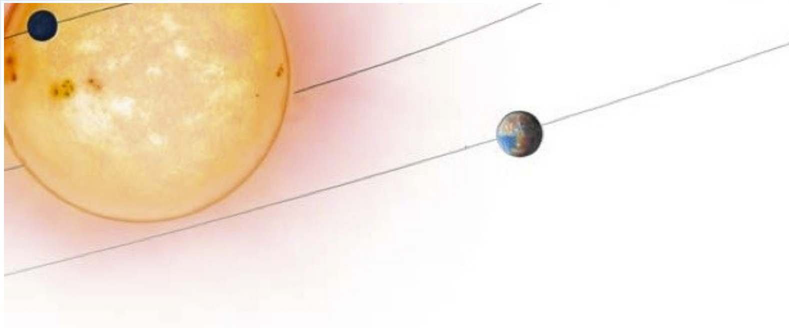
PLATO:
instrument performance

1) Noise level requirements

2) Expected white noise level

3) Long-term drift



PLATO: instrument performance

1) **Noise level requirements**

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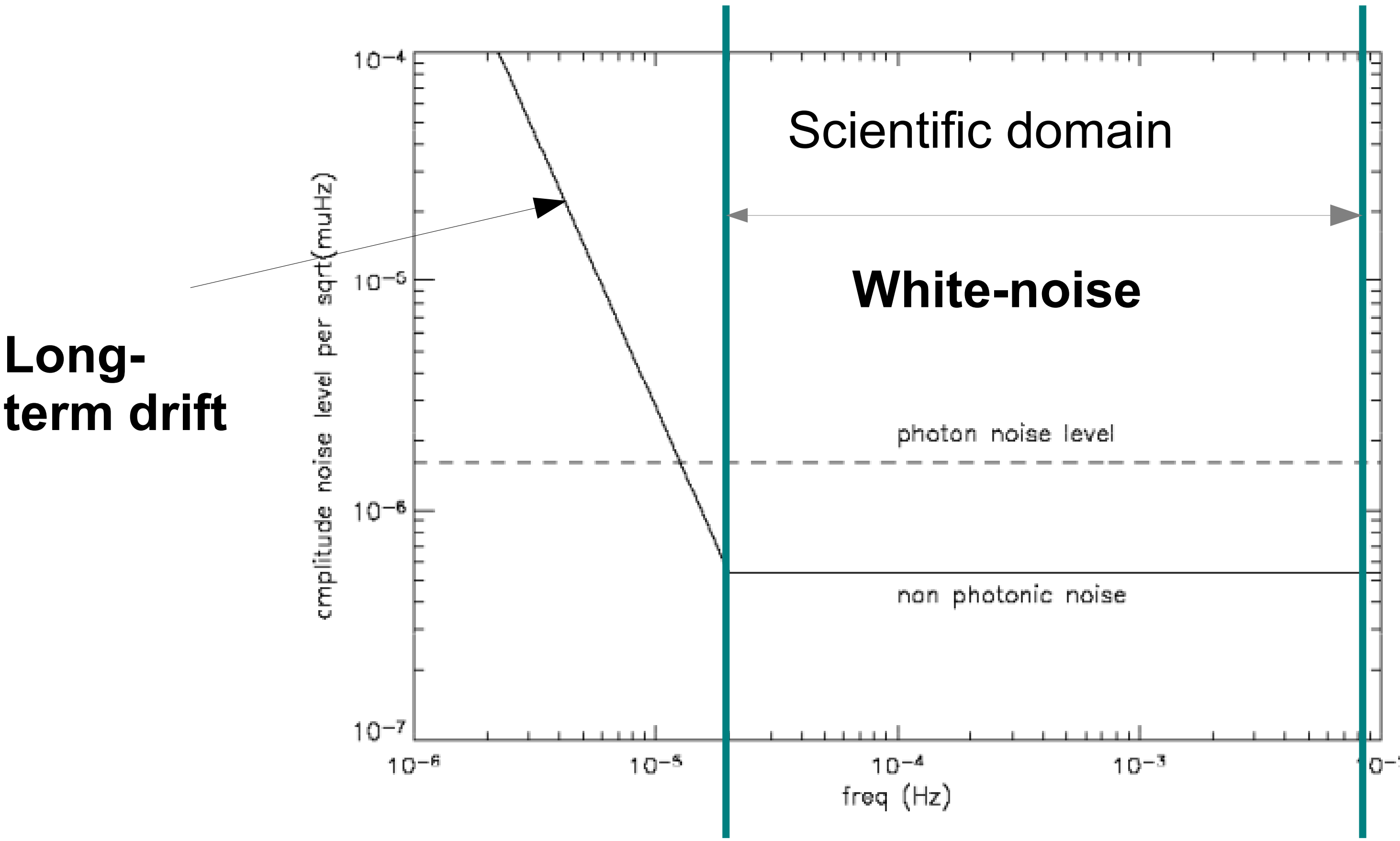
Noise level requirements



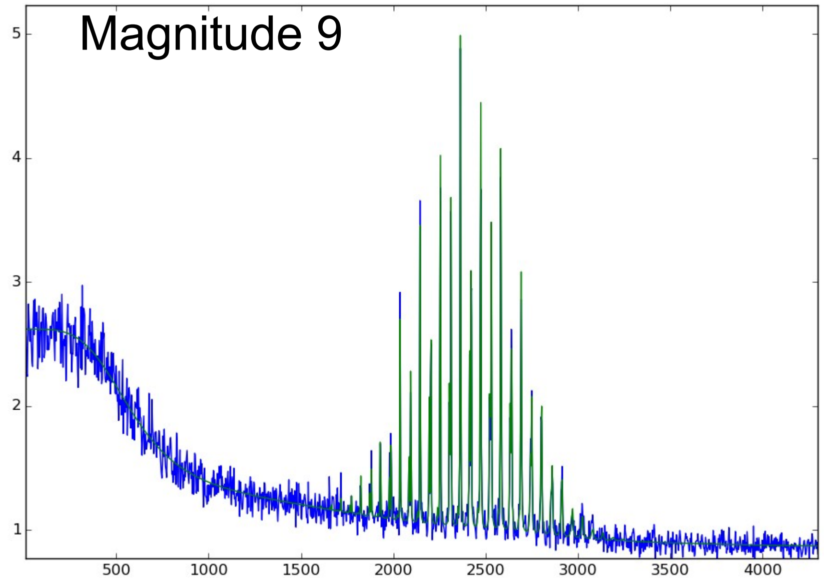
Non photonic noise requirements for stars with $m_v = 11$: **1/3 of the photon noise** in *total*

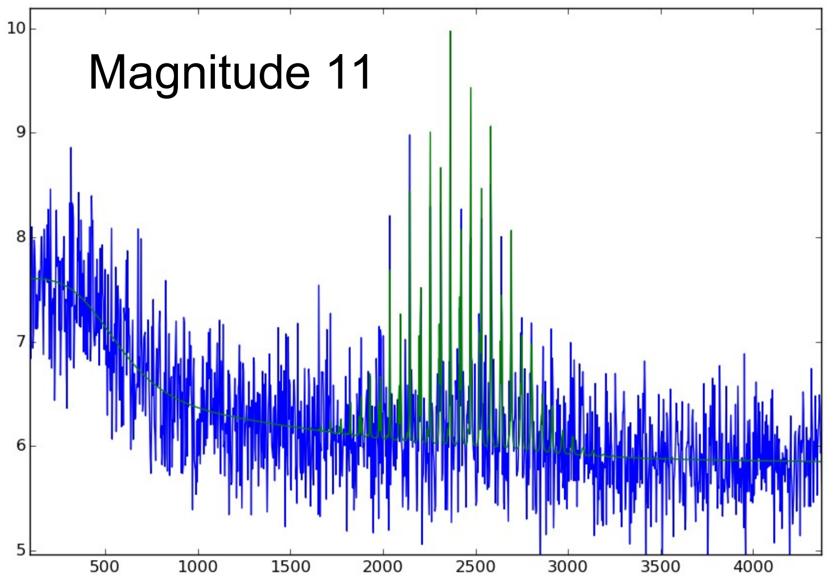
Noise level requirements

Reference noise level for 32 telescopes at V=11 :

- Photon noise 27 ppm in 1 hr
- Non-photonic noise = photon noise / 3
- Total : **28.5 ppm in 1 hr**

Light-curve of a MS solar-like pulsator simulated with the Stellar Light-curve Simulator (**SLS**)





PLATO:
instrument performance

1) Noise level requirements

2) **Expected white noise level**

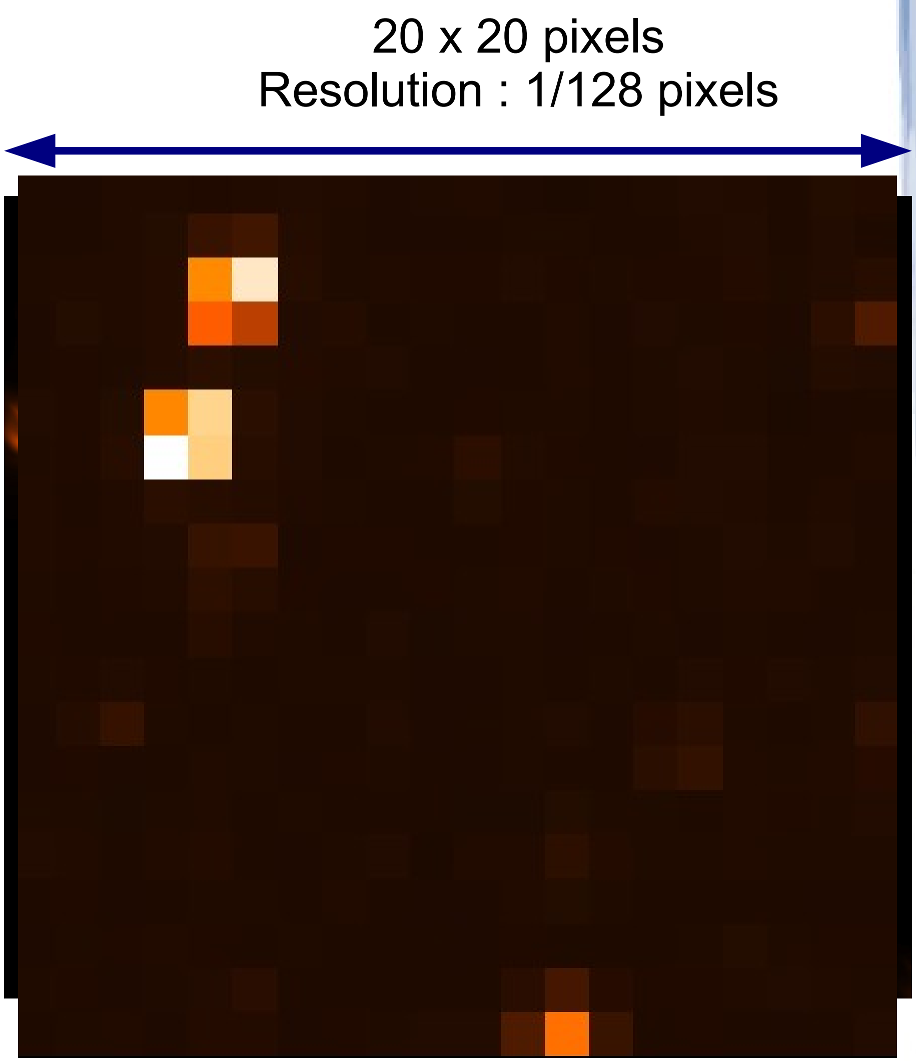
3) Long-term drift

Simulations of imagettes time-series

- Time-series of imagettes of size 20 x 20 pixels generated with the **Plato Image Simulator** (**PIS**) developed at LESIA

