The SODISM space telescope, its PSF, and the solar limb…

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and the PICARD-SODISM team

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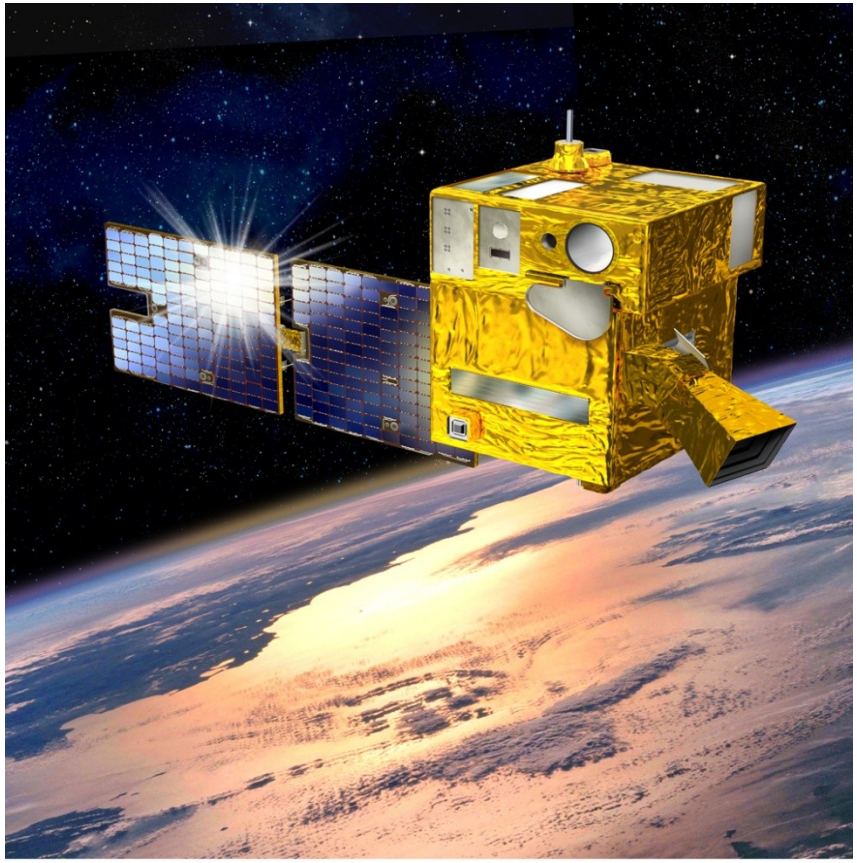
The PICARD space mission

- PICARD: a scientific program dedicated to the evolution of solar effects on climate

- The payload of the eponymous CNES space mission includes:
  - Two radiometers
    - PREMOS (CH)
    - SOVAP (B)
  - An imaging solar telescope
    - SODISM (F)

- Successful launch on 15 June 2010



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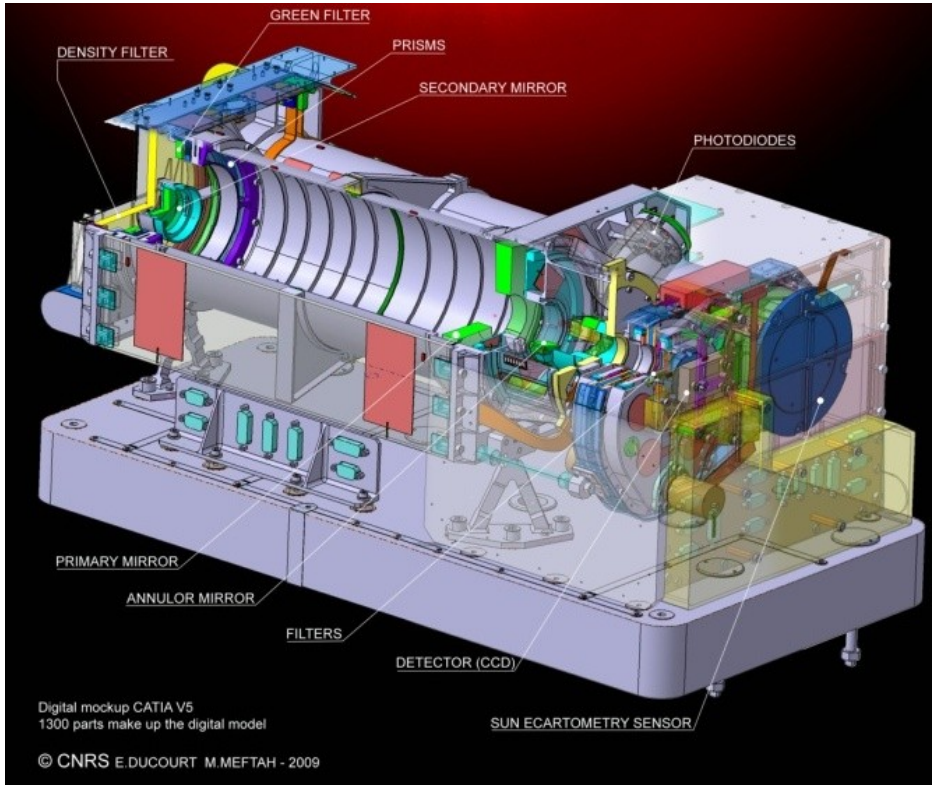
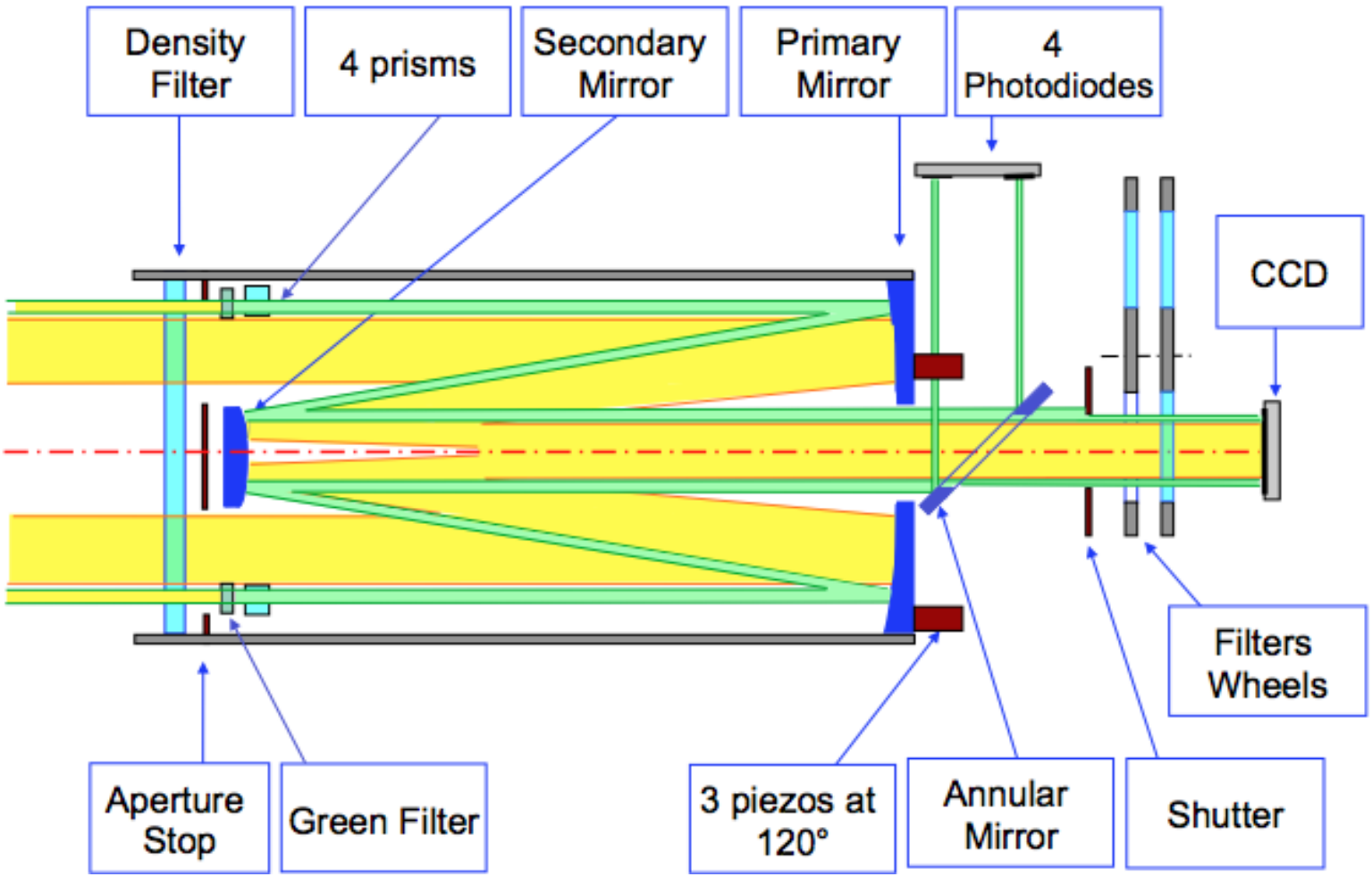
SODISM
the Solar Diameter Imager and Surface Mapper

