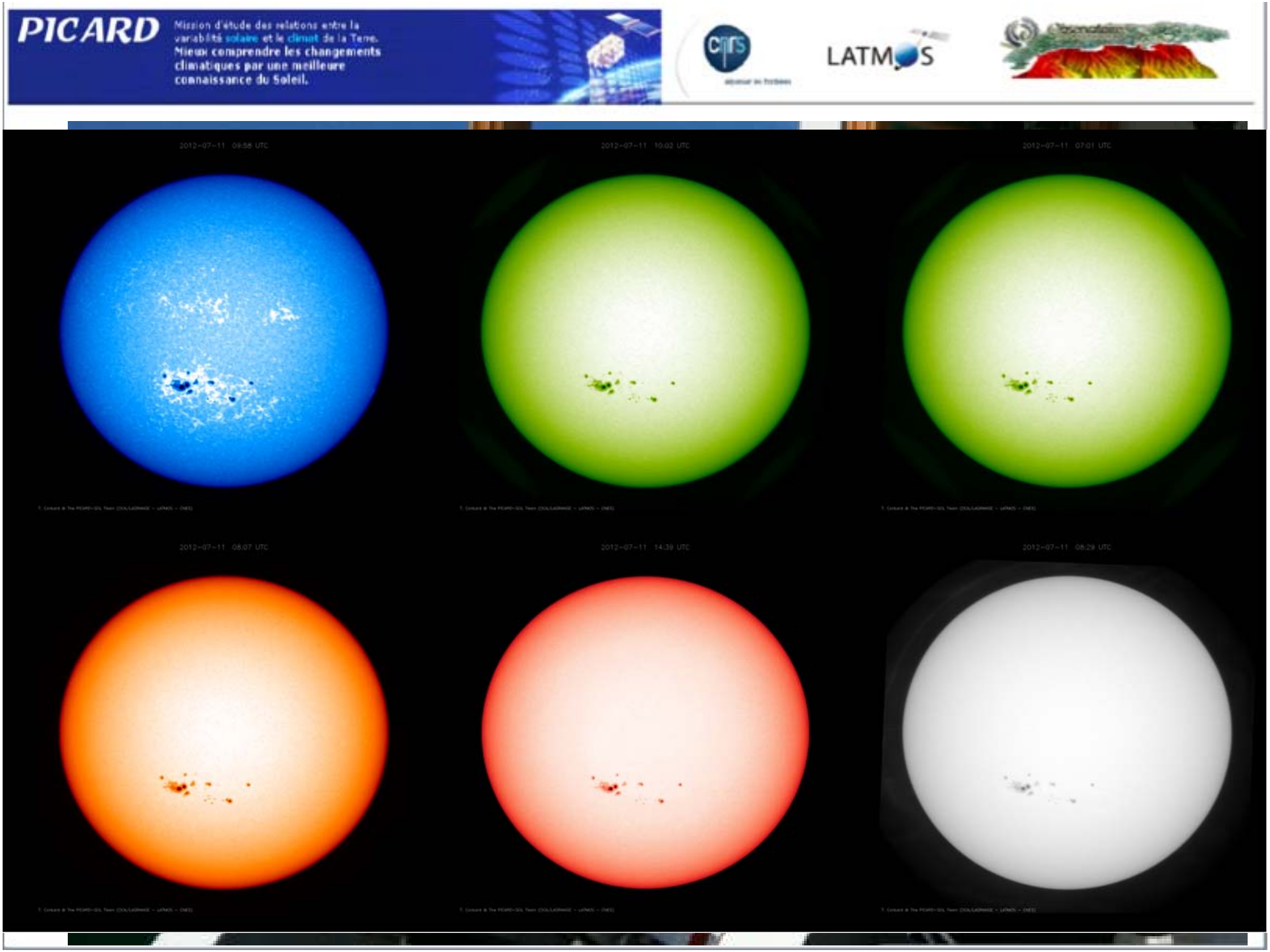
Seeing measurements for ground based solar astrometry

Rabah Ikhlef
and the Picard-Sol team

09 / 10 / 2014

Outline of the presentation

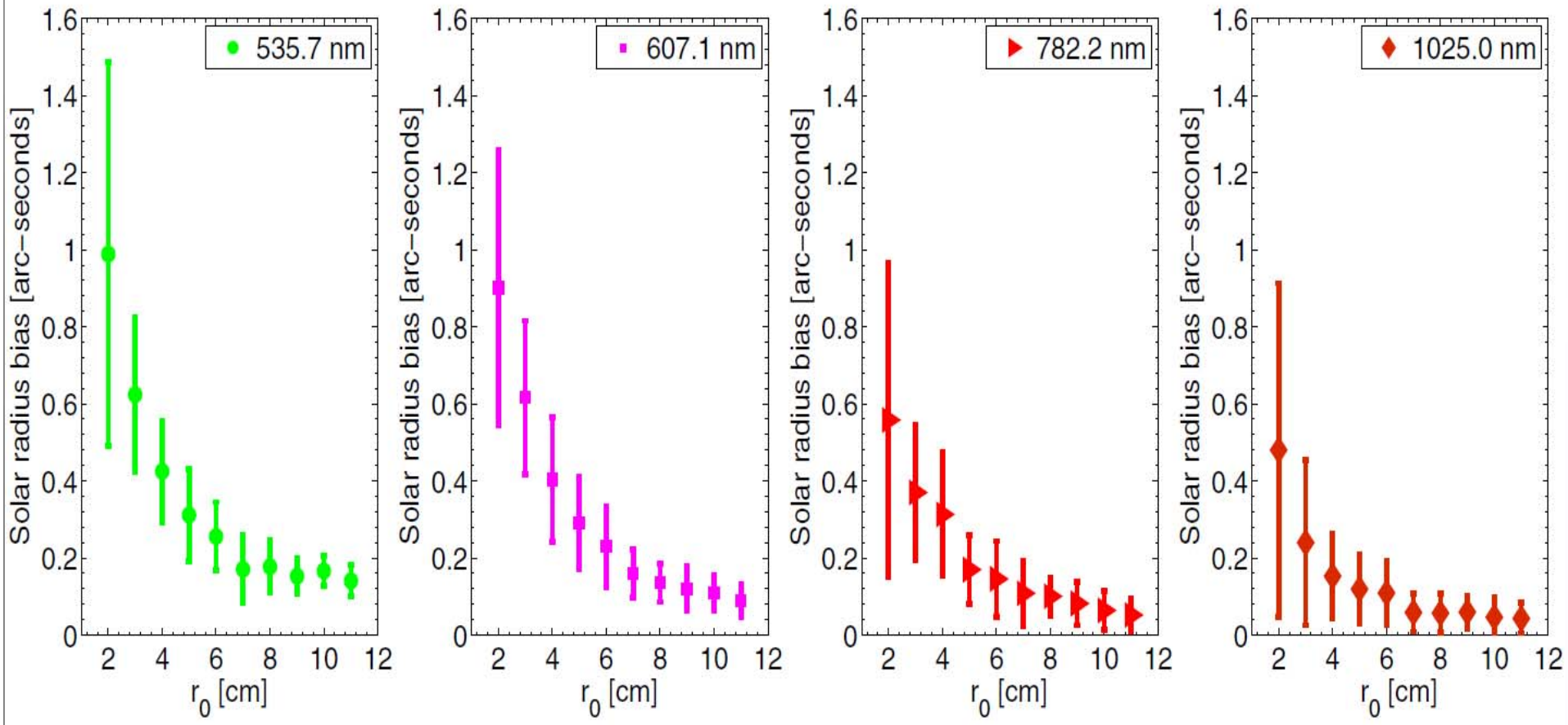
- Introduction
- Picard-Sol instruments
- Turbulence measurements methods overview
- Seeing estimation from full disk long exposure solar images
- Correction of radius measurements from seeing effects
- Conclusion


PICARD
Mission d'étude des relations entre la variabilité solaire et le climat de la Terre.
Mieux comprendre les changements climatiques par une meilleure connaissance du Soleil.
LATMOS
2012-07-11 09:58 UTC
2012-07-11 10:02 UTC
2012-07-11 07:01 UTC
2012-07-11 08:07 UTC
2012-07-11 14:39 UTC
2012-07-11 08:29 UTC

Daytime turbulence

- Optical turbulence affects strongly ground based observations.
- Variations in temperature → fluctuations in the index of refraction of air n → turbulent wavefront.
- Daytime turbulence localised near the surface.
- Most of the dispersion in radius measurement is due to seeing.
- Importance of estimating the seeing and the characteristic time.
- Simulations of bias introduced by turbulence.

Simulation of the bias due to Fried parameter on SODISM2 measurements



Meftah et al. 2014

Daytime seeing estimation techniques

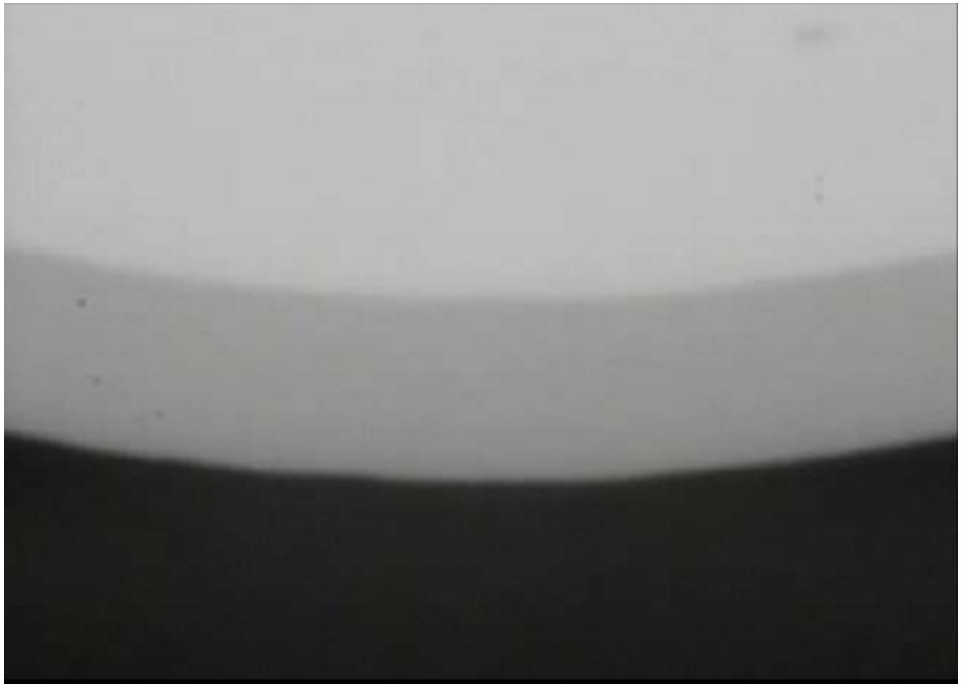
Main estimation techniques

- Solar Differential image Motion Monitor (S-DIMM)
- SODAR
- SHAdow BAnd Ranger (SHABAR): consisting of an array of solar scintillometers for the measurement of the atmospheric structure constant $Cn^2(h)$
- Shack-Hartmann of a solar adaptive optics system.
- MISOLFA: Angle-of-arrival fluctuations from solar limb images→ spatial parameters (r0, L0(h), $Cn^2(h)$

Intensity fluctuations in pupil plane→ $\tau 0$, r0, L0

- MTF of long exposure images: r0

Solar DIMM



$$\sigma^2 = K_l \, \lambda^2 \, r_0^{-5/3} \, D^{-1/3}.$$

$$K_l = 0.364 \left(1 - 0.532 \, b^{-1/3} - 0.024 \, b^{-7/3}\right)$$

Beckers 2001
Özişik et al. 2004

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SODAR (SOnic Detection And Ranging) is a wind profiler to measure the scattering of sound waves by atmospheric turbulence.

