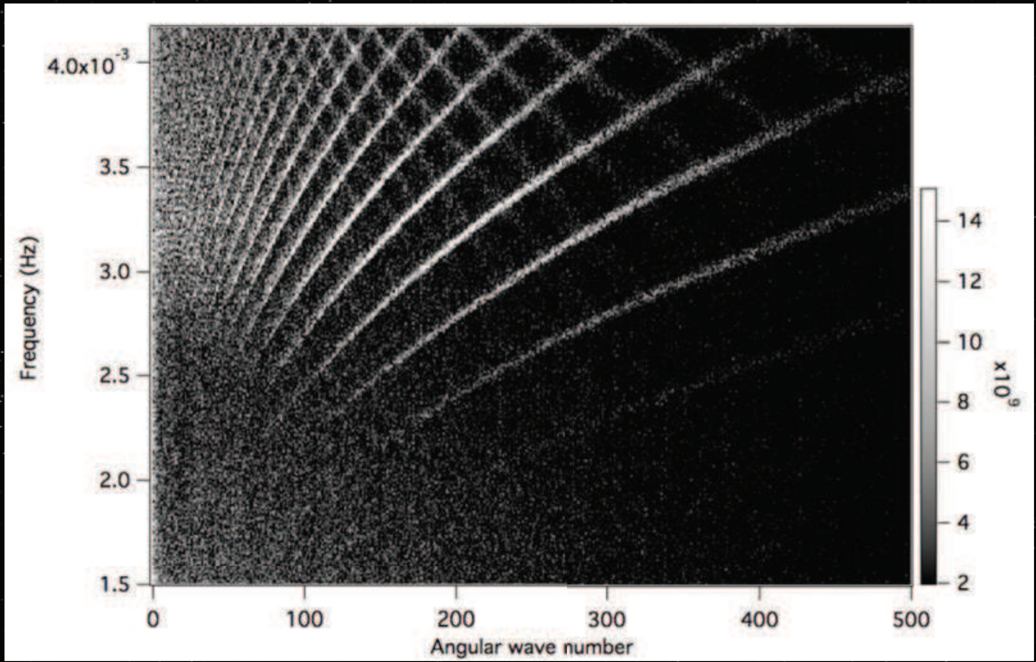
Helioseismology

4 – Scientific results

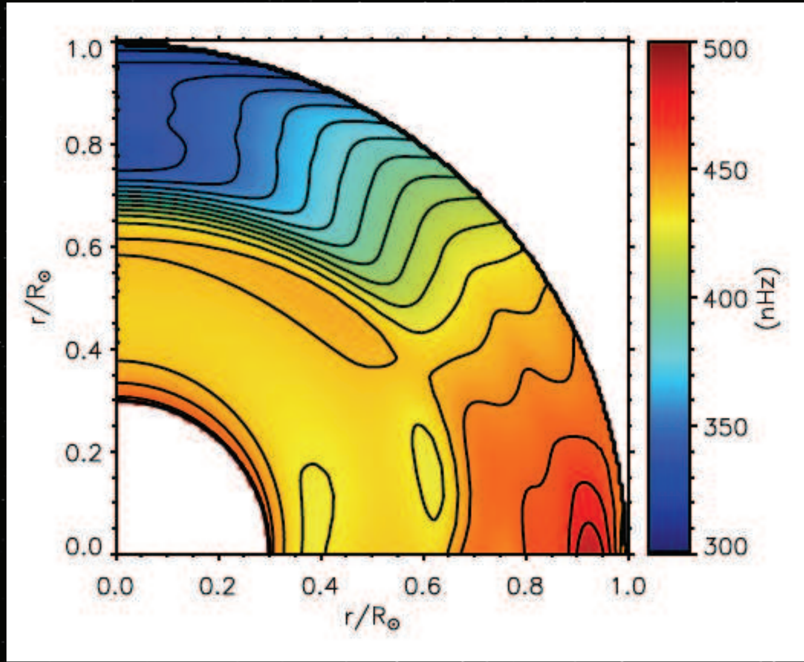
Helioseismology

- 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).

Hauchecorne et al, 2013

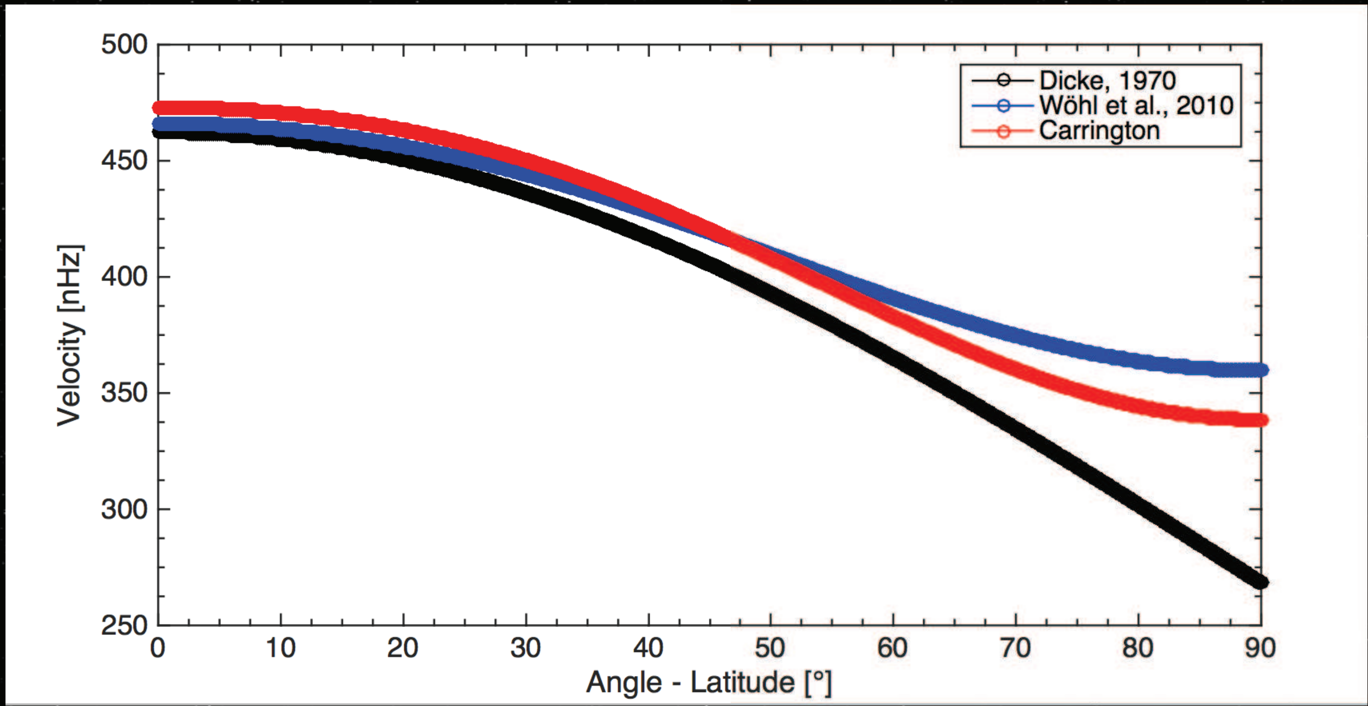


Symmetric part of the internal solar rotation rate with respect to the equator (with SODISM intensity images over the period from April to November 2011).