- PRNU (3%)
- Read-out noise
- **Satellite jitter:**
  - Compliant with the specifications
  - Uncorrelated between telescopes
- Long-term effects *neglected* (e.g. differential aberration)

➔ PSF : optical design from March 2011
➔ Extend and complete the Phase A assessment study (PLATO-GS-TN-235-LESIA)



Requirements in terms of pointing errors

Pointing requirements

- <u>Below 40 mHZ (>25s) :</u>

➔ Flat in the frequency domain

➔ 0.23"/sqrt(Hz)

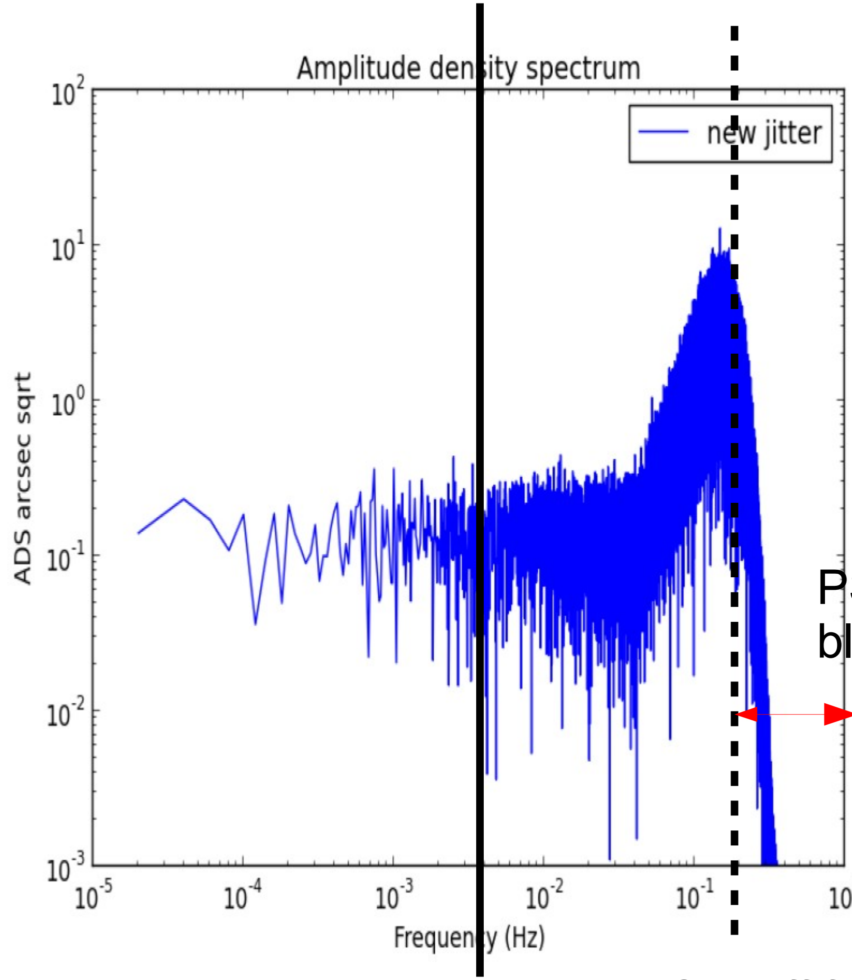
- <u>Above 40 mHz</u> (<25s) :

➔ In the time domain

➔ 3" at 95 % confidence level

➔ ~ 1.5" rms = 0.1 pixels rms

See PLATO Pointing Requirements Definition Document, SRE-PA/2010.065, Issue 2, Rev. 0

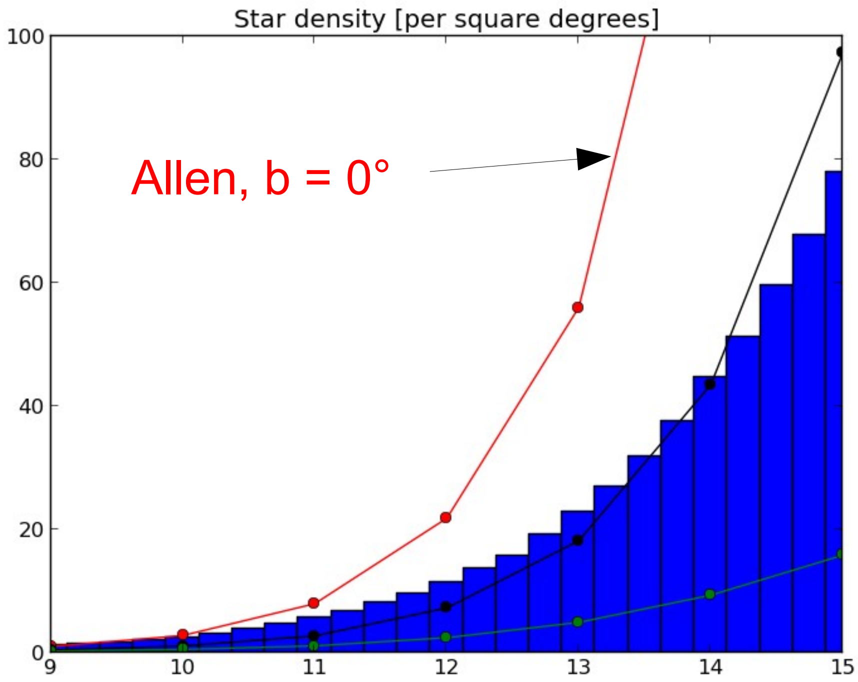


PSF blurring

40 mHz (<25s)

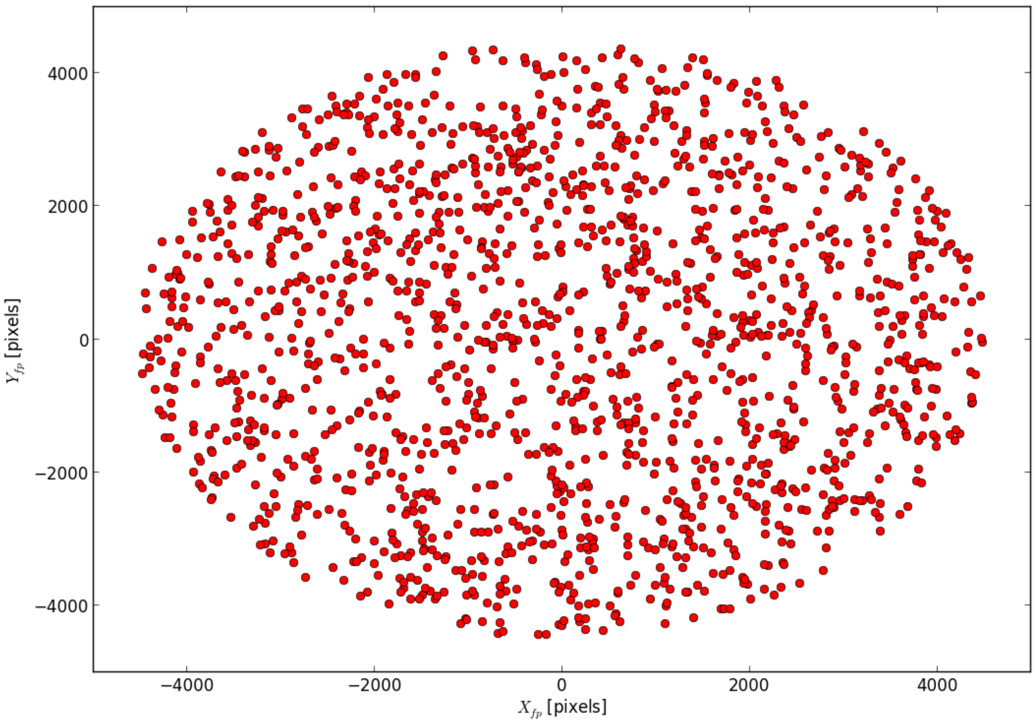
Cut-off frequency : 2 seconds

Stellar field



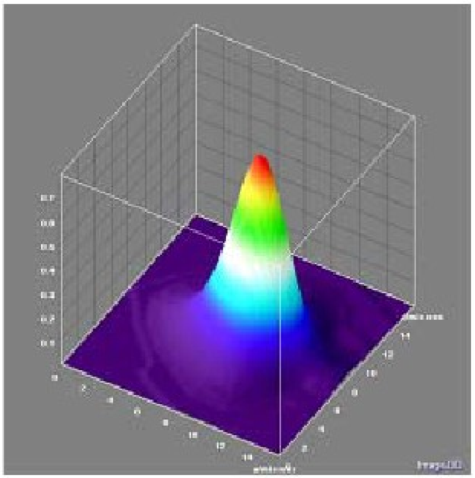
- Synthetic stellar population model (Besançon model)
- Galactic latitude : -30°, l = 253° (first proposed pointing direction)
- Size : 300 sq. degrees
- Up to magnitude 18

Field of view

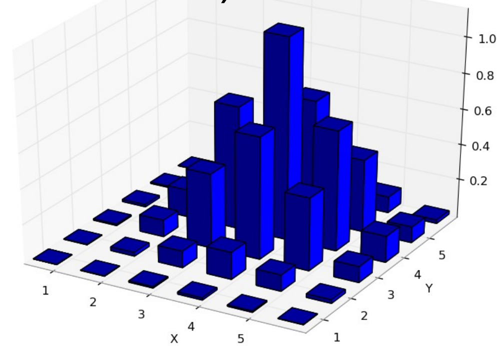


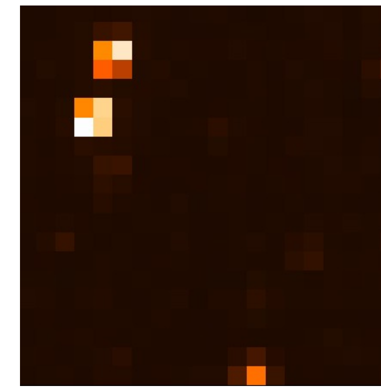
- Normal Telescope (group 1) → not aligned with the Fast Telescopes
- About **1 500 imagettes** centred around stars between V= 9 and V = 13

Weighted mask based photometry



weighted mask
(e.g. Gaussian)

