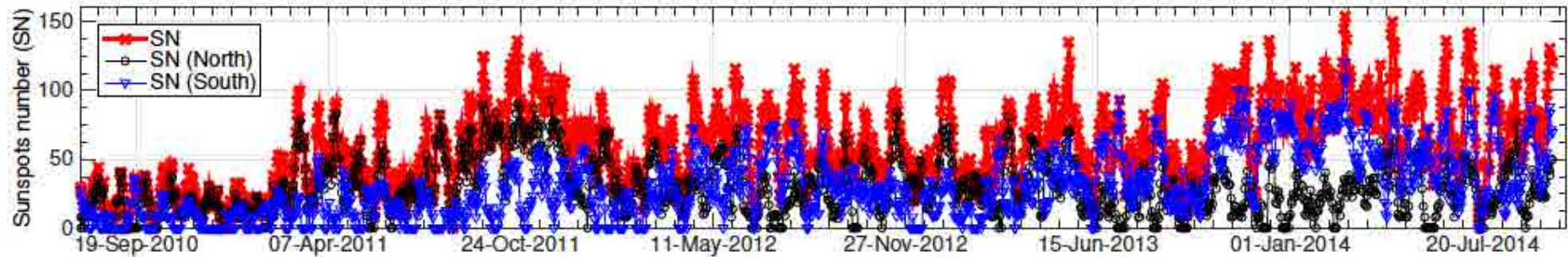
- 6 days variations ? (very small)
- 13 days, 27 days (very small variations)
- 40 days (very small variations)
- 60 days (very small variations), etc...

## 4 – Scientific results



# 4 – Scientific results

## A & B) PICARD measurements



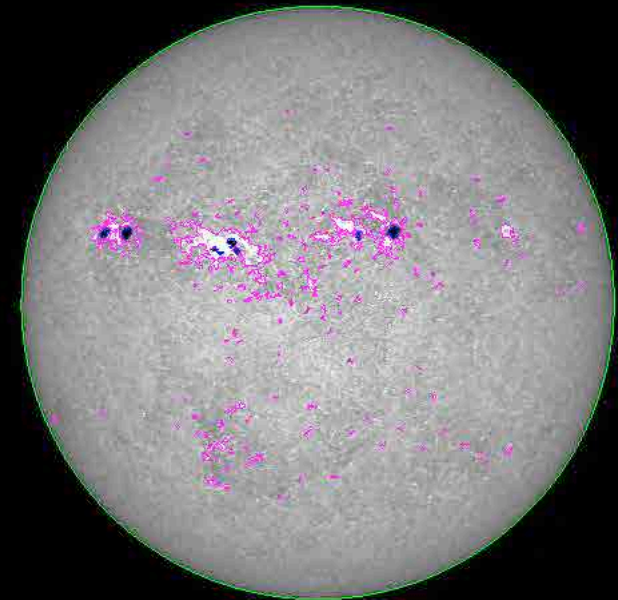
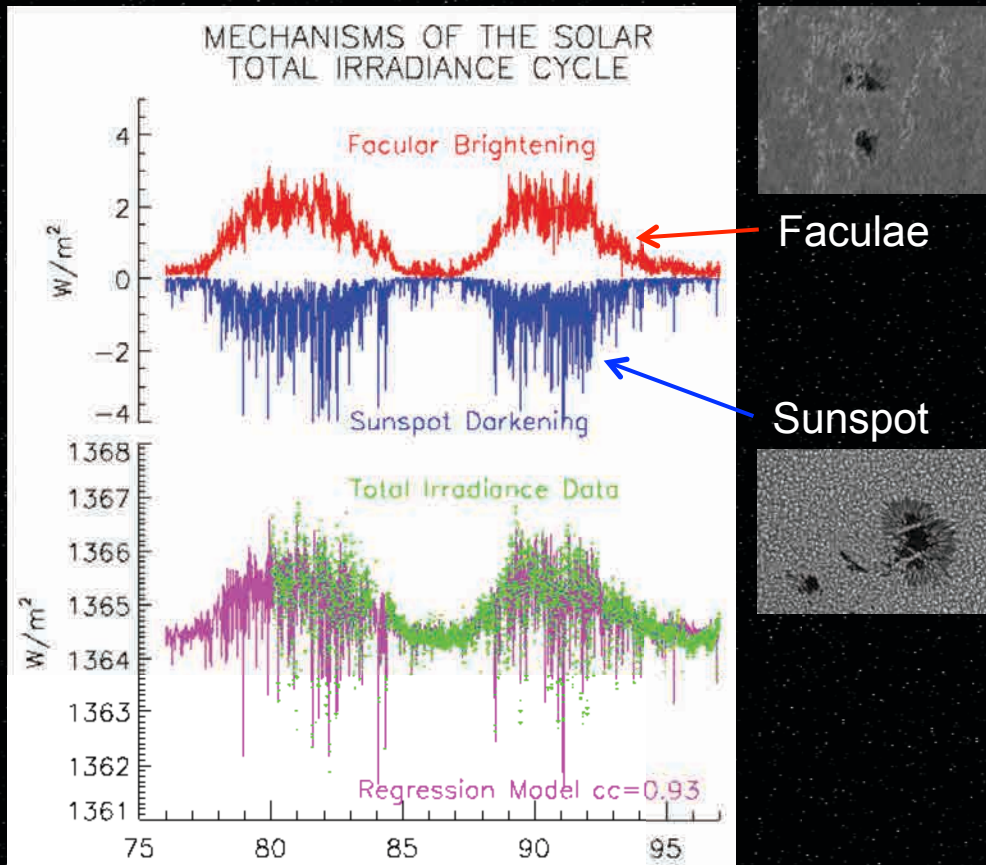
## 2) Photometry