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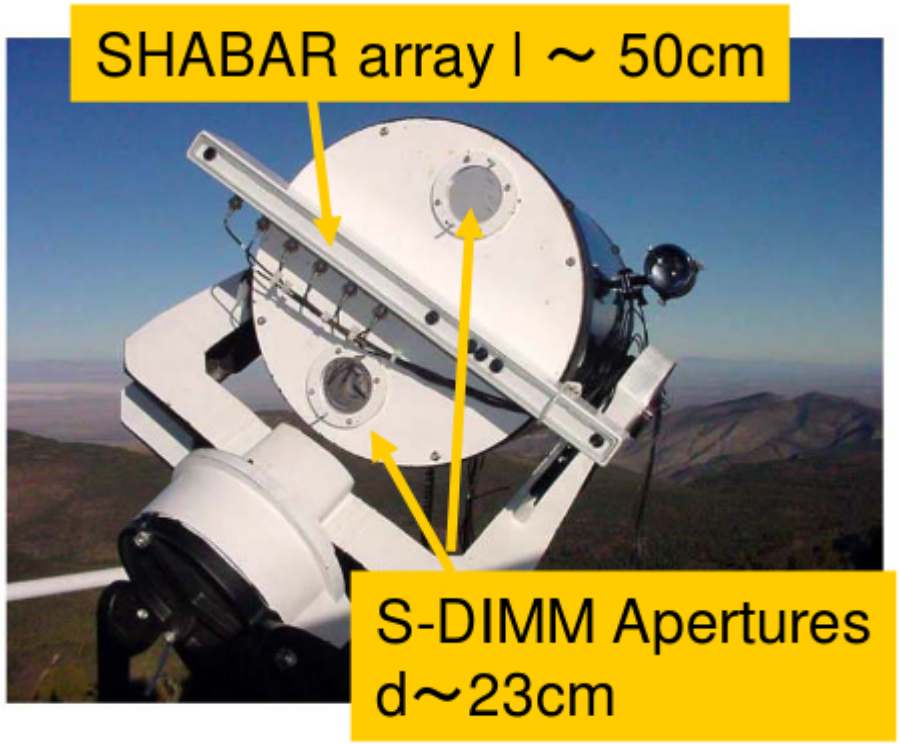
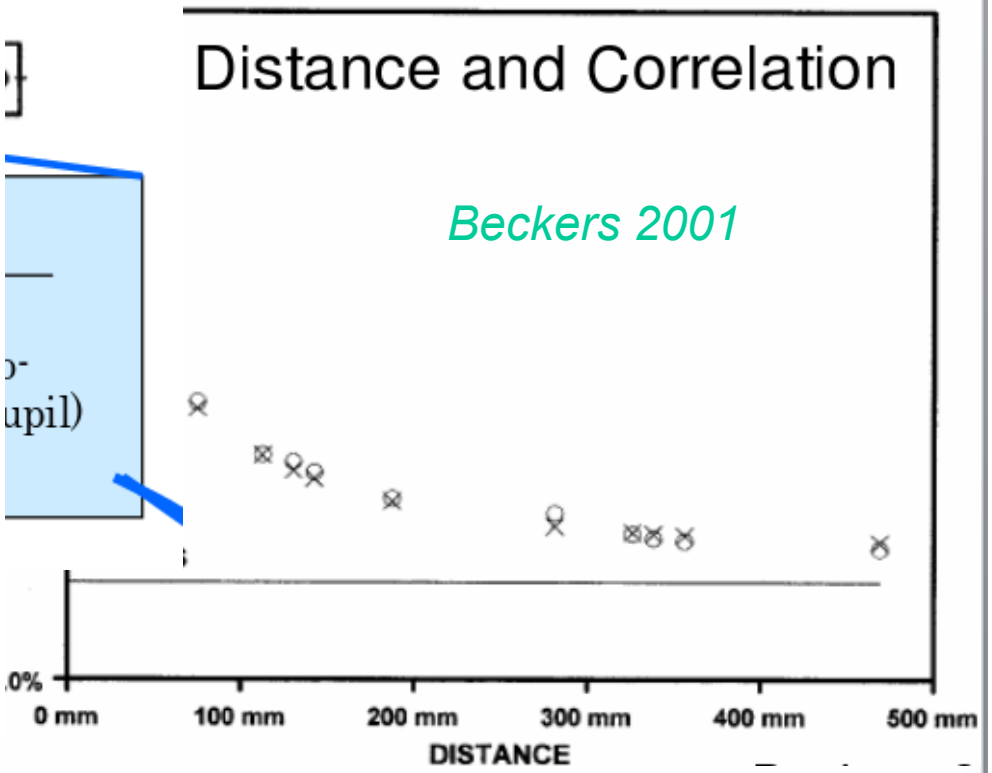
PICARD Mission d'étude des relations entre la variabilité solaire et le climat de la Terre. Mieux comprendre les changements climatiques par une meilleure connaissance du Soleil.

SHABAR Array





σ_I^2 stars: $1 \sim 10^{-3}$ the Sun: $10^{-6} \sim 10^{-8}$

– Fried parameter and scintillation: anti-correlation

Main estimation techniques

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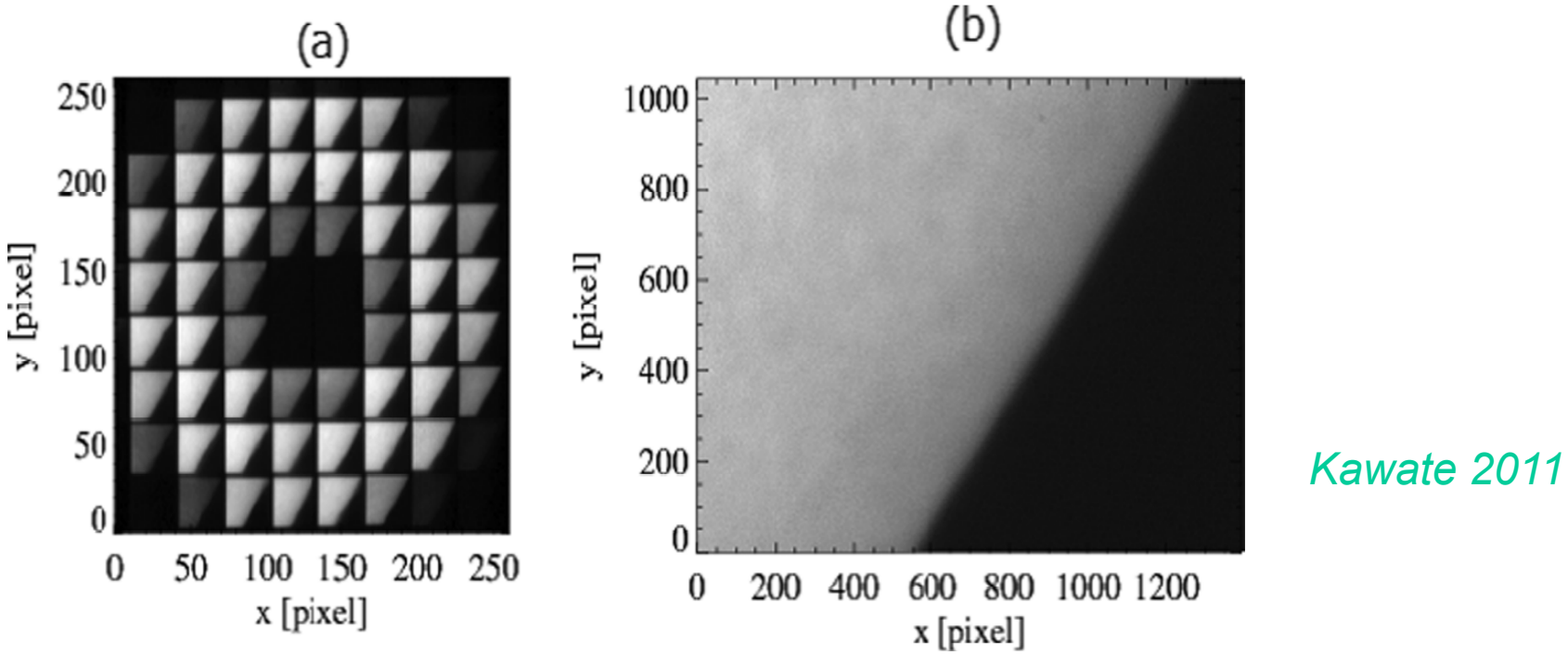
Shack-Hartmann



Kawate 2011

- Use of a solar adaptive optics part to measure seeing
- Each paire of subapertures is regarded as a DIMM
- r0 is estimated from differential image motions
- Method of Sarazin & Roddier 1990

Main estimation techniques

- Solar Differential image Motion Monitor (S-DIMM)
- SODAR
- SHAdow BAnd Ranger (SHABAR): consisting of an array of solar scintillometers for the measurement of the atmospheric structure constant $Cn^2(h)$
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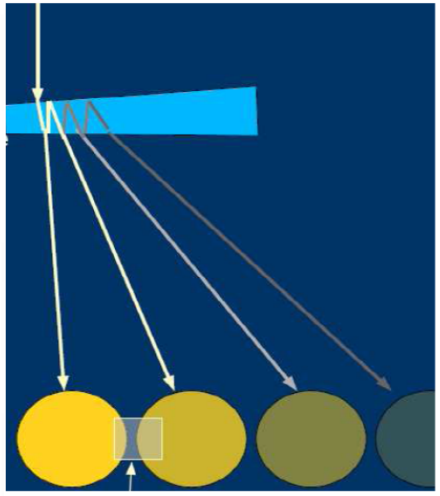
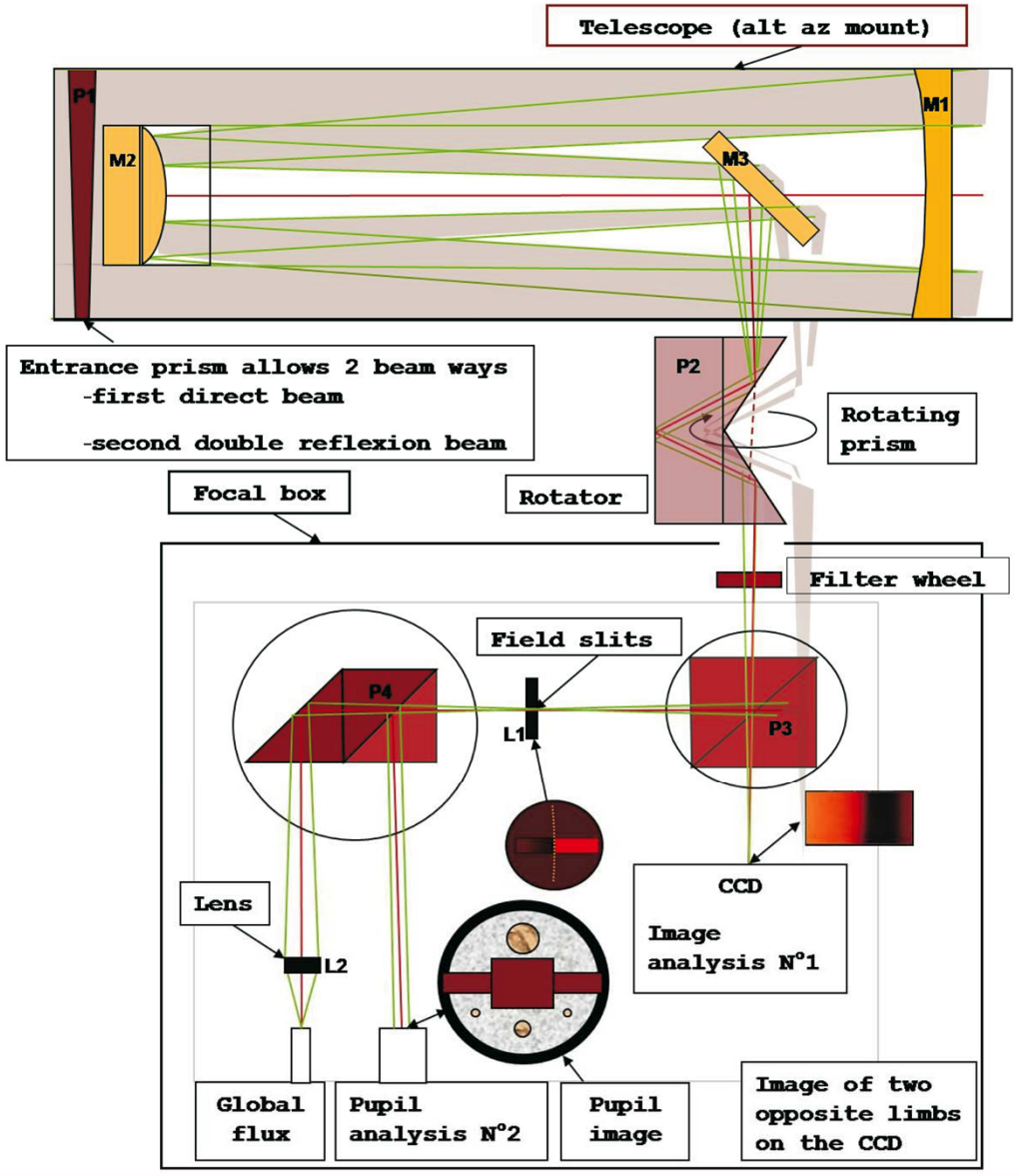
Picard-Sol instruments

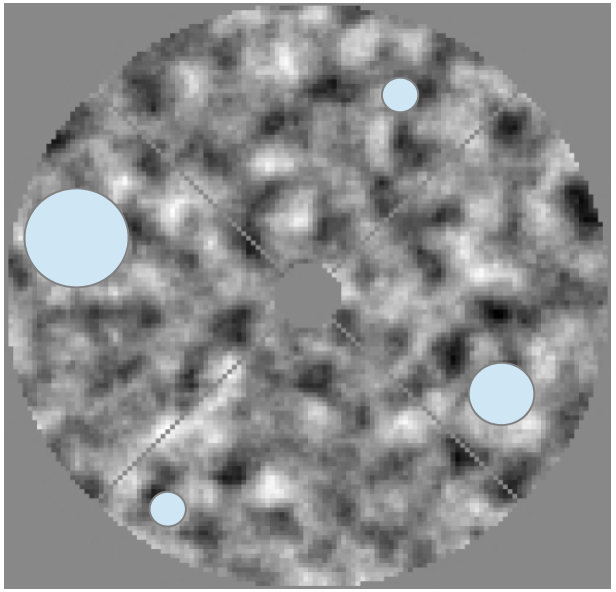
MISOLFA




Telescope (alt az mount)
P1
M1
M2
M3
Entrance prism allows 2 beam ways
-first direct beam
-second double reflexion beam
P2
Rotating prism
Rotator
Focal box
Filter wheel
Field slits
P4
L1
P3
CCD
Image analysis N°1
Lens
L2
Global flux
Pupil analysis N°2
Pupil image
Image of two opposite limbs on the CCD

