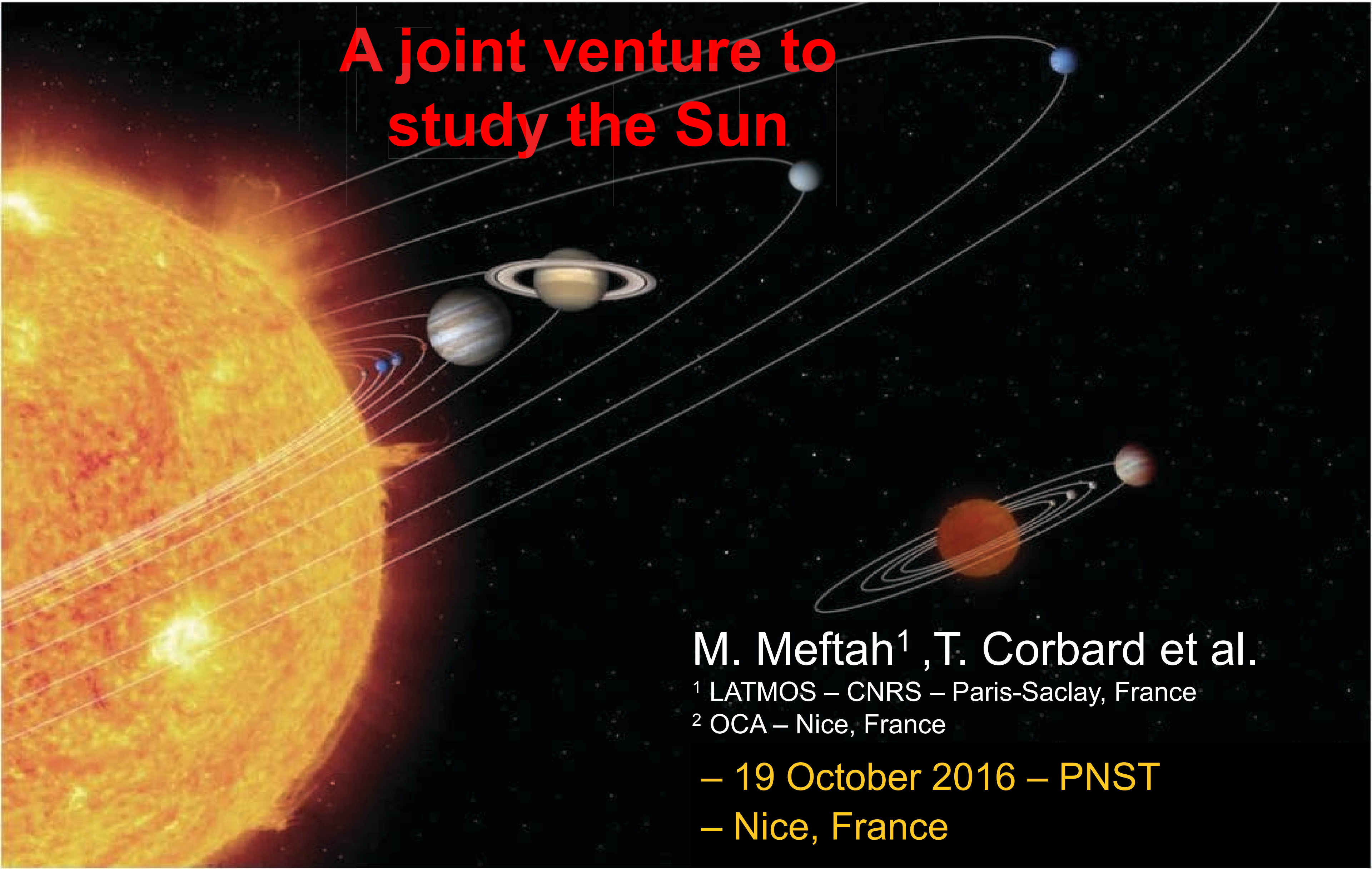
PICARD ground-based and space observatories:

A joint venture to study the Sun



M. Meftah[1] ,T. Corbard et al.

[1] LATMOS – CNRS – Paris-Saclay, France

[2] OCA – Nice, France

– 19 October 2016 – PNST

– Nice, France

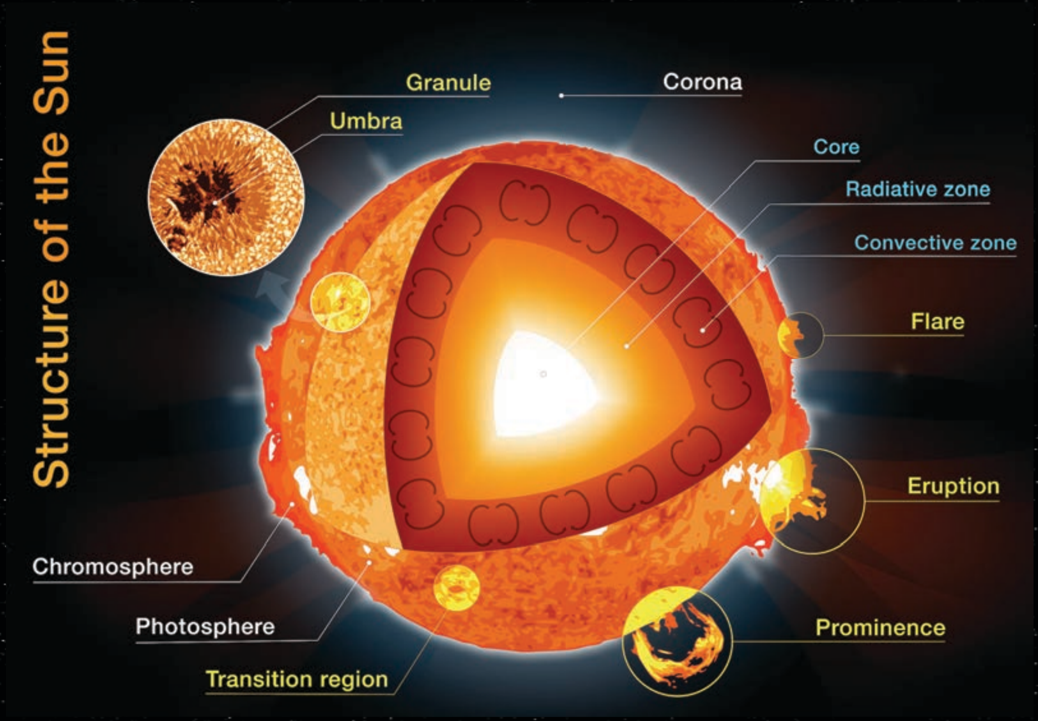
Presentation outline

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

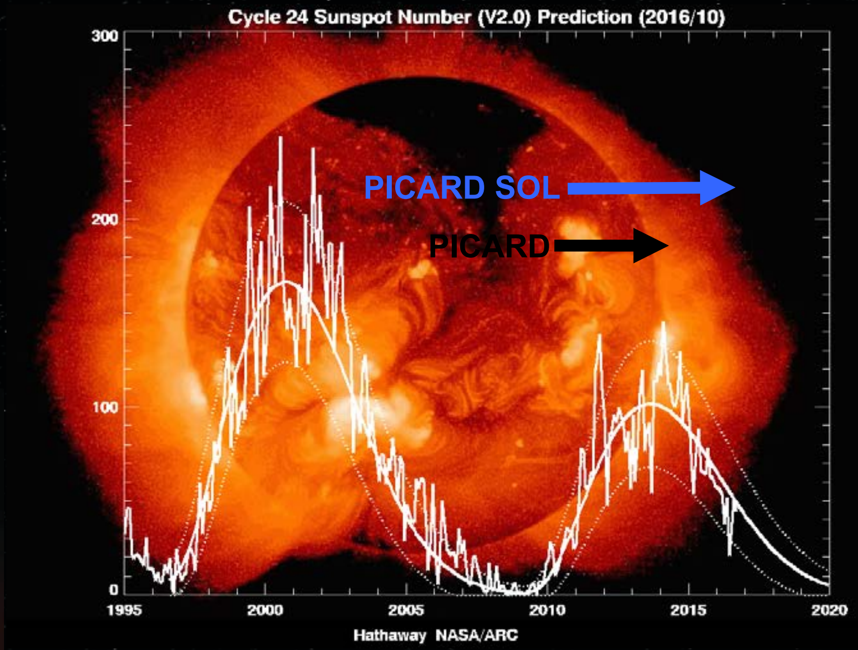
1 – The PICARD mission and the scientific objectives (1/5)

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

The 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.

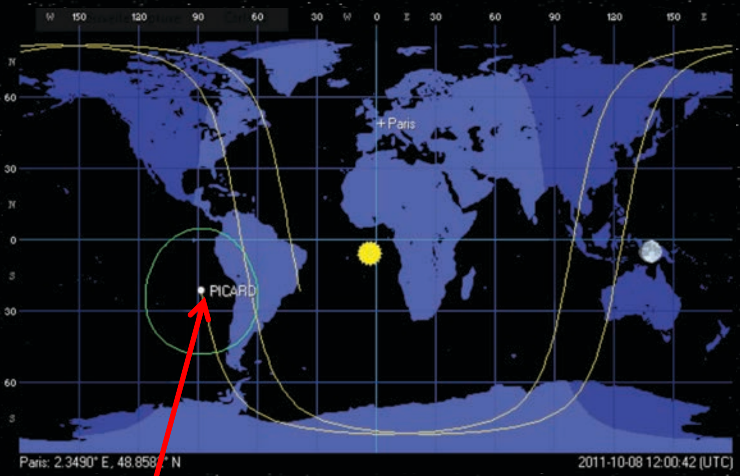


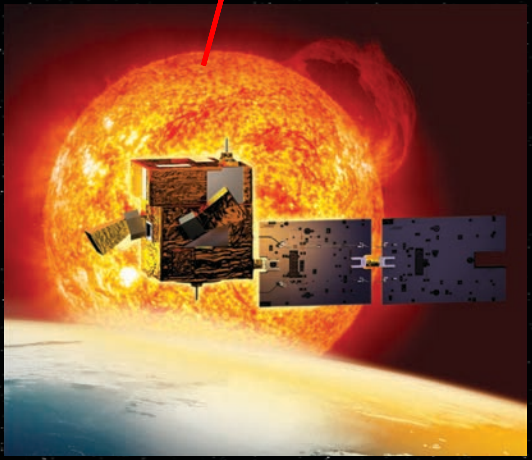
Six Years of Solar Observation



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

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



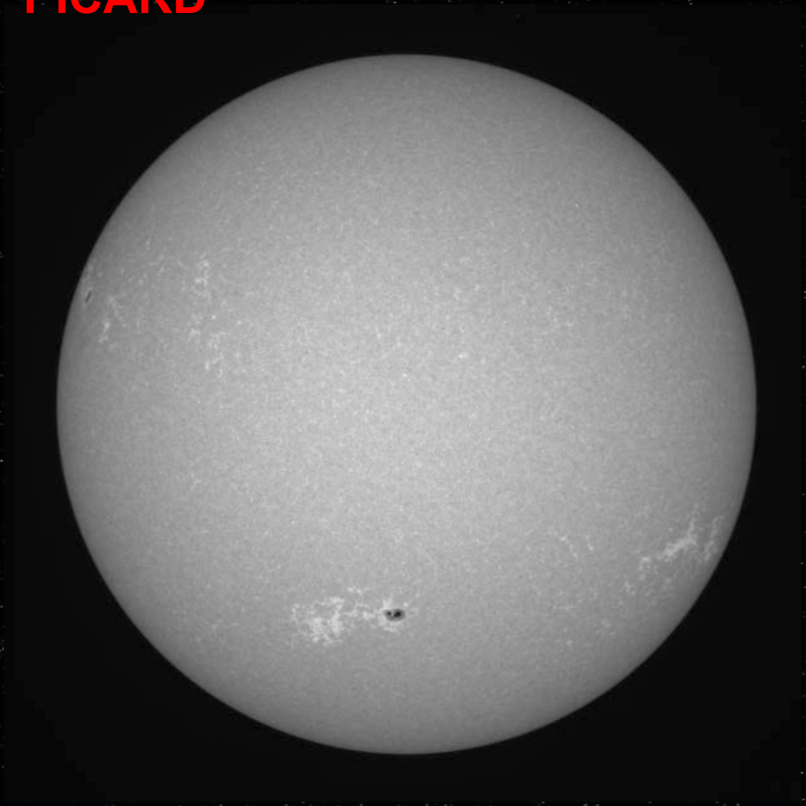


PICARD is a space-based mission, which was launched on 15 June 2010 into a Sun synchronous dawn-dusk orbit (735 km, Inclination: 98.29°).