Measure the spectral solar irradiance variations over time.

Work in progress...

# 4 – Scientific results

From Lean and Fröhlich (1998)



Development of technics for faculae area with SODISM 393.37 nm images (blind deconvolution)

- SSI reconstructions during PICARD mission
- Contributions on TSI variations during PICARD mission
- ...

More than 90% of TSI variance are due to dark sunspots and bright faculae.

Any residual TSI variations from slower changes in e.g. solar diameter or convective patterns ?

## 4 – Scientific results

### Threshold technique

Curto et al. (Solar Physics, 2008) for example

- + Combination of different mathematical tools (morphological operators, filters, threshold) seems to be easier
- + Most of the tools are already implemented
- + Only improvements to be done
- + Possible improvements: data fusion of results obtained with other wavelengths, region-growing or shrinking, additional filters, ...
- How to find or determine the threshold?
- The threshold may depend on the input image (contrast, ...)
- Detection of sunspots is easier than detection of faculae

### MRF (Markov Random Field) approach

Turmon et al. (Solar Physics, 2010)

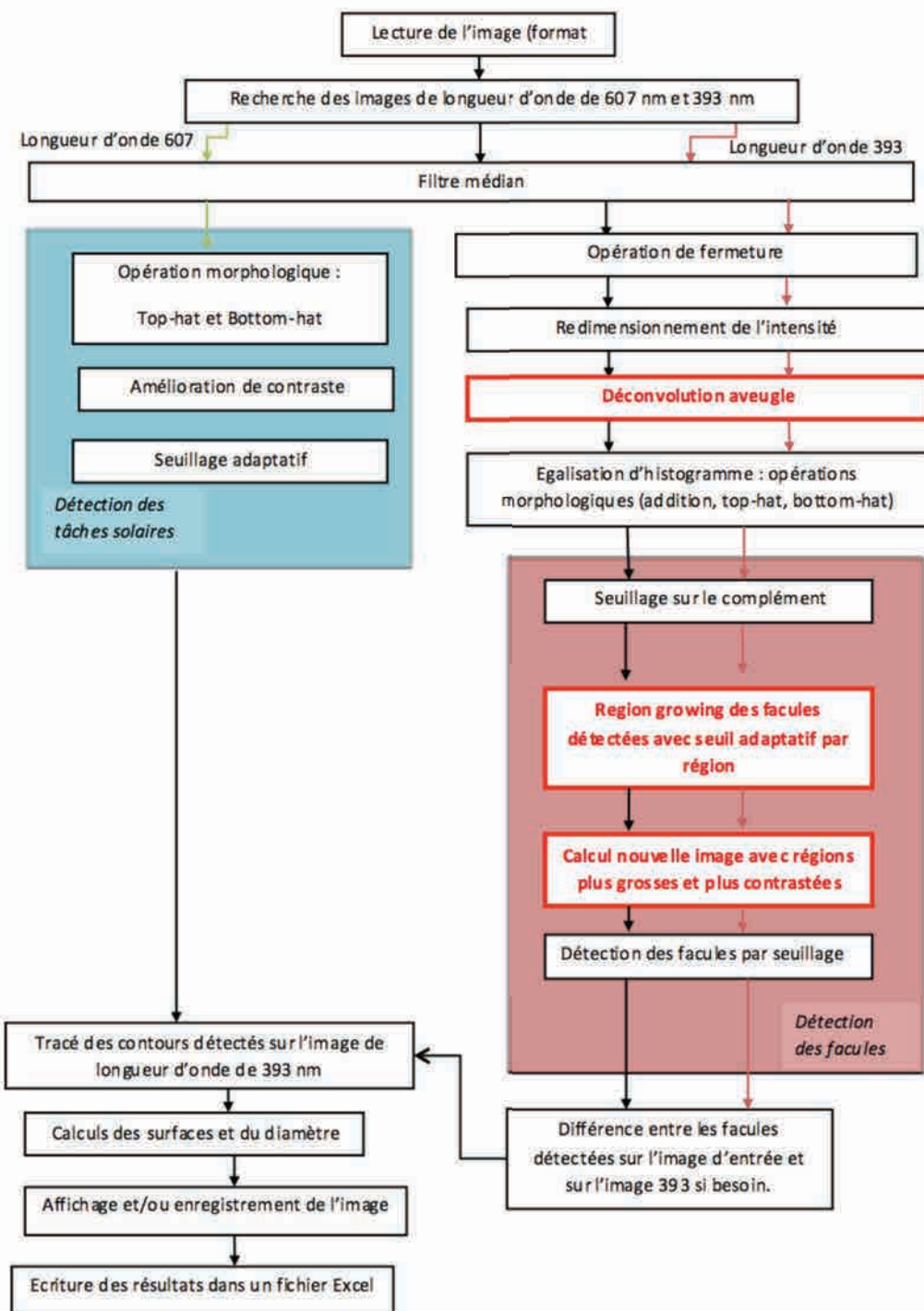
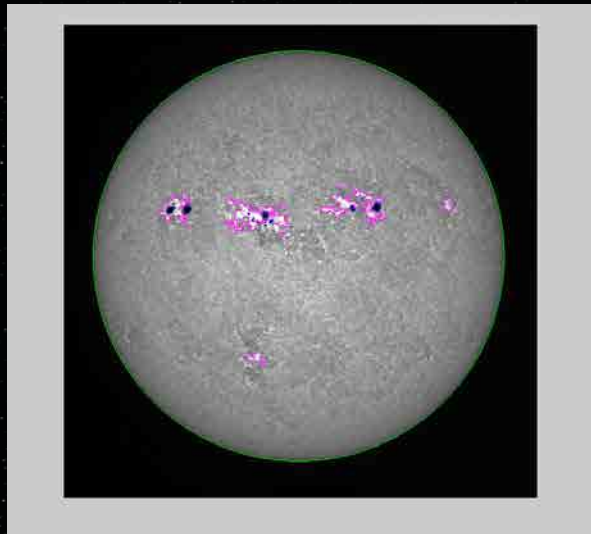
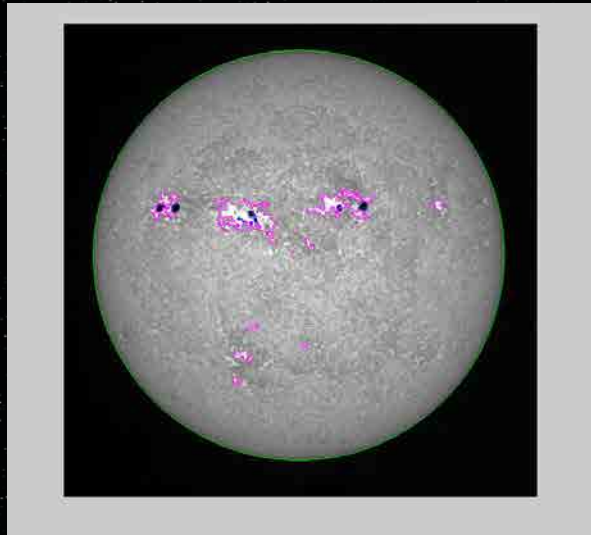
- + Possibility to work with multidimensional data (magnetic field, intensity, equivalent width)
- + Modeling of solar images in relation to solar physics
- + MRF prior allows to take into account spatial coherence of labels
- Bayesian framework: more complex computations, possible longer time of execution
- Hypothesis on likelihood model and priors: GMM (Gaussian Mixture Model) or IHM (Interpolated Histogram densities): similar results
- Estimation step of unknown model parameters: Expectation-Maximisation, Gibbs sampler
- Need of a training set or a threshold segmentation for a first estimation?

Contact with Turmon on 09/01/2015...