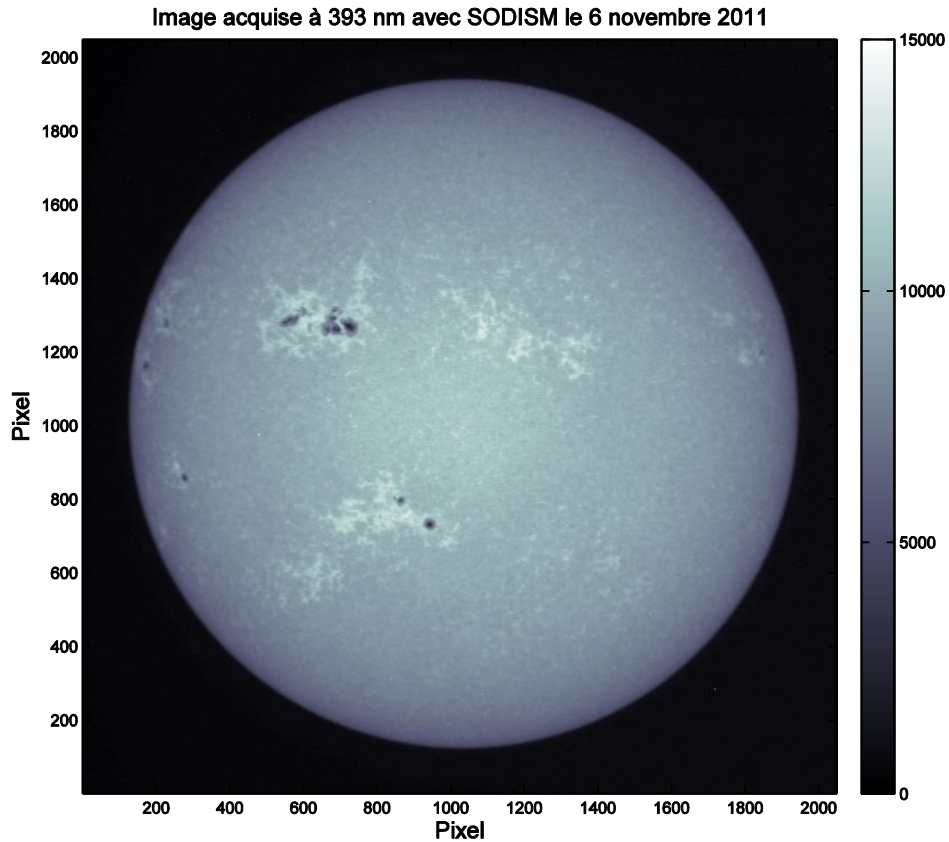
- Designed to perform
  - fine metrology of the solar limb
    - Geometric & radiometric
    - Goal: few milli-arcsec ("mas")
  - in 5 NUV-VIS spectral passbands
    - 215 & 393 nm
      - Chromosphere
    - 535, 607, 782 nm
      - Photospheric continuum (outside absorption lines)
- Main characteristics
  - 11 cm Ritchey Chretien
  - 27.7 kg
  - 2.2 Gbits per day
  - Thermally regulated
  - 2626 mm focal length
  - 2k x 2k CCD
    → 35 arcmin/FOV, 1.06 arcsec/pxl



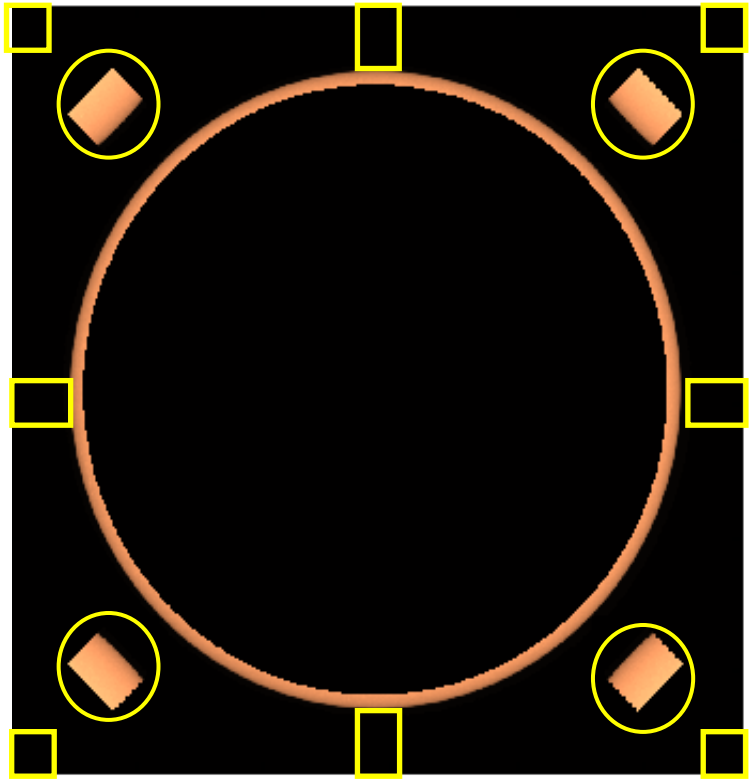
Optical scheme



Typical observations



Solar chromosphere (Ca K at 393nm) on 6 Nov. 2011



Data masking used to match the telemetry budget

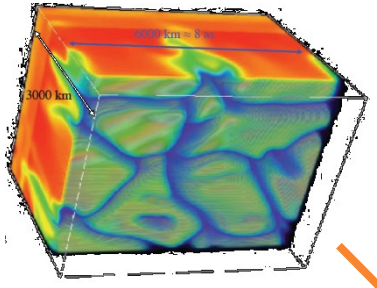
SODISM original science fields

Solar limb metrology (Sci.field.1)	• Radial profile of the limb • Angular profile of the solar disc (asphericity and higher moments) • Temporal evolution of the above
Helioseismology (Sci.fld.2)	• Helio-seismic diameter • Solar intensity oscillations, and especially g-modes
Solar spectral irradiance (Sci.fld.3)	• Contribution to the reconstruction of the SSI (solar spectral irradiance)
Other solar physics studies (Sci.fld.4)	• Surface motions and their evolution • Study of magnetic activity features • Serendipity…
Solar-terrestrial relationships & aeronomy (Sci.fld.5)	• Space Weather • Studies of the Earth atmosphere via occultations, albedo studies, etc. • Contribution to understanding the Sun-Earth connection and climate

Metrology of the solar limb

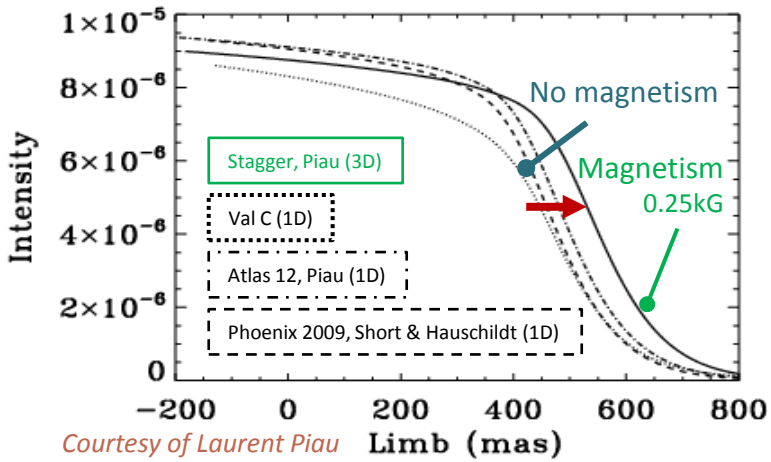
- Radial profile

Solving equations of state (turbulent convection w/ or w/o magnetism)