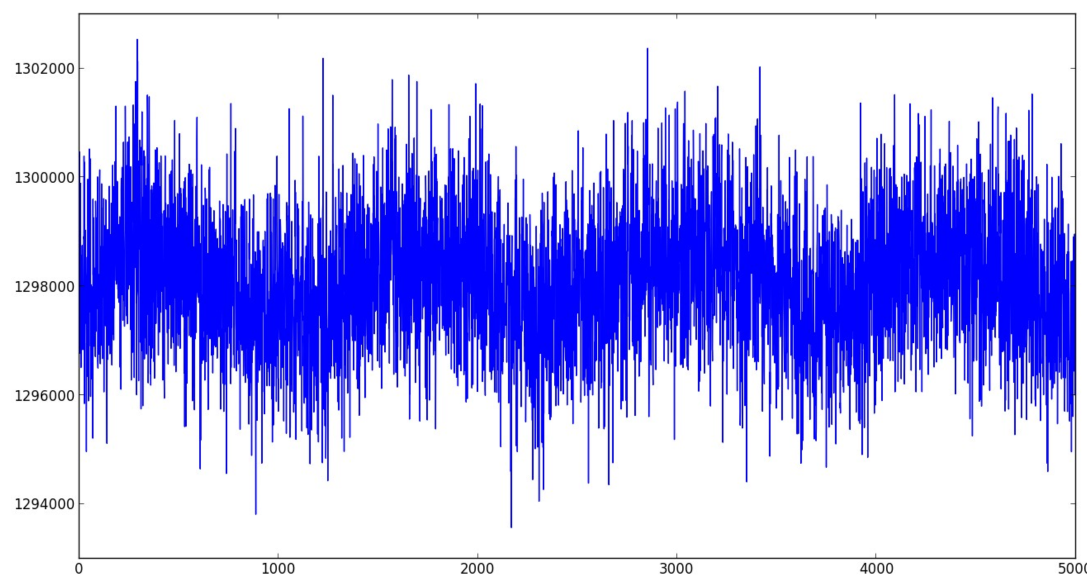




Mask width :

$$\delta(\theta) = 1 + \frac{1}{2}\left(\frac{\theta}{14.14}\right)$$

Computed light-curve :

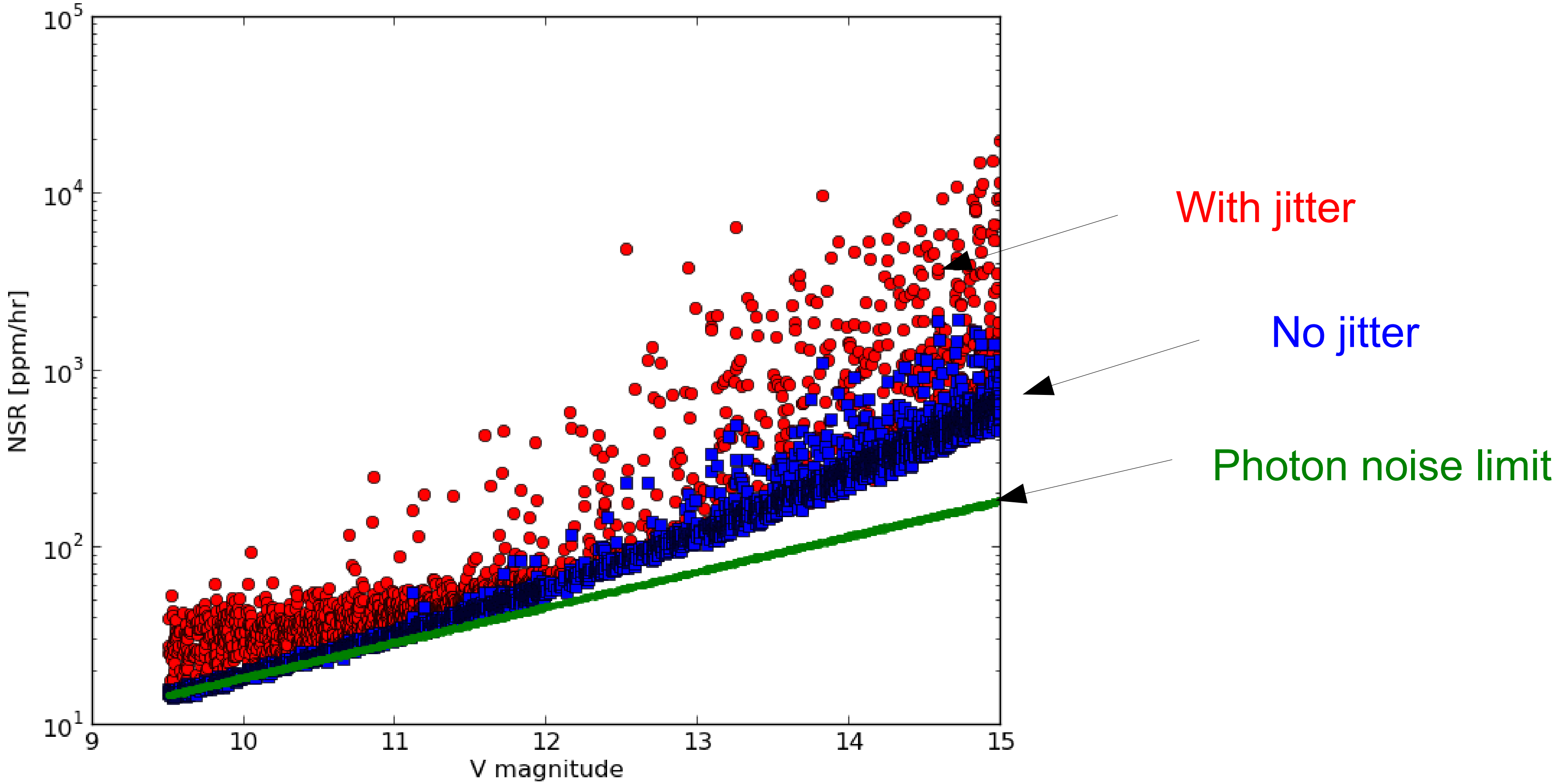


Raw results

$$NSR = 10^6 \sqrt{\frac{2\Delta T}{3600 n}} \frac{\sigma}{\bar{s}}$$

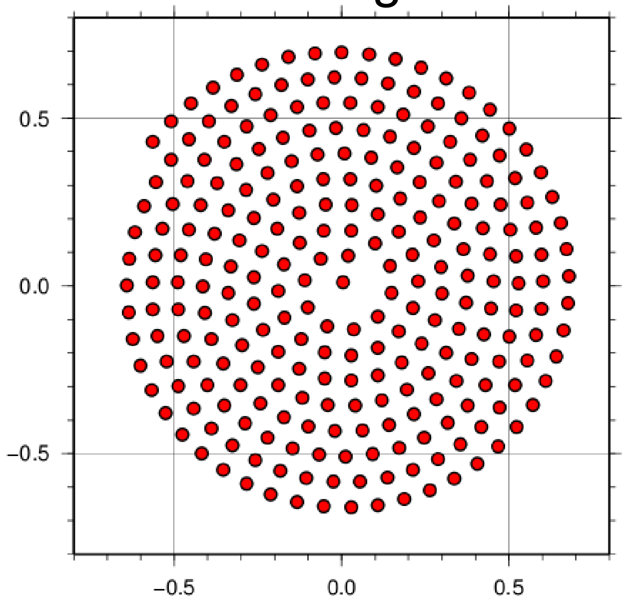
Assumptions :

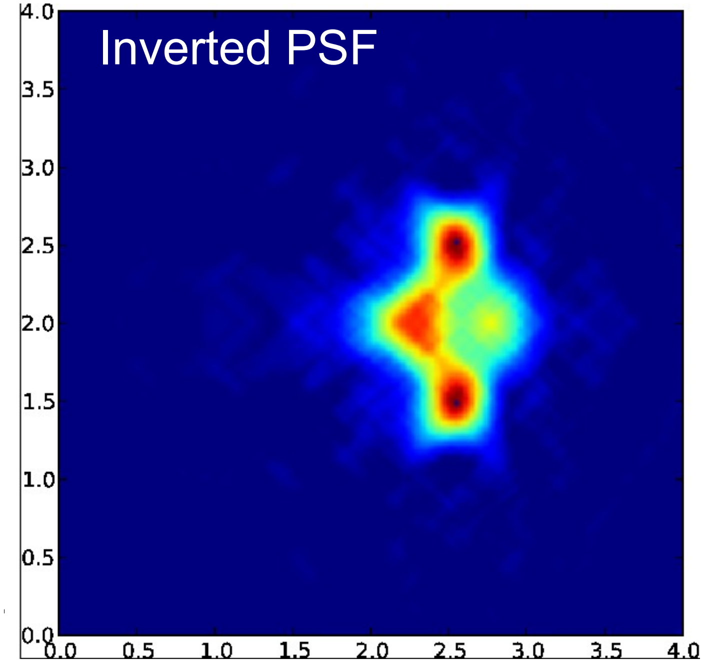
- 32 telescopes
- **un-correlated noises** between telescopes

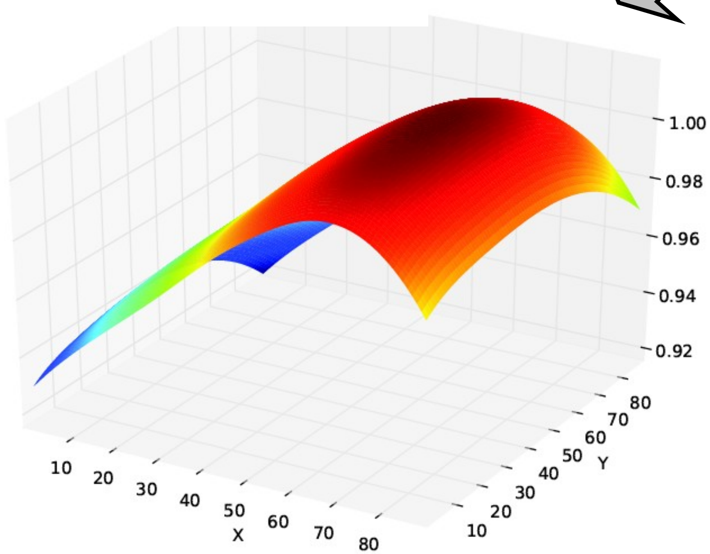


PSF modeling

Microscanning







Surface for jitter correction

Results after jitter correction

	Total	Photon noise	Photon noise + 1/3	Contaminants	Read-out	Sky background
Magnitude range	ppm/hr	ppm/hr	ppm/hr	ppm/hr	ppm/hr	ppm/hr
9.00- 9.50	**14.7**	12.8	13.5	0.3	2.7	2.3
9.50-10.00	**17.8**	16.2	17.1	1.0	4.2	3.5
10.00-10.50	**22.5**	20.4	21.5	1.5	6.7	5.7
10.50-11.00	**29.1**	25.5	26.9	2.2	10.5	8.9
11.00-11.50	**37.0**	32.0	33.7	3.2	16.4	13.8
11.50-12.00	**51.9**	40.9	43.1	5.0	26.9	22.7