Corbard et al, 2013

4 – Scientific results

Solar rotation surface



$$\Delta_\odot = \varepsilon_q + \varepsilon_s \simeq \frac{3}{2} J_2 + \frac{1}{2} \frac{\Omega^2 R_\odot^3}{G M_\odot},$$

Link between solar oblateness and solar roation surface

$$\Delta_\odot = (R_{eq} - R_{pol}) / R_{pol}$$

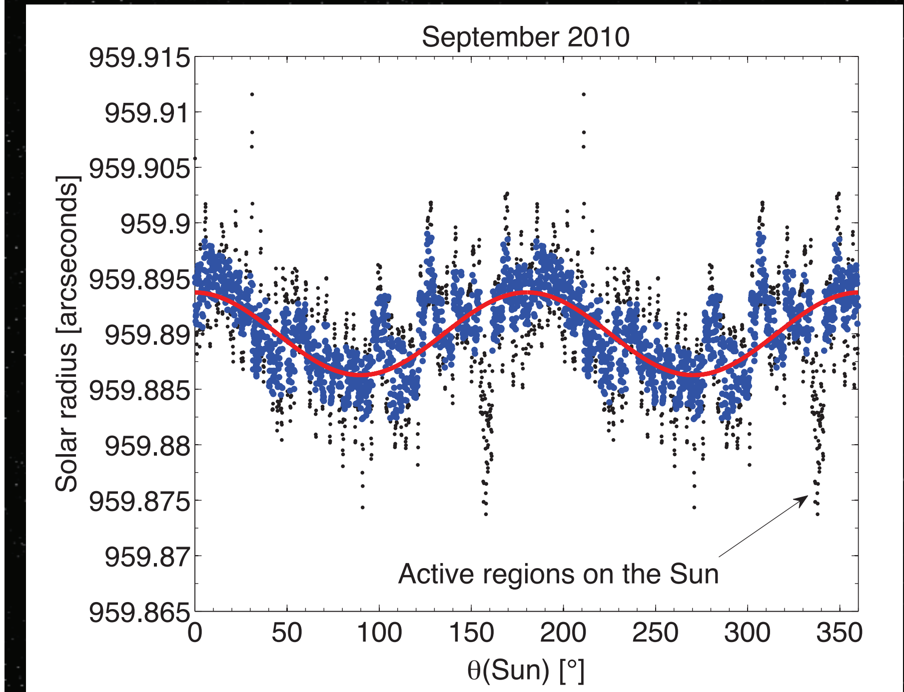
ε_q is a measure of the distortion of the gravitational potential produced by internal rotation, and ε_s is linked to the oblateness produced by the surface rotation.

J_2 is the gravitational quadrupole moment.

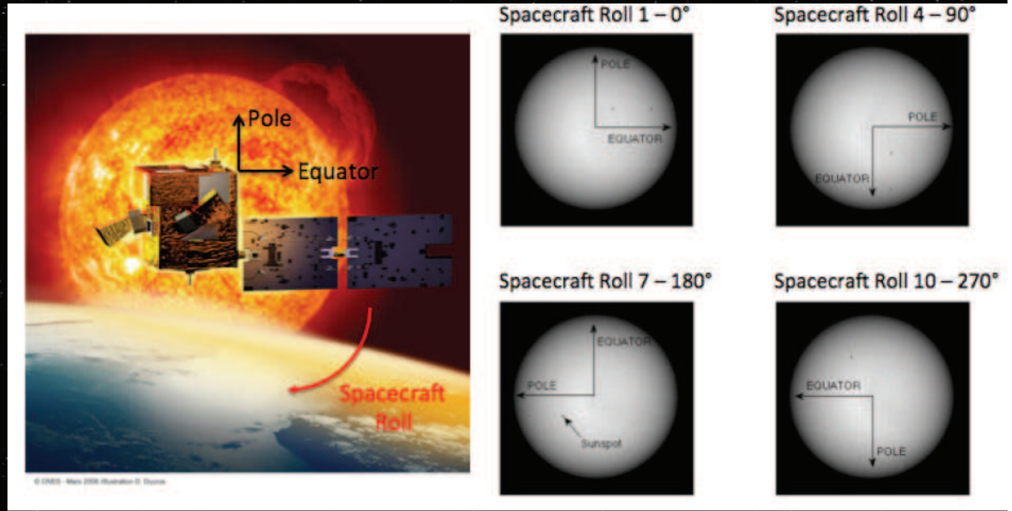
Solar oblateness

4 – Scientific results

Solar oblateness



Solar oblateness determination during such campaigns.



The spacecraft revolve around the PICARD-Sun axis by steps of 30° (distortion) and during a full orbit for each step (thermal evolution).

Method

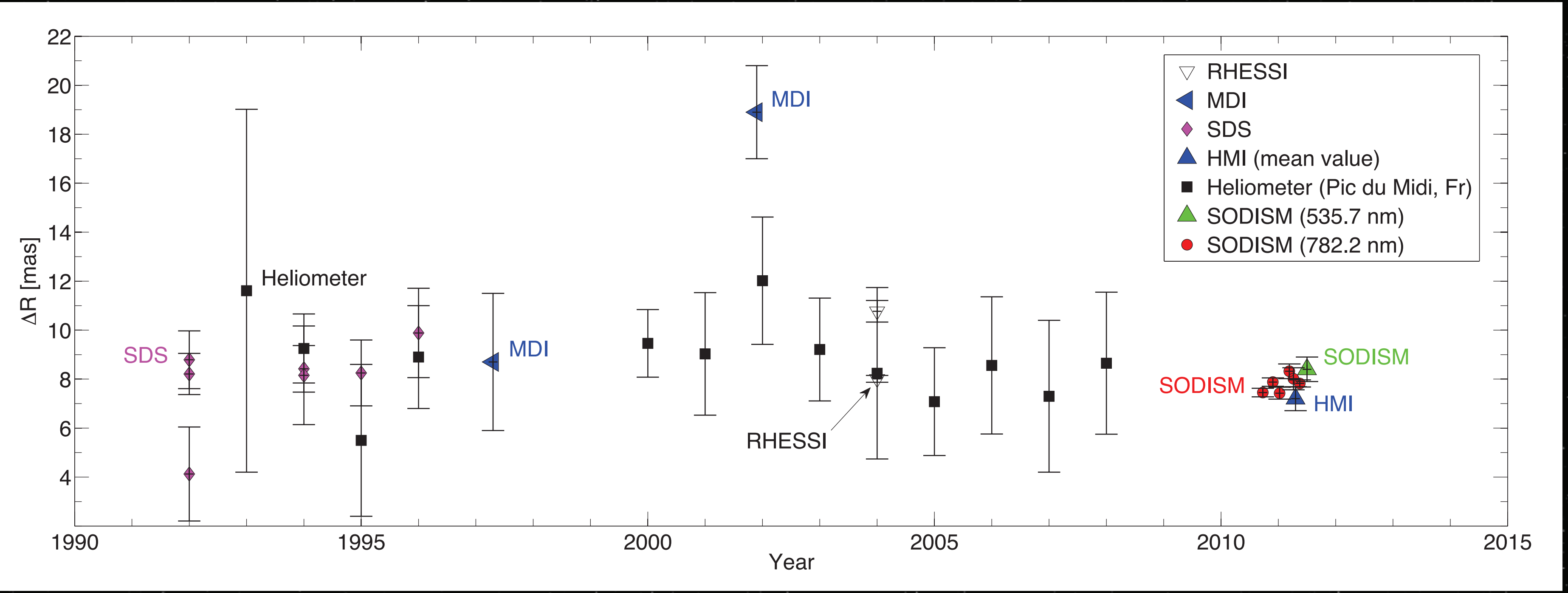
$$\langle R\rangle = \frac{1}{N \times N_\theta} \sum_{m=1}^{N} \sum_{n=1}^{N_\theta} R_{(m,n)}$$