Data processing

Pupil plane



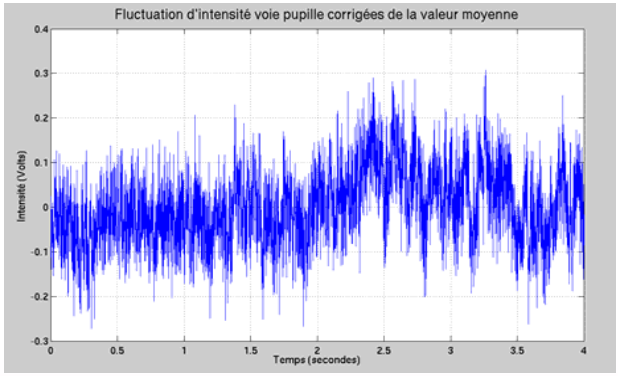
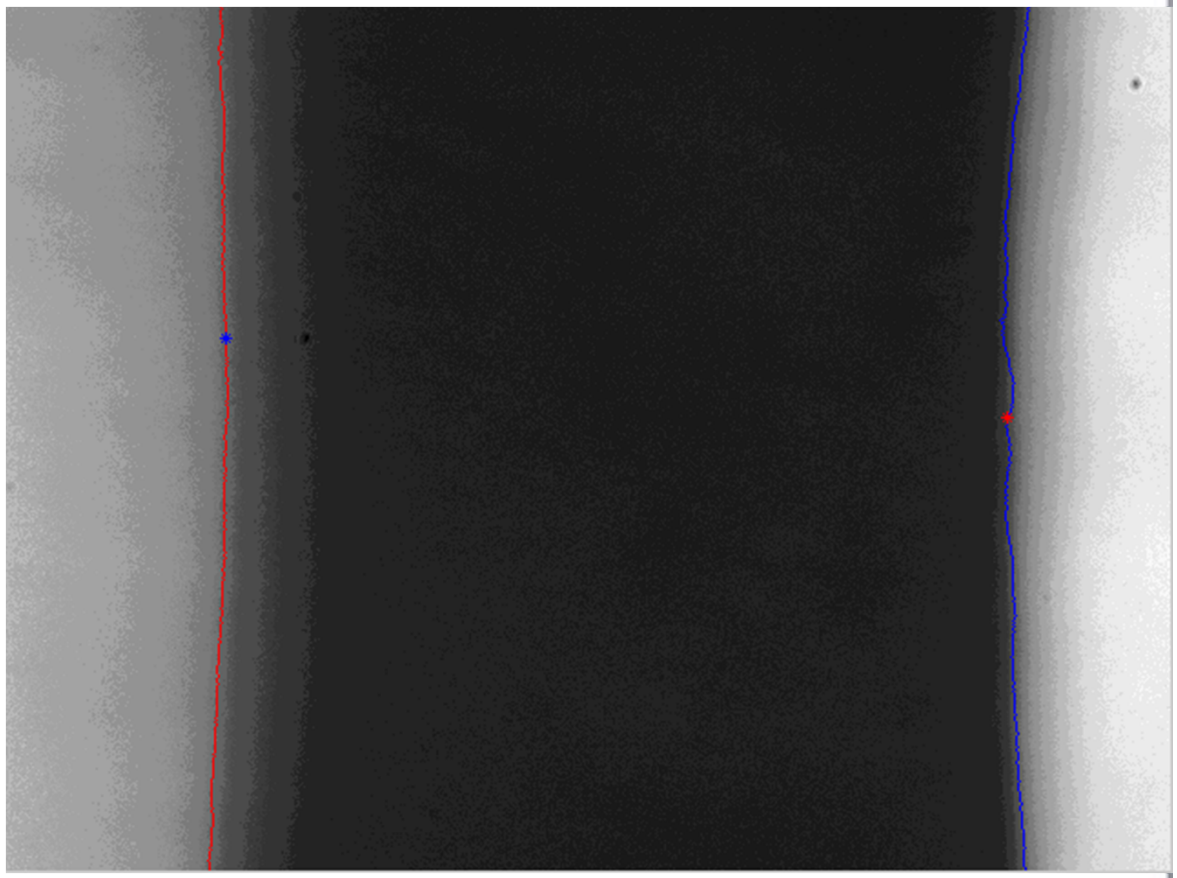
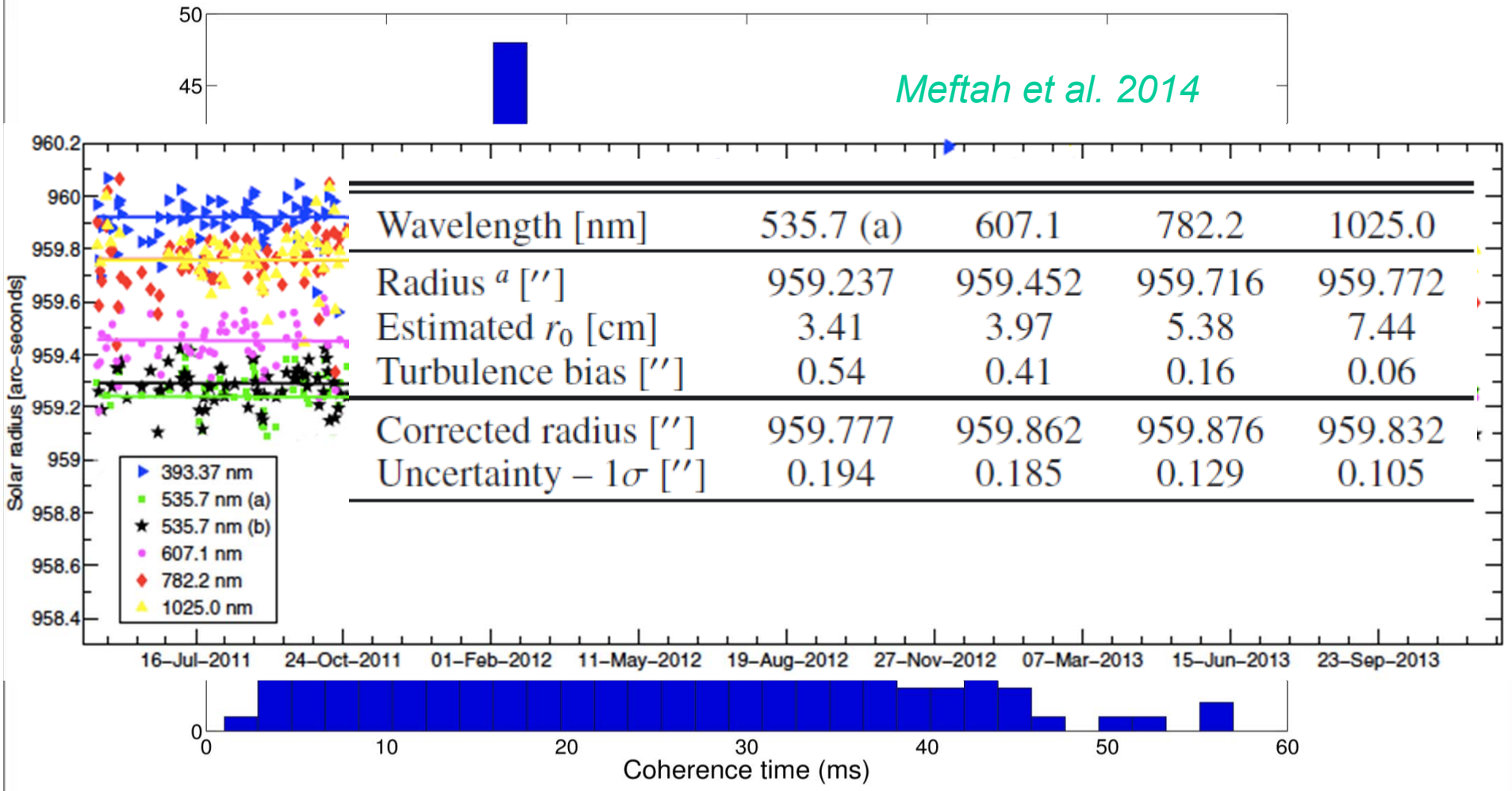


Image plane



Some results from MISOLFA: image and pupil plane



Wavelength [nm]	535.7 (a)	607.1	782.2	1025.0
Radius [a] [″]	959.237	959.452	959.716	959.772
Estimated r_0 [cm]	3.41	3.97	5.38	7.44
Turbulence bias [″]	0.54	0.41	0.16	0.06
Corrected radius [″]	959.777	959.862	959.876	959.832
Uncertainty – 1σ [″]	0.194	0.185	0.129	0.105

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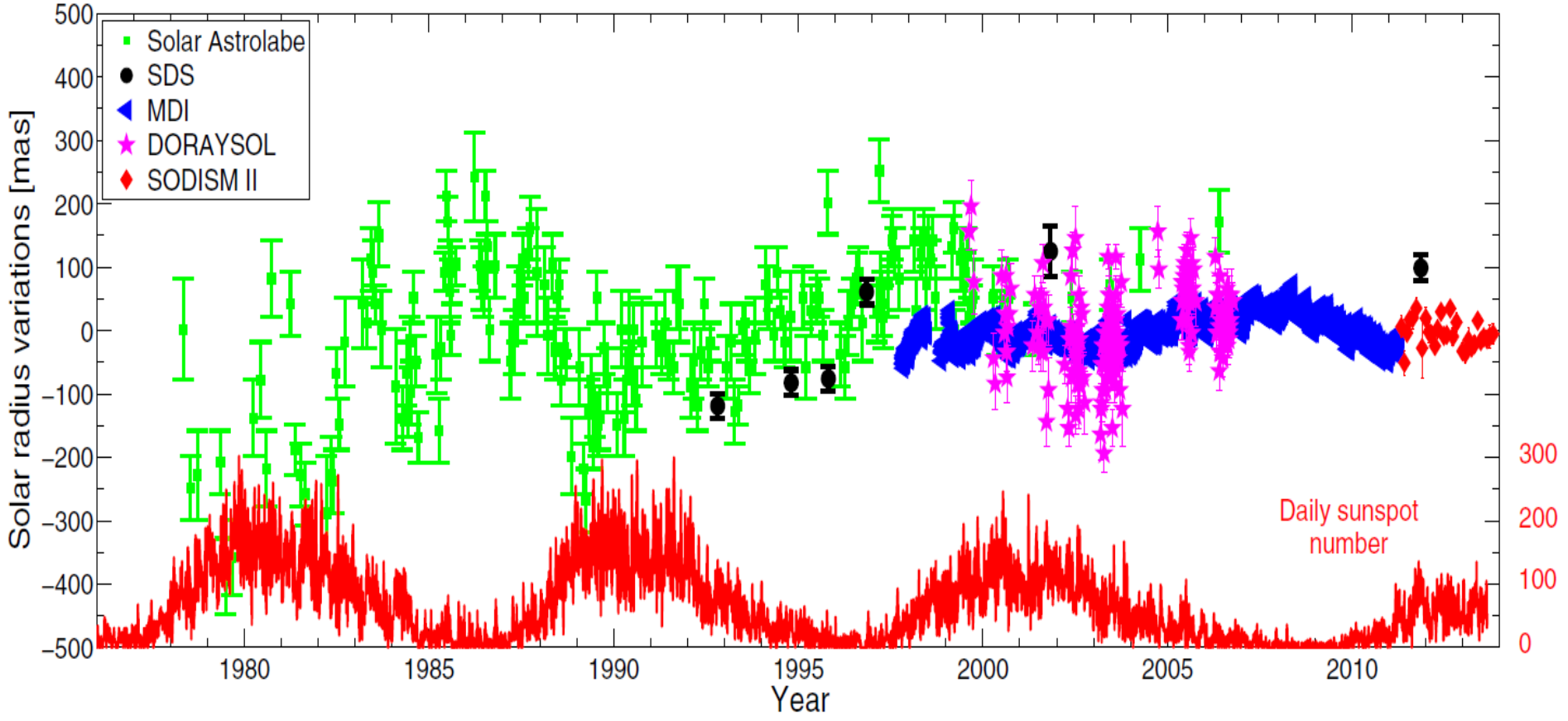
Picard-Sol results after seeing effect correction

A&A 569, A60 (2014) *Meftah et al. 2014*



Estimation of r0 using long exposure images MTF

Method

Bell, Hill and Harvey 1999

- Recorded image of the Sun:

$$o(\lambda, x, y) = i(\lambda, x, y) \otimes \psi(\lambda, x, y) + \cancel{n(\lambda, x, y)}$$

- In the Fourier domain (circularly symetric): Hankel transform

$$O(q) = I(q)\Psi(q)$$

- The modulation transfer function can be expressed for long exposure images as :

$$\Psi(q) = e^{-3.44(\lambda q/r_0)^{5/3}}$$

- In the general case:

$$\Psi(q) \approx e^{-3.35(\lambda q/r_0)^{n}}$$

- Introducing a diffusion term as a Lorantzian in MTF equation gives:

$$\Psi(q) = (1-\epsilon)e^{-3.35(\lambda q/r_0)^{n}} + \epsilon e^{-Aq}$$

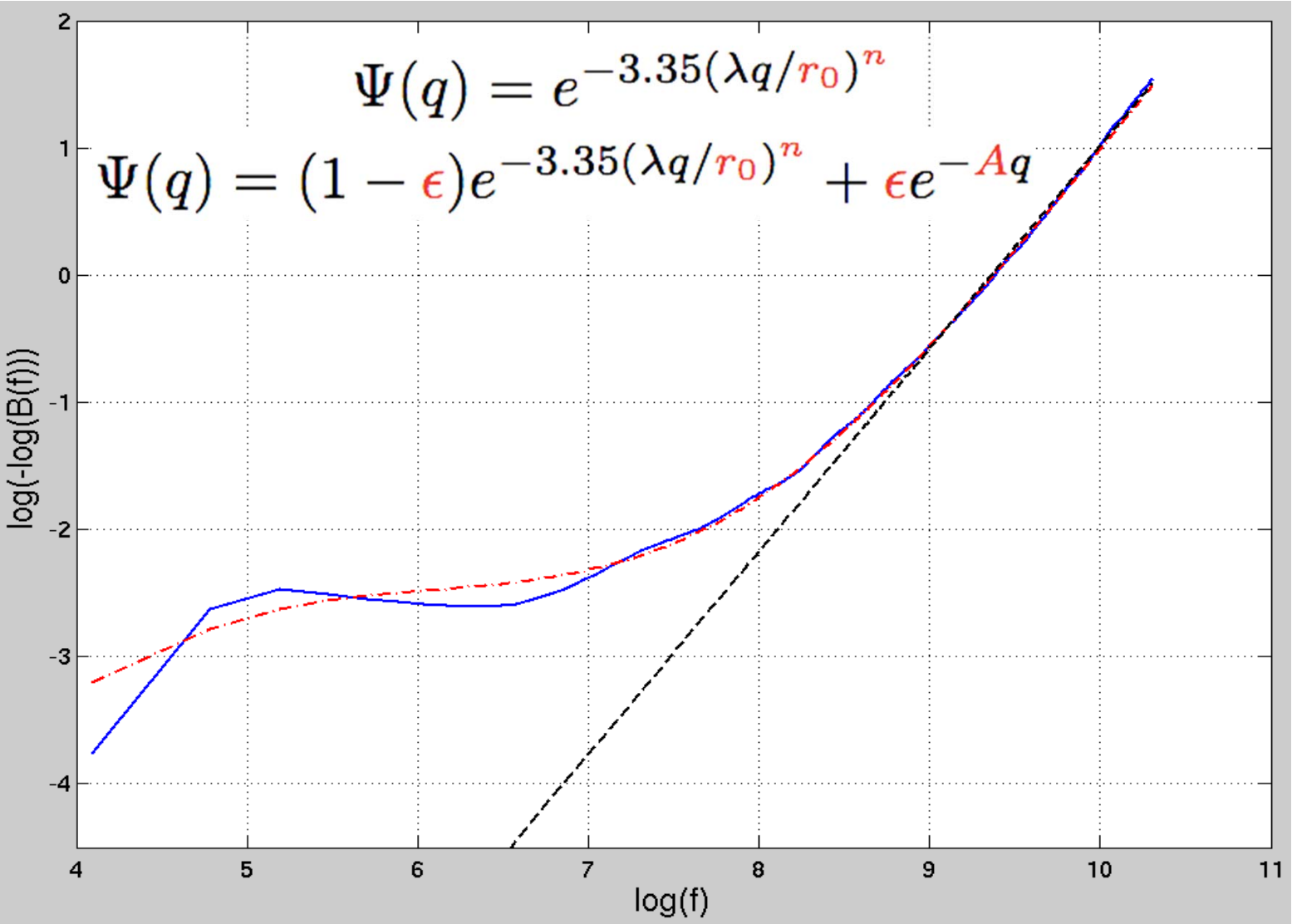
MTF estimation from full disk images

Toner & Jefferies 1993

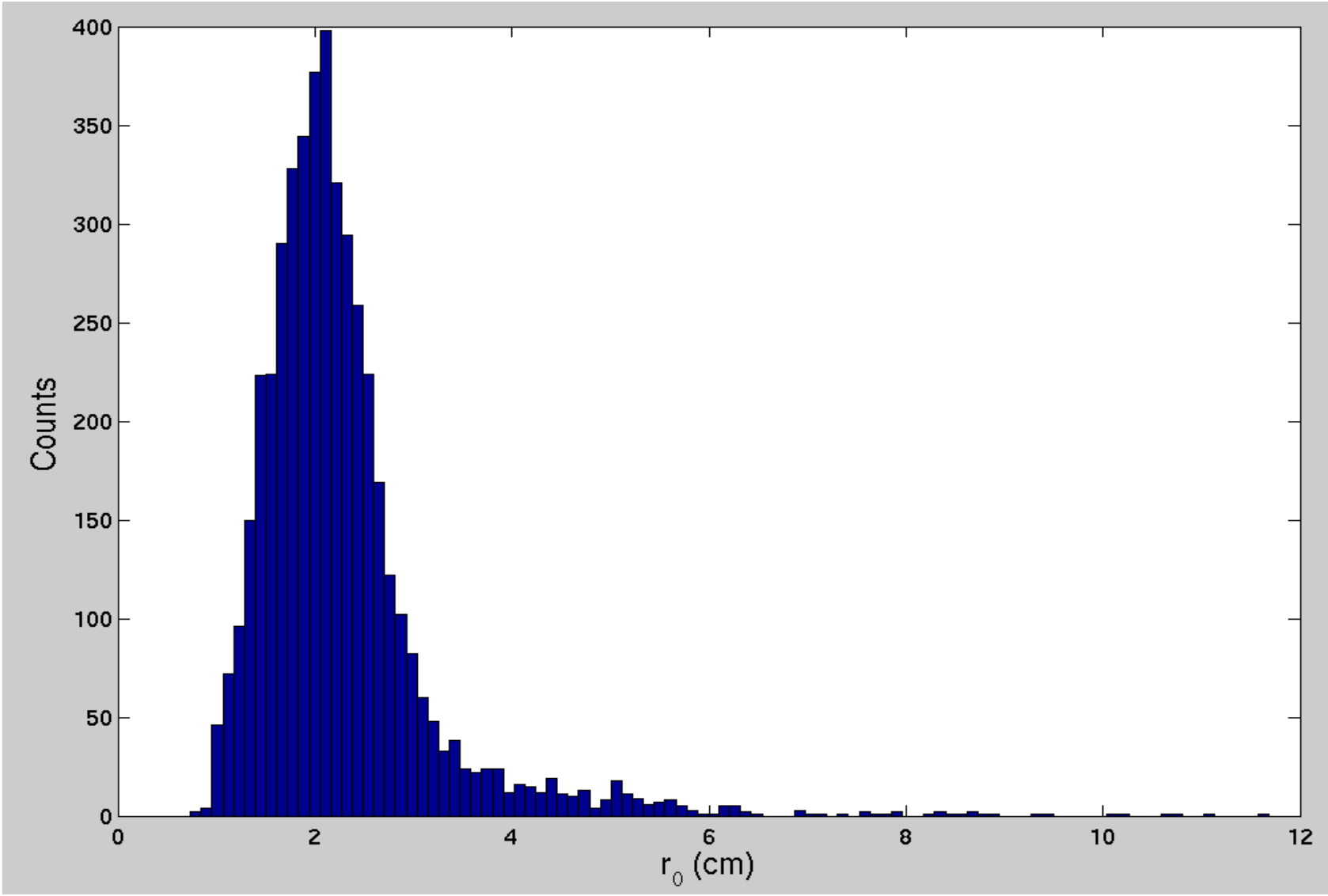
- Accurate determination of the full disk geometry, fit by an ellipse.
- Generation of the radial intensity profile (mediane in succesive annuli) rejecting pixels contaminated by activity.
- Application of the Hankel transform.
- Determination of the positions of the zeros crossings the tranformed data.
- Least square minimization to determine limb darkening coefficients, ellipse parameters and mean radius.
- Estimation of the MTF for the image.

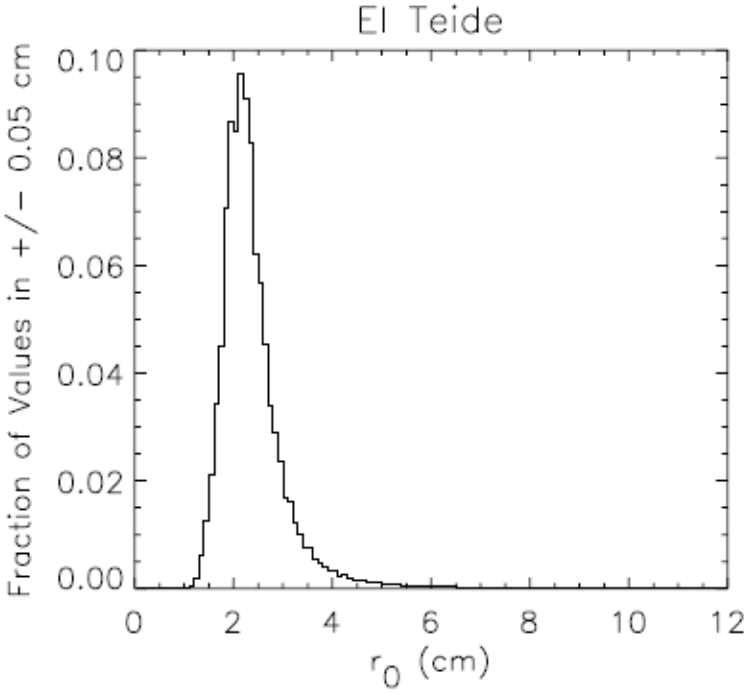
MTF estimation from SODISM2 images

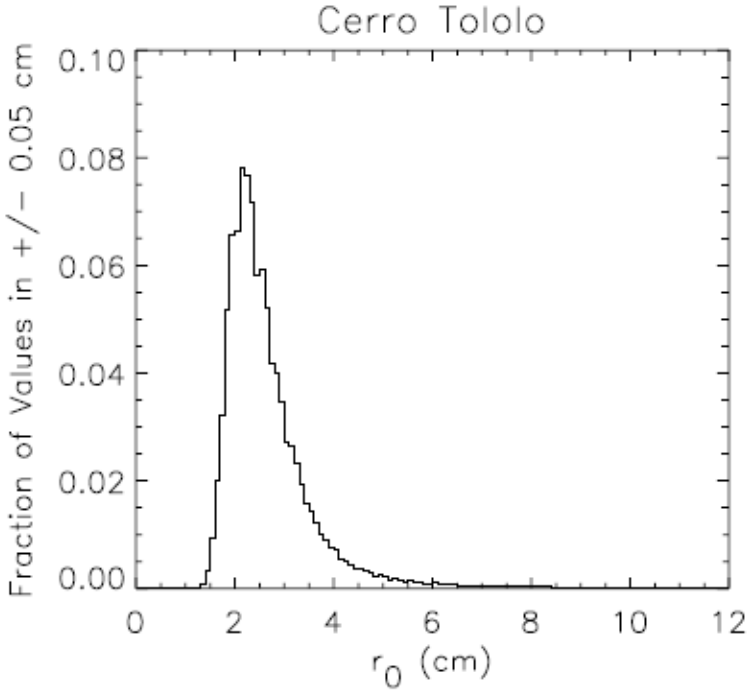
-
-

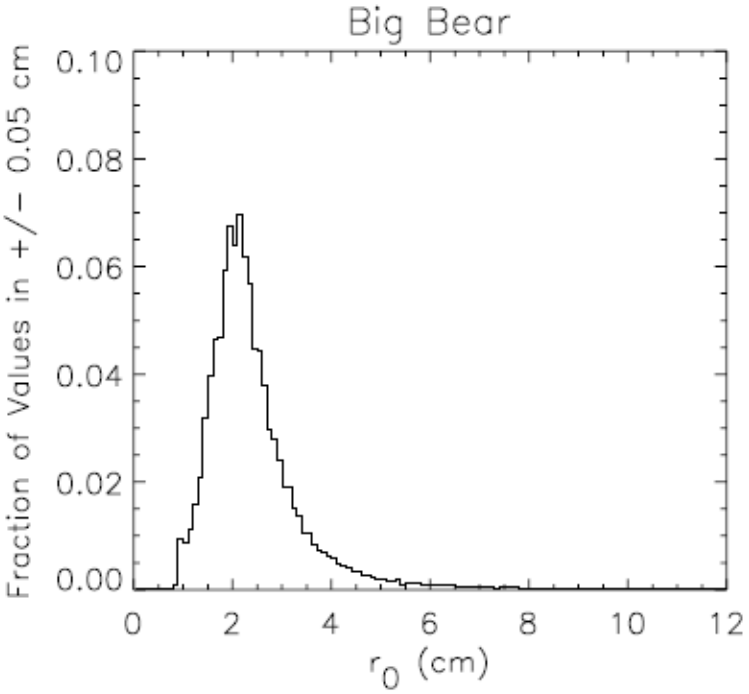


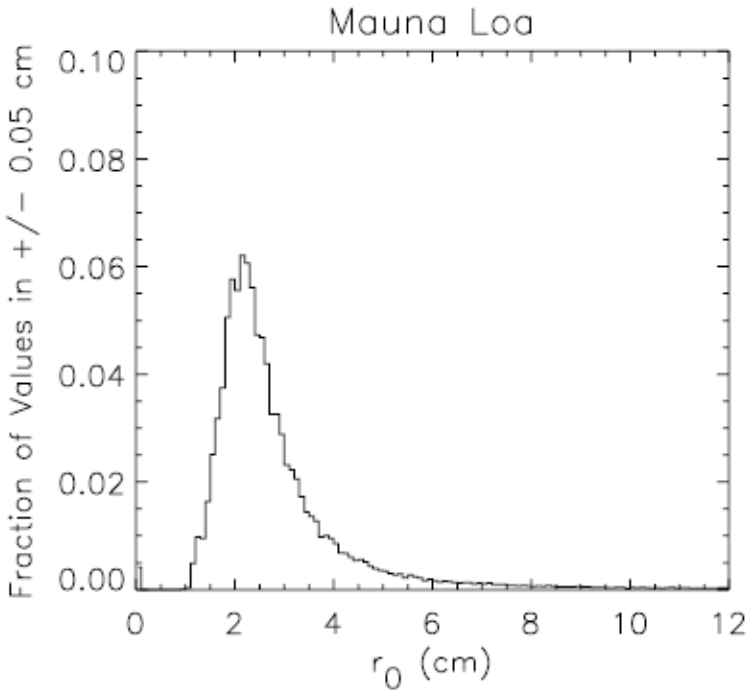
Histogram @ 607nm




El Teide
Fraction of Values in +/- 0.05 cm
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
12
r0 (cm)


Cerro Tololo
Fraction of Values in +/- 0.05 cm
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
12
r0 (cm)


Big Bear
Fraction of Values in +/- 0.05 cm
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
12
r0 (cm)


Mauna Loa
Fraction of Values in +/- 0.05 cm
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
12
r0 (cm)

Conclusions and perspectives

- Simple parametrization allows us to estimate a mean value of Fried parameter together with the image MTF and limb darkening coefficients for each SODISM2 images.
- MISOLFA also provides estimates to the instantaneous Fried parameter values.
- Need to be calibrated with other instruments (S-DIMM, PBL).
- Knowledge of seeing allow image restoration and correction of measured radii.
- MISOLFA provides estimates of turbulence coherence time -> Reconstruction the optical turbulence part of the long exposure MTF and help to separate the different contributions of the global MTF.
- Scattering effect appears to be negligible in comparison to seeing..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Mieux comprendre les changements climatiques par une meilleure connaissance du Soleil.