- At V=11.25 we are slightly **ABOVE 1/3** of the photon noise
- Important contribution of the **read-out noise** (here 68e-) and **sky-background** (150 e-/s/pixel)
- Better **mask parameters** must lead to slightly better performance

PLATO:
instrument performance

1) Noise level requirements

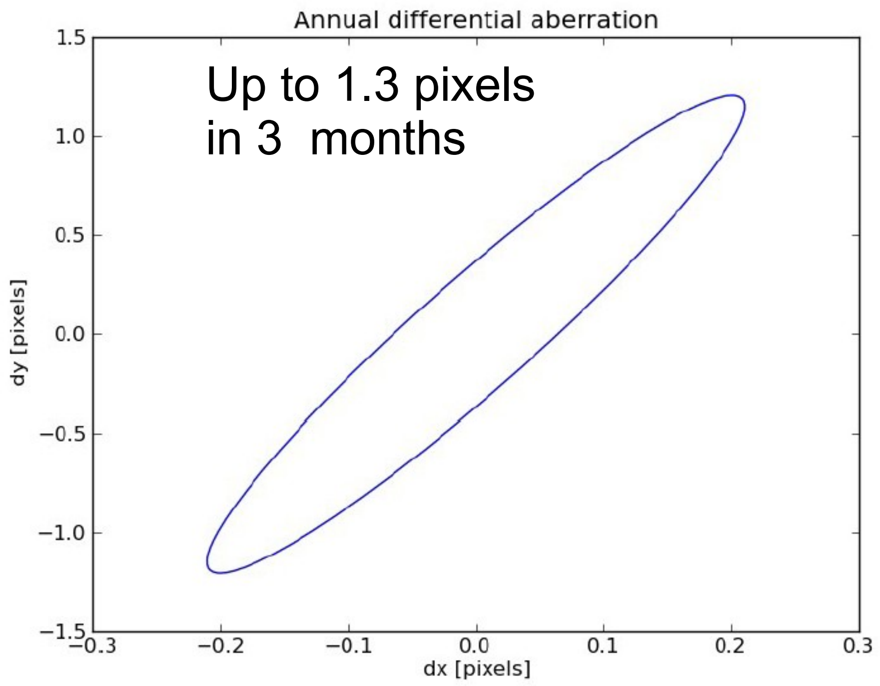
2) Expected white noise level

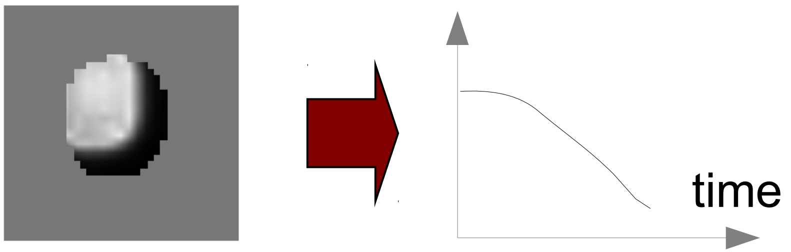
3) **Long-term drift**

Long-term drift

Origins :

- **Kinematic** aberration
- **Thermoelastic** variation of the **pointing direction** of a given telescope :
  - Thermoelastic variations of the **telescope structure**
  - Thermoelastic variations of the **plateform structure**

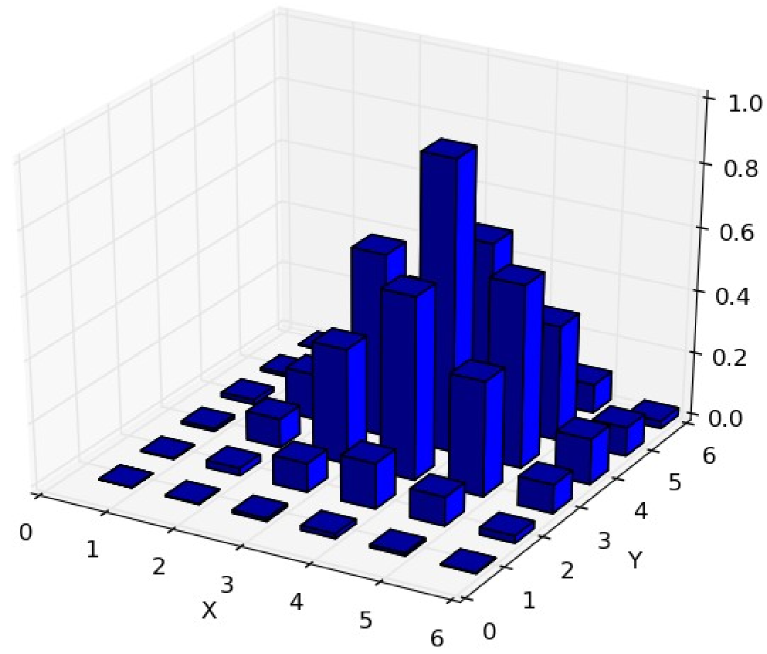




Weighted mask

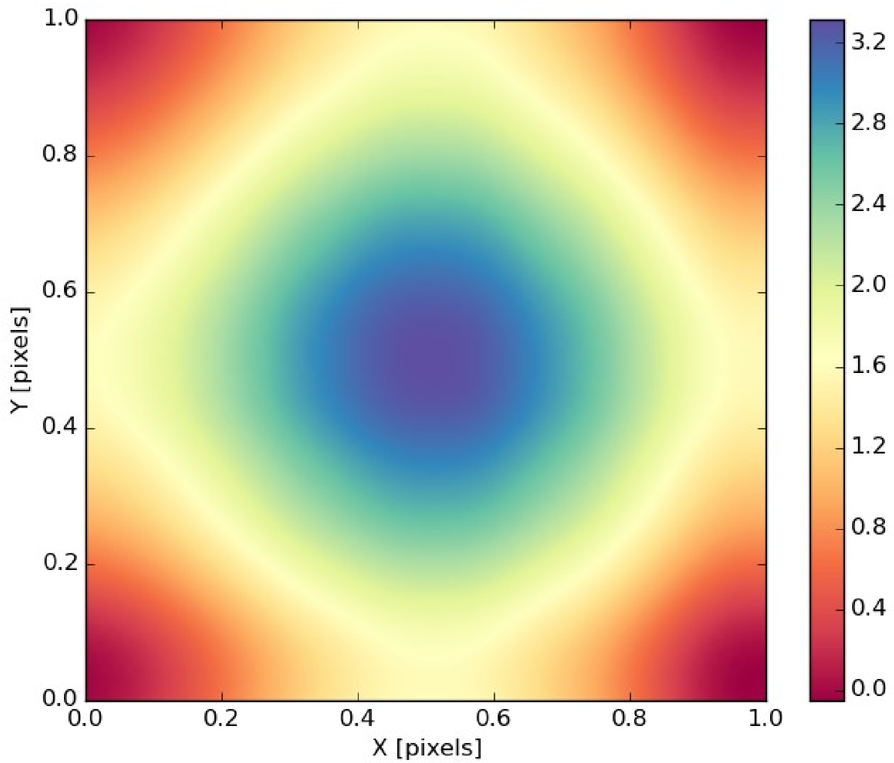
Illustrative case of a *Gaussian* mask:

$$M(x_i, y_i) = \exp\left[-\frac{1}{2}\left(\left(\frac{x - x_0}{\sigma_x}\right)^2 + \left(\frac{y - y_0}{\sigma_y}\right)^2\right)\right]$$



Mask update

Residual flux variation

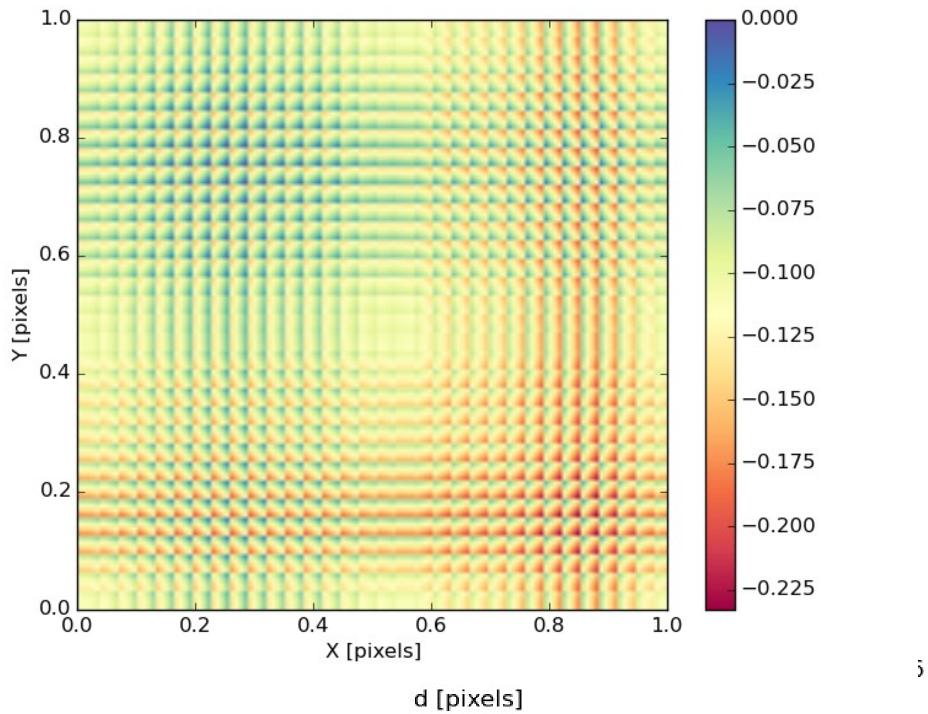


PSF : at 18.4° ; mask width : 1.6 pixels

- ➔Gaussian mask updated every 1/128 pixels (resolution of the PSF)
- ➔Residual of the order of ~ 3 % (worst case → edge of the FoV)
- ➔Can be corrected as we do the **jitter correction using a PSF model**