$$Rc_{(i,j)} = R_{(i,j)} + \left(\langle R\rangle - \frac{1}{N_\theta}\sum_{n=1}^{N_\theta} R_{(i,n)}\right) + G \times \left(T_{(i)} - \frac{1}{N}\sum_{m=1}^{N} T_{(m)}\right) + k_{(j)} \times \left(\langle R\rangle - \frac{1}{N}\sum_{m=1}^{N} R_{(m,j)}\right)$$

→ ΔR = **8.1± 0.6 mas** (from the mean value of the two PICARD wavelengths)

4 – Scientific results

Re - Rp = 5.9 ±0.5 km (PICARD)



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

Using differential methods (spacecraft rotation) allows to obtain good results (low uncertainty).

Indeed, the source (the Sun) does not change during the measurement, only the instrument evolves (thermal, etc.).

4 – Scientific results

Solar shape and Legendre polynomial

$$r(\Theta) = <r> \times \left(1 + \sum_{l=2,4} C_l \times \bar{P}_l(\cos(\Theta))\right) =$$

$$<r> \times \left(1 + C_2 \times \frac{1}{4} \times (3 \times \cos(2\Theta))\right) +$$

$$<r> \times \left(C_4 \times \frac{1}{64} \times (35 \times \cos(4\Theta) + 20 \times \cos(2\Theta))\right)$$

$$\Delta r_a = r\left(\frac{\pi}{2}\right) - r(0) = <r> \times \left(-\frac{3}{2}C_2 - \frac{5}{8}C_4\right),$$

PICARD - 535 nm (Irbah et al., 2014)
July 2011
C_2 = (−5.71 +/- 0.36) 10^{-6}
C_4 = (−0.36 +/- 0.43) 10^{-6}

PICARD – 782 nm (Meftah et al., 2014)
May 2011
C_2 = (−5.98 +/- 0.33) 10^{-6}
C_4 = (−1.38 +/- 0.40) 10^{-6}

C_2 (quadrupole coefficient)
C_4 (hexadecapole coefficient) determination is very difficult.

Mercury's perihelion precession:	574 arcseconds/century
Newtonian perturbations from other planets:	531 arcseconds/century
GR correction:	43 arcseconds/century
Newtonian correction from Dicke bulge:	3 arcseconds/century

PICARD
ΔR = **8.1± 0.6 mas**

Here's the data, again from Will's book:

Amount predicted by conventional solar models	0.2 km, 0.1 ppm
Dicke-Goldenberg (1966)	52 km, 40 ppm
Hill (1973)	2 km, 1 ppm
Hill (1982)	10 km, 7 ppm
Dicke (1985)	24 km, 12 ppm

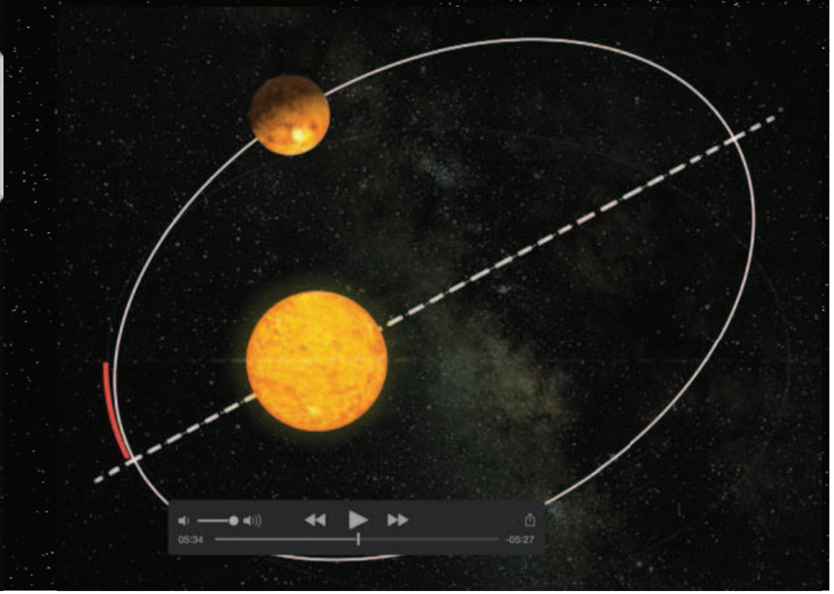
Estimates of the gravitational quadrupole moment **J2** were found by Pijpers (1998) and Antia et al. (2008) with helioseismic data. J2 is close to 2.2 10^{-7}. Thus, ΔR is close to 8 mas.

4 – Scientific results

$$\Delta\omega = \frac{6GM_{\odot}}{a\left(1-e^{2}\right)} + J_{2}\frac{R_{\odot}^{2}\left(3\sin^{2} i - 1\right)}{a^{2}\left(1-e^{2}\right)^{2}}$$

The result is a value that agrees with general relativity.
The results again give a quadrupole moment on the order of 10^{-7}, too small to affect the agreement between general relativity and the observed advance of Mercury's perihelion.