Solving radiative transfer

Modeled **"limb darkening function" (LDF)**, here at 500 nm



Courtesy of Laurent Piau

Sub-surface magnetism seems to make the LDF "swell" by ~100 mas

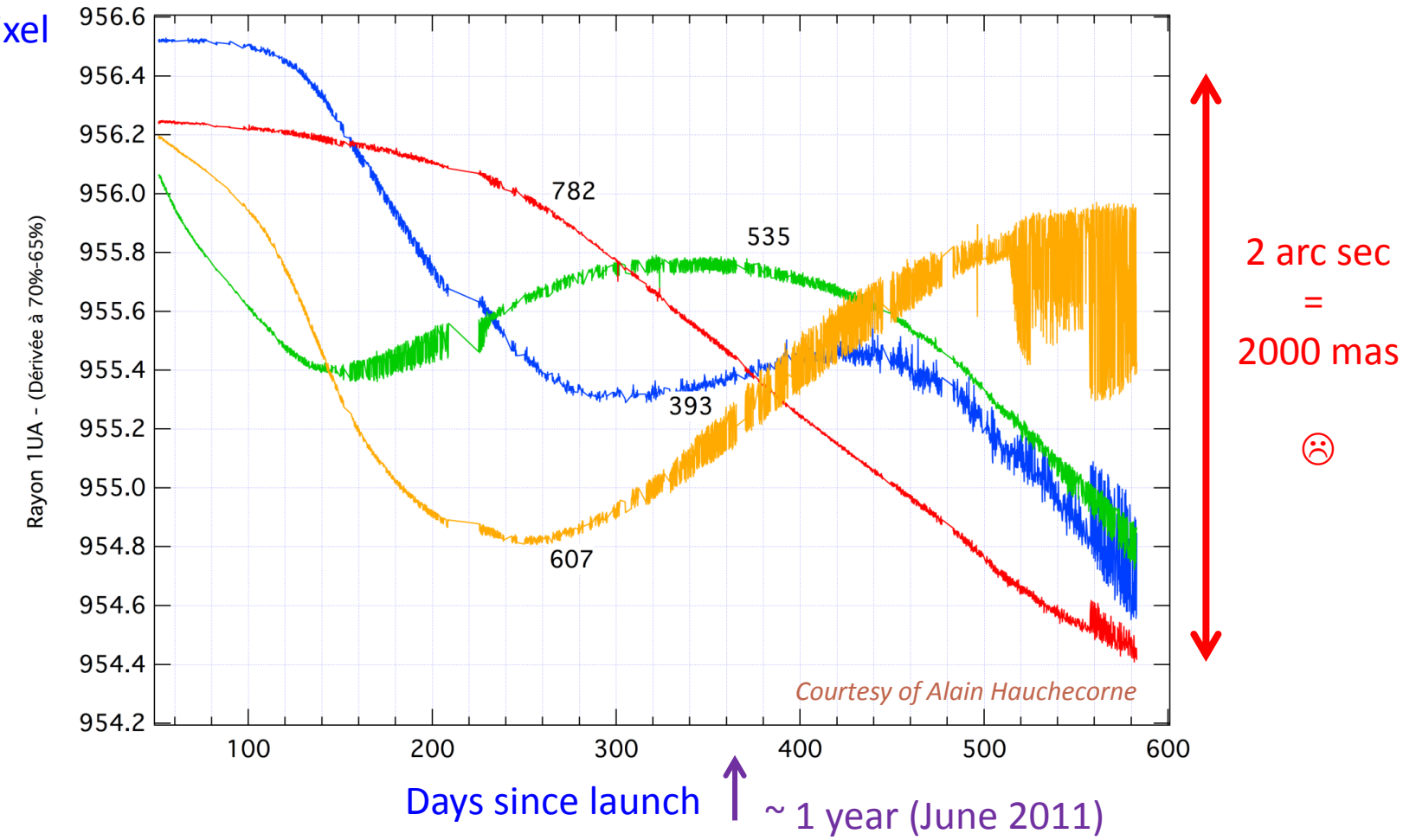
- Asphericity
  - Asphericity and oblateness depict angular dependency of the LDF (or an additive pedestal to it)
  - Has important astrophysical interests
  - Of order 8 -15 mas; may vary with solar activity and its cycle
  - NB: Measuring LDF is prerequisite to measuring asphericity

- Time dependency
  - Long term (11-yr) dependency is a matter of hot debate
  - short term (e.g. 25 days) dependency?
  - Has important astrophysical and climatic interests
  - Knowledge of the LDF (and, in principle, of the asphericity too) are prerequisite

SODISM anomaly [1/3]

Long term evolution of the observed radius

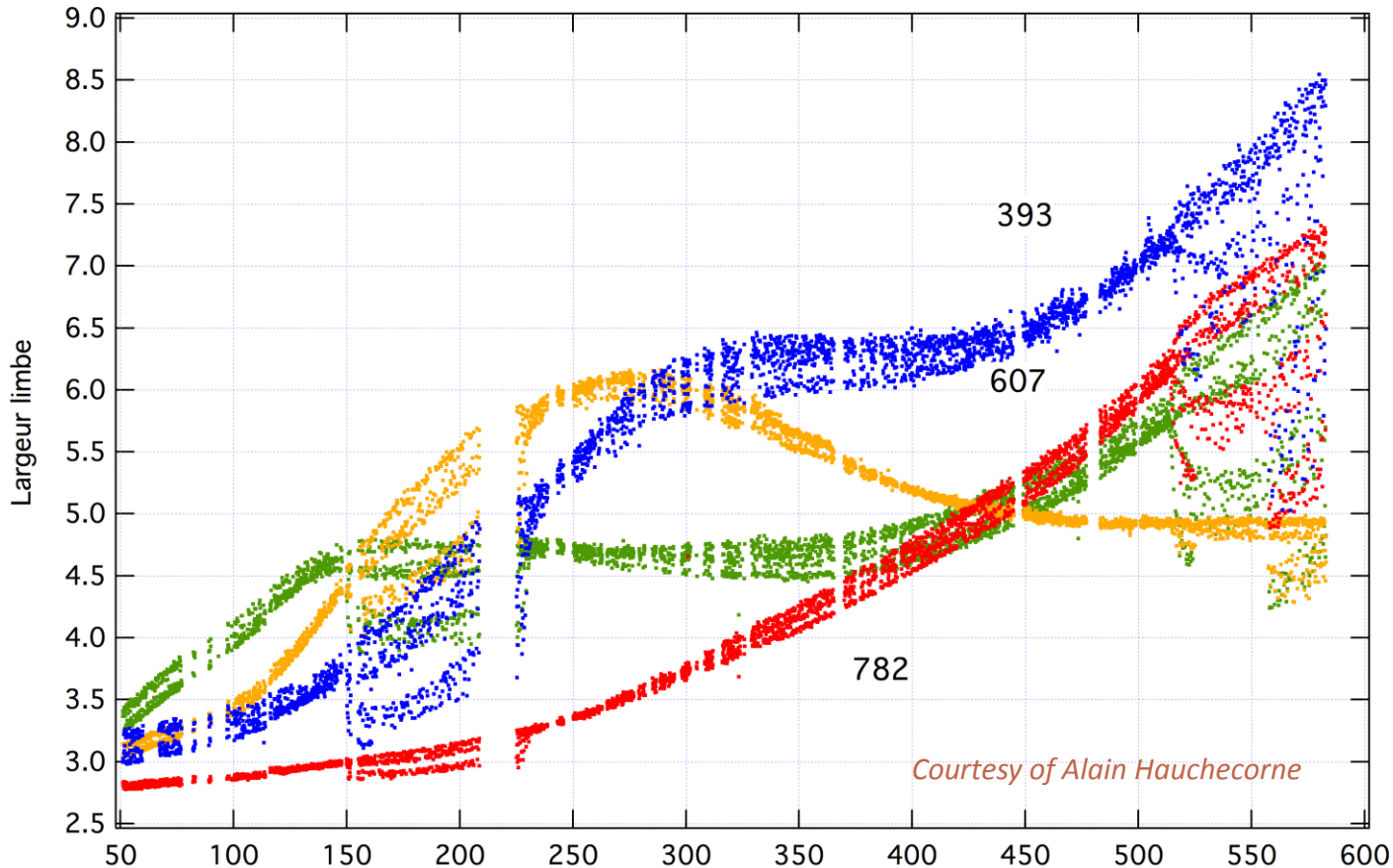
Radius in pixel at 1 AU



SODISM anomaly [2/3]