Mask update

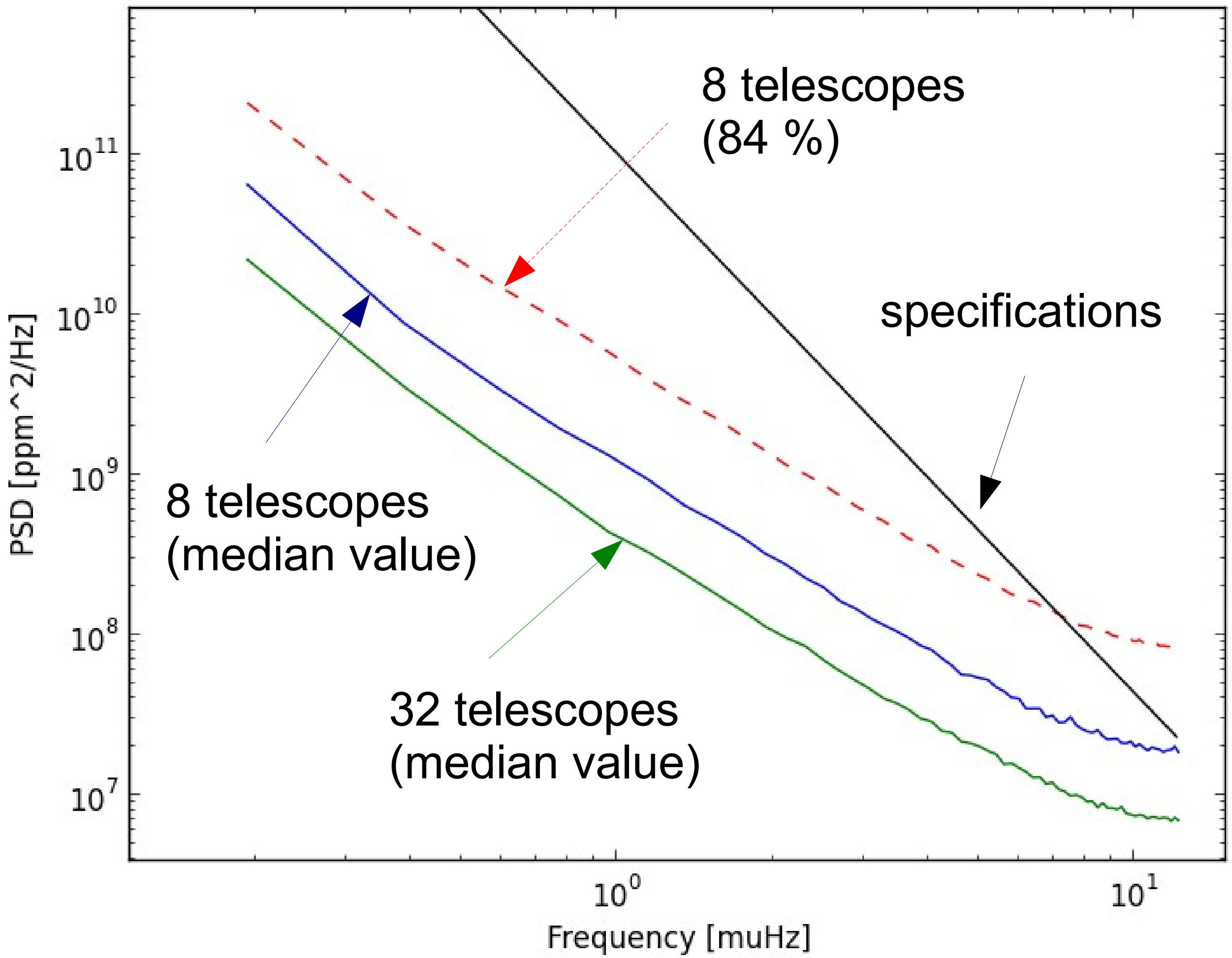
Residual after (on-ground) correction



- The mask update leaves a variation of up to ~ 3 % (**worst case** → edge of the FoV)
- Correction using theoretical **PSF** (resolution of 1/32) reduce the variation to ~ 0.2 % peak-to-peak and dispersion of 0.05 % rms
- Residuals **uncorrelated** between telescopes

- Correction efficiency **strongly depends on the quality of the PSF model**
- Can also be reduced if we **change adequately the width and shape of the weighted mask**

Mask update :
residual in the Power Spectral Density



- PRNU included : 0.8 % rms
- Error in the **knowledge** of the PRNU : 0.3 % (rms)

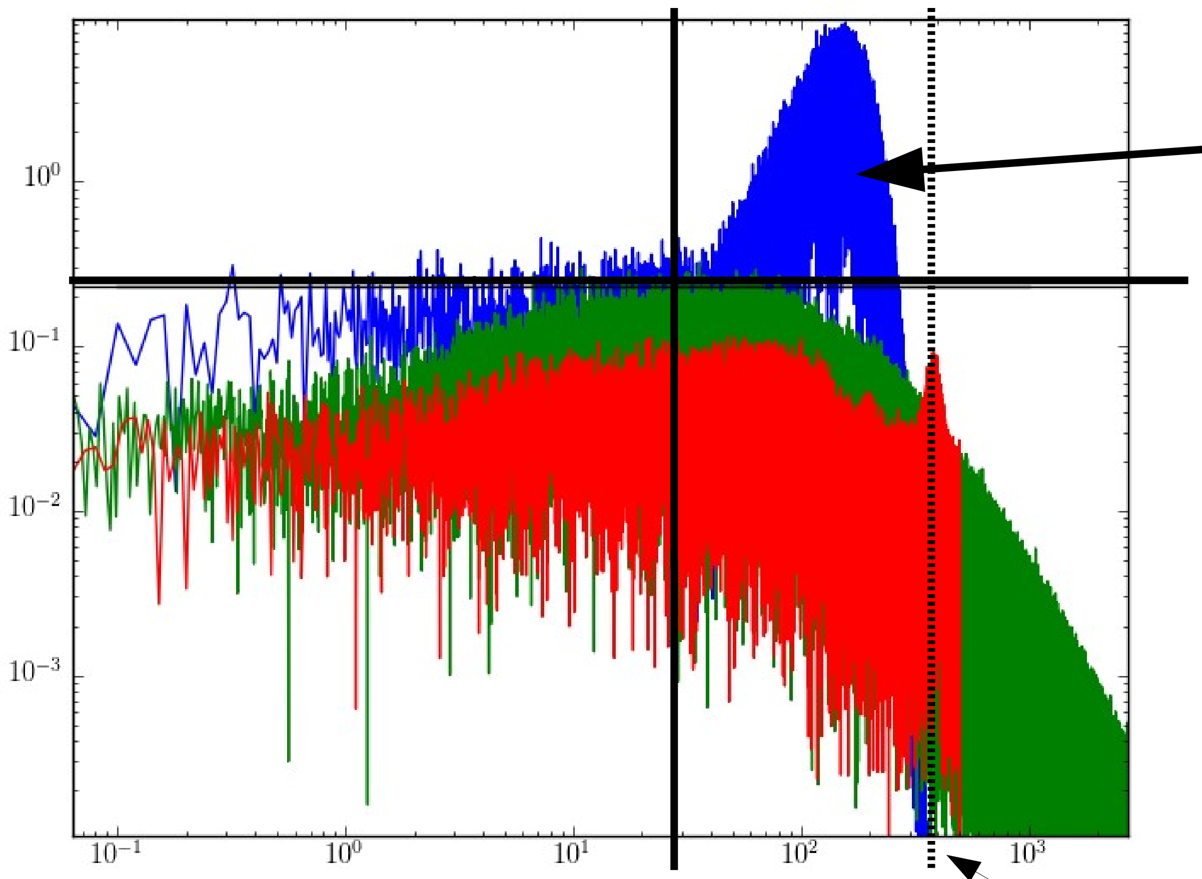
Thank you !

Jitter noise and PRNU

	With PRNU			No PRNU			No jitter
Magnitude range	Raw NSR ppm/hr	Jitter correction ppm/hr	Correction efficiency ppm/hr	Raw NSR ppm/hr	Jitter correction ppm/hr	Correction efficiency	
9.00- 9.50	25.2	14.9	86.6	24.4	13.8	95.5	13.3
9.50-10.00	29.2	18.8	86.0	29.1	17.6	95.8	17.1
10.00-10.50	32.7	23.3	88.7	33.2	22.3	98.2	22.1
10.50-11.00	37.9	29.2	92.6	37.4	28.6	98.9	28.5
11.00-11.50	44.0	37.5	94.2	43.8	36.7	106.0	37.1
11.50-12.00	56.8	51.3	69.6	56.6	50.9	74.0	48.9
12.00-12.50	74.0			74.5			69.2
12.50-13.00	103.2			102.6			99.1
13.00-13.50	150.9			150.8			140.5
13.50-14.00	215.4			216			208.8
14.00-14.50	327.1			325.1			310.5
14.50-15.00	518.8			518.5			480.7

- **PRNU** has a **negligible** contribution
- Very efficient jitter correction (at least up to V<12)
- **Inverted** PSF almost as efficiency than true ones
- Intra-pixel sensitivy (IRNU) : not yet assessed

Satellite jitter : constraints from Industries



Specifications :
PLATO Pointing Requirements Definition Document, SRE-PA/2010.065, Issue 2, Rev. 0

Pointing performance : preliminary feedbacks from industries

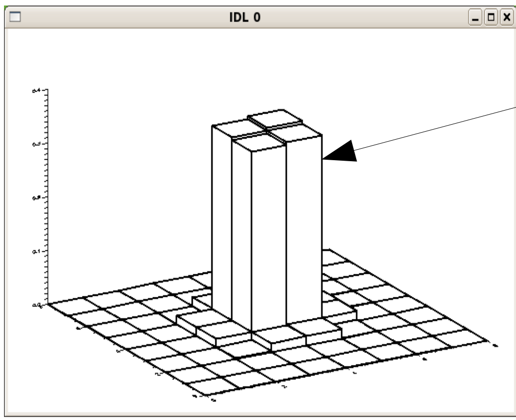
40 mHZ

Cuttoff : 2s

Magnitude	NSR **Spec. jitter**	NSR **Industry**	**No** Jitter	NSR **Photon noise**
9.00- 9.50	24.1	13.2	13.2	12.8
9.50-10.00	28.8	16.7	16.5	16.1
10.00-10.50	32.9	21.5	21.5	20.5
10.50-11.00	39.2	28.4	28.0	25.6
11.00-11.50	45.3	37.7	37.6	32.2
11.50-12.00	58.4	51.3	51.1	40.5
12.00-12.50	77.4	70.9	70.8	50.8
12.50-13.00	109.1	103.9	103	64.2
13.00-13.50	165.9	157.3	156.2	82
13.50-14.00	244.2	235.2	231.2	103.3
14.00-14.50	374.5	358.9	354.8	129
14.50-15.00	571.6	542.8	539.4	161.6

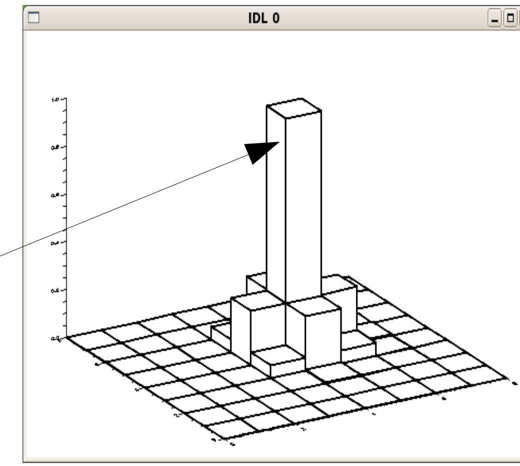
➔ Much **lower** NSR with satellite jitter given by the industries

Saturation limit : N-camera



20% of
the flux

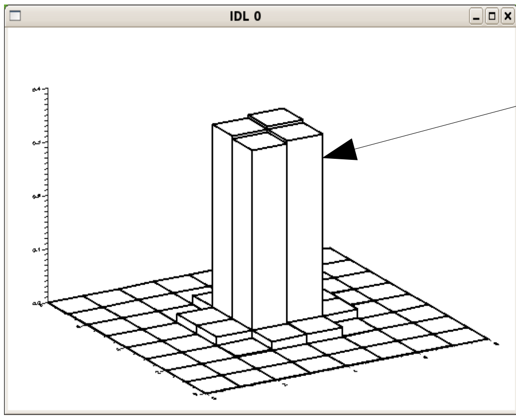
70 % of
the flux !