PICARD SOL is the ground-based 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)

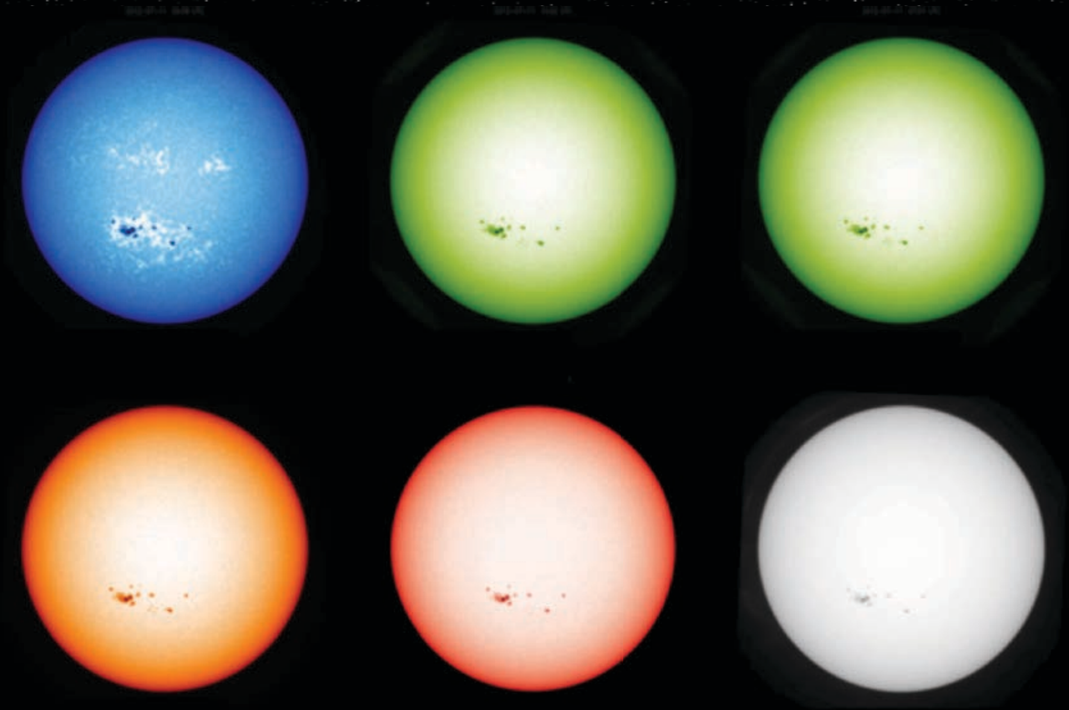
PICARD



~ 1,300,000 images acquired

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

PICARD SOL



~ 150,000 images acquired

PICARD SOL operates nominally since 2011.

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

- Solar Astrometry

Measure the solar diameter and the solar oblateness (absolute values) and their changes over time.

- Radiometry and photometry

Measure the total solar irradiance (TSI) in absolute and over time.
Impact on the climate.

Establish the relationship: variation of the solar diameter / change of the TSI (solar parameter W).

Measure the variations of the solar spectral irradiance in the UV (influence on ozone and climate).

- Helioseismology

Observations of low-frequency acoustic oscillations and detection of the p-modes (detailed study of the nuclear core and his dynamics).

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

- Solar radius

• During the last 40 years, solar radius measurements from ground have been performed. In particular, Francis Laclare started in 1975 a series of radius measurements at Calern (Observatoire de la Côte d'Azur, France).

• These observations showed various evolutions of the solar radius at time scale of the 11-year solar cycle.

• The origin of these variations is unclear. It may be due to the observer, the atmosphere (turbulence) or the Sun itself..

• If a correlation between the solar radius and the solar activity is proved, it may serve as a proxy to reconstruct the evolution of the past solar irradiance for climate modeling.

• Solar radius can be derived from observations during solar eclipses since the 18th century.

• Simultaneous measurements from space and from ground using the same instrument could allow to separate the atmospheric effect from the true solar variation.

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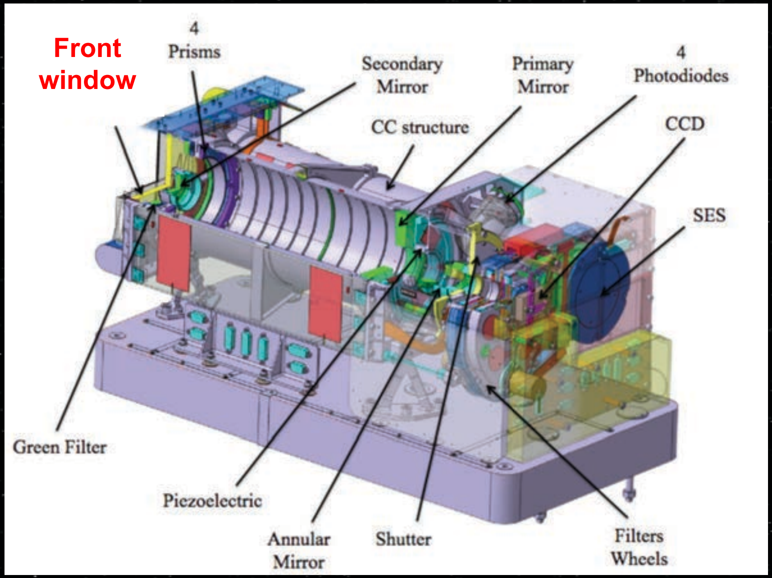
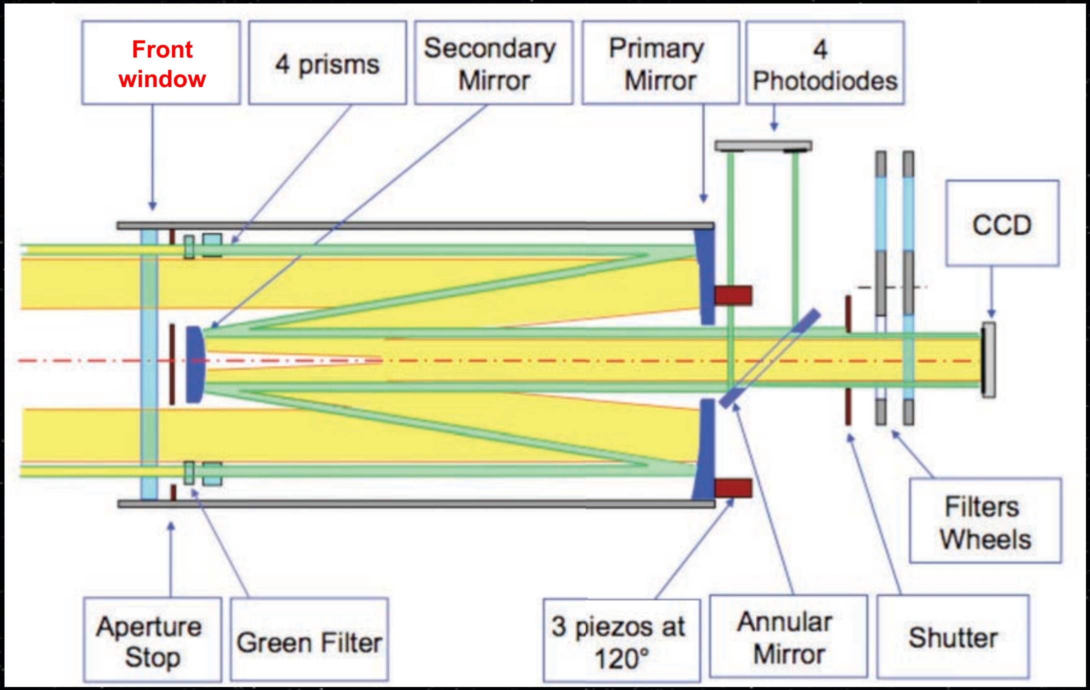
2 – The SODISM telescope of the PICARD space-based mission

SODISM is an 11-cm Ritchey-Chretien imaging telescope associated with a 2Kx2K Charge-Coupled Device (CCD), taking solar images at five wavelengths (215, 393.37, 535.7, 607.1 and 782.2 nm).



SODISM main characteristics:

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



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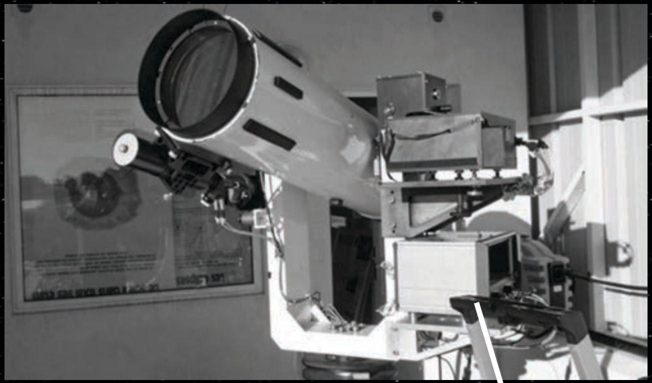
3 – PICARD SOL, our ground-based facility

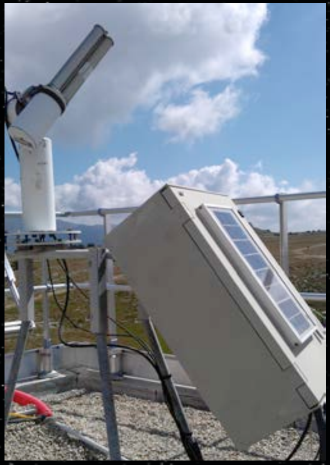
The main objectives of the PICARD SOL mission are:

- To understand the influence of the atmosphere on the solar radius measurements,
- To continue solar radius measurements with ground-based instruments.