Long term evolution of the observed limb width

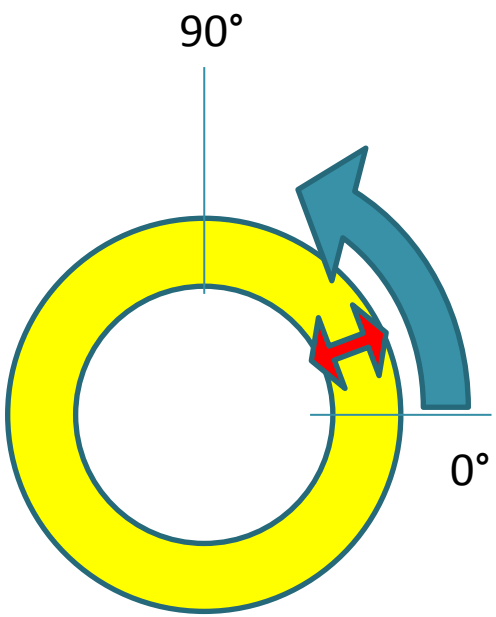
Limb width
in pixel
at 1 AU

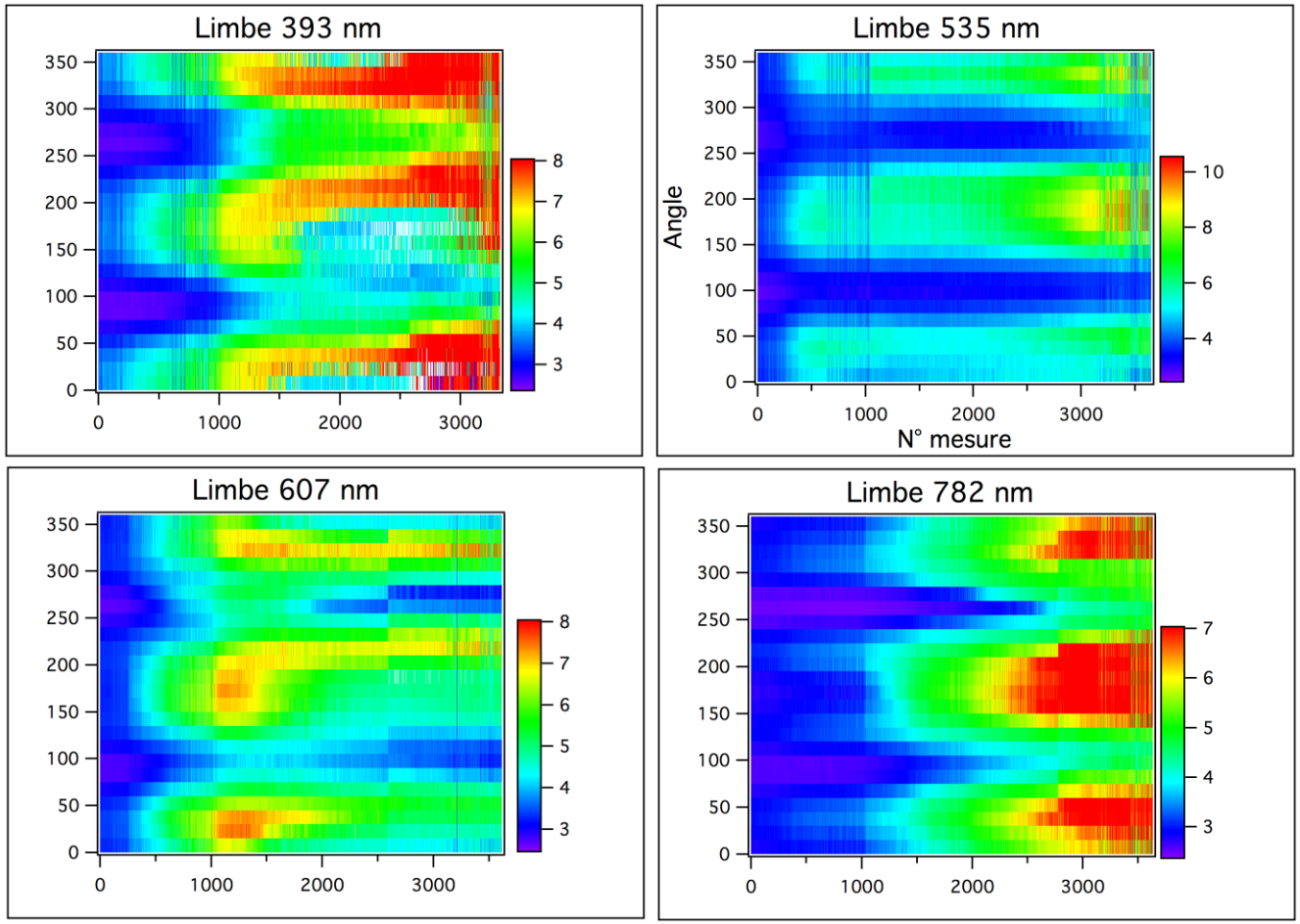


Days since launch ↑ ~ 1 year (June 2011)

SODISM anomaly [3/3]

Evolution of the dependency of limb width to angle



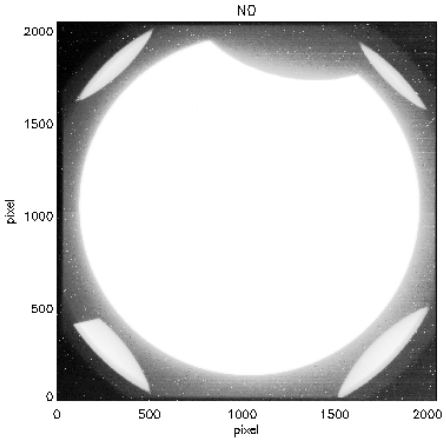


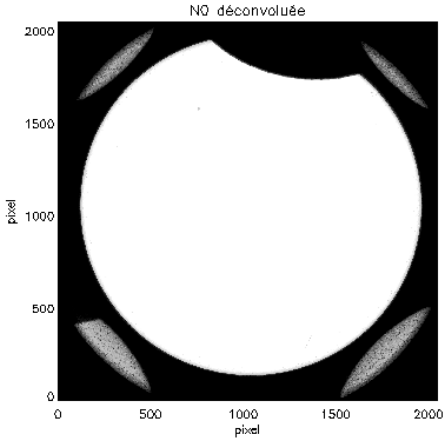
Courtesy of Alain Hauchecorne

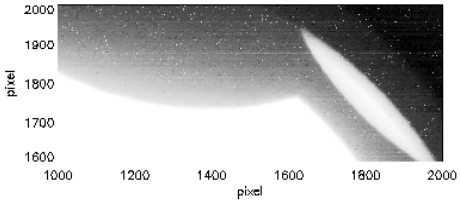
The point spread function - PSF

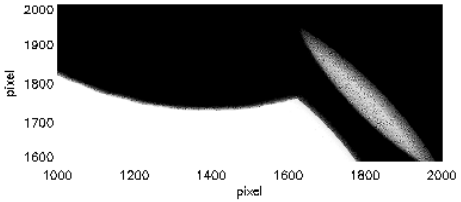
- The PSF accounts for
  - Diffraction
  - Kinematic blur
  - Scattered light (PSF wings)
  - Defocus and other aberrations

- Here, the PSF is
  - Non isotropic, non axisymmetric
  - Non shift-invariant
  - Evolutionary
  - Currently unknown (not predictable from thermo-optical modeling)
    - Blind deconvolution must be foreseen









PSF parameterized as Gaussian + Lorentzian
Deconvolution using Lucy 1974
Stéphane Ferron & JF Hochedez

Ways to reconstruct SODISM PSF

1. Eclipses
   - Sharp lunar limb ☺
   - Which can reach FOV center ☺
   - 1D degeneracy ☹
   - 2 to 4 eclipses per year ☹
   - Internal pointing off ☹
     → non representative blur

2. Stellar pointings
   - *Direct* PSF measurement but star must be bright enough
   - Non representative thermal configuration ☹
     - Model needed to bridge telescope configurations