Transmission	P0 [mag]	P1 [mag]	P2 [mag]	P3 [mag]
1% coating	8.35	8.96	8.86	9.51
2% coating	8.21	8.82	8.72	9.37

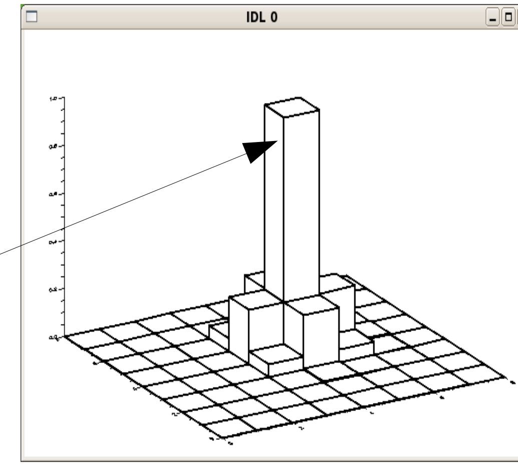
For more details see PLATO-DLR-PL-TN-003

Saturation limit : F-camera



20% of
the flux

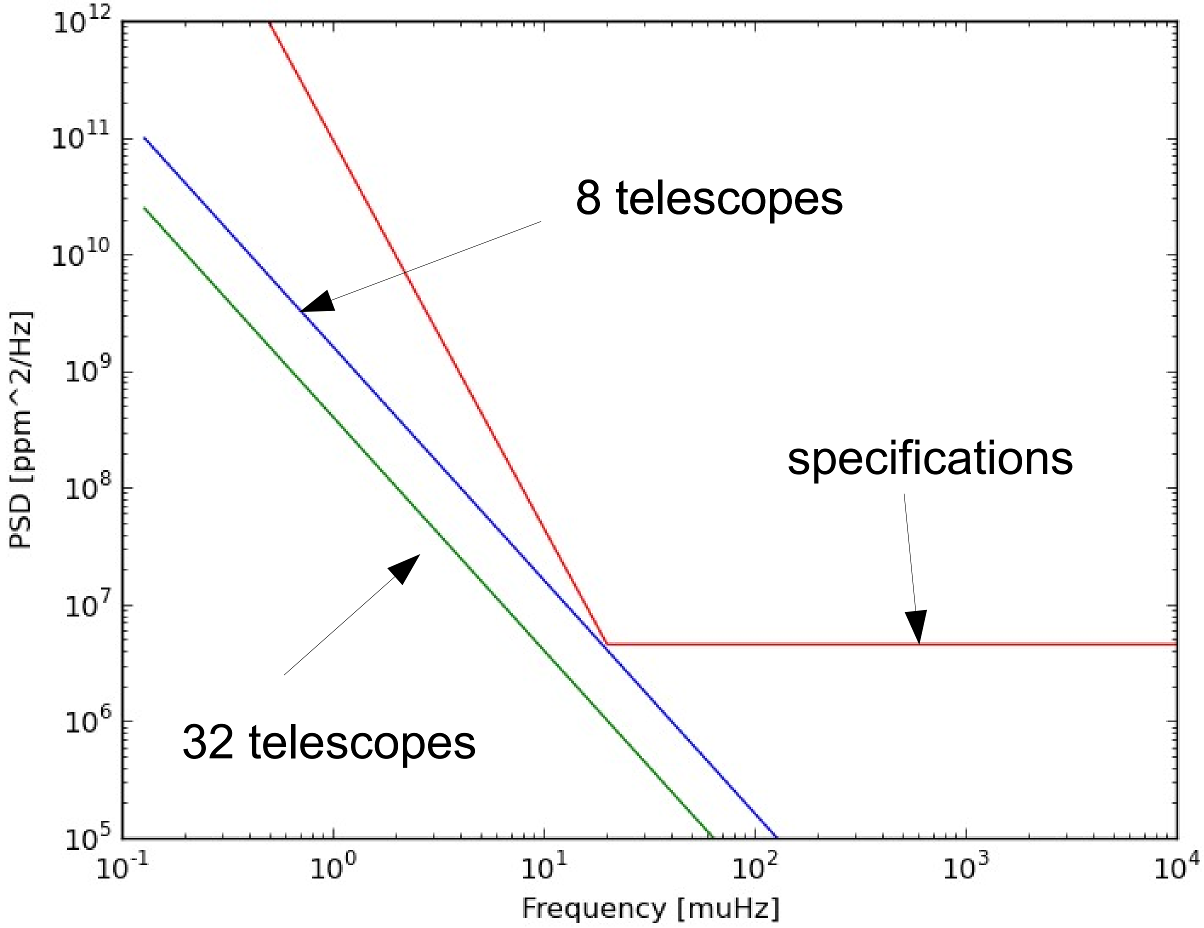
70 % of
the flux !



Transmission	Filter	P0 [mag]	P1 [mag]	P2 [mag]	P3 [mag]
1% coating	blue	5.23	5.84	5.73	6.38
	red	4.94	5.55	5.45	6.09
2% coating	blue	5.09	5.70	5.59	6.24
	red	4.80	5.41	5.30	5.95

For more details see PLATO-DLR-PL-TN-003

Mask update : residual in the Power Spectral Density



Residual :

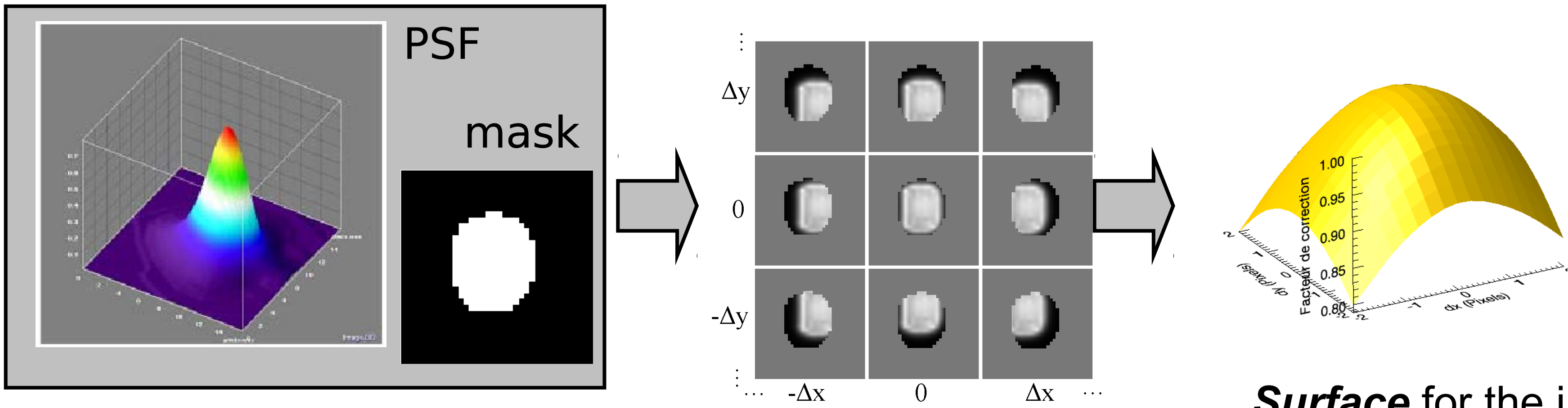
- assumed to be a linear variation of ~ **0.2 %** in **3 months** (for one telescope)
- **uncorrelated** between telescopes

Raw results

Magnitude	NSR 10 %	NSR 50%	NSR 90 %	NSR Photon noise
9.00- 9.50	15	24.1	37	12.8
9.50-10.00	20.9	28.8	40.5	16.1
10.00-10.50	24.8	32.9	44.8	20.5
10.50-11.00	30.9	39.2	49.9	25.6
11.00-11.50	38.4	45.3	55	32.2
11.50-12.00	50.6	58.4	70.3	40.5
12.00-12.50	67.1	77.4	93.9	50.8
12.50-13.00	90.3	109.1	194.3	64.2
13.00-13.50	133.6	165.9	688.9	82
13.50-14.00	197.4	244.2	620.7	103.3
14.00-14.50	288.3	374.5	1318.8	129
14.50-15.00	447.9	571.6	1486.8	161.6

Jitter correction

WP 325 100 : F. Fialho



Surface for the jitter correction

- Thanks to a PSF model, we can predict the perturbations induced by any displacements :

  Fialho et al (2007, PASP)

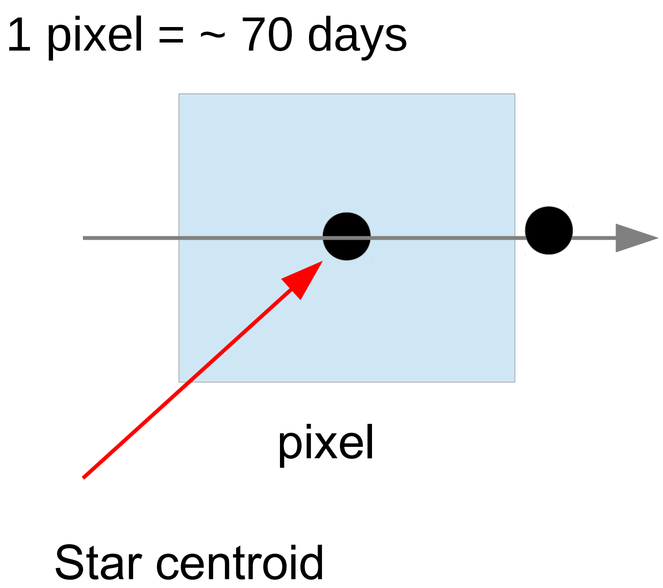
- Also corrects the **long-term drifts**
- Require accurate star displacements (Δx, Δy) as well as PSF !
- The surface correction must take into account the presence of contaminants
- GAIA : positions and intensities of the contaminants known a priori