Solar diameter telescope (SODISM II)

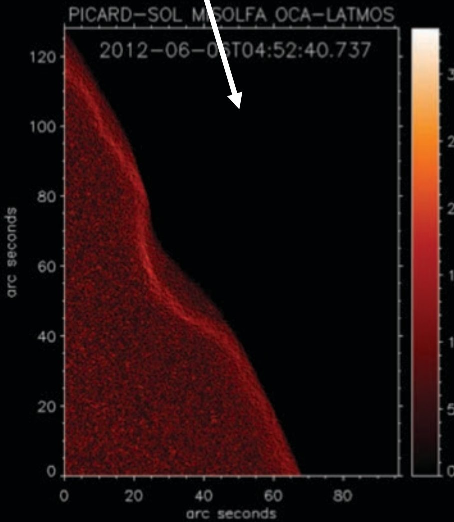


Turbulence monitor



Photometer

Pyranometer



During the 2012 transit of Venus

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- The PICARD mission and the scientific objectives
- The SODISM telescope of the PICARD space-based mission
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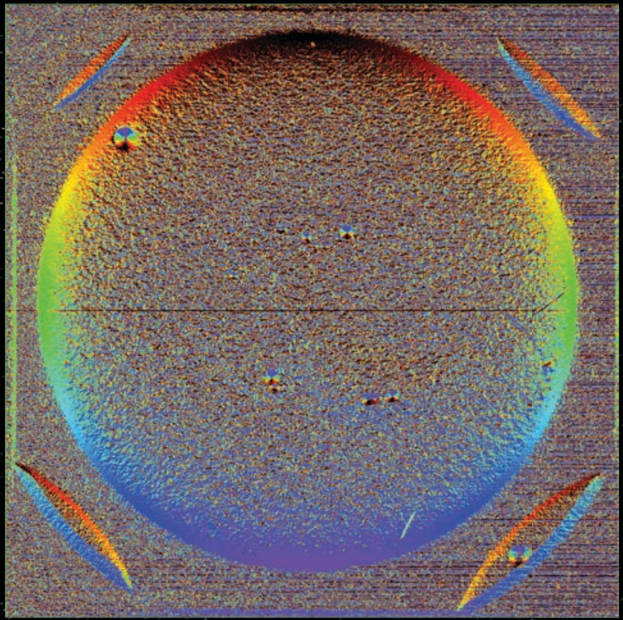
- Scientific results (solar radius absolute value)
- Conclusion

4 – Scientific results: solar astrometry (absolute value)

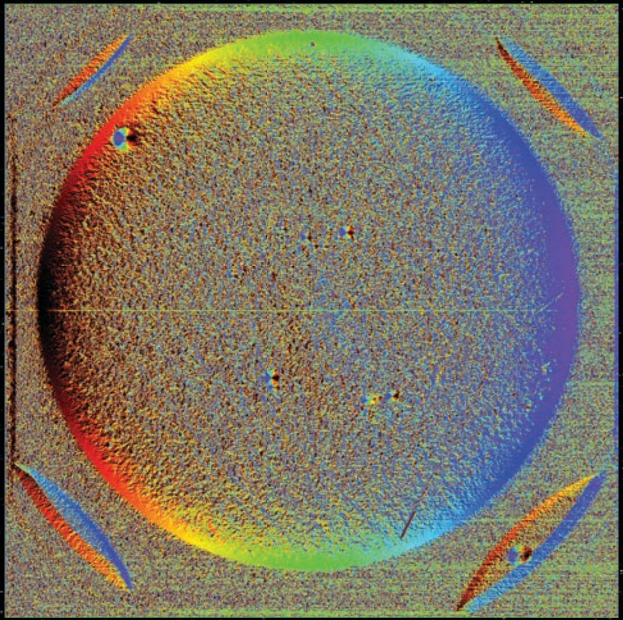
The transit of Venus on June 2012 provided a unique opportunity **to determine the absolute radius of the Sun** using solar imagers. The transit was observed from space by the PICARD spacecraft.

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

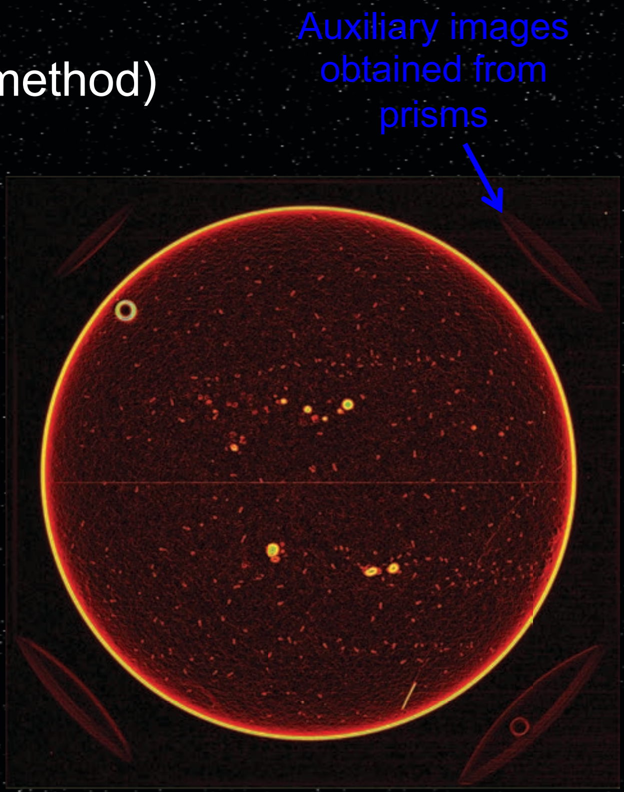
- Noise removal (median filter to remove outlier pixels then a Gaussian blur is applied to smooth the edges in the image).
- Extracting contours (using a Sobel filter and the Canny method)



Horizontal gradient



Vertical gradient

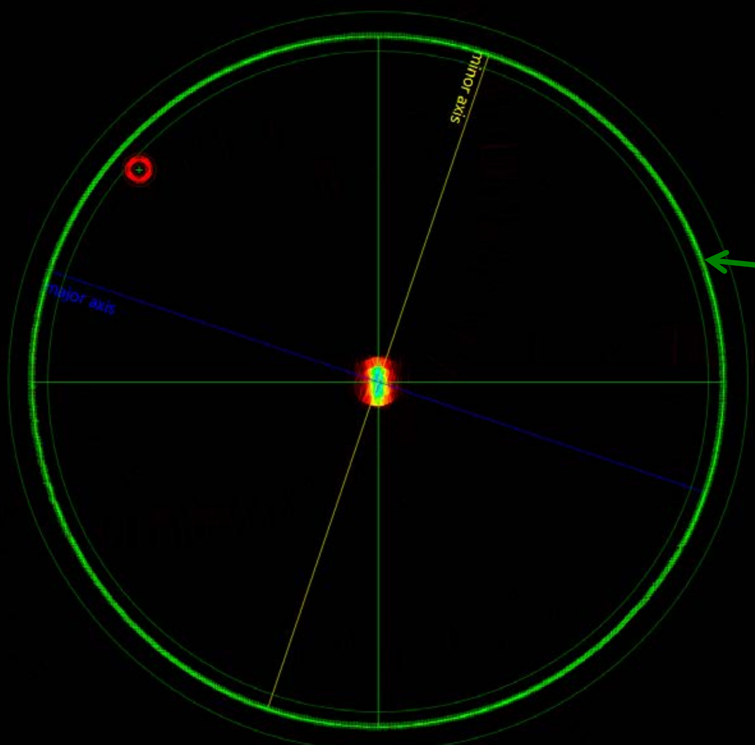


Norm of the gradient

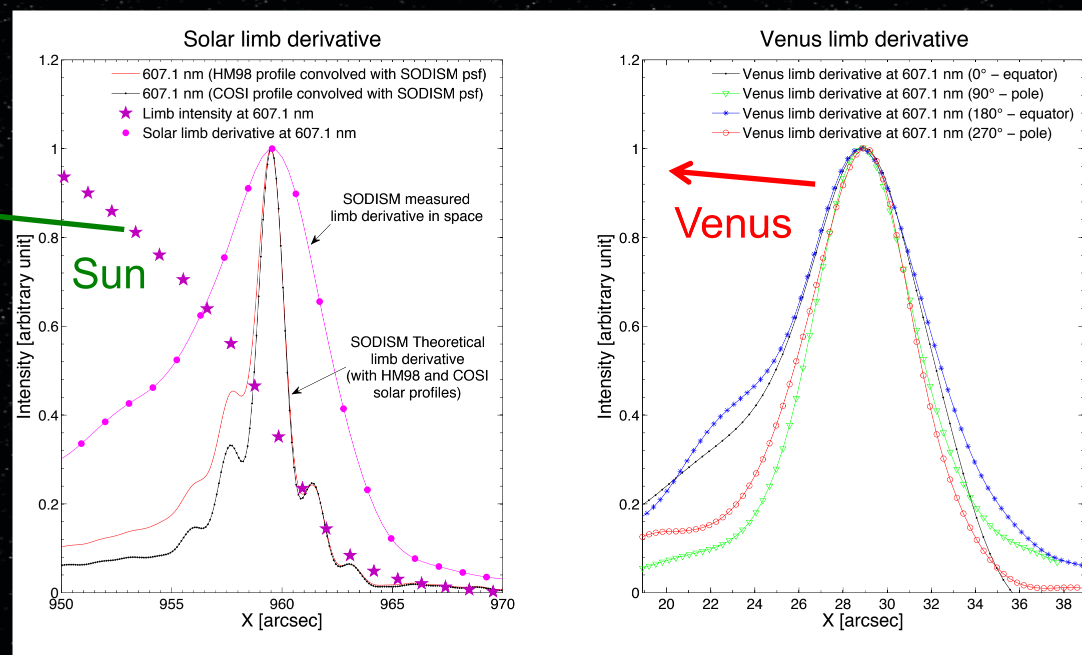
4 – Scientific results: solar astrometry (absolute value)

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: solar astrometry (absolute value)

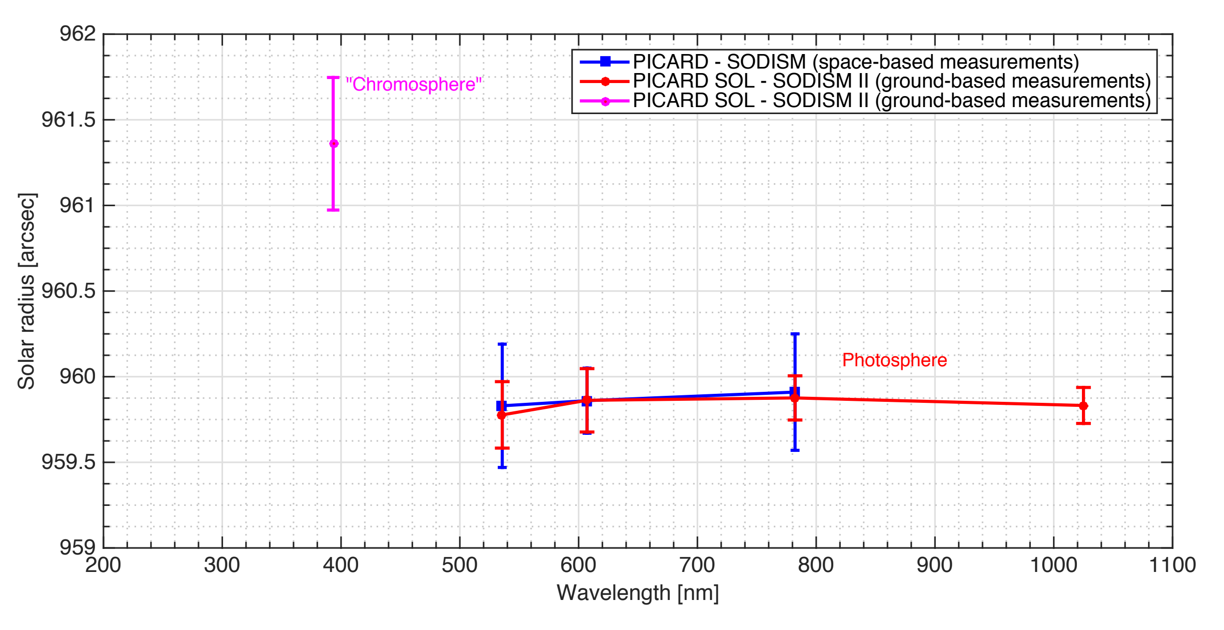
Summary of the PICARD solar radius observations at different wavelengths