Thank you !


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Mission d'étude des relations entre la variabilité solaire et le climat de la Terre.
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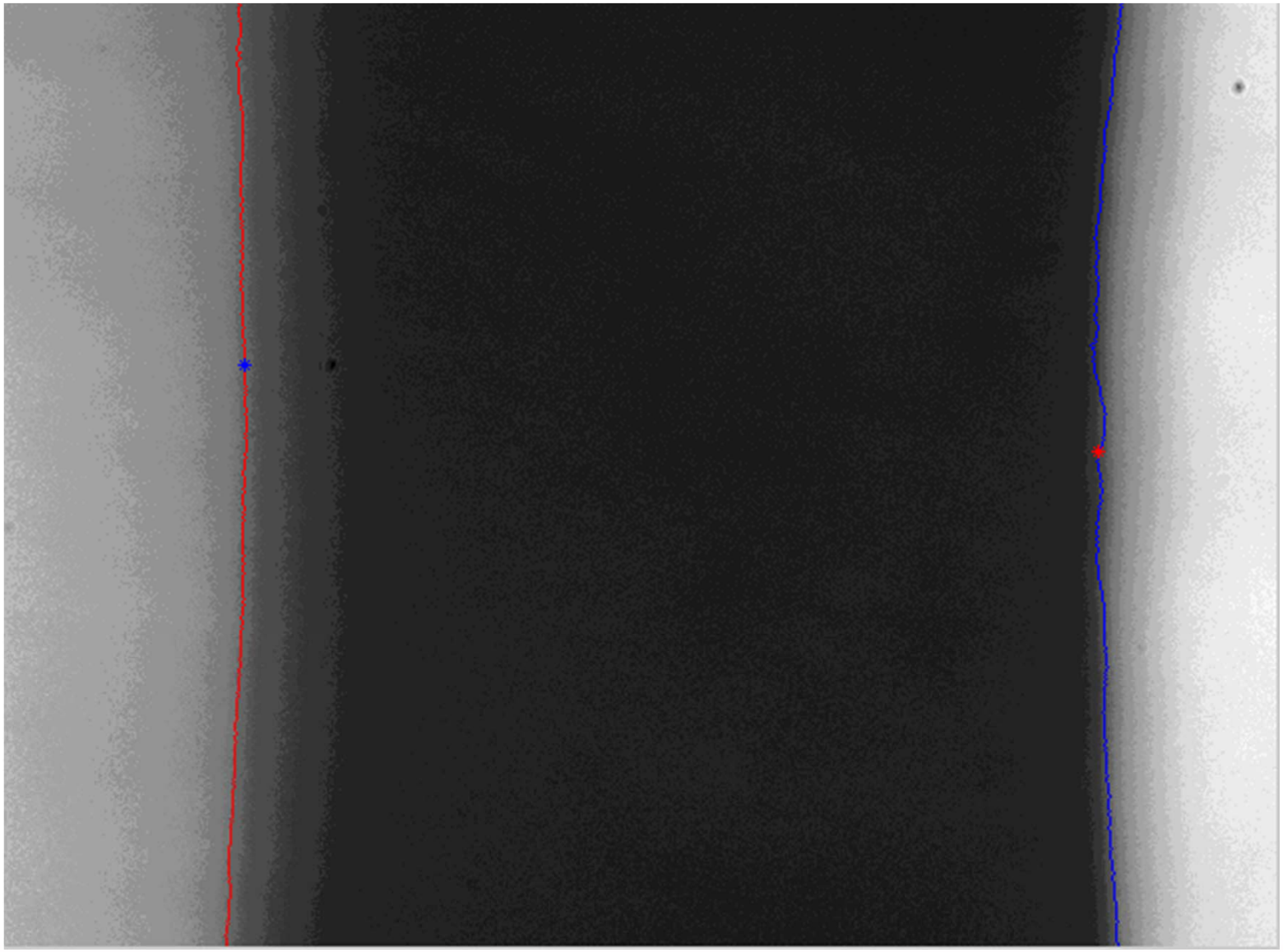
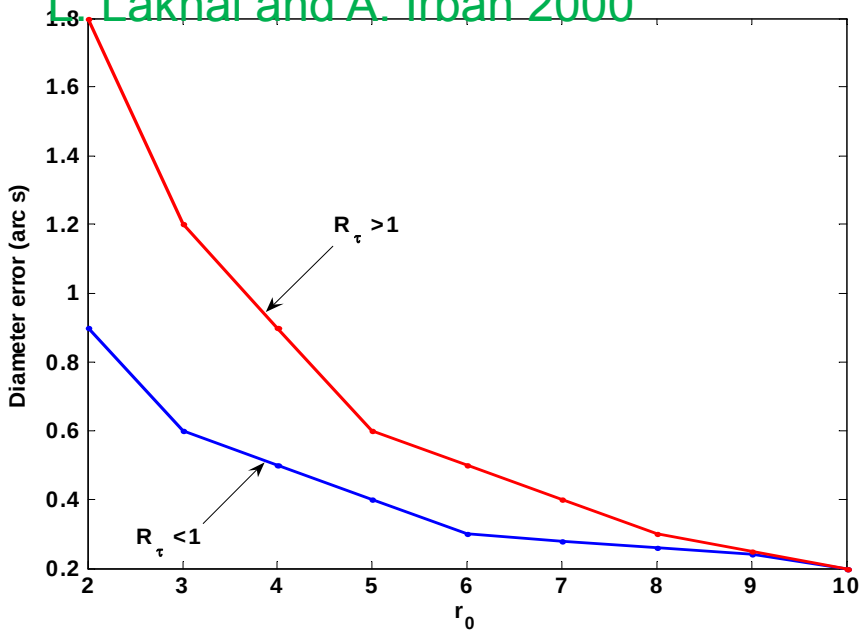
Image plane

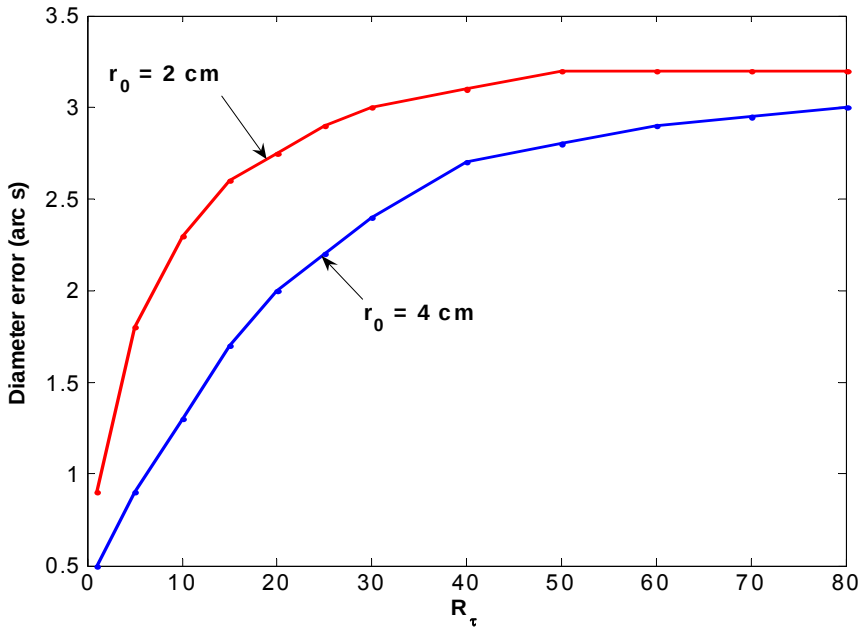


Seeing effect: Why MISOLFA ?

Atmospheric turbulence effects on solar diameter measurements : validation of numerical simulation using data recorded at Calern Observatory (with Doraysol)

L. Lakhal and A. Irbah 2000





Estimated errors on diameter estimates as a function of the Fried's parameter r0 for two values of Rτ (ratio between the exposure time and the correlation time) **(left)** and as a function of Rτ for two values of r0 **(right)**

Irbah et al., Solar Physics, 1994 Lakhal, Irbah et al., A&A, 1999

Multi-layers atmosphere with Von Karman turbulence model

- *Atmospheric Structure constant $C^2_n(h)$*

- Fried's parameter r_0 is the diameter of the coherence zone of the degraded wave-front. It corresponds also to the image resolution obtained with the telescope of diameter r_0 placed outside the atmosphere.

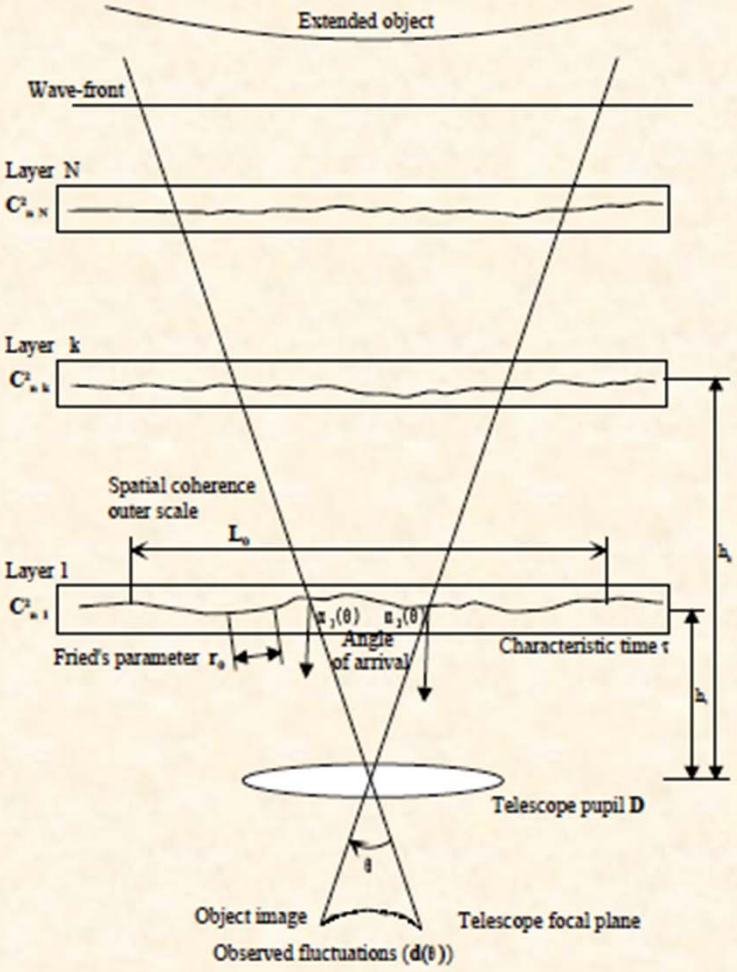
$$r_0 = \left[16.7\lambda^{-2} \int_0^{+\infty} dh\, C_n^2(h) \right]^{-\frac{3}{5}}$$

- *The spatial coherence outer scale L_0* defines the maximal size of wave-front perturbations remaining cohe-rent. It traduces of low frequency evolution of the wave-front.

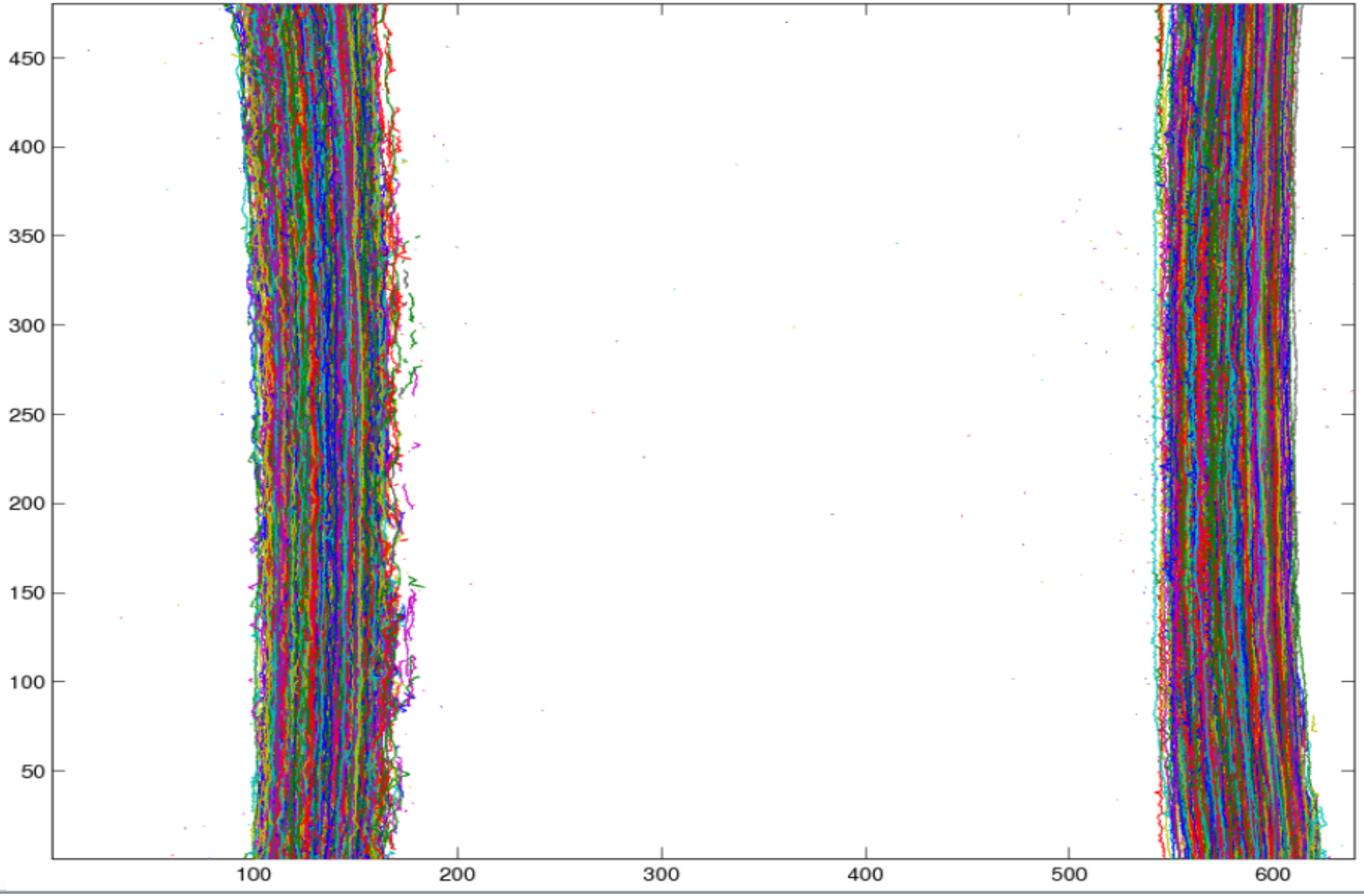
$$L_0 = \left[\frac{\int_0^{+\infty} dh\, \mathbf{L}_0^{\frac{1}{3}} C_n^2(h)}{\int_0^{+\infty} dh\, C_n^2(h)} \right]^3$$

- *Isoplanatic patch θ_0* is the angle where *AA* or speckles remain correlated.