42.98 arcseconds per century

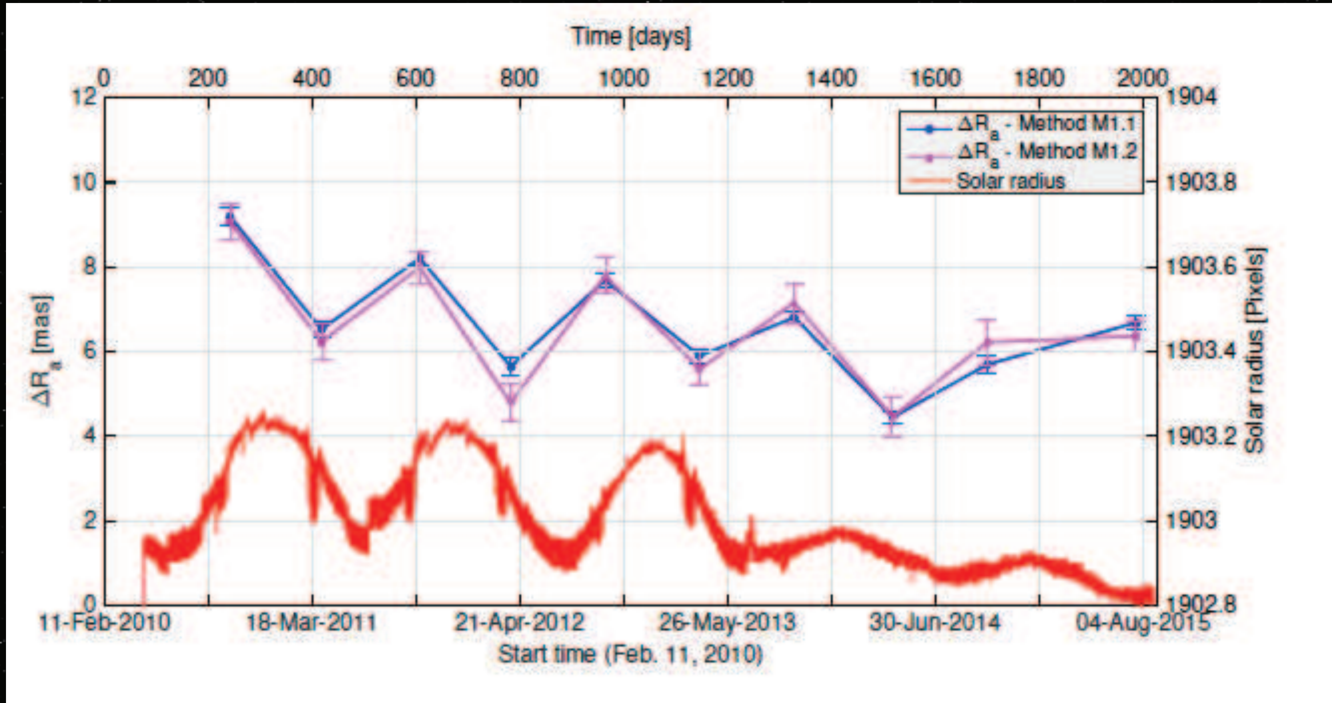


4 – Scientific results

Date	Authors	ΔR [mas]	Instrument
1961-2003	Pitjeva (2005)	8.05 ±0.04	Radar Observations
1992	Egidi et al. (2006)	4.13 ±1.92	SDS
1993-2008	Reis Neto et al. (2003)	13 ±4	Rio de Janeiro solar astrolabe
1994	Egidi et al. (2006)	8.16 ±2.02	SDS
1995	Egidi et al. (2006)	8.25 ±1.34	SDS
1996	Egidi et al. (2006)	9.88 ±1.82	SDS
1997	Emilio et al. (2007)	8.7 ±2.8	SoHO/MDI
1998-2000	Damiani et al. (2011)	8.8 ±1.7	Pic du Midi heliometer
2001	Emilio et al. (2007)	18.9 ±1.9	SoHO/MDI
2002-2008	Fivian et al. (2008)	8.01 ±0.14	RHESSI/SAS
2010-2011	Meftah et al. (2015b)	7.9 ±0.3	PICARD/SODISM
2010-2012	Kuhn et al. (2012)	7.2 ±0.49	SDO/HMI
2011	Irbah et al. (2014)	8.4 ±0.3	PICARD/SODISM

4 – Scientific results

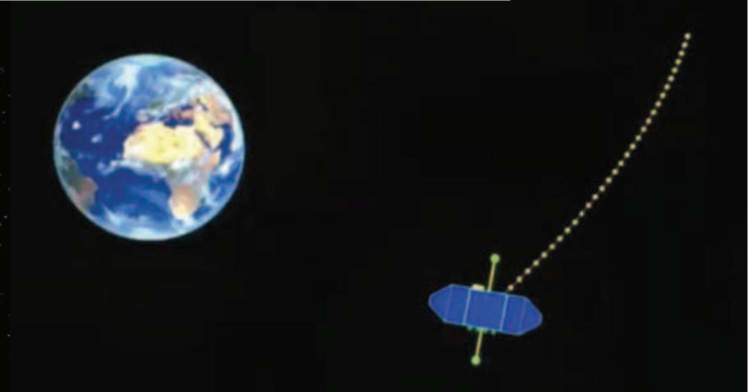
Application of our method on SDO-HMI



New method (work in progress)

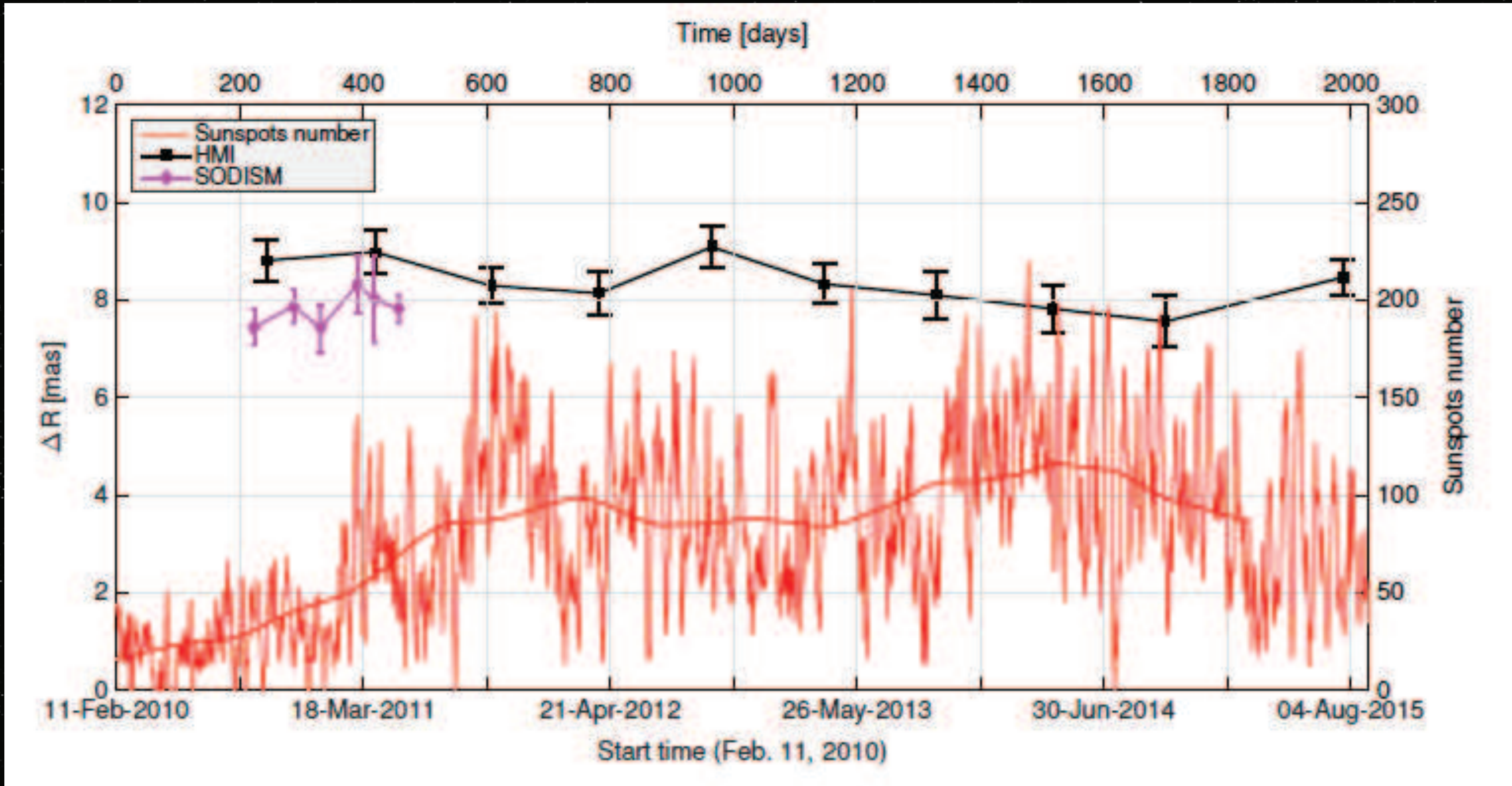
$$< R >= \frac{1}{N \times N_\theta} \sum_{m=1}^{N} \sum_{n=1}^{N_\theta} R_{(m,n)}$$