λ [nm]	Δλ [nm]	Radius at 1 AU [(a)]	S (arc-seconds)	A (arc-seconds)	Experiment
535.7	0.5	959.83 arc-seconds	±0.15	±0.36	SODISM
607.1	0.7	959.86 arc-seconds	±0.06	±0.20	SODISM
782.2	1.6	959.91 arc-seconds	±0.19	±0.34	SODISM
393.37	0.7	961.360 arc-seconds	±0.106	±0.387	SODISM II
535.7	0.5	959.777 arc-seconds	±0.125	±0.194	SODISM II
607.1	0.7	959.862 arc-seconds	±0.126	±0.185	SODISM II
782.2	1.6	959.876 arc-seconds	±0.099	±0.129	SODISM II
1025.0	6.4	959.832 arc-seconds	±0.181	±0.105	SODISM II

Space-based

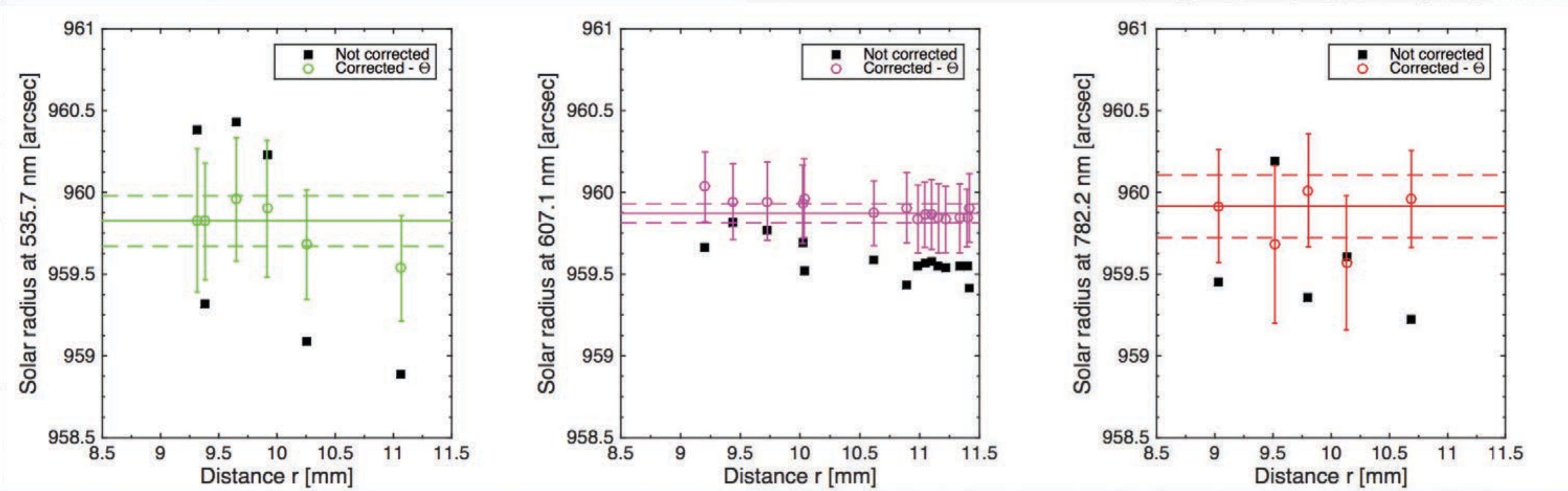
Ground-based

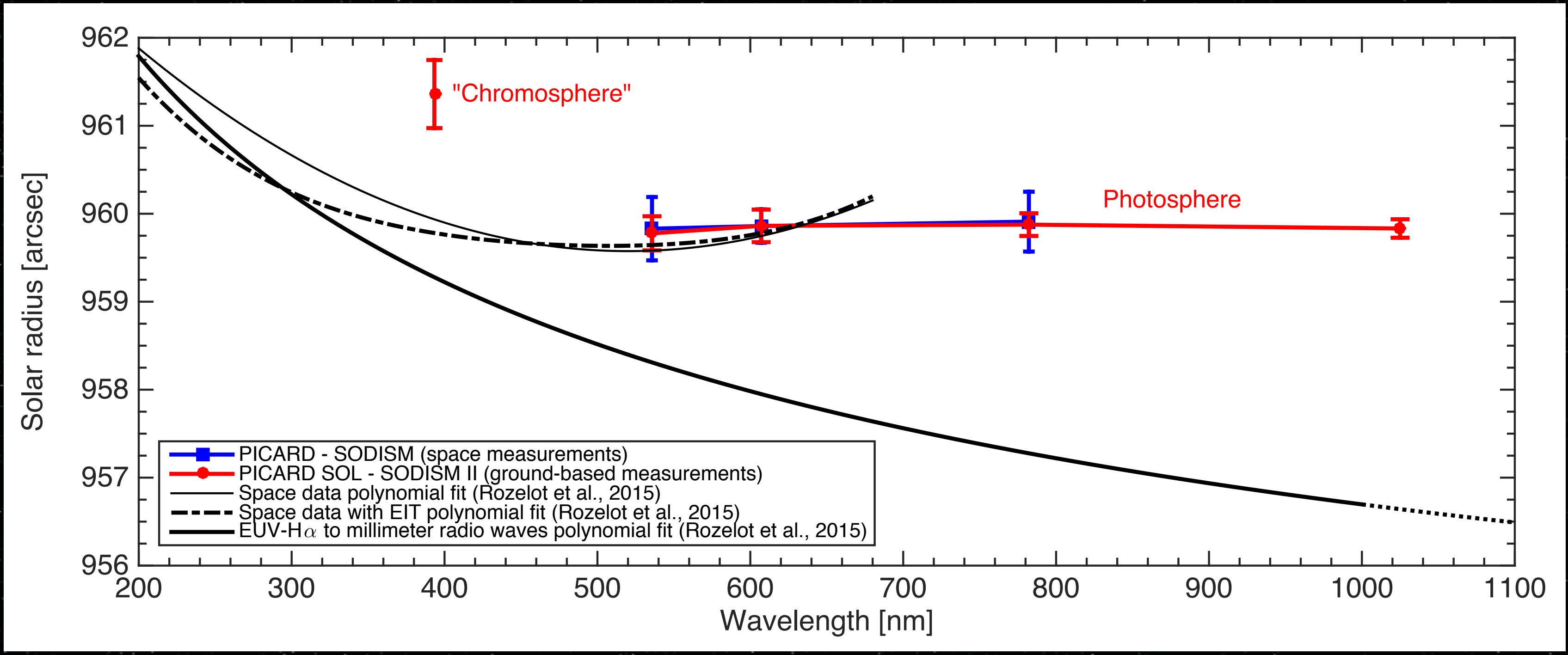
- S represents the standard deviation of the mean value (σ=1).
- A represents the absolute uncertainty (σ=1) in the determination of the solar radius with random and systematic errors.



R = 696,156 ±145 km
(PICARD) – 607.1 nm

4 – Scientific results: solar astrometry (absolute value)





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4 – Scientific results: solar astrometry (solar radius variations)

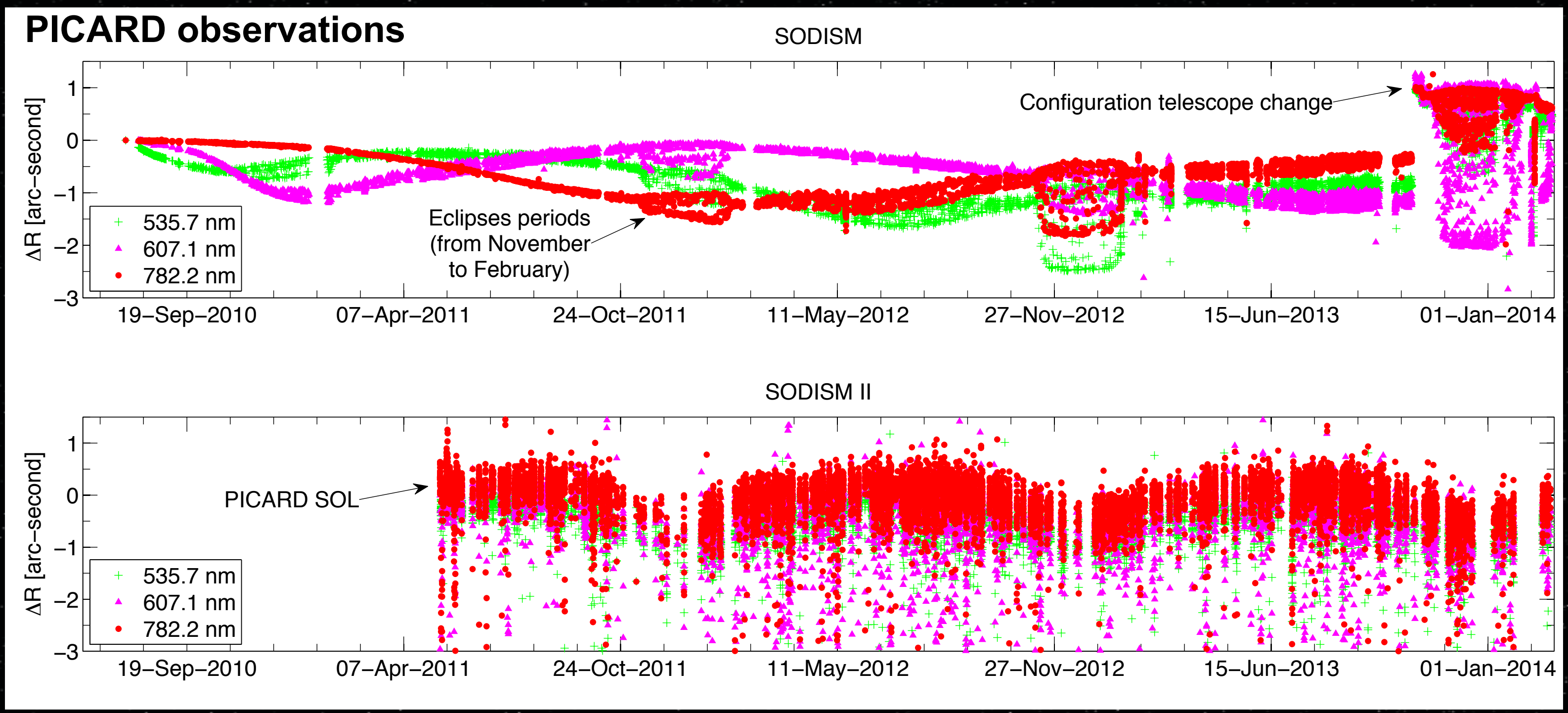
Measurements of the solar radius are of great interest within the scope of the debate on the role of the Sun in climate change.

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.