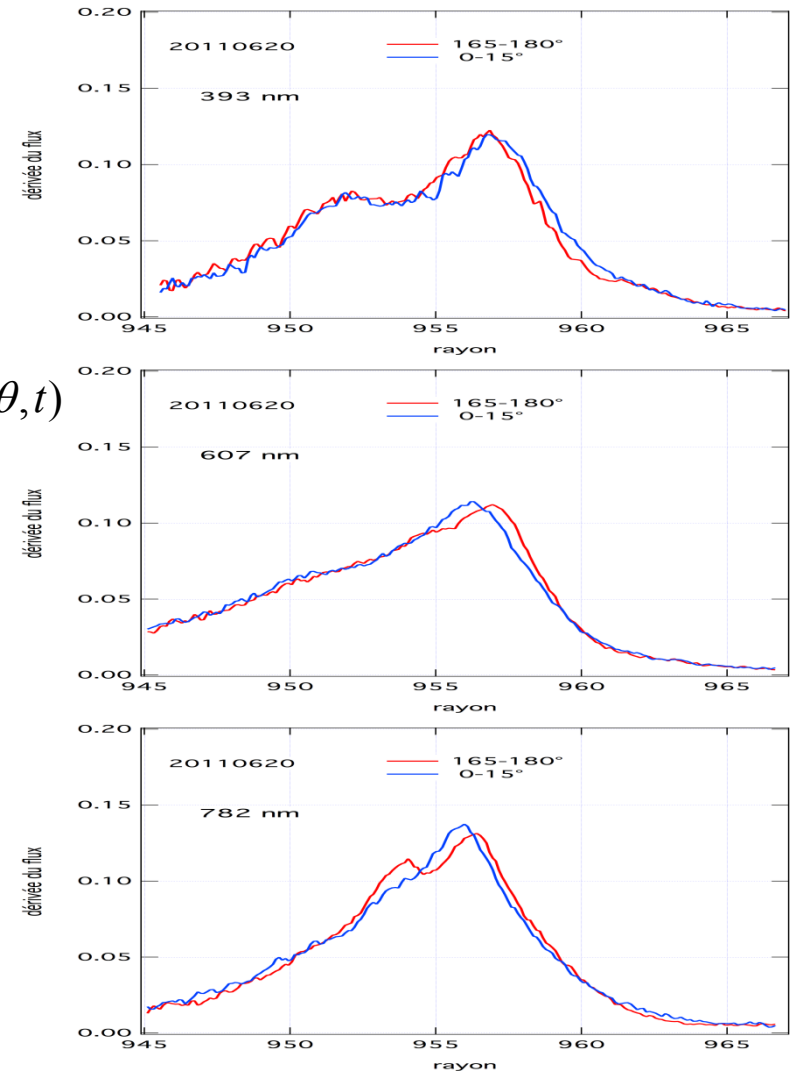
3. Solar limb inversion
   - Radial profile not perfectly known
     2nd order issue
   - 1D degeneracy ☹
   - Doable only at solar limb ☹
   - Continuous time coverage ☺
   - Representative conditions ☺
     - Pointing-wise
     - Thermally

4. Optical modeling
   - Goal would be to match modeling with observations
   - Can alleviate the limitations of approaches 1-2-3 ☺
   - Instrumental scenario missing ☹
   - To be deduced from diagnostics provided by approaches 1-2-3

This present (rustic) inversion

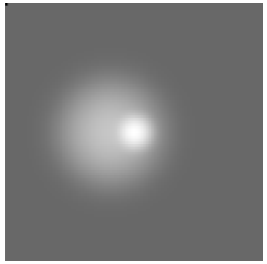
[1/2] PSF parameterization

- The derivative of the LDF became double-peaked
- Parameterization of the PSF as two Gaussians + a pedestal thus appears to be a reasonable guess



$$PSF(\theta,t) = \alpha_a(\theta,t)\frac{e^{\vec{x}^2/2\sigma_a^2(\theta,t)}}{2\pi\sigma_a^2(\theta,t)} + \alpha_b(\theta,t)\frac{e^{(\vec{x}-\vec{X}_\theta(\theta,t))^2/2\sigma_b^2(\theta,t)}}{2\pi\sigma_b^2(\theta,t)} + \alpha_c(\theta,t)$$

- 6 parameters:
  1. Amplitude of the centered Gaussian
  2. Scale of the centered Gaussian
  3. Radial shift of the secondary Gaussian
  4. Amplitude of the secondary Gaussian
  5. Scale of the secondary Gaussian
  6. Amplitude of the pedestal



- Reduced to 5 parameters
  - Thanks to PSF normalization
  - depending on time, angle and spectral channel

Courtesy of Alain Hauchecorne

This present (rustic) inversion

[2/2] limb parameterization, model, and optimization

- A "*reliable enough*" limb darkening function (LDF)
  - Neckel, Solar Physics, 229, 1 (2005)

$$\mu = \sqrt{1-\rho^2} = \cos(\theta)$$

$$LDF(\lambda,\mu) = a_{00} + \frac{a_{01}}{\lambda} + \left(a_{10} + \frac{a_{11}}{\lambda} + \frac{a_{15}}{\lambda^5}\right)\mu + \left(a_{20} + \frac{a_{25}}{\lambda^5}\right)\mu^2 + \left(a_{30} + \frac{a_{35}}{\lambda^5}\right)\mu^3 + \left(a_{40} + \frac{a_{45}}{\lambda^5}\right)\mu^4 + \left(a_{50} + \frac{a_{55}}{\lambda^5}\right)\mu^5$$

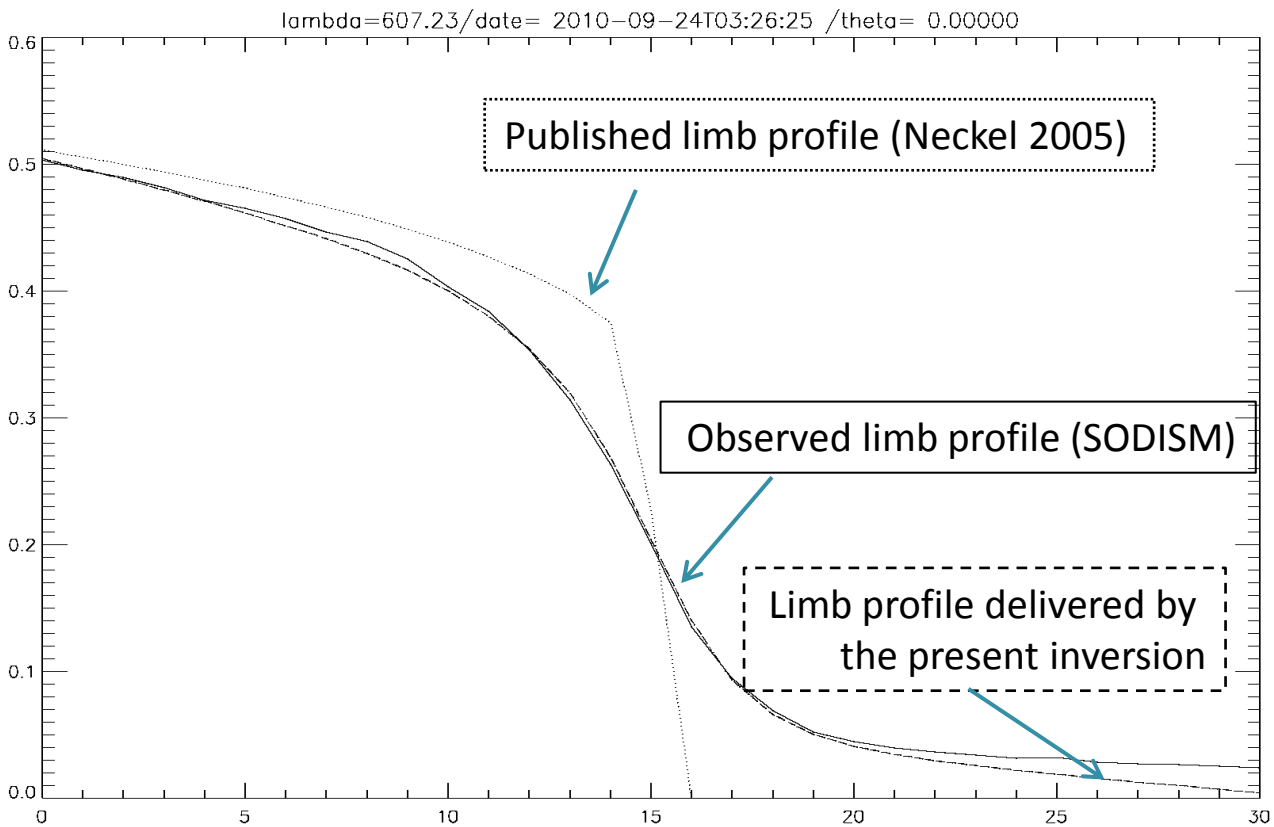
- Forward model
  - Convolution of above LDF with above PSF
    - both "assumed good enough"
    - 2D & super-resolved