$$Rc_{(i,j)} = R_{(i,j)} + \left(< R > - \frac{1}{N_\theta} \sum_{n=1}^{N_\theta} R_{(i,n)} \right)$$



A solar oblateness measurement campaign is made in less than 7hours (10 minutes without acquisition followed by 7.5 minutes of observing time for each position during the roll).
The HMI instrument needs more than five hours to have a state of equilibrium (transient steady state before the roll maneuver). Cooperation between SDO-HMI team and PICARD team.

4 – Scientific results



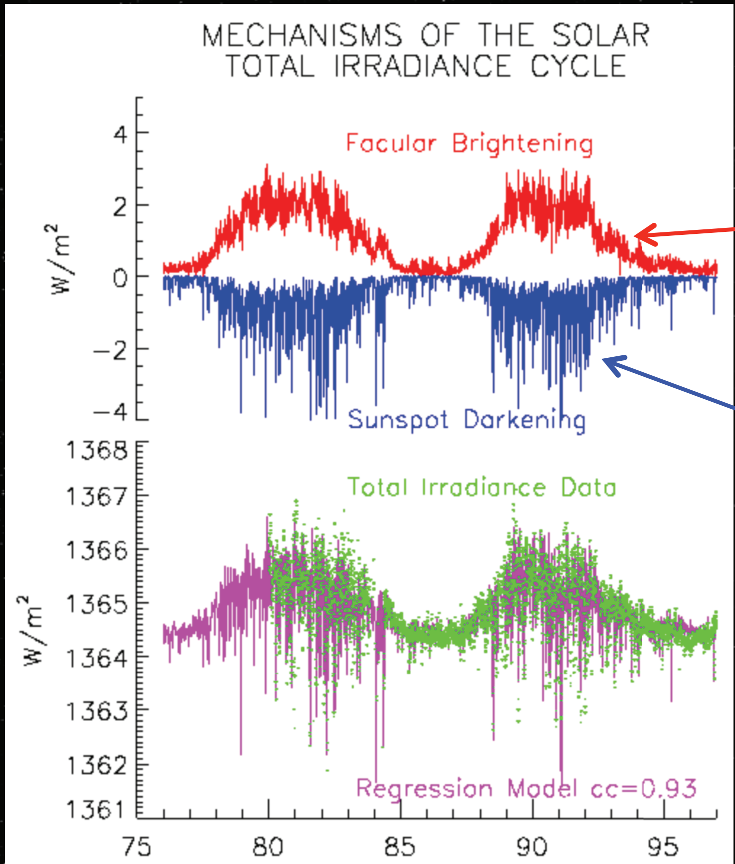
Photometry

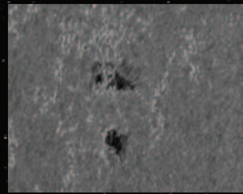
Measure the spectral solar irradiance variations over time.

Work in progress…

4 – Scientific results

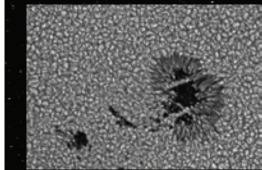
From Lean and Fröhlich (1998)

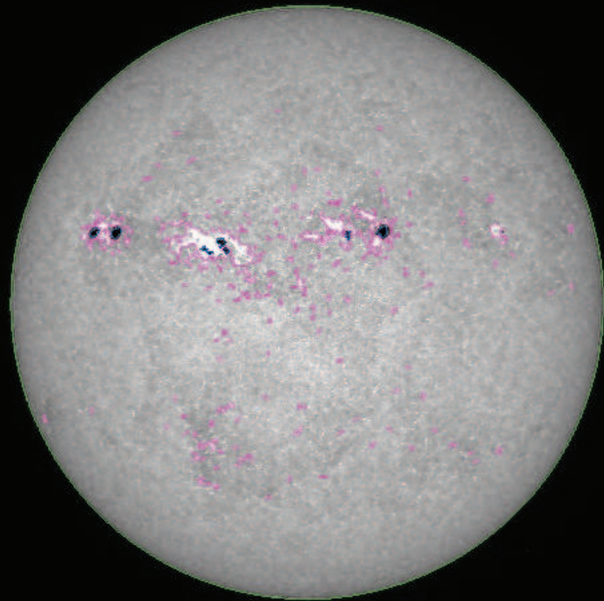




Faculae

Sunspot





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
→ …

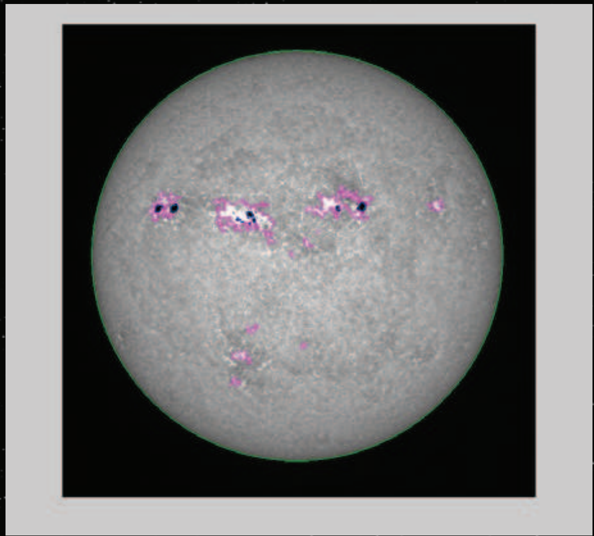
More than 90% of TSI variance are due to dark sunspots and bright faculae.

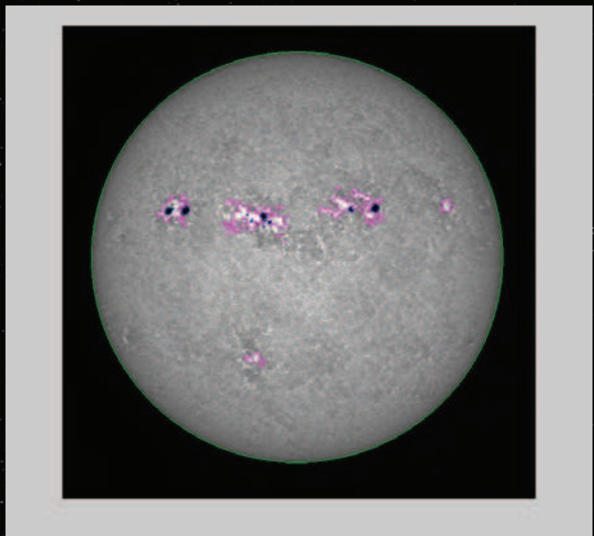
Any residual TSI variations from slower changes in e.g. solar diameter or convective patterns ?