Before corrections



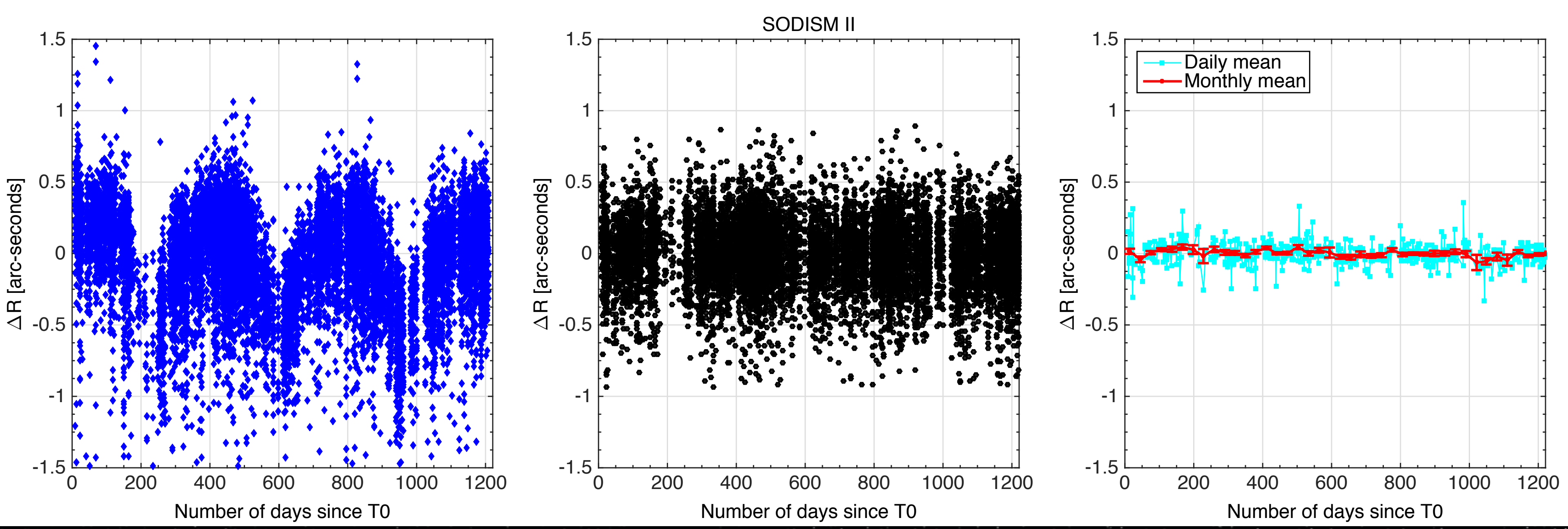
B) PICARD/SODISM space-based instrument

A) PICARD SOL ground-based facility

4 – Scientific results: solar astrometry (solar radius variations)

A) PICARD ground-based facility corrections – Refraction and turbulence

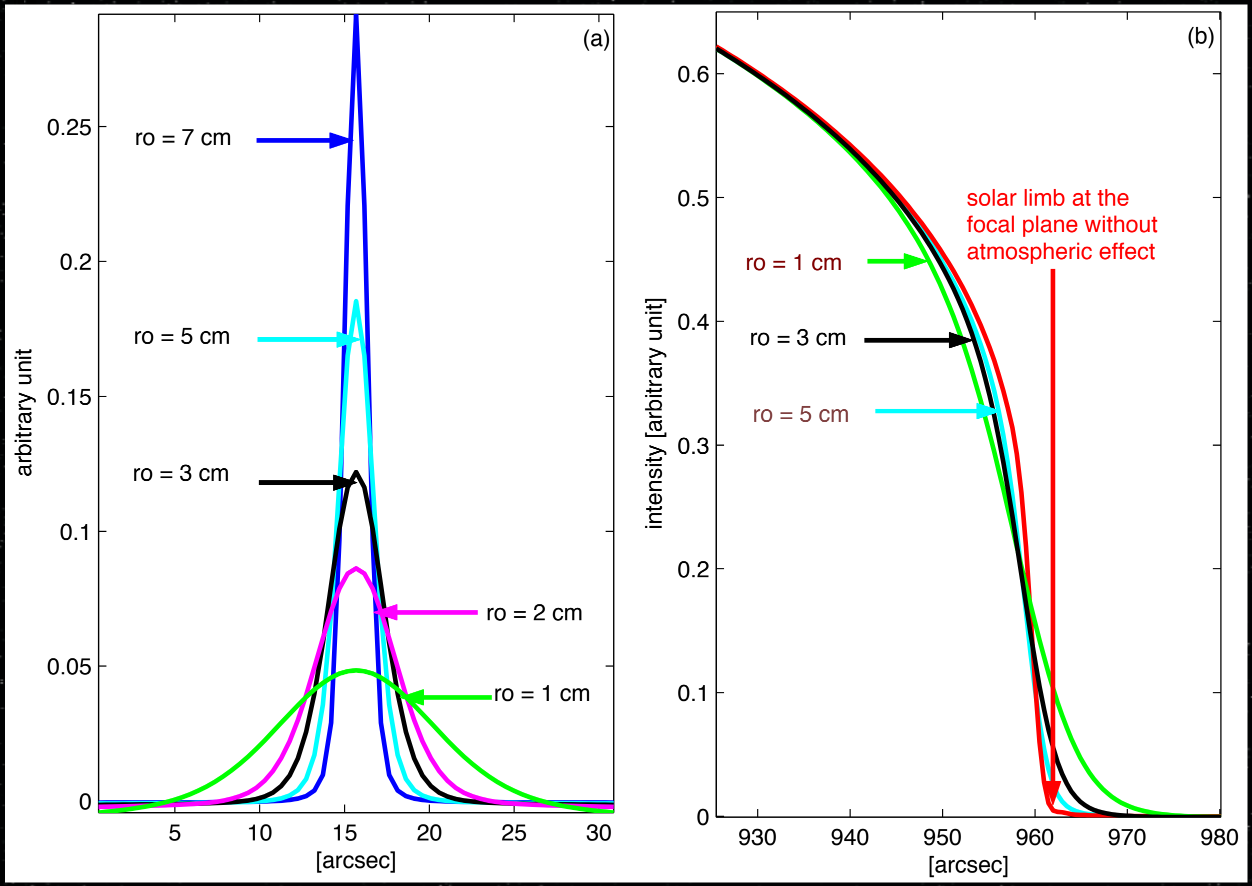
Astronomical refraction (Ref) influences the solar radius measurements (more than 1 arc-seconds for observations made above 70° of zenith distance) that we obtain from images taken with SODISM II.

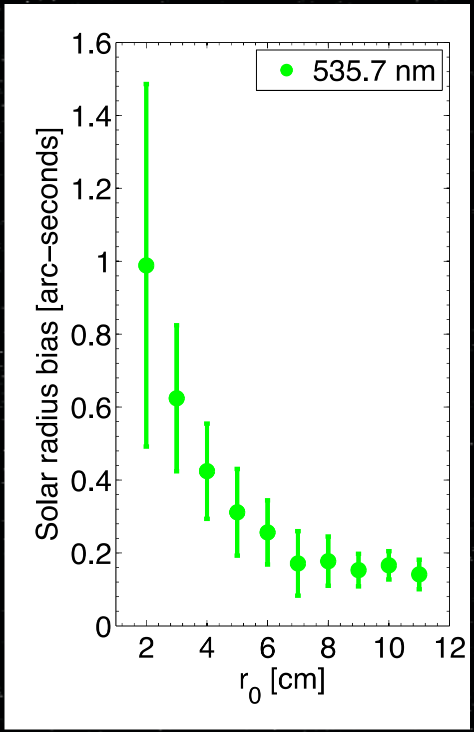


(Left) Evolution of the solar radii at one astronomical unit (uncorrected and corrected data for refraction with mean value of k) since the first measurements carried out by SODISM II in May 2011.

Corrections are classics. Our ground-based results (PICARD SOL) were corrected for the effects of refraction by numerical methods.

4 – Scientific results: solar astrometry (solar radius variations)





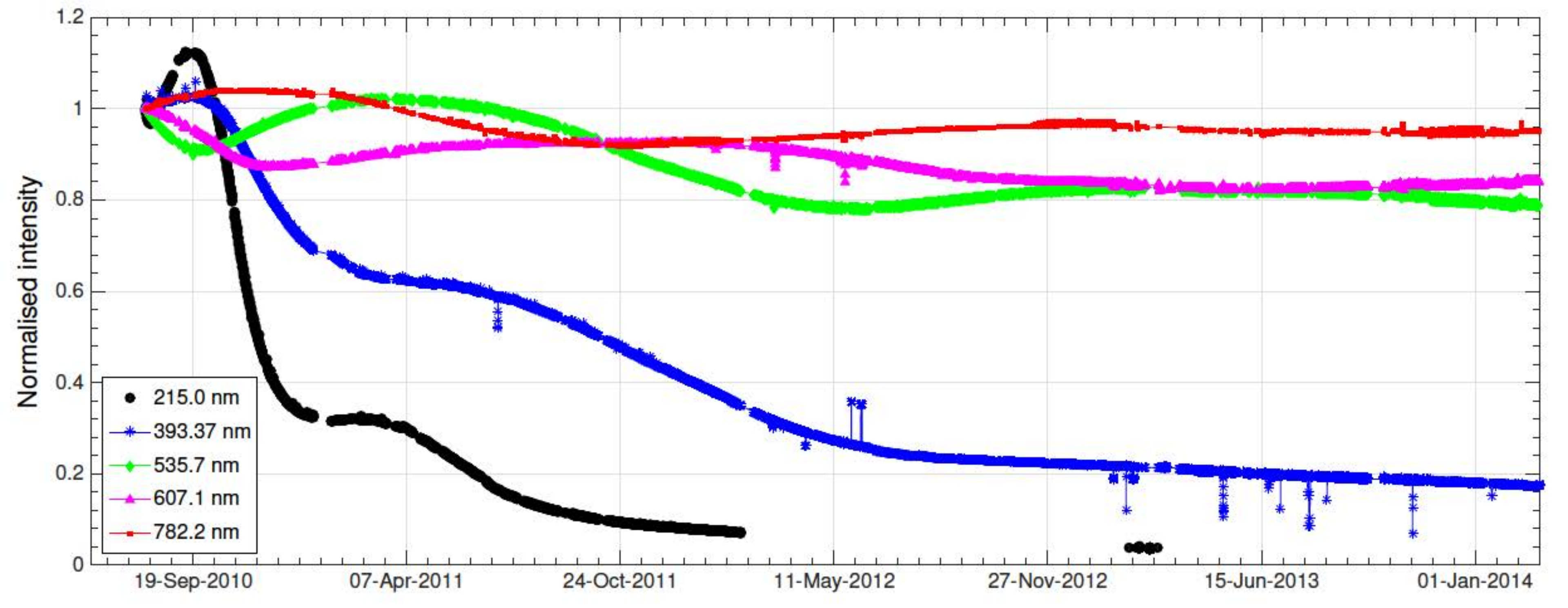
Our ground-based results (PICARD SOL) were corrected for the effects of (systematic bias linked with the Fried parameter (r0)). See Ikhlef et al., 2016

4 – Scientific results: solar astrometry (solar radius variations)

B) PICARD SODISM space-based instrument solar radius variations and corrections

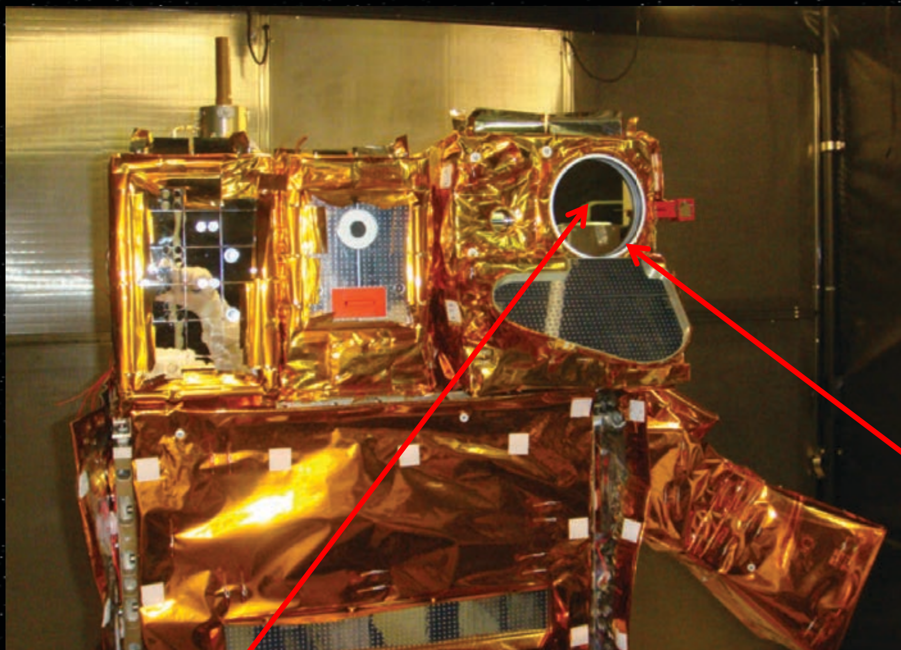
Several physical phenomena can lead to severe degradation of the optical performance of our space-based results (PICARD). In the case of SODISM, these effects entail solarization and polymerization of molecular contamination (**during the launch and in space**).