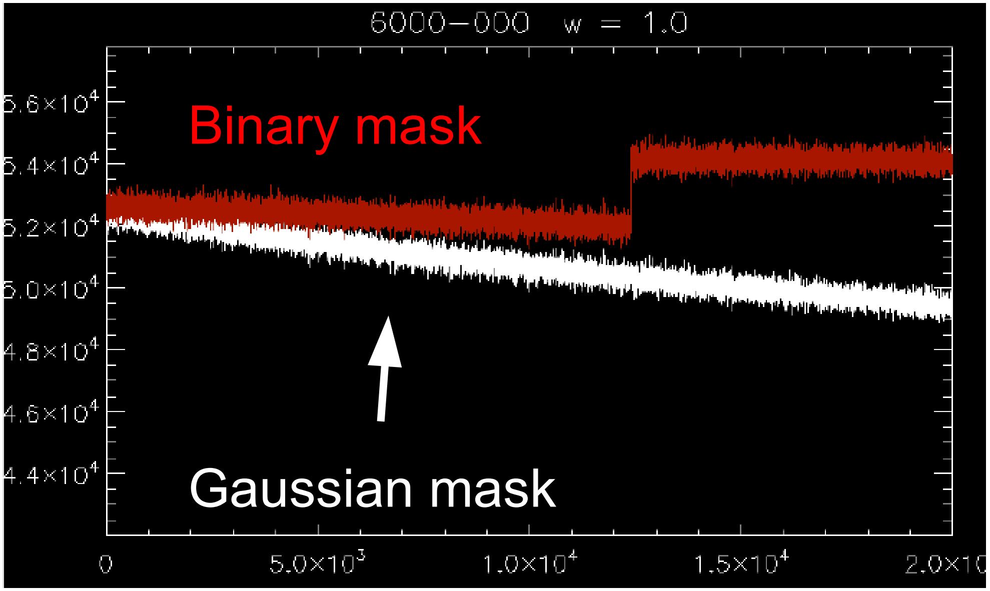
Global performance assessment

For further details see :

- Phase A – assessment study, PLATO-GS-TN-235-LESIA, December 2011
- Phase B1 - assessment study, PLATO-LESIA-PDC-RP-0012, November 2014
- Estimation of the correlated noise induced by the satellite jitter, PLATO-LESIA-PDC-TN-012, February 2015

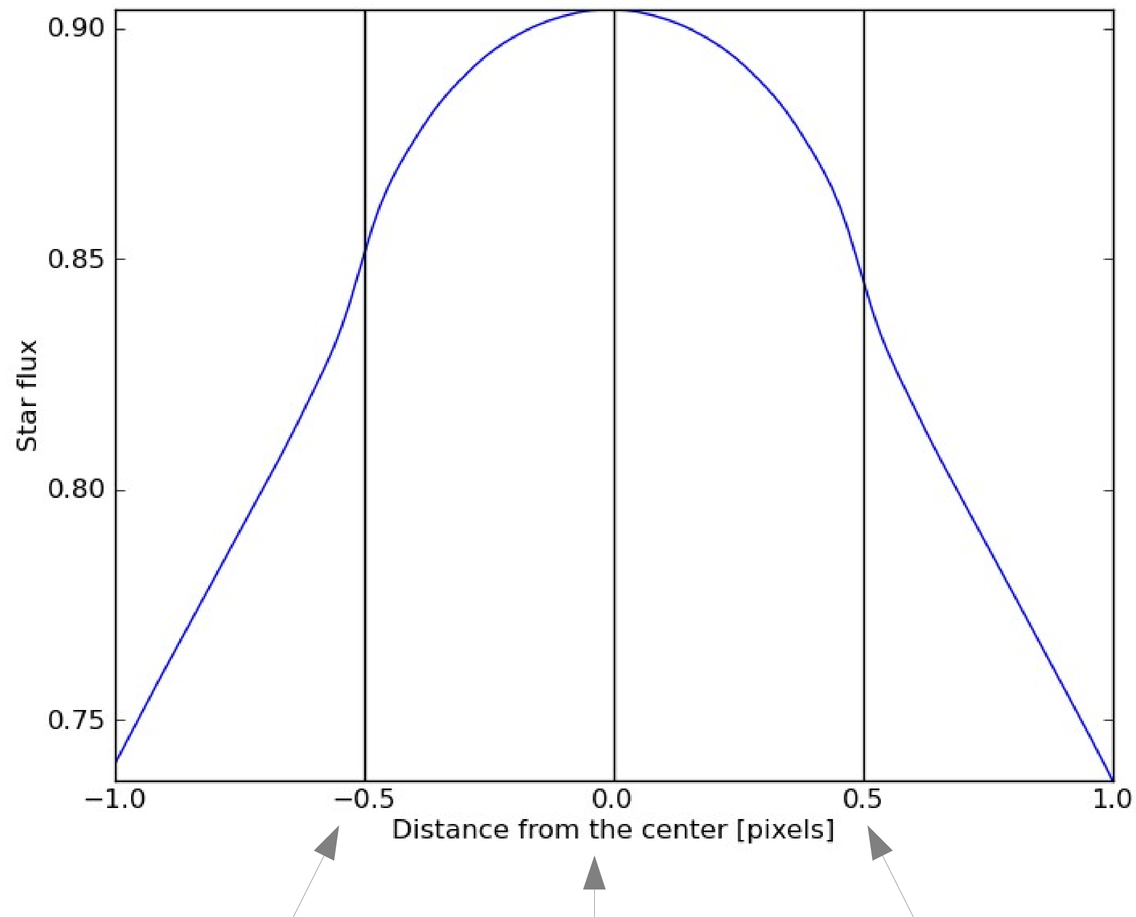
Binary mask or weighted mask ?





(credit : M. Auvergne)

Long-term drifts



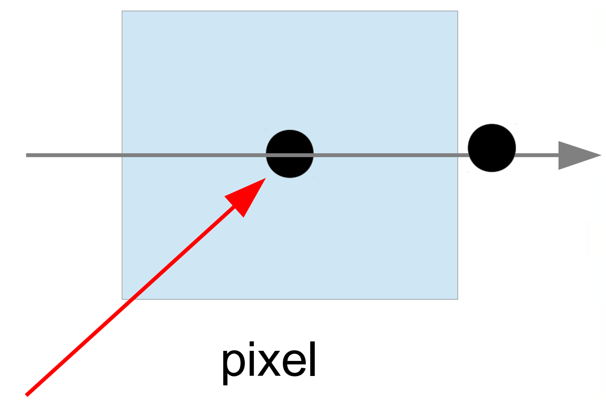
Pixel border (left)

Pixel center

Pixel border (right)

Gaussian weighted mask centered in the middle of a pixel

1 pixel = ~ 70 days



Star centroid

Mask updates : how to proceed ?

$$M(x,y) = F(x-x_{0,} y-y_0)$$

(X_0,Y_0) : star centroid at a given instant

$$x_0 = f(t) \qquad y_0 = g(t)$$

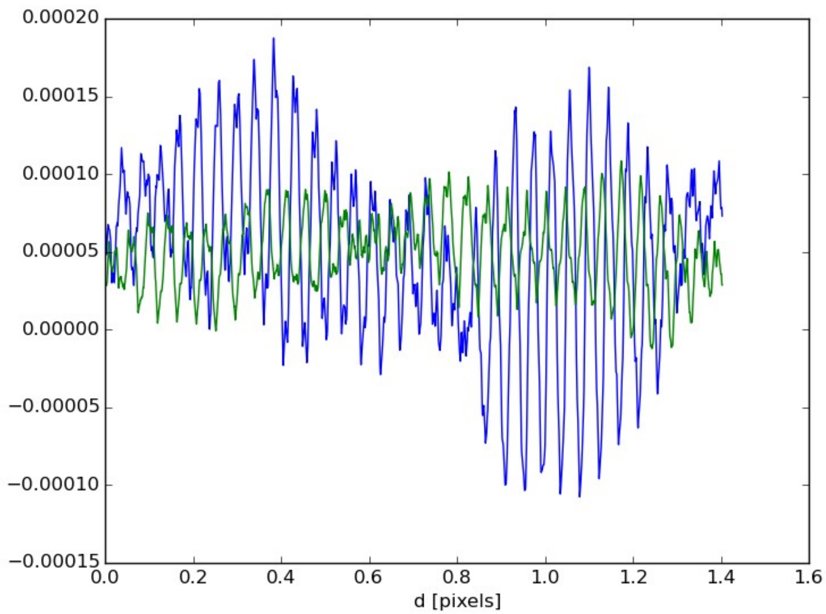
➔ The mask is computed on the basis of an analytical function (e.g. Gaussian)

The star centroid (x_0,y_0) moves due to:

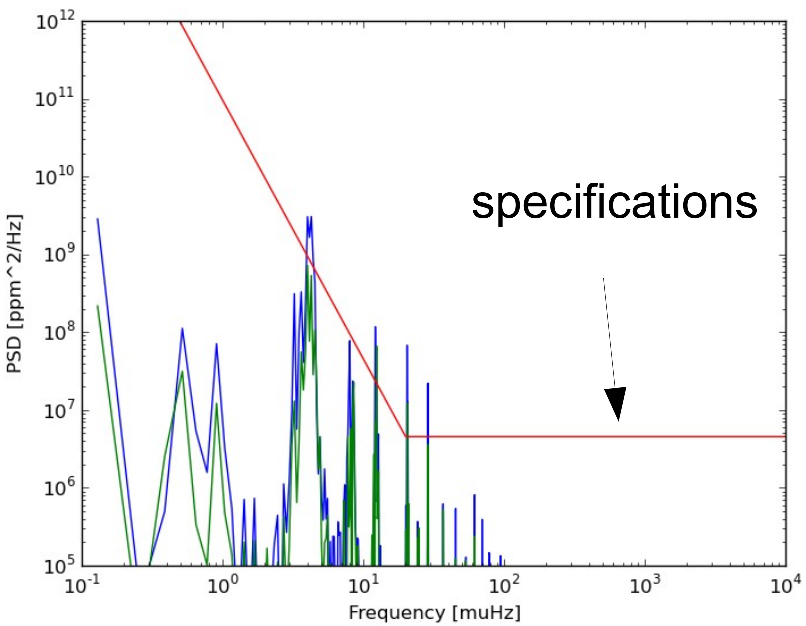
- The kinematic differential aberration → *fully predictable*
- The movements of the satellite (jitter) → corrected a posteriori on-ground
- The thermoelastic differential aberration → regular update of the attitude calcuation : on board ?