- *Correlation time τ_0* is the time where the atmosphere may be considered as frizzed for the considered structures (AA, speckles). They keep their coherence



Edges detection



Processing steps

- Image cleanning by wavelet denoising (sunspots)
- Solar edges extraction
- Angle-of-arrival fluctuations structure function

$$d_{\alpha_\perp Exp}(\theta) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{\theta_m-\theta}\sum_{k=1}^{\theta_m-\theta}\left[\alpha_\perp(k)-\alpha_\perp(k+\theta)\right]^2$$

- Non linear curve fitting assuming Von Karman model (Levenberg-Marquadt)

$$C_\alpha(\theta) = 0.0716\lambda^2 r_0^{-\frac{5}{3}}\int_0^{+\infty} df\ f^3\left(f^2+\frac{1}{L_0^{\ 2}}\right)^{-\frac{11}{6}}\left[J_0(2\pi f\theta\ h)+J_2(2\pi f\theta\ h)\right]\left[\frac{2J_1(\pi Df)}{\pi Df}\right]^2$$

$$D_\alpha(\theta) = 2[C_\alpha(0)-C_\alpha(\theta)]$$

Examples

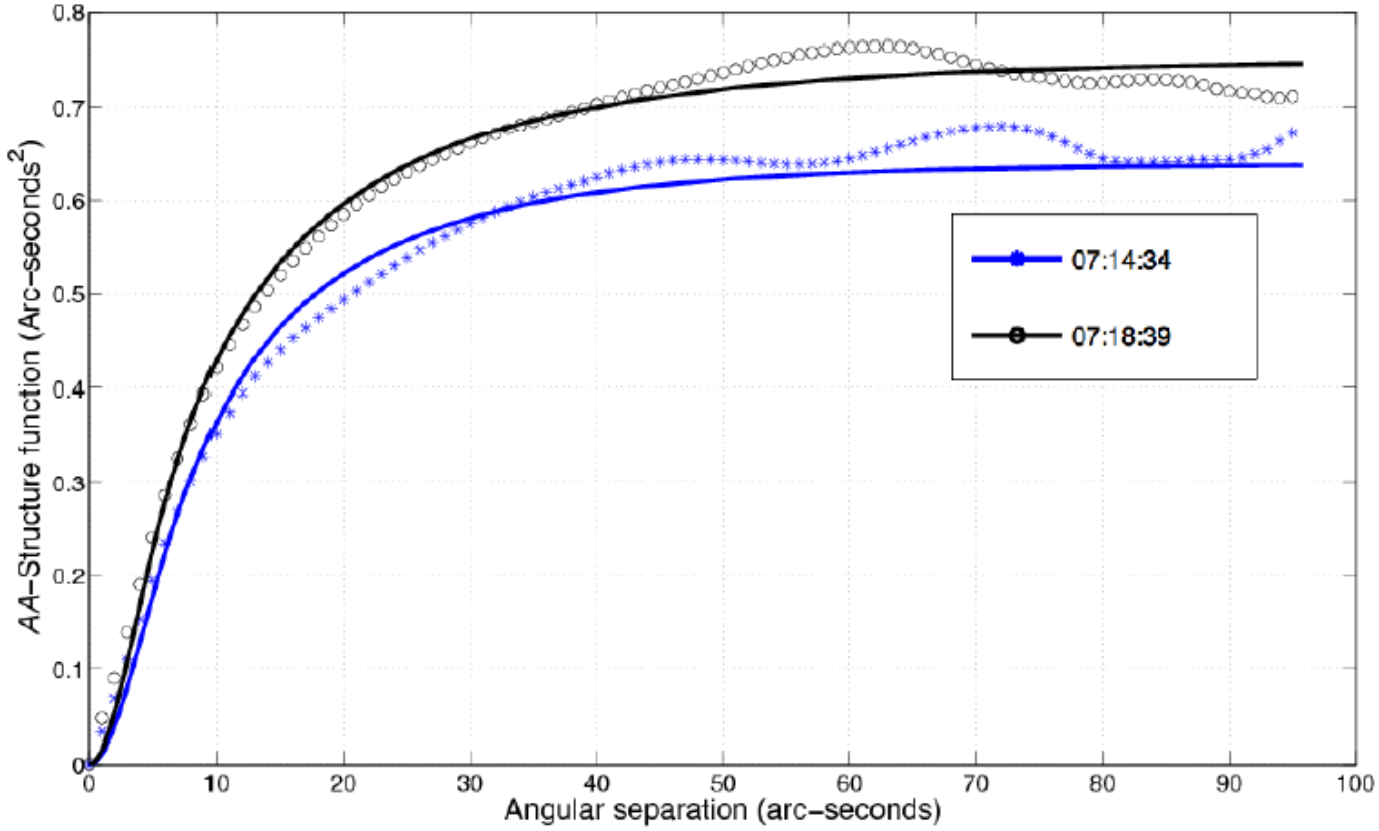
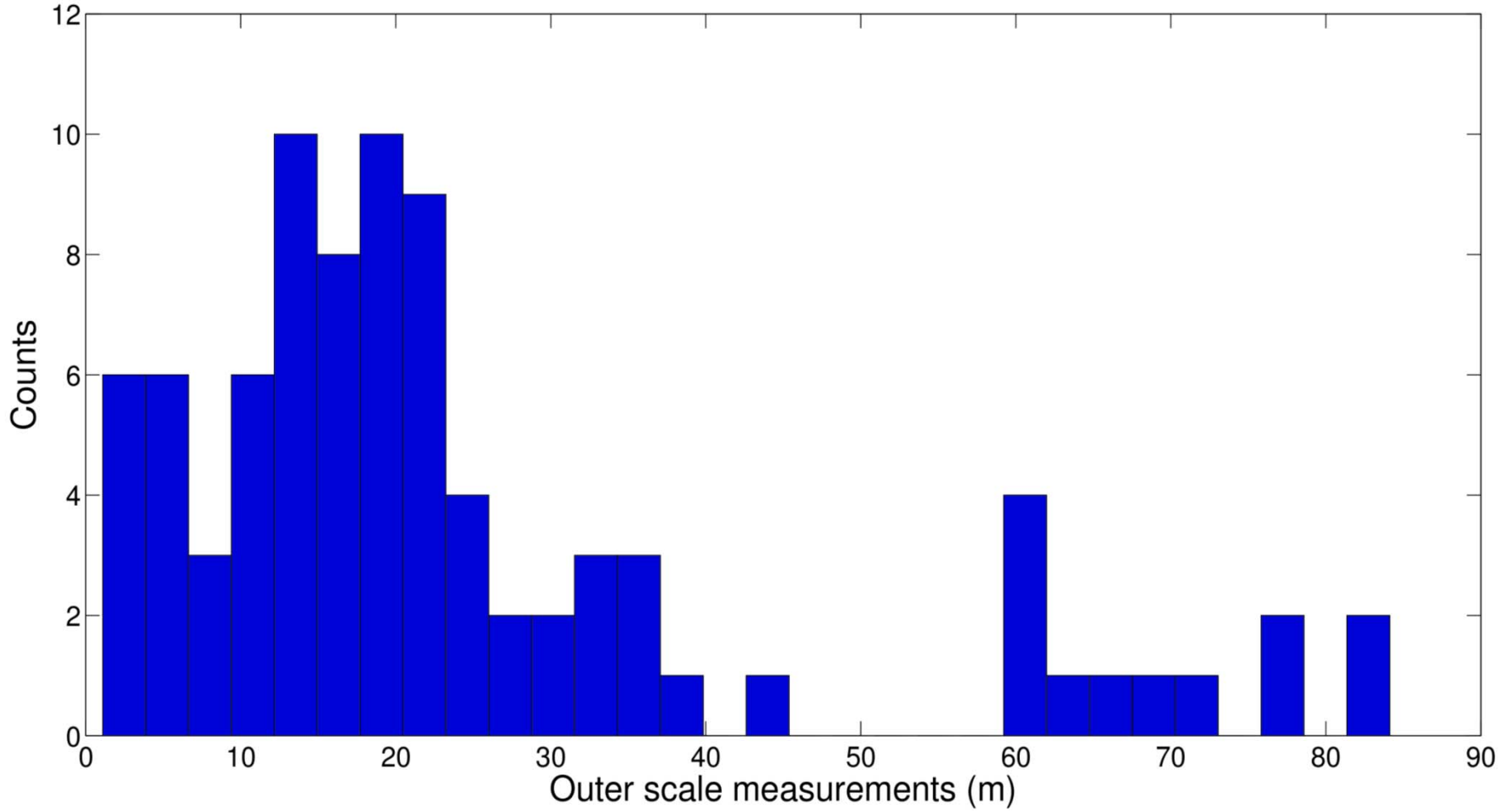
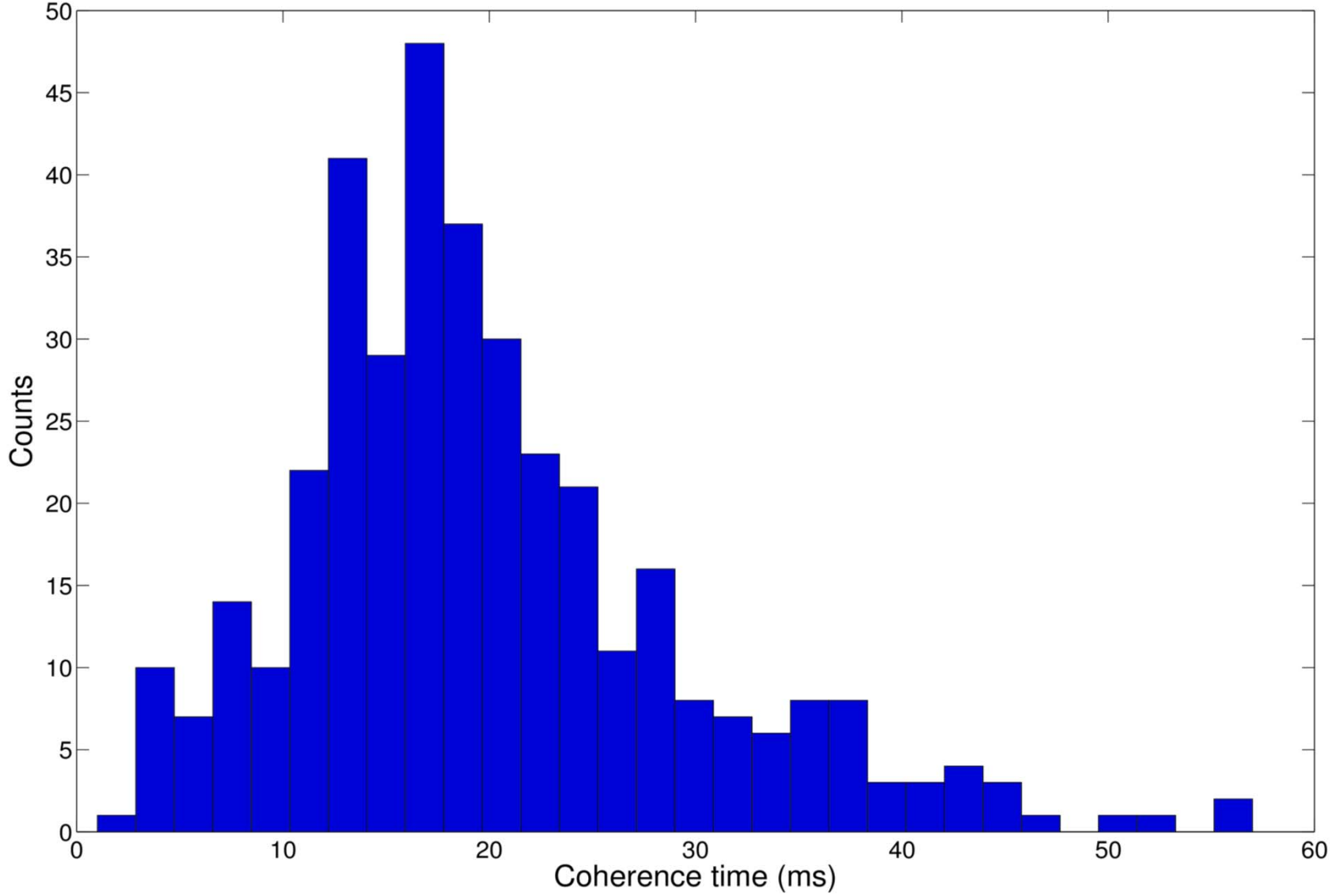


Figure 7. Exprimental structure functions obtained on september 30^{th} 2013. The non linear curve fitting (solid lines) allowed to extract spatial parameters. Values obtained are $h = 9152m$, $r_0 = 5.02cm$ and $\mathcal{L}_0 = 10.35m$ for the first curve (07:14:34) and $h = 9463m$, $r_0 = 4.56cm$ and $\mathcal{L}_0 = 9.66m$for the second one.