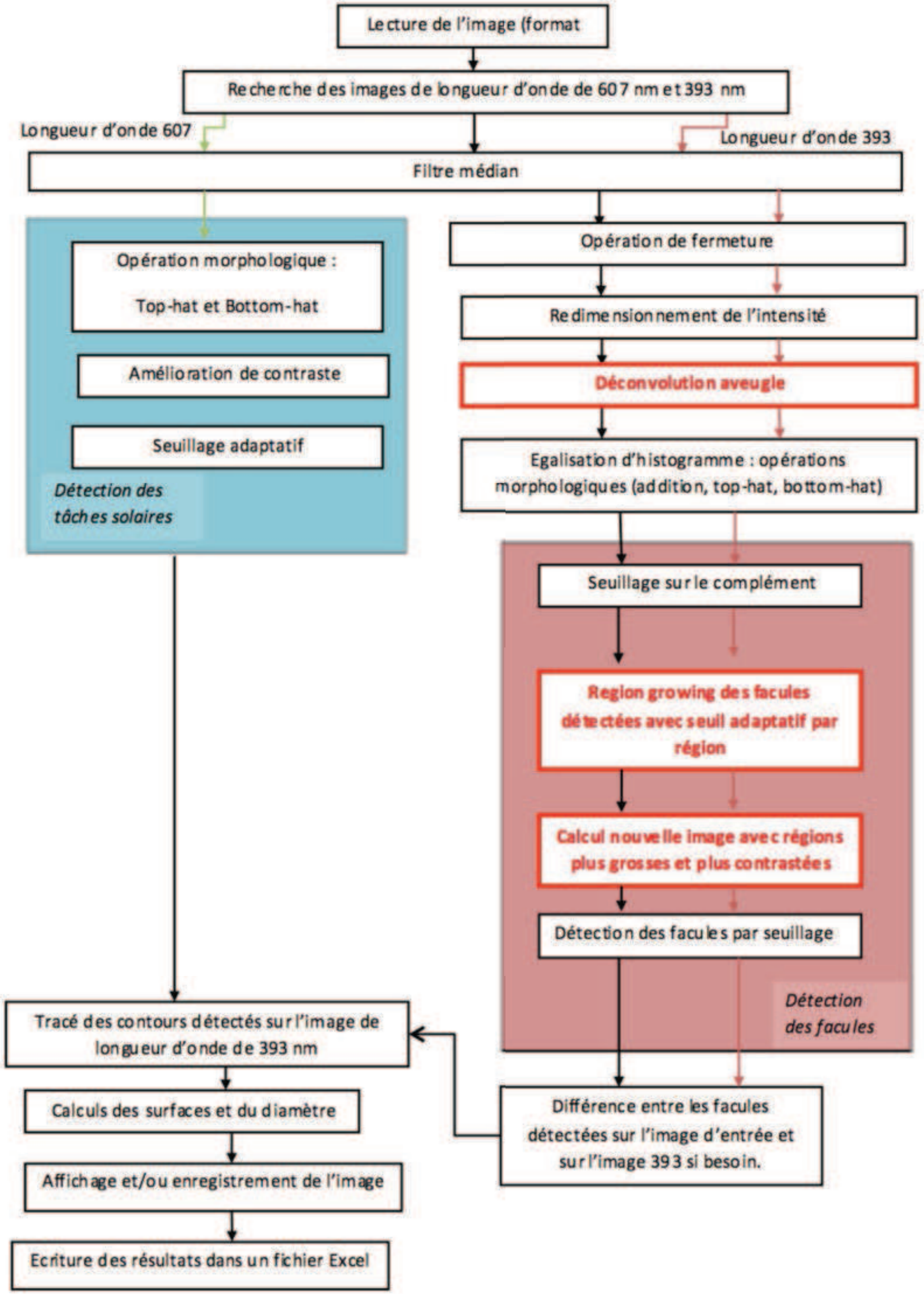
4 – Scientific results

Threshold technique Curto et al. (Solar Physics, 2008) for example	MRF (Markov Random Field) approach Turmon et al. (Solar Physics, 2010)
+ 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	+ 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? <u>Contact with Turmon on 09/01/2015…</u>
Both techniques need a pre-processing step. Possible improvement: remove limb-darkening spatial attenuation,…	