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



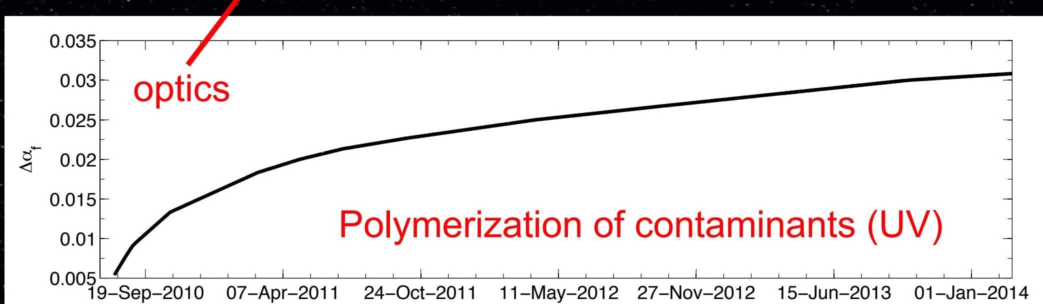
4 – Scientific results: solar astrometry (solar radius variations)

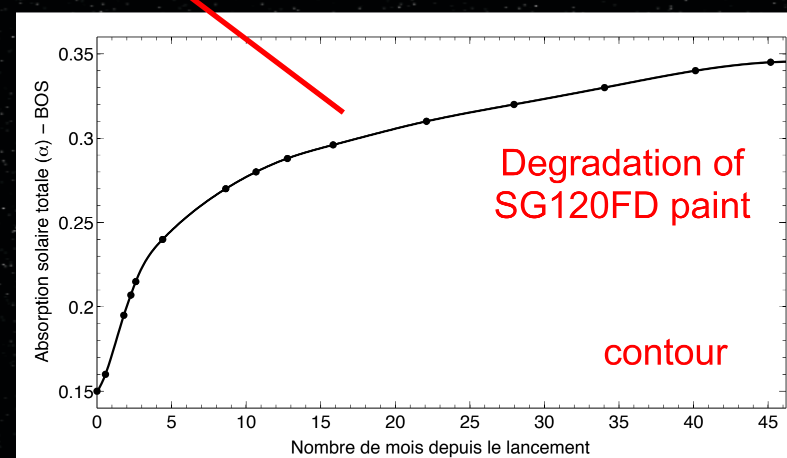
B) PICARD SODISM space-based instrument solar radius variations and corrections



Two different solar absorption evolutions (optics, contour)

→ **There is a very strong contamination of the satellite (due to solar panels, during the launch, etc.)**





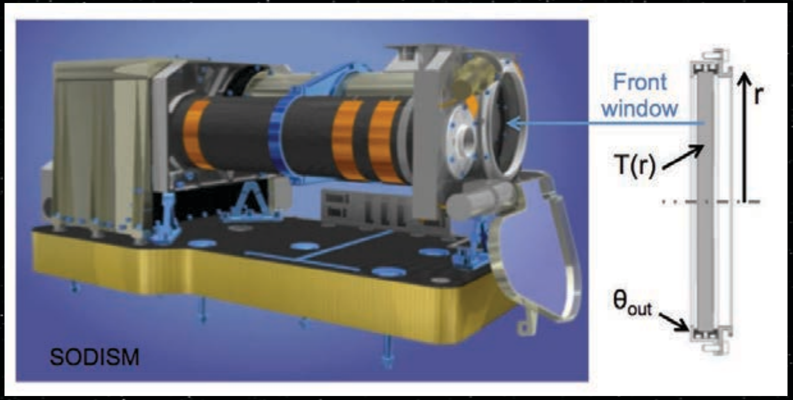
4 – Scientific results: solar astrometry (solar radius variations)

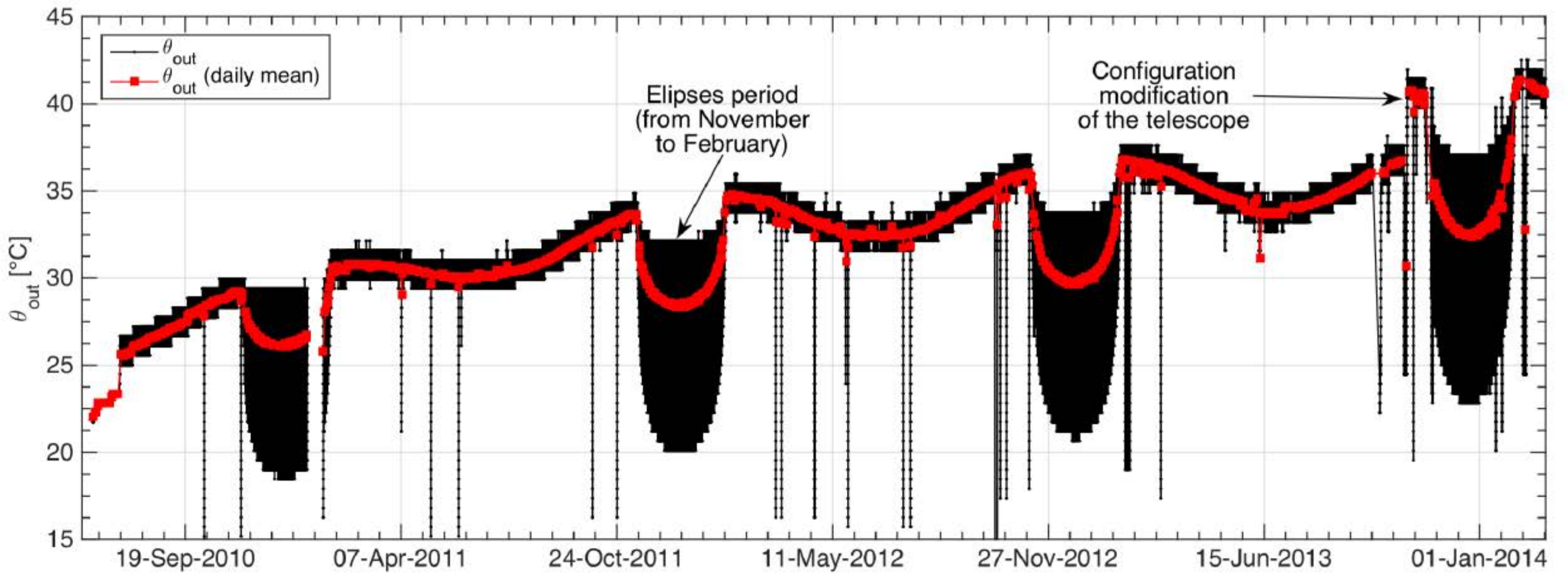
B) PICARD SODISM space-based instrument solar radius variations and corrections

--- 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: solar astrometry (solar radius variations)

B) PICARD SODISM space-based instrument measurements

We developed a end-to-end simulator to correct the "data" (thermo-optical effect).

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

SODISM intensities

Front window temperatures as function of housekeeping data

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

Wave-front and Zenike polynomials

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

Front window refractive index vs. temperature

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

$$E = \exp\left(2i \times \pi \times W_0\right)$$

Complex Wave-front

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

$$PSF_{SODISM} = \left(FFT2\left(E\right)\right)^2$$

Point Spread Function

Bi-dimensional fast Fourier transformer

Many instruments have this problem.

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

Limb darkening function → LDF_{SODISM}

Convolution

4 – Scientific results: solar astrometry (solar radius variations)

Optical model

$$w_0 = \sum_{k=1}^{36} C_k \times Z_k(\rho, \theta) \quad (1a)$$

$$C_3 = \frac{\delta \times D_{PS}^2}{16 \times \lambda \times f_S^2} + \frac{1}{2 \times \lambda} \times \frac{\partial n}{\partial T} \times h_w \times \Delta T(\alpha_f) \quad (1b)$$

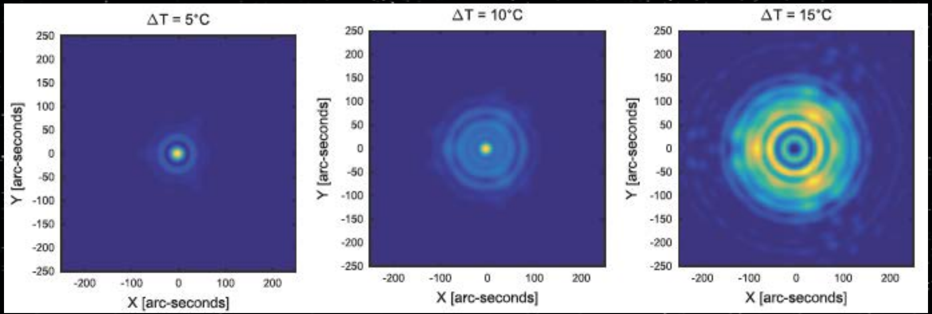
$$\frac{\partial n}{\partial T} = A_0 + A_1 \times \exp\left|\frac{-\lambda}{B_1}\right| + A_2 \times \exp\left|\frac{-\lambda}{B_2}\right|, \quad (1c)$$

$$W(P_x, P_y) = A_{D_{PS}} \times e^{2i \times \pi \times w_0} \quad (2a)$$

$$\mathrm{PSF_{SODISM}}(x, y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} W(P_x, P_y) \times e^{2i \times \pi \times (x \times P_x + y \times P_y)}\, dP_x\, dP_y \quad (2b)$$

$$\mathrm{LDF}(r_S, \lambda) = \sqrt{1 - r_S^2}^{\,\alpha_S(\lambda)} \quad (2c)$$

$$\mathrm{LDF_{SODISM}} = \int_{y_1}^{y_2} \mathrm{PSF_{SODISM}}(x, y)\, dy \otimes \mathrm{LDF}(r_S, \lambda). \quad (2d)$$



Model equations:

$$T_{it+1}(r, t) = T_\infty + \frac{\mathrm{Flux}(t)}{\varepsilon_{out} \times \sigma_b \times \overline{T(t)}} + C_1(t) \times J_0(i \times r \times C(t)) + C_2(t) \times Y_0(i \times r \times C(t)) \quad (3a)$$

$$\mathrm{Flux}(t) = \alpha_f(t) \times \varphi_S(t) + \varepsilon_{out} \times fv_{ir}(t) \times \varphi_{IR}(t) + \alpha_f(t) \times fv_a(t) \times \varphi_A(t) \quad (3b)$$

$$\overline{T(t)} = (T_\infty + T_{it}(r, t)) \times \left(T_\infty^2 + T_{it}(r, t)^2\right) \quad (3c)$$

$$C(t) = \sqrt{\frac{\varepsilon_{out} \times \sigma_b \times \overline{T(t)}}{\Lambda \times h_w}} \quad (3d)$$

$$C_1(t) = \left(-\theta_{out}(t) \times Y_1(i \times r_c \times C(t))\right) / \left(J_1(i \times r_c \times C(t)) \times Y_0(i \times r_{out} \times C(t)) - J_0(i \times r_{out} \times C(t)) \times Y_1(i \times r_c \times C(t))\right) \quad (3e)$$