- Inversion via iterative optimization
  - Merit function = average of the residual image
    - Progressively tightened around the limb
  - Gradient descent
    - Adaptive step strategy: parameter variations adjusted to last gain in merit
  - Solar radius and the 5 parameters of the PSF *simultaneously* estimated
    - Radius maintained frozen unless no other choice

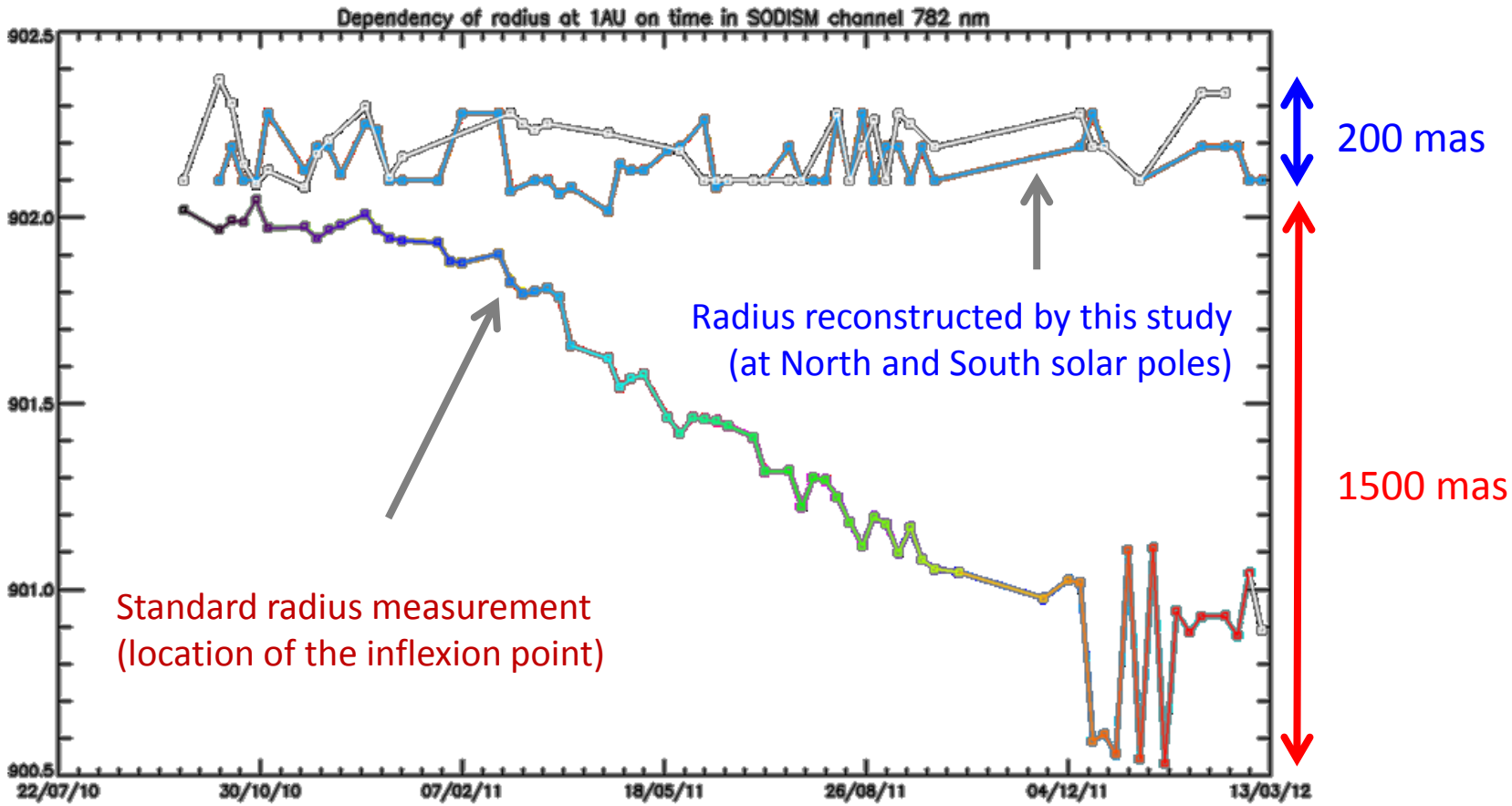
Illustration of the inversion

Published, observed, and modeled limb profiles

607 nm - 24 sep 2010 – West equator (*i.e.* at 0°)



Reconstruction of the solar radius along the lifetime of the PICARD mission



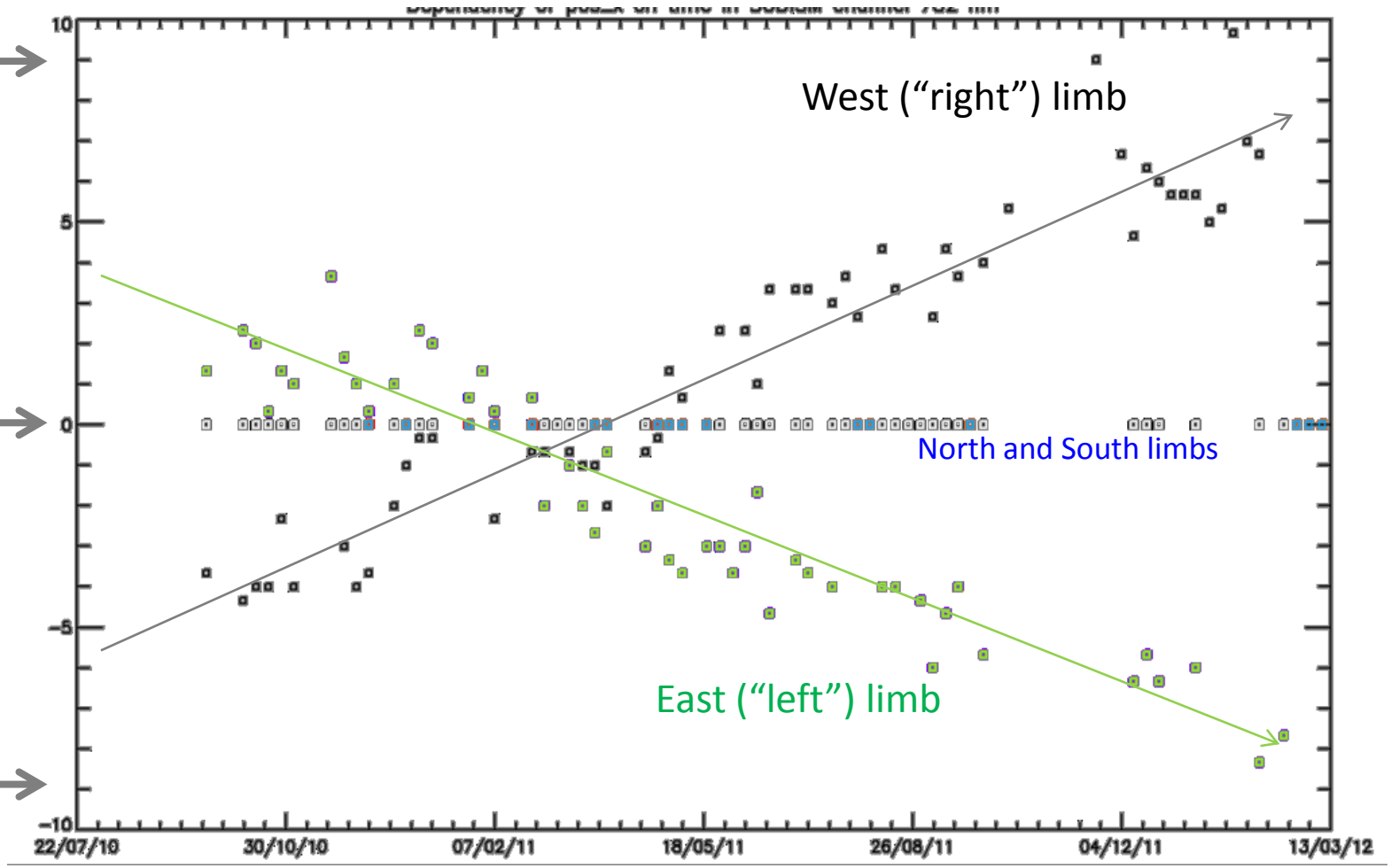
Instrumental diagnostics as a by-product of the inversion