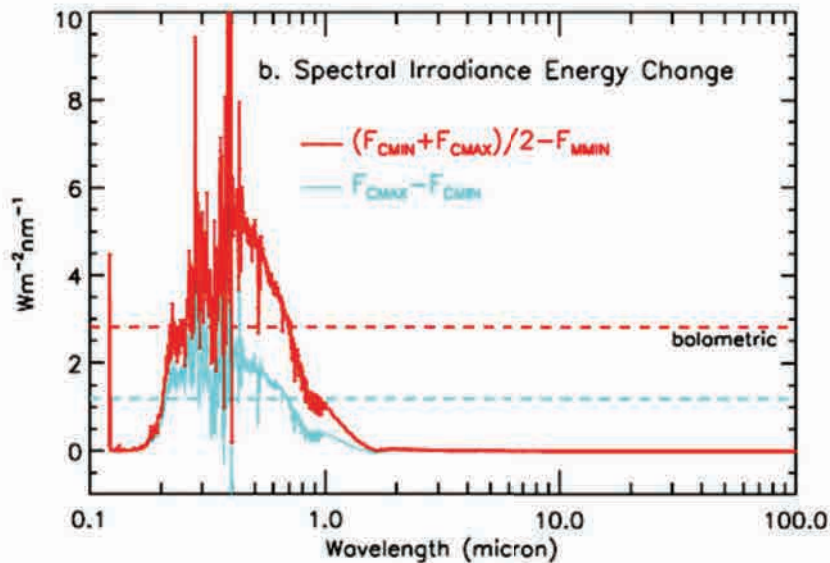
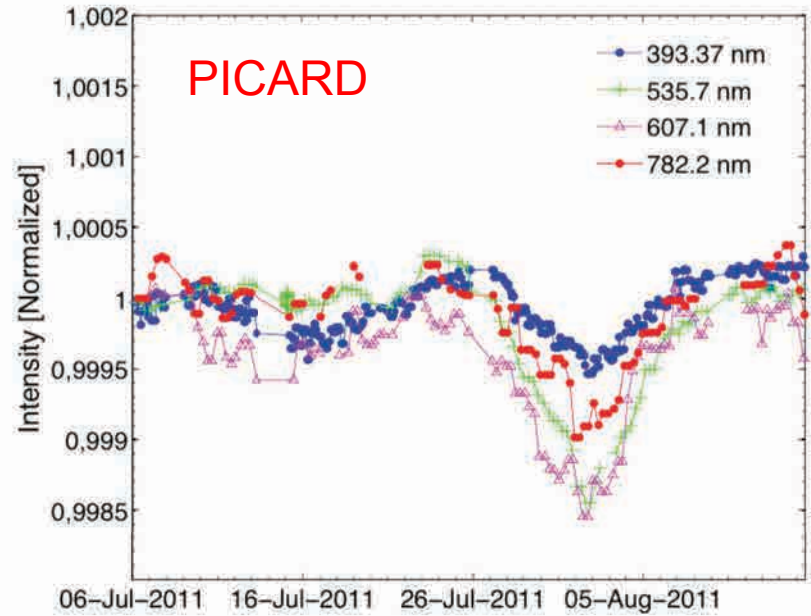
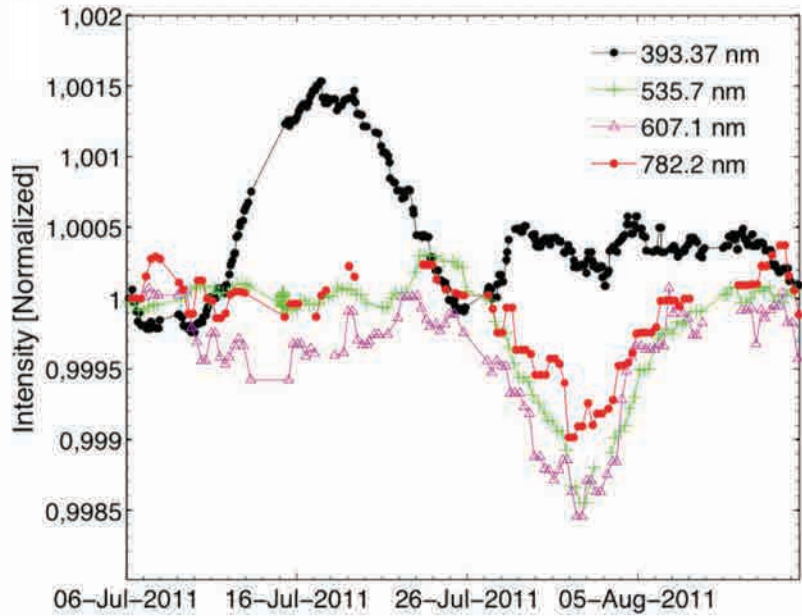
Both techniques need a pre-processing step.

Possible improvement: remove limb-darkening spatial attenuation,...

# 4 – Scientific results



# 4 – Scientific results



## Spectral solar irradiance evolution

From minimum to maximum of the solar cycle (blue)

From the Maunder Minimum to the present day (red)



Conclusion

# Conclusion

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Achievable scientific objectives  
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- Measurement of the photospheric diameter during the transit of Venus
- Solar radius variability with SODISM and SODISM 2

Thank you for your attention...