Counts
Outer scale measurements (m)
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90

Pupil plane results



PICARD

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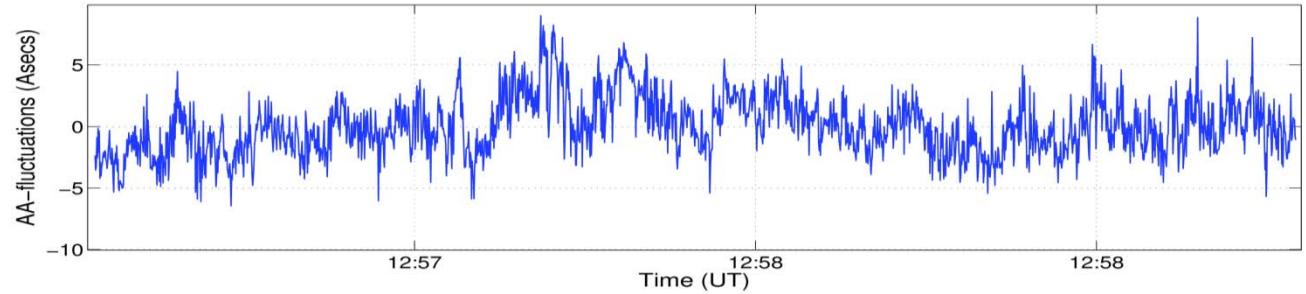
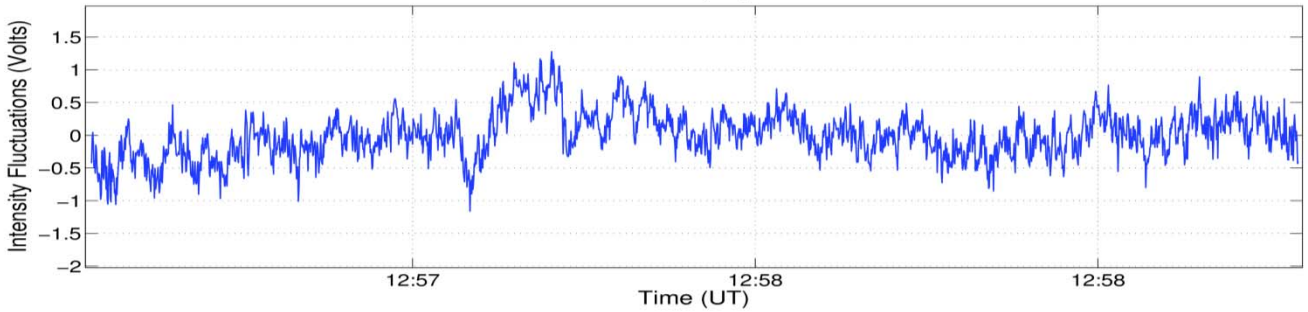
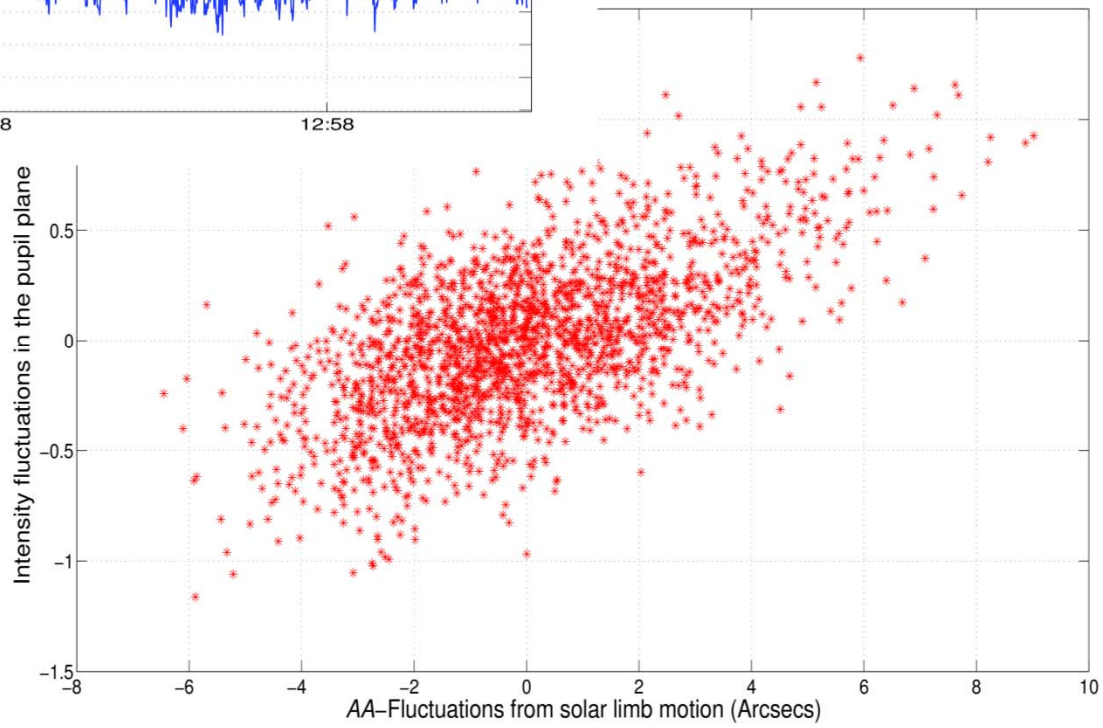
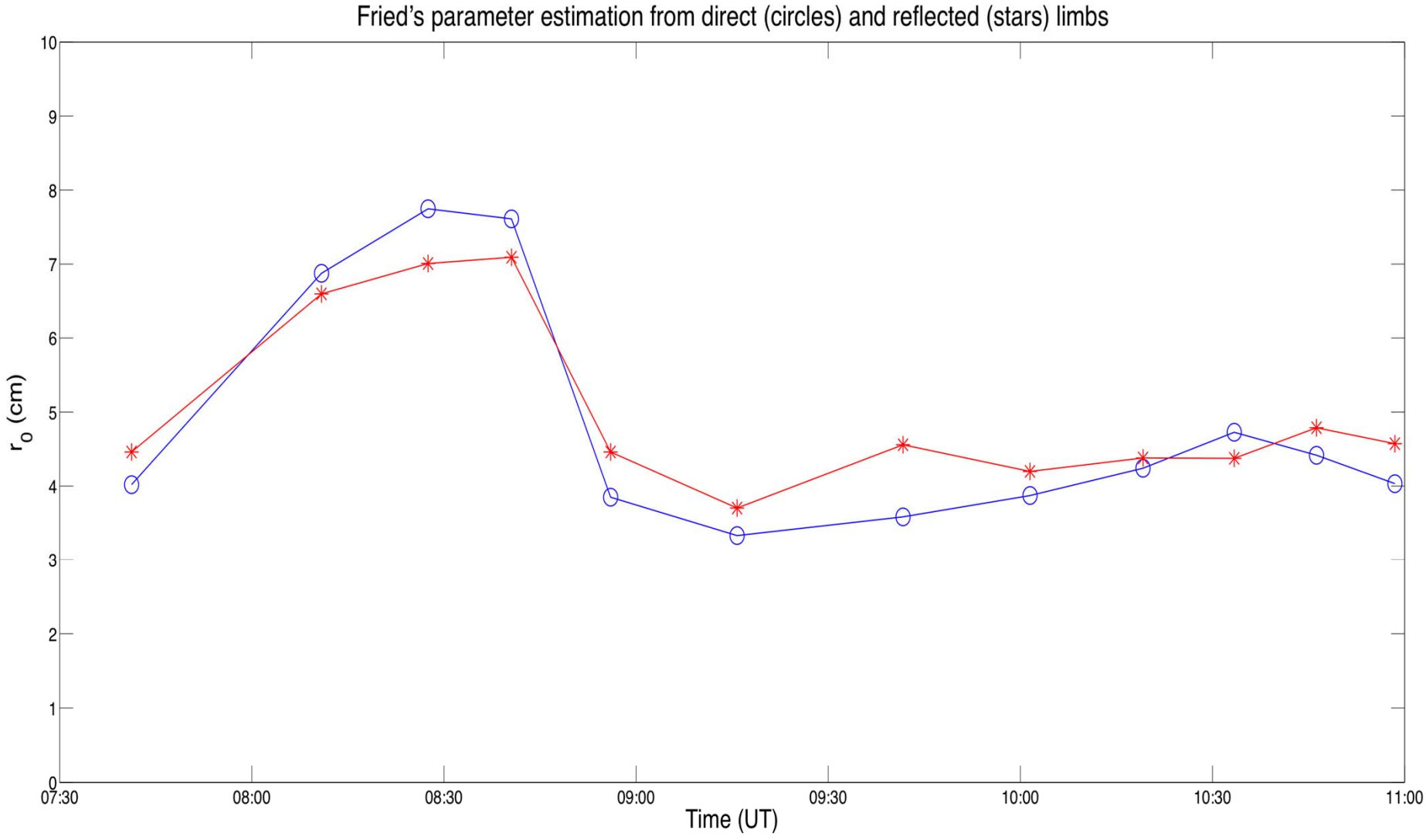
Mieux comprendre les changements climatiques par une meilleure connaissance du Soleil.

Calibration

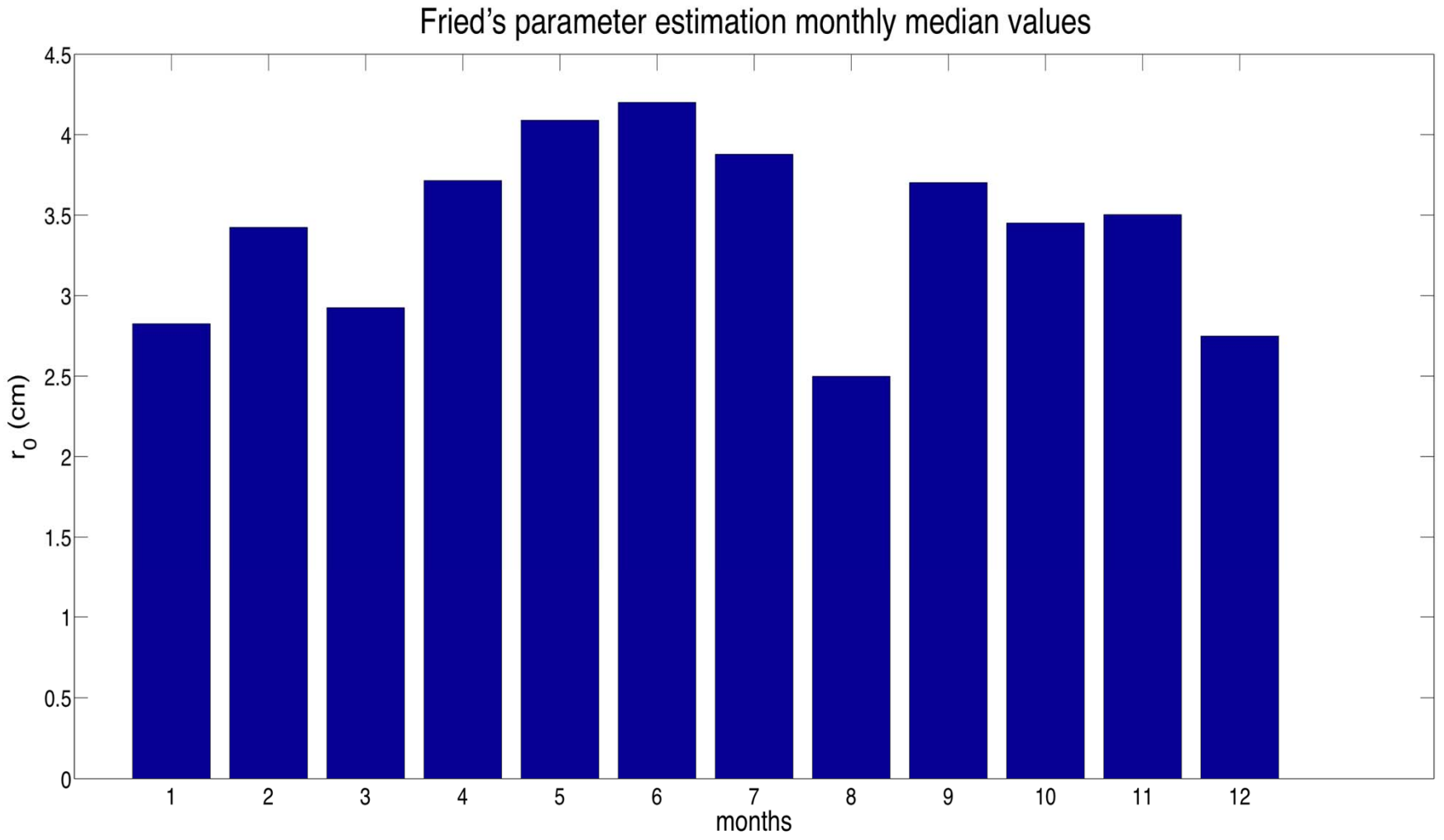






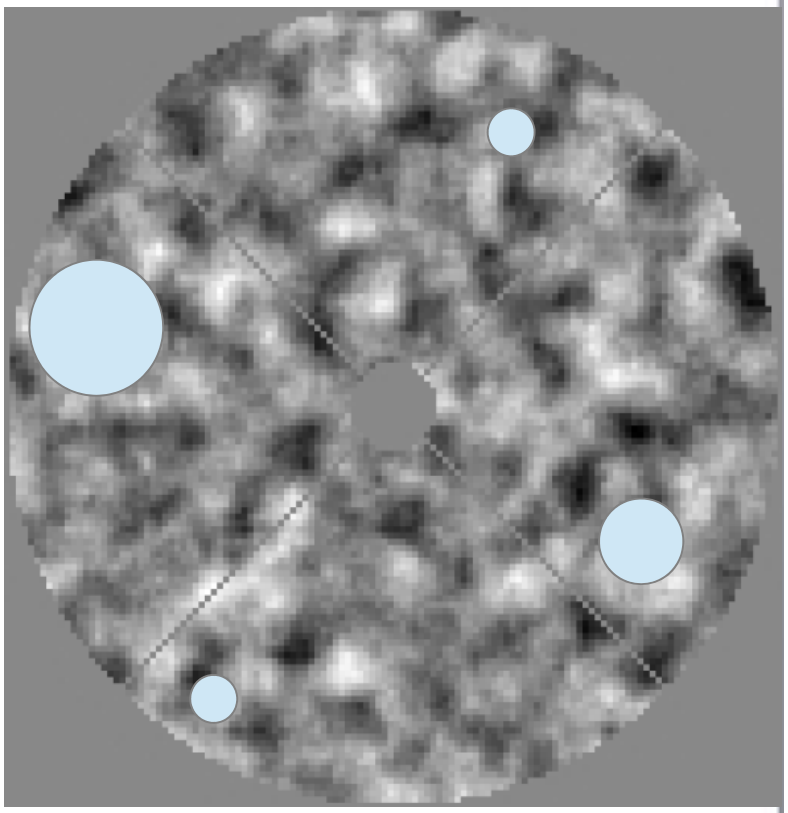

Fried's parameter estimation from direct (circles) and reflected (stars) limbs
r0 (cm)
Time (UT)
0
1
2
3
4
5
6
7
8
9
10
07:30
08:00
08:30
09:00
09:30
10:00
10:30
11:00