East-West shift of the secondary PSF at 782 nm

Eastward shift by 3 pxl (9 super-pixels)

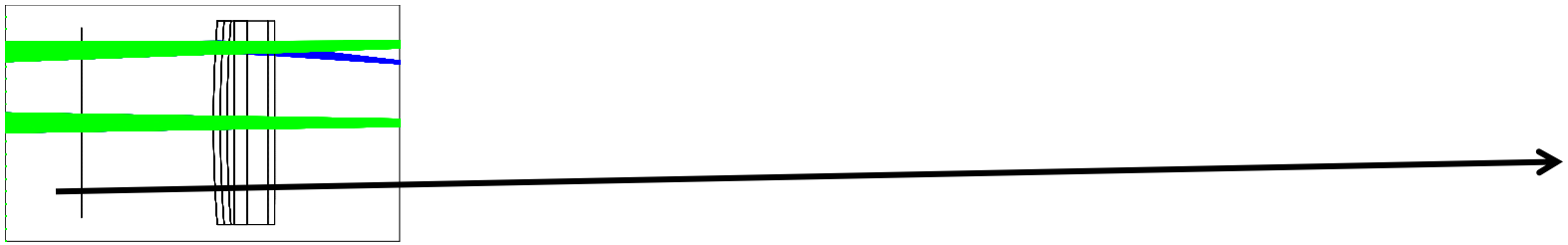
Both PSF peaks Co-aligned

Westward shift by 3 pxl (9 super-pixels)



*The non centered (secondary) PSF peak moves **inwards** with time (centripetal shift)*

Provisional instrumental scenario



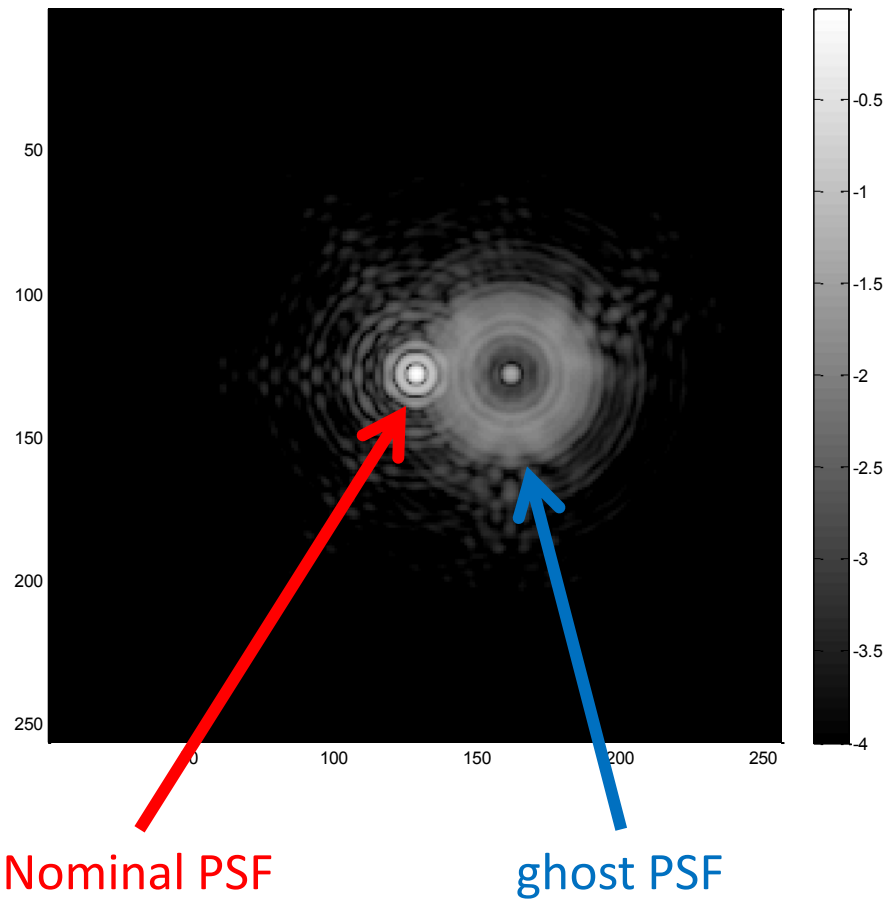
In **green**:
Nominaux rays from M2 to CCD (diverging)

In **blue**:
Ghost resulting from unwanted reflection within the stack of interference filters

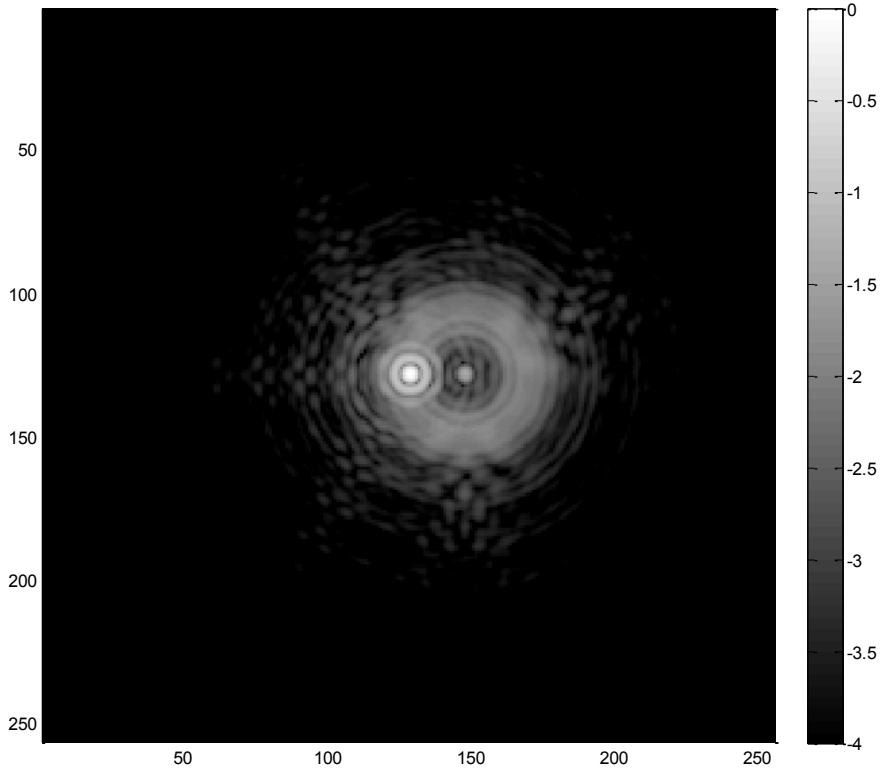
Filter element including:
semi-reflecting Inconel
+ wide band interference layer
+ narrow band interference layer

ZEMAX computation of the PSF for the West limb at 550 nm « nominal + intra filter ghost »