Mask update : residual in the Power Spectral Density

Residual after (on-ground) correction



PSF 1/32 pixels
Residuals un-correlated btw telscopes

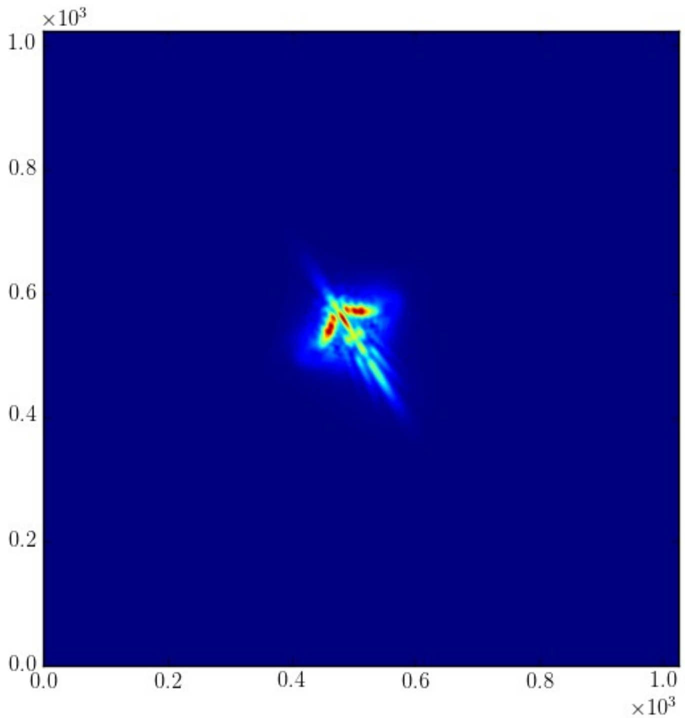


Peaks will be lower :
- Long-term drifts are not linear in time
- Sampling effects can be reduced (eg. interpolation of the PSF)

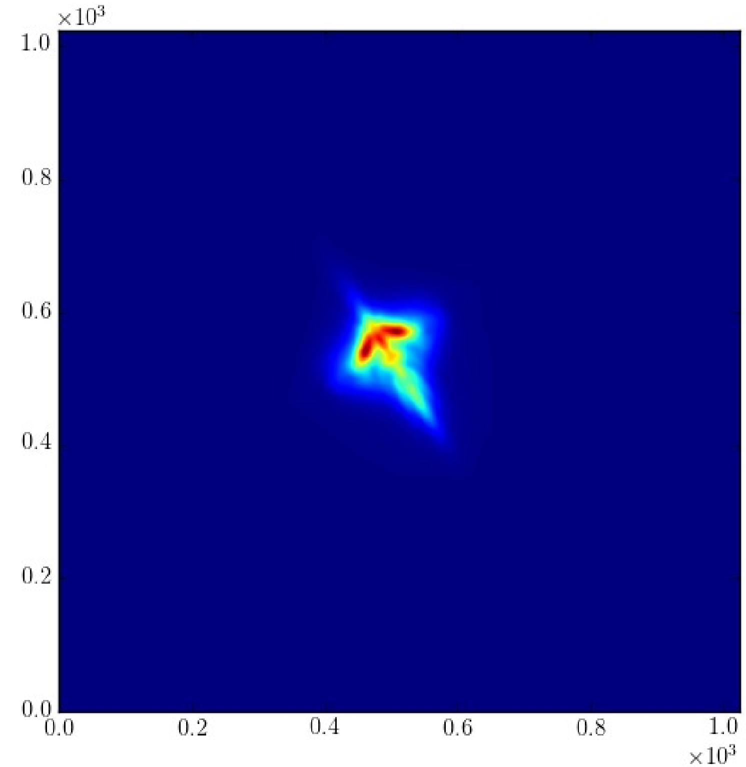
Open issues (among others...)

- **PSF modeling**:
  - Feasibility of the microscanning to be further studied
  - All sources of error must be taken into count
  - PSF breathing to be quantified and modeled
- **Jitter correction**:
  - Correlated noise to be included in performance calculations
  - All sources of error must be taken into count
  - Constraints on the positions and amplitudes of contaminants ?
- **Photometry**:
  - Optimal adjustement of the mask shape and size
- **Attitude estimation and calibration of the field of view model** (eg. optical distortion):
  - Accuracy ?
  - Frequency ?
  - On board ?

PSF blurring



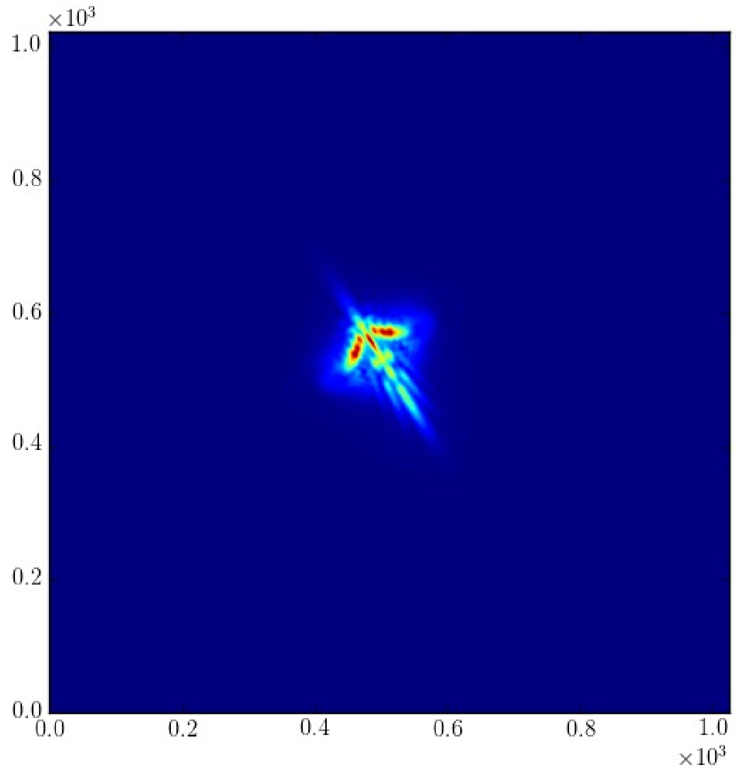
Original **PSF**



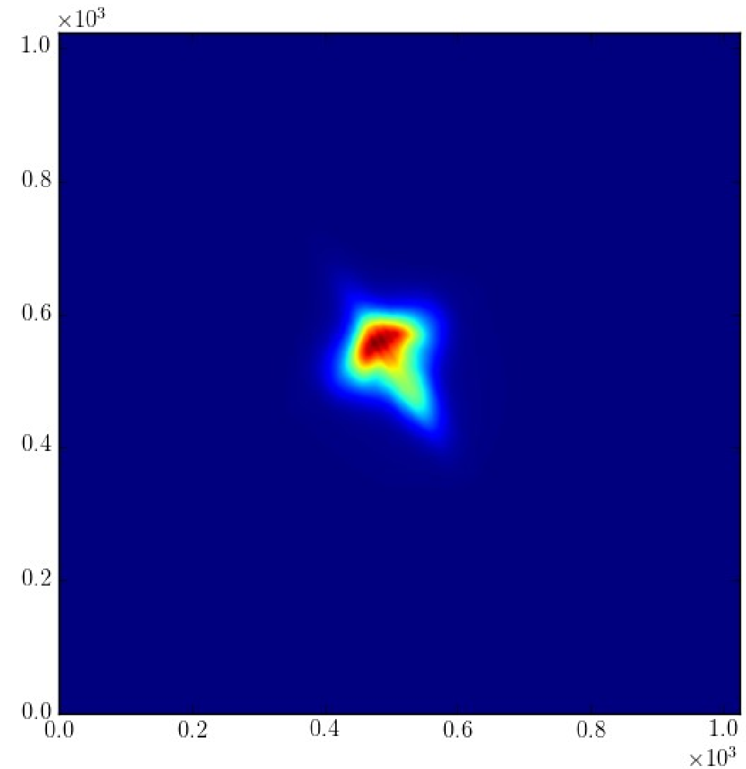
Blurred **PSF**
Cuttoff : **2** seconds

- ➔ Blurring (<u>due to movements shorter than 2.2s</u>) has a low impact on the performance
- ➔ The model of blurring must be consolidated

Blurring due to the integration time



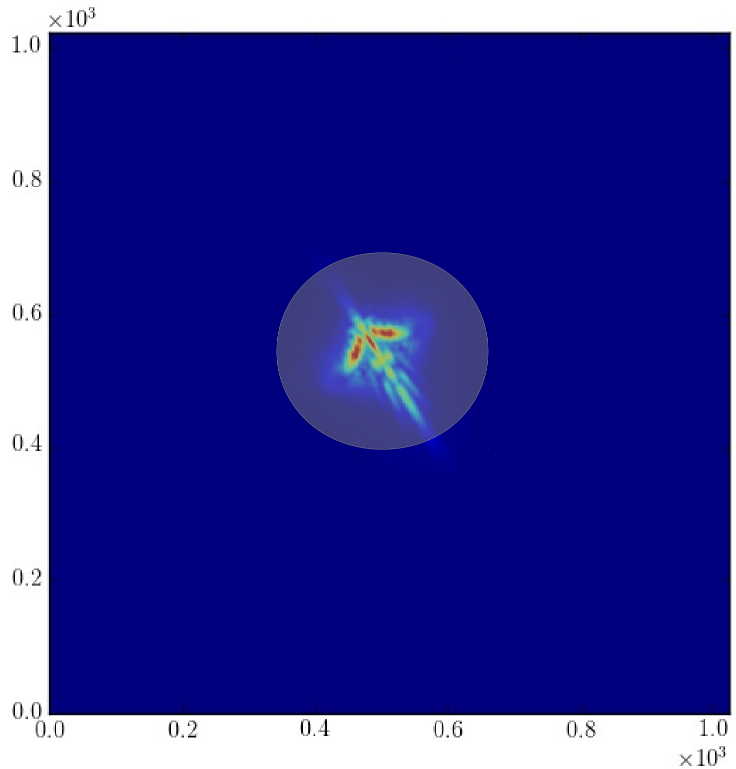
Theoretical **PSF**
(instantaneous)



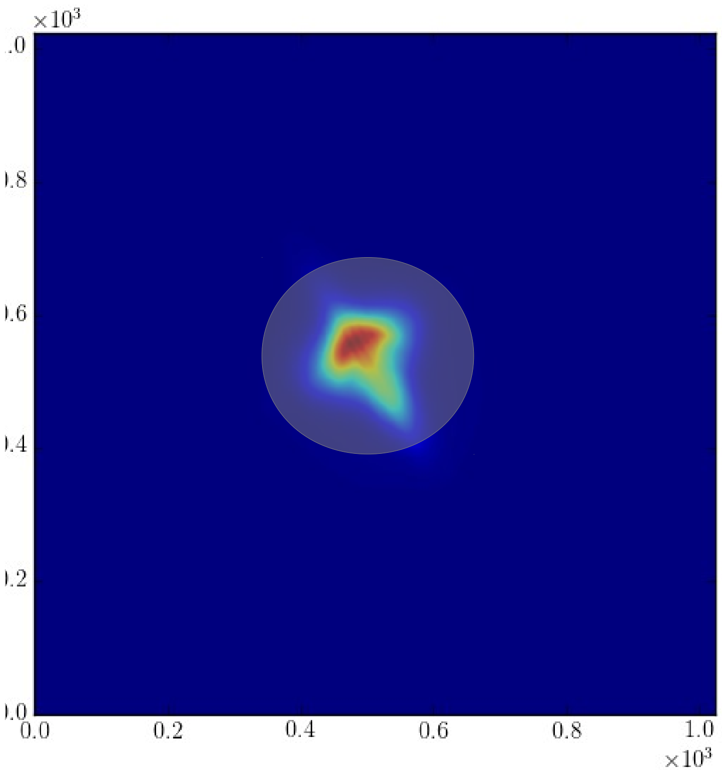
Blurred PSF with **specified jitter**
22 seconds integration time

Blurring due to the integration time

22 seconds integration time



Blurred PSF with **Airbus jitter**



Blurred PSF with **specified jitter**

Data Processing Algorithms
Pointing meeting

1) Photometric perturbations induced by satellite jitter

2) Photometry performance assessment