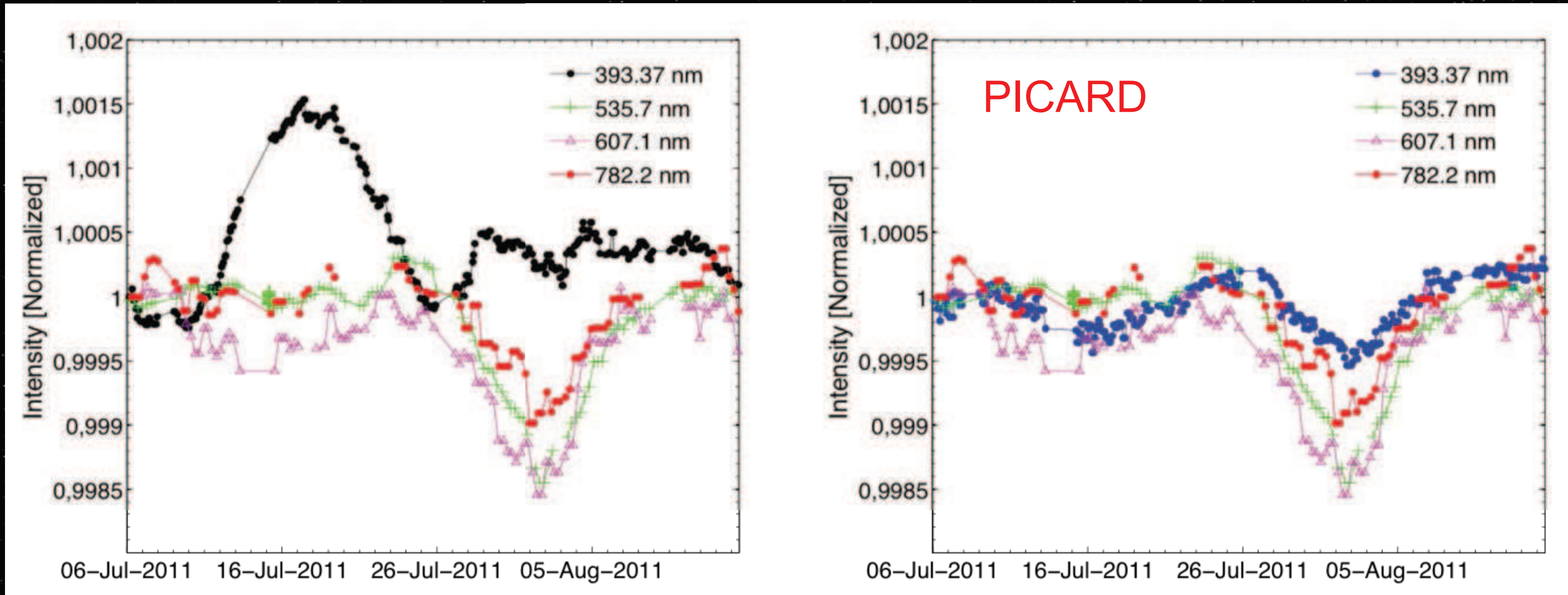
4 – Scientific results

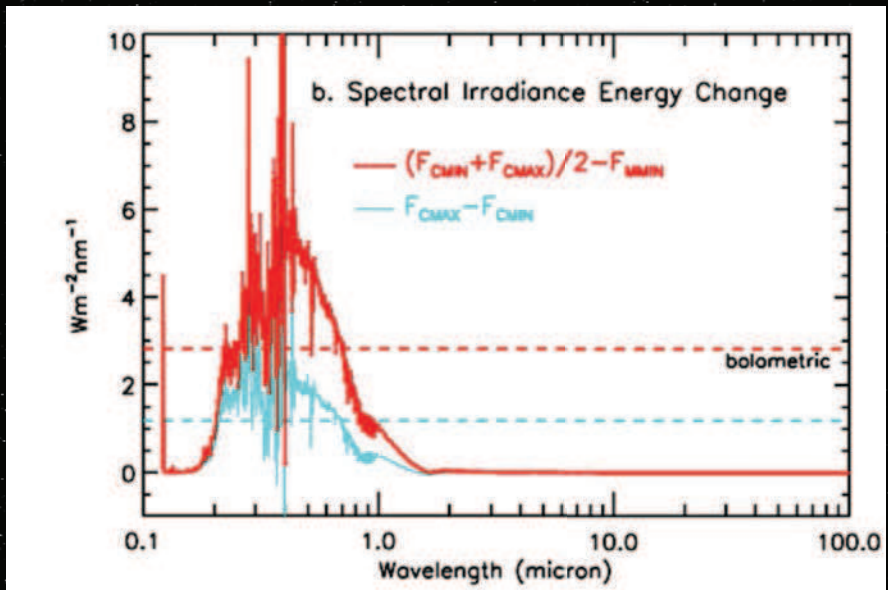






4 – Scientific results





Lean, 2000

Spectral solar irradiance evolution

From minimum to maximum of the solar cycle (blue)

Form the Maunder Minimum to the present day (red)

Radiometry

Measure the total solar irradiance variations over time.
Link with the solar diameter.

Work in progress…

4 – Scientific results

Radiometry and photometry

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

Total Solar Irradiance (TSI)

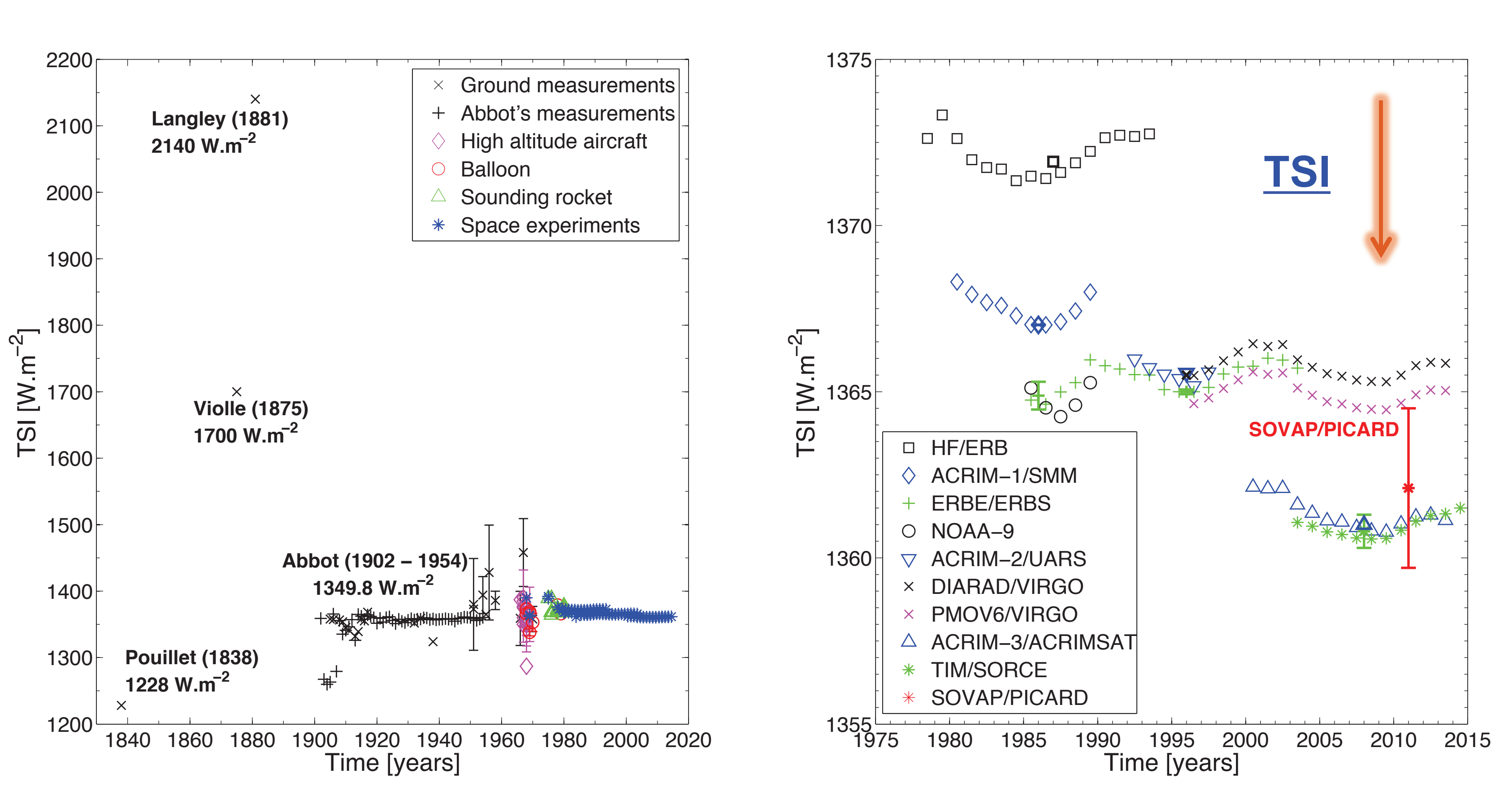
Instrument	Years	TSI	References
ERB/NIMBUS 7	**1978-1993**	**TSI ~ 1371 W.m^{-2}**	**Hickey et al., 1980, 1988 Kyle et al., 1994**
ACRIM 1/SMM	1980-1989	TSI ~ 1367 W.m^{-2}	Willson et al., 1981 (1368.31 W/m2)
ERBE/ERBS	1984-2003	TSI ~ 1365 W.m^{-2}	Lee et al., 1987
ERBE/NOAA 9	1985-1989	TSI ~ 1364 W.m^{-2}	Barkstrom et al., 1990
ERBE/NOAA 10	1986-1987	TSI ~ 1364 W.m^{-2}	Barkstrom et al., 1990
ACRIM2/UARS	1991-2001	TSI ~ 1365 W.m^{-2}	Willson & Mordvinov, 2001
SOVA 1/EURECA	1992-1993	TSI ~ 1365 W.m^{-2}	Crommelynck et al., 1993
DIARAD/VIRGO on SOHO	1996-present	TSI ~ 1365 W.m^{-2}	Dewitte et al., 2004
PMO6V/VIRGO on SOHO	1996-present	TSI ~ 1365 W.m^{-2}	Finsterle et al., 2006 Fröhlich et al., 1997
ACRIM3/ACRIMSAT	2000-present	TSI ~ 1365 W.m^{-2}	Willson & Helizon, 1999
TIM/SORCE	2003-2013	TSI ~ 1361 W.m^{-2}	Kopp et al., 2005
PREMOS/PICARD	**2010-present**	**TSI ~ 1361 W.m^{-2}**	**Schmutz et al., 2013**
SOVAP/PICARD	**2010-present**	**TSI ~ 1362 W.m^{-2}**	**Meftah et al., 2014 (Solar Phys.)**