Flat Inconel surface

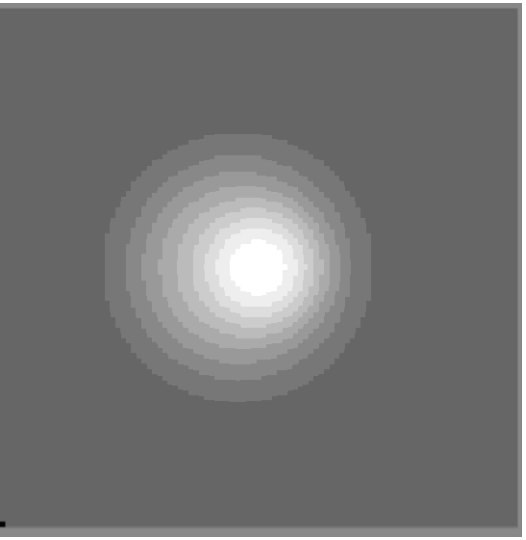


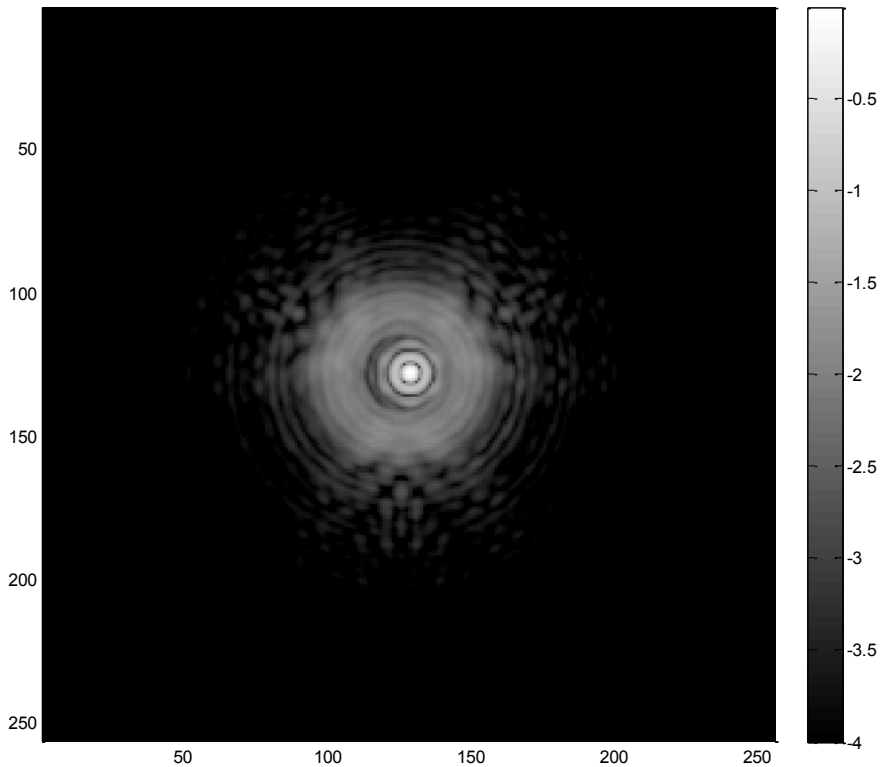
Inconel surface radius = 20 m



Inconel surface radius = 8 m

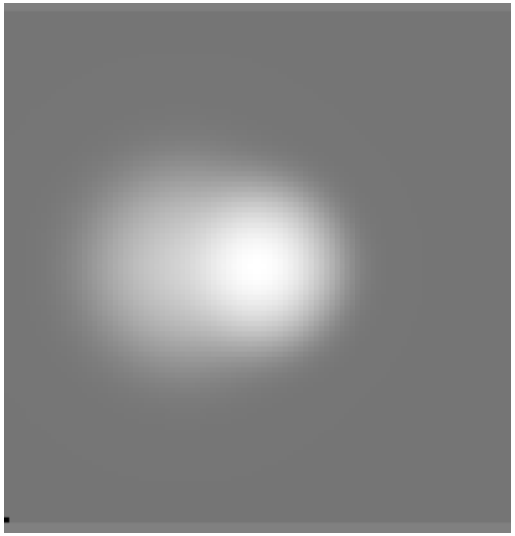
Double Gaussian PSF reconstructed
For Sep 2010 at 535nm

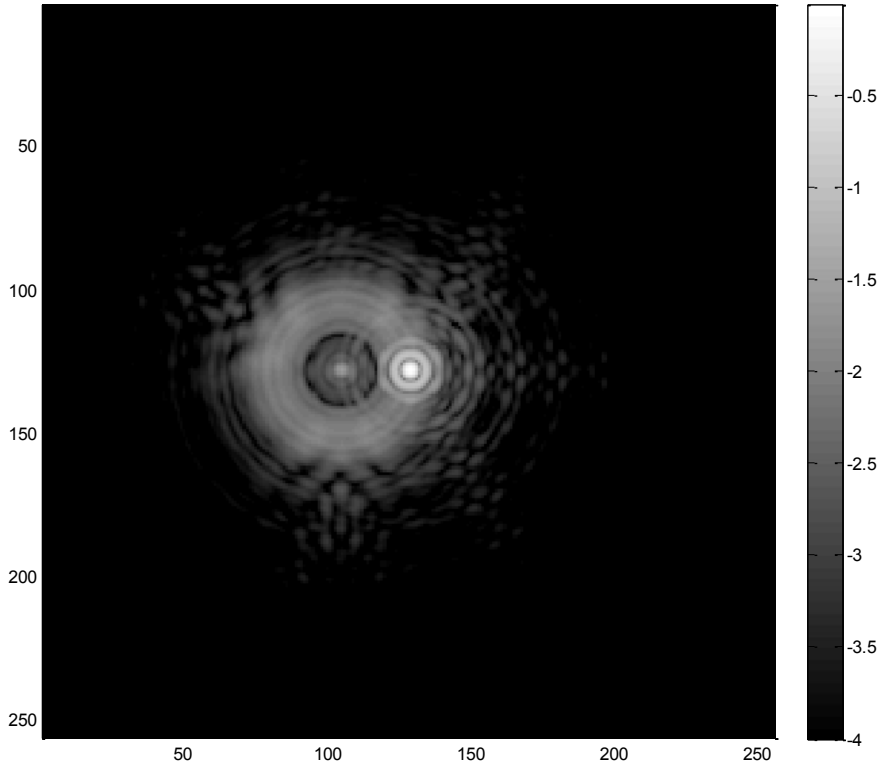




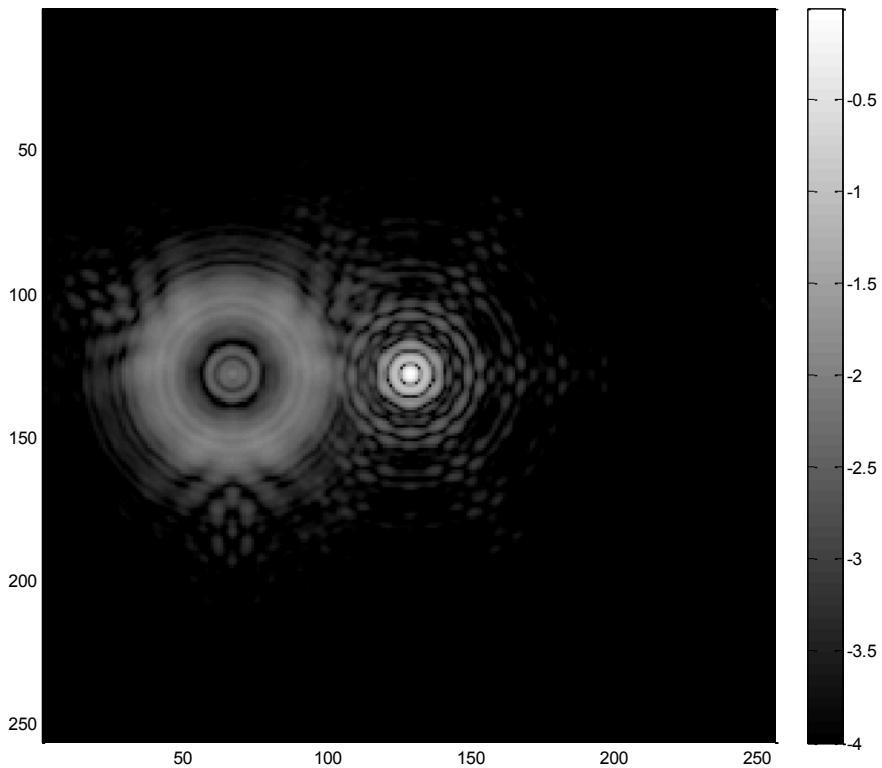
Inconel surface radius = 5 m

Double Gaussian PSF reconstructed
For Sep 2011 at 535nm





Inconel surface radius = 3 m



Call for ideas and/or collaboration

- Short term strategy is to validate an instrumental scenario, which in turn would enable better PSF modeling
- Hope that time helps separating PSF components, or that the secondary component informs on the main one
- Nevertheless, as of today, the problem is not yet solved though tens of MEURO invested
- Guest Investigator AO just released on May 15, 2012
  - http://smsc.cnes.fr/PICARD/A_research_announcement.htm
  - Proposals due date: 20 June 2012
  - Contact jfhochedez@gmail.com or Support-PICARD@cnes.fr
  - Financial support possible for French labs

How to make the best scientific return out of the petabytes of data available from SDO, STEREO, Hinode, SOHO, and soon ATST, IRIS, Solar Orbiter?

Invited speakers:
- Prof. Alfred Hero (U. Michigan, USA)
- Dr. Said Moussaoui (ICCRYN, Nantes, France)
- Dr. Kevin Reardon (Arcetri Observatory, Italy)

Splinter sessions:
1. Tracking solar features
2. 3D reconstruction of corona
3. Solar information processing techniques
4. Accessing, browsing, retrieving data

Deadline for abstract submission : 15 June 2012

Travel support for students from the US and from ESA countries available