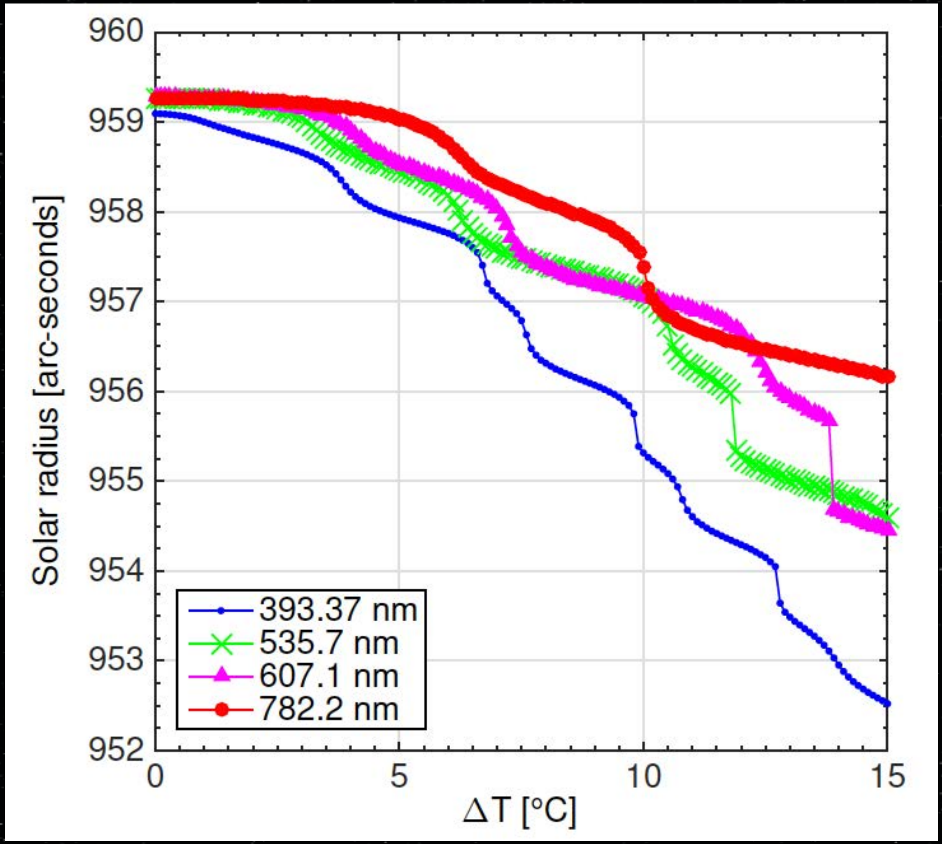
$$C_2(t) = \frac{-C_1(t) \times J_1(i \times r_c \times C(t))}{Y_1(i \times r_c \times C(t))}, \quad (3f)$$

Thermal model with Bessel functions

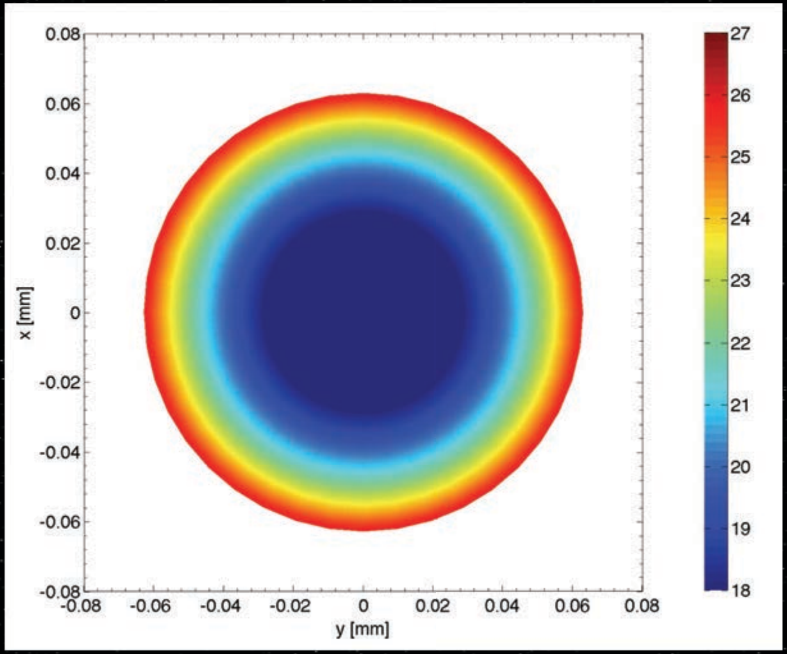
4 – Scientific results: solar astrometry (solar radius variations)

B) PICARD SODISM space-based instrument measurements

Relation between solar radius as seen by the instrument and the temperature gradient



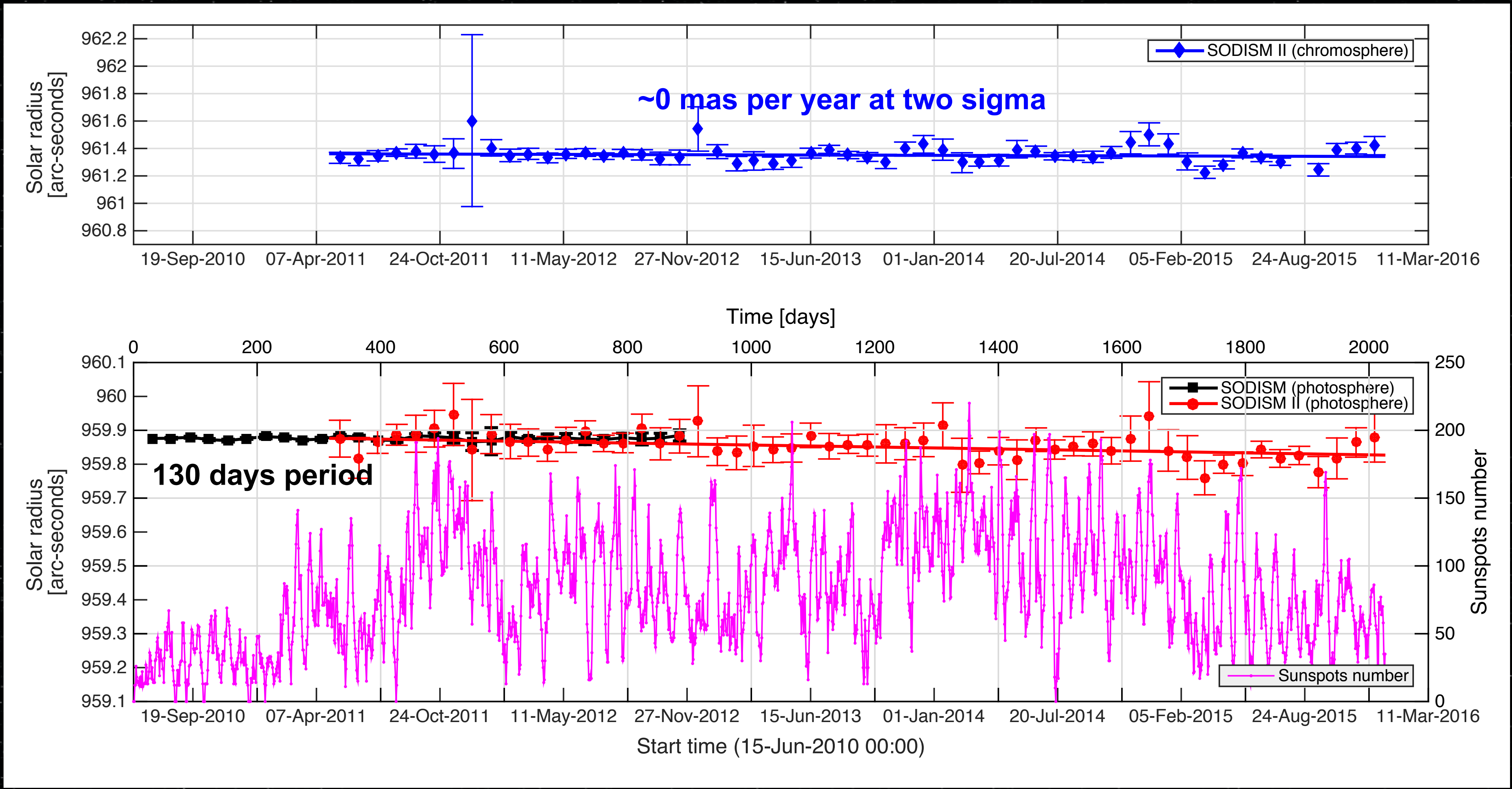
Evolution of the solar radius (determined by the inflection point position method) as a function of a temperature gradient for different wavelengths.



Temperature gradient on the SODISM front window

4 – Scientific results: solar astrometry (solar radius variations)

After corrections



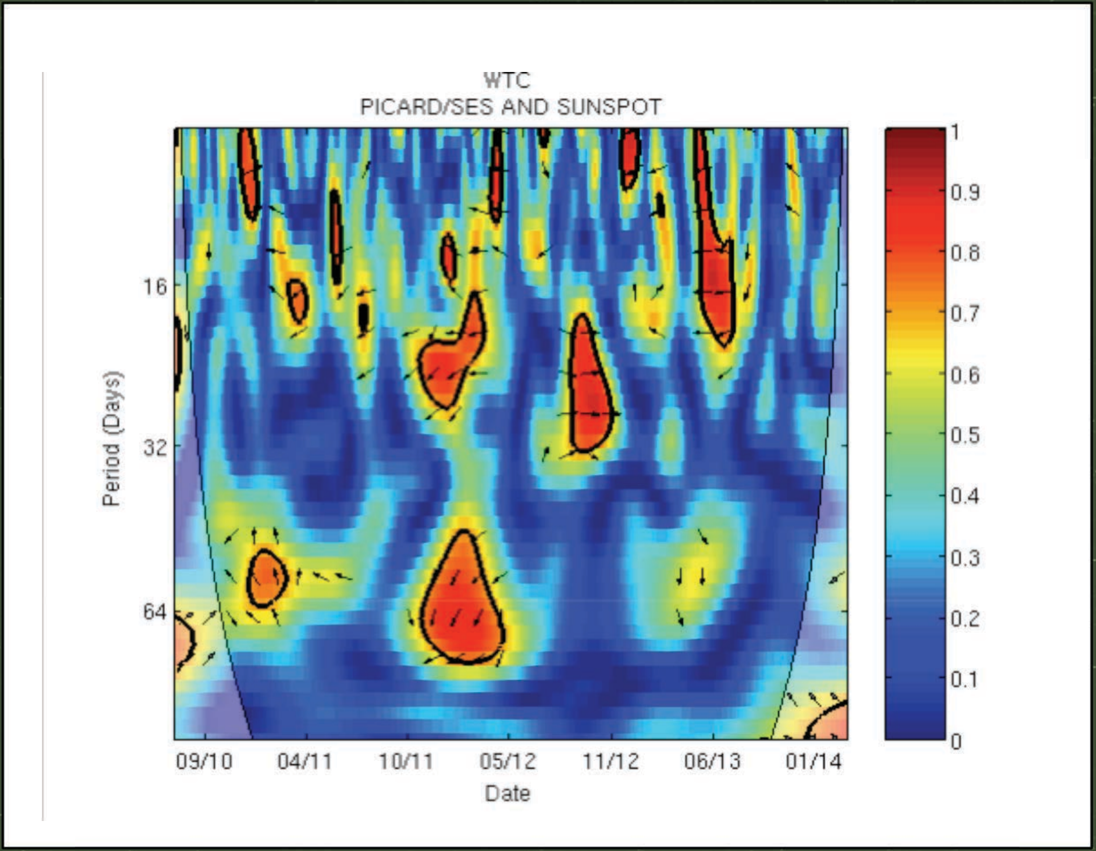
-7.5 +/-8 mas per year at two sigma (solar ? Instrumental Atmospheric ? Data analysis?) → very small variation