Based on measurements collected from various spacecraft instruments over the last 35 years, the TSI has incrementally declined from 1371 W.m^{-2} in 1978, to 1365 in the 1990's, and to around 1362 W.m^{-2} in 2014, mainly due to calibration.

4 – Scientific results

Total Solar Irradiance (TSI)

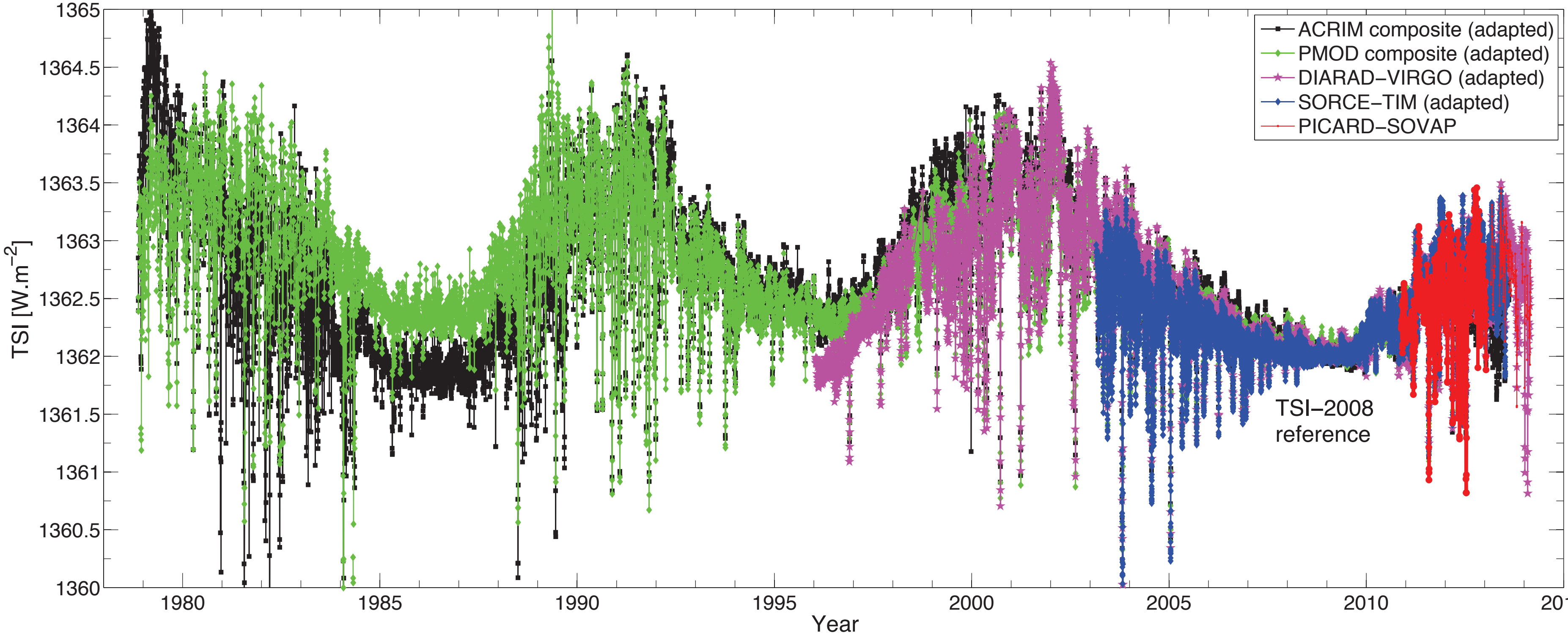
1362 **±2.4** W.m^{-2} (PICARD)



Importance of uncertainty budgets and calibration.

4 – Scientific results

Total Solar Irradiance (TSI) changes over time



The TSI variation during a solar cycle is easier to measure than the absolute value (ground and space calibration are needed).

Conclusion

Conclusion

Achievable scientific objectives

- Measurement of the solar oblateness at different wavelength

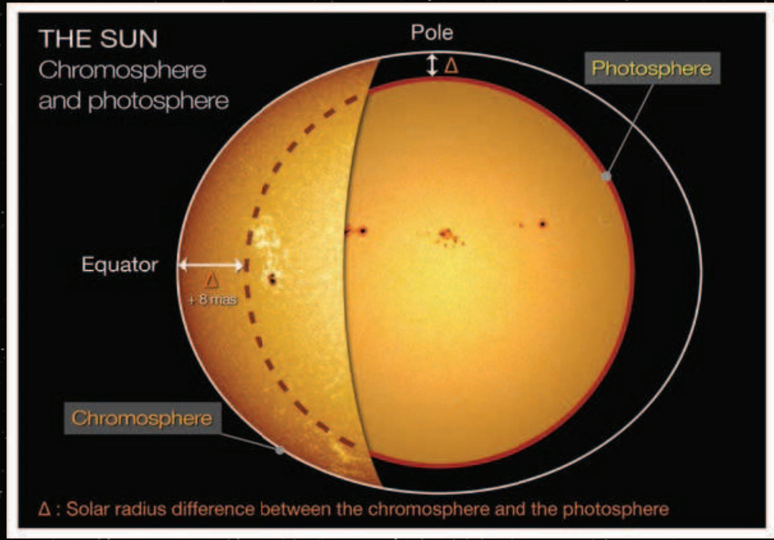
- Measurement of the photospheric diameter during the transit of Venus

- Solar radius variability with SODISM (short time scale in space) and SODISM 2 (long time scale on ground)

- I-v diagram at 535.7 nm and 393.37 nm

…

- Solar radius: 696,156± 145 kilometers
- TSI (luminosity of the Sun): 1,362± 2.4 $W.m^{-2}$
- Solar oblateness: 5.9± 0.5 kilometers
- Solar radius variations less than 15 km



Thank you for your attention