Monthly average of Fried parameter

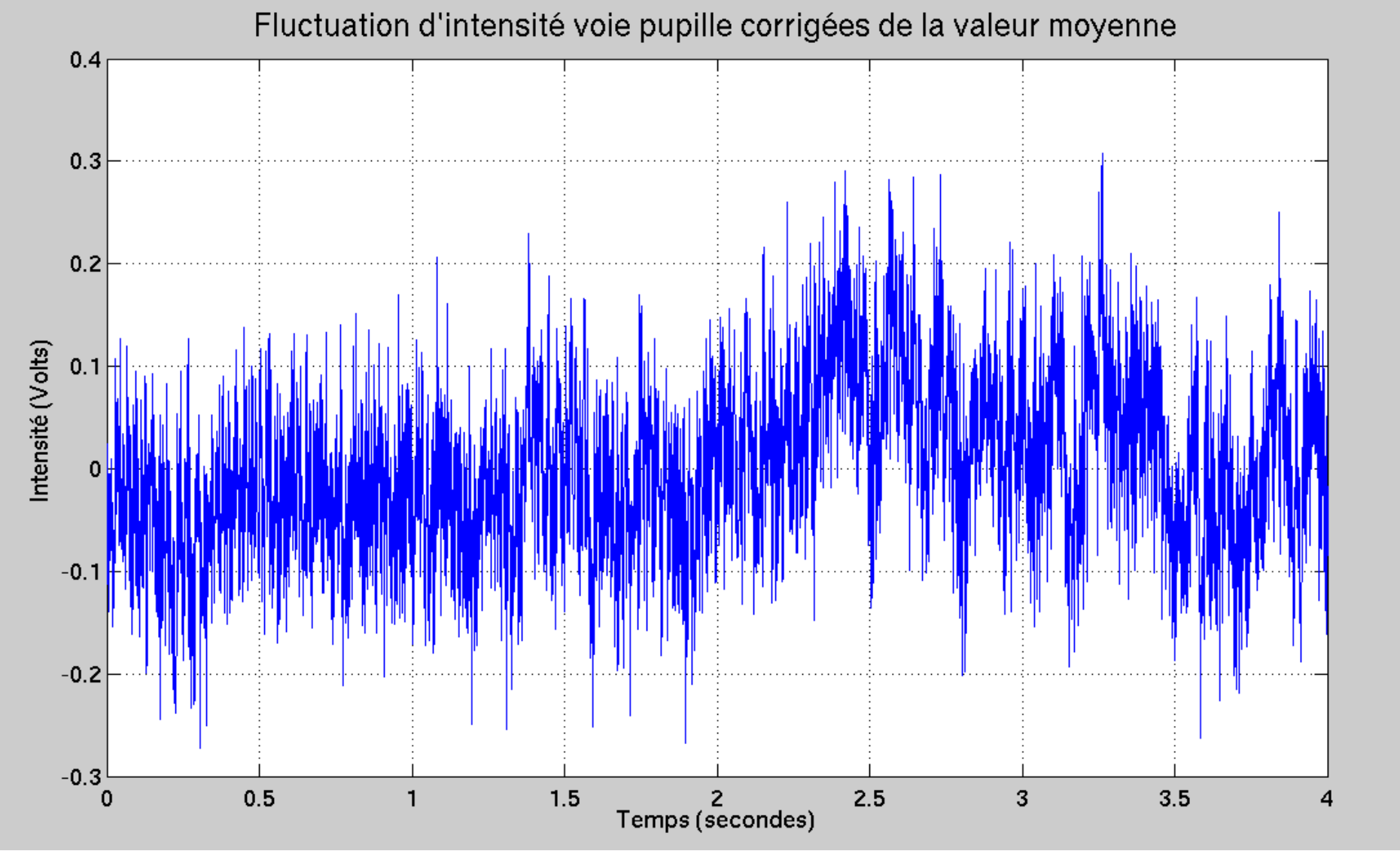


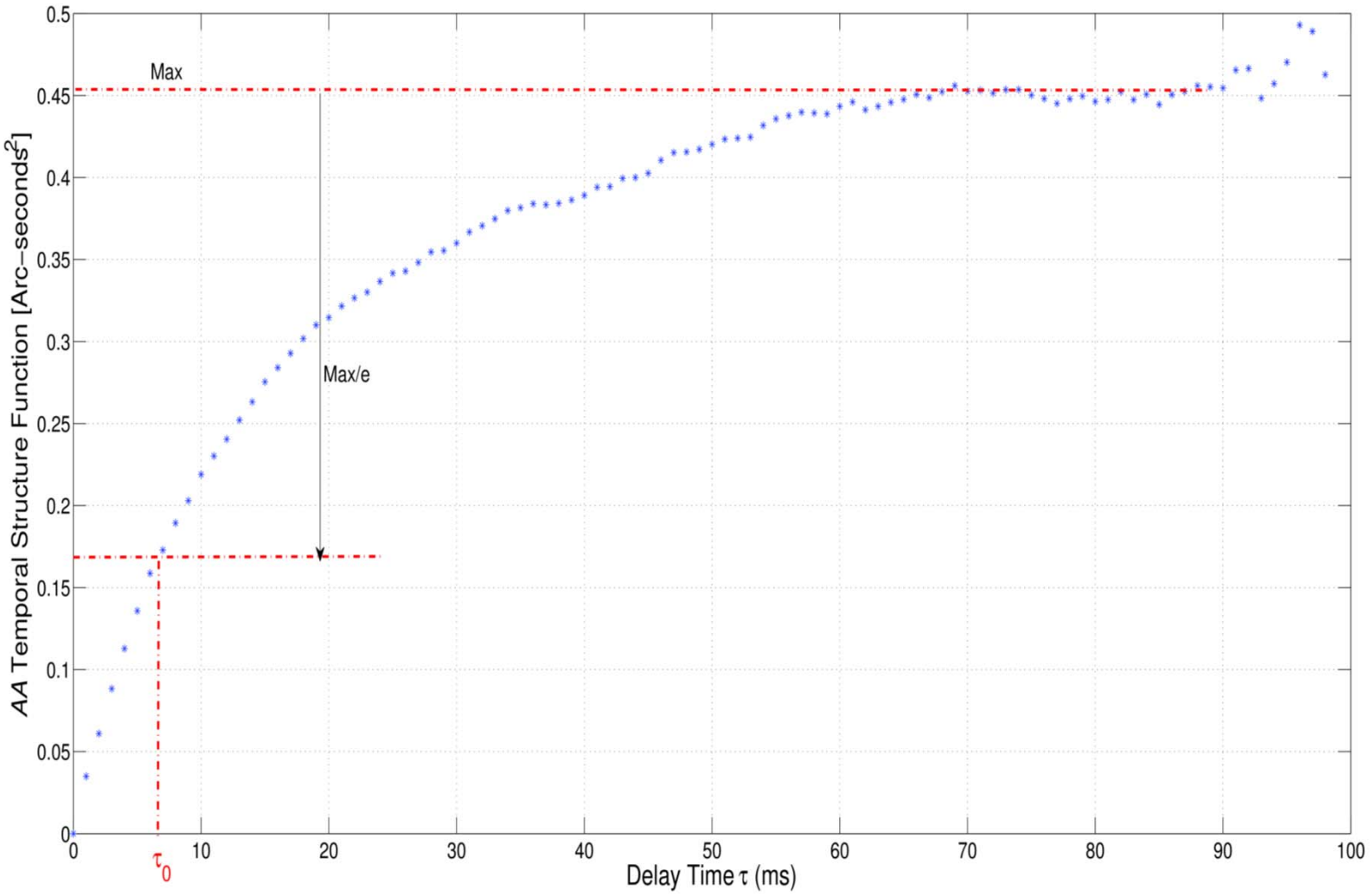
Pupil plane

- Telescope pupil is observed by means of a lens through a narrow slit placed on the solar limb image. The diaphragm size is 2" wide and 40" arcseconds length. The pupil image intensity (flying shadows) present fluctuations which are proportional to the AA-fluctuations
- Optical fiber and photodiodes are used
- Low noise amplification
- Temporal structure functions from signals allow to measure temporal characteristic time
- Spatial parameters can be measured by use of a pair of photodiodes



Example signal: fiber 0,5mm




Max
Max/e
τ_0
AA Temporal Structure Function [Arc−seconds^2]
Delay Time τ (ms)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0
10
20
30
40
50
60
70
80
90
100

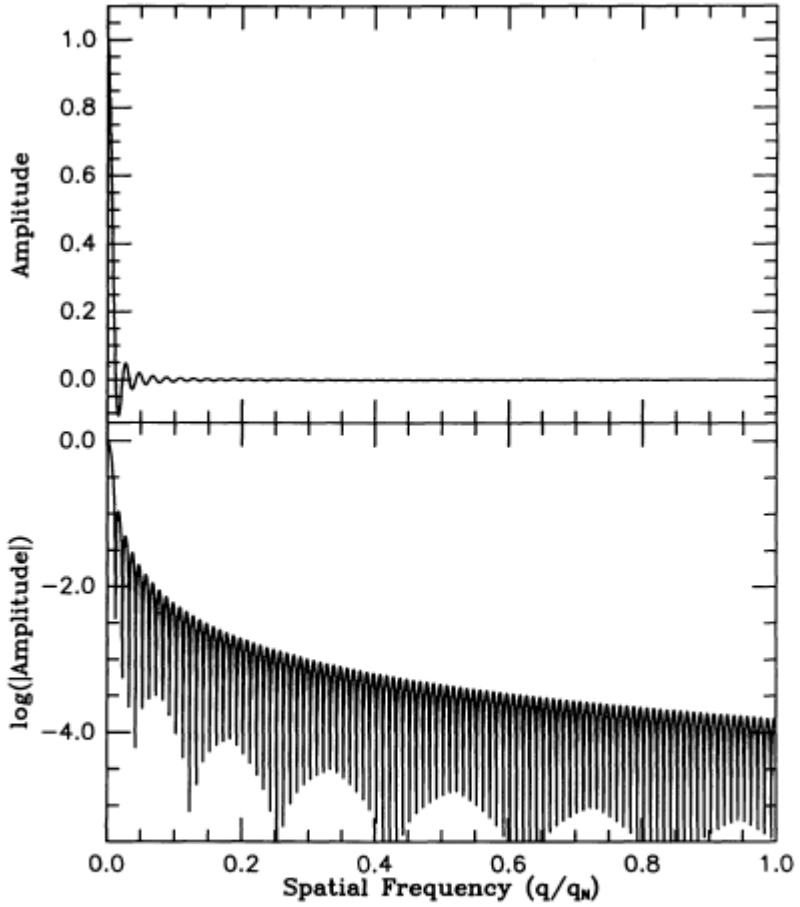


FIG. 1.—An example of the Hankel transform of the limb-darkening function defined by eq. (2) with $N = 2$. The x-axis is the spatial frequency relative to the Nyquist frequency. The upper panel shows the amplitude spectrum, while the lower panel shows the logarithm of its modulus.

$$i(\lambda, r) = \sum_{n=0}^{n=N} a_n(\lambda)\mu^n(r) , \qquad (2)$$

where

$$\sum_{n=0}^{n=N} a_n(\lambda) = 1 ,$$

$\mu(r) = [1 - (r/R_T)^2]^{1/2}$ and R_T is the true radius

The hankel transform (def): $F(q) \equiv 2\pi \int_0^\infty f(r) J_0(2\pi r q) dr$

The hankel transform of the limb darkening function:

$$I(q) = \beta R_T \sum_{n=0}^{n=N} \frac{a_n 2^{n/2} \Gamma[(n+2)/2] J_{(n+2)/2}(\beta q)}{(\beta q)^{(n+2)/2}} , \qquad (6)$$

where $\beta = 2\pi R_T$, and Γ is the gamma function (Bevington 1969, p. 122).