4 – Scientific results: solar astrometry (solar radius variations)

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

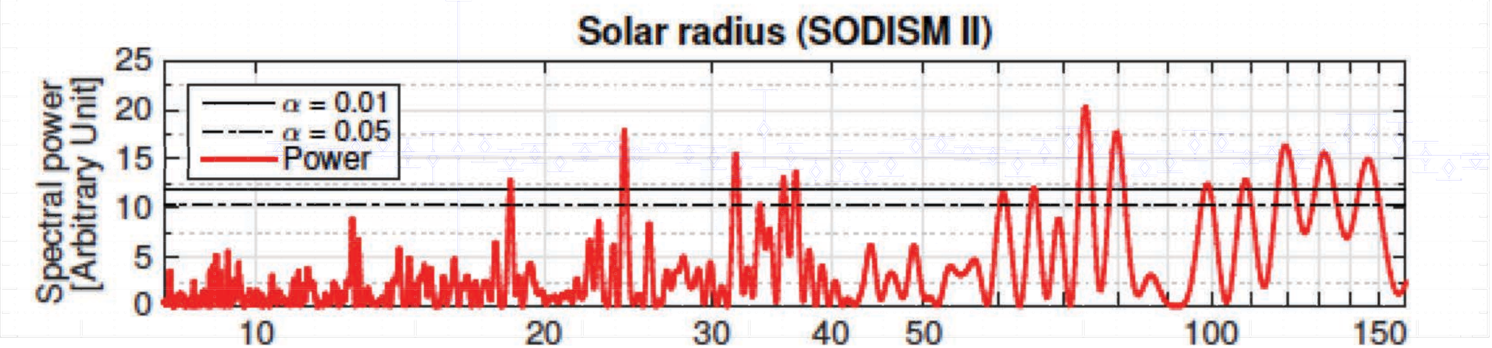
The most outstanding feature is an area of strong significant coherence centered around 59.5 days but extending vertically to about 45 and 80 days, and lasting for about seven months (from the end of 2011 to mid-2012). Smaller patches of strong coherence can also be found over the interval of the 16-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

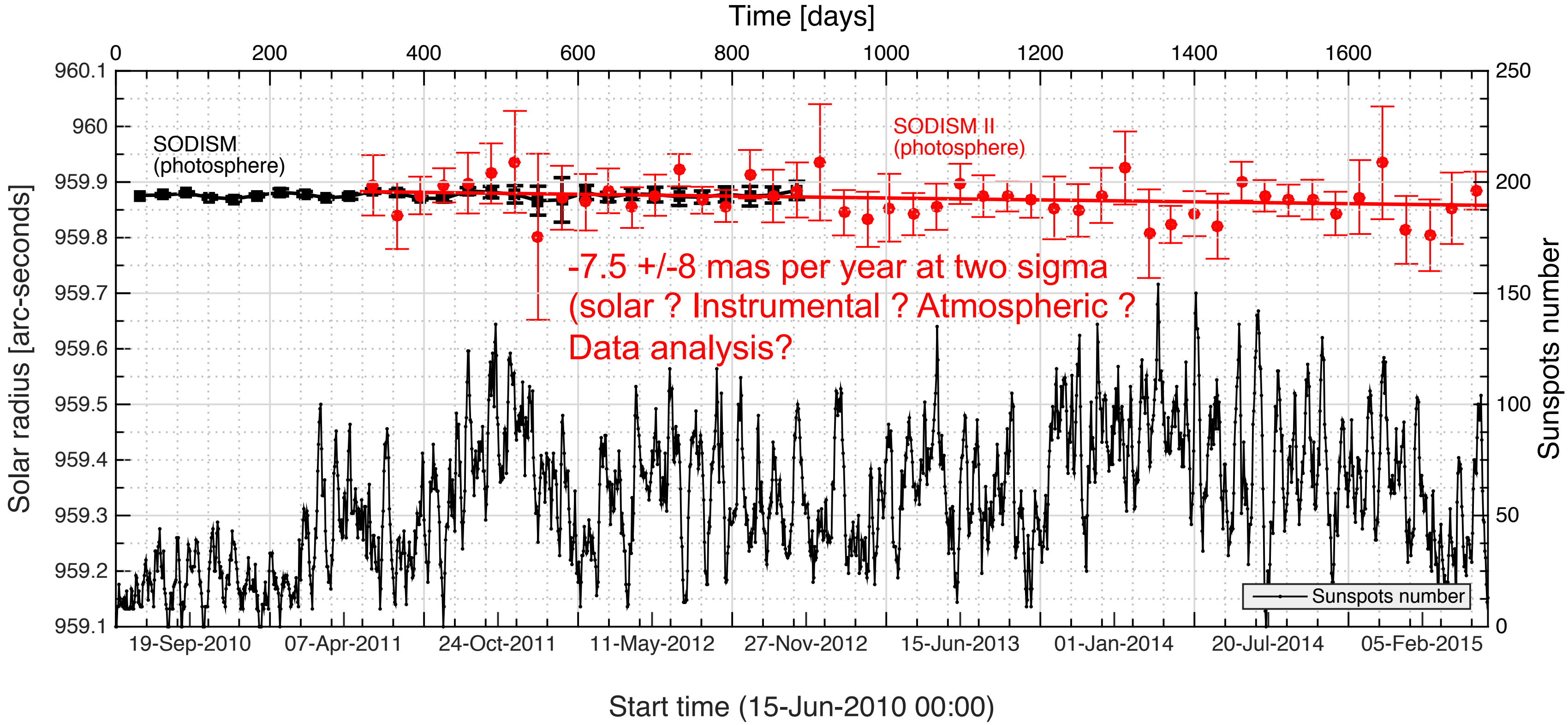
Wavelet Transform Coherence (WTC) between sunspot and SES. Solid contour lines represent the 95 %confidence level. Arrows represent the relative phase between sunspot and SES time series. The cone-of-influence is represented by the pale areas at the vertical edges of the figure.



4 – Scientific results: solar astrometry (solar radius variations)

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

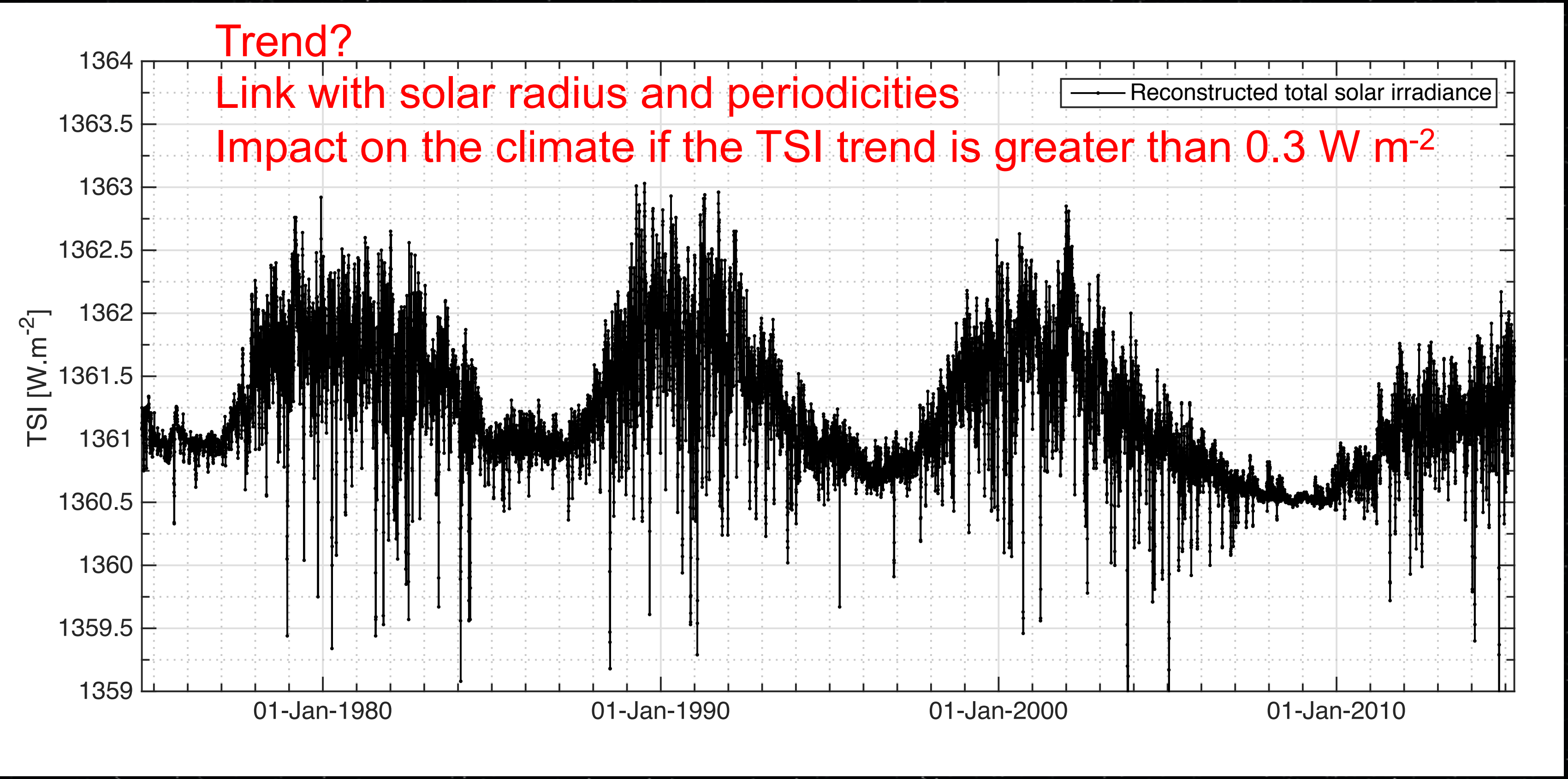




4 – Scientific results: solar astrometry (solar radius variations)

It's important to continue to measure this essential climate variable.

- The total solar irradiance (TSI) is measured to vary by approximately of +/-0.05 % (over the last three 11-year cycles).
- Composite TSI time series (ACRIM, PMOD), TSI space-based radiometers, or models (SATIRE) highlight differences for the solar minima.



Presentation outline

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

Conclusion

The measurements taken by the instruments on board the *PICARD* satellite were completed by the ground-based measurements.

This has made it possible to understand and model the disruptive effect of the Earth's atmosphere on solar observations conducted from the ground. Among the ground-based instruments, a replica of the SODISM imaging telescope coupled to a MISOLFA turbulence monitor were and continue to be used.

Measurements performed by instruments on the PICARD mission have allowed us to establish the evolution of the solar radius during the rising phase of solar cycle 24. It highlights the complementarity of the measurements made on the ground and outside the atmosphere. For this, we developed specific methods in order to correct the various measurements.

<u>Main results:</u>

- Determination of the absolute value of the solar radius
- Weak wavelength dependence of the solar radius
- Solar radius variations less than 20 mas

Thank you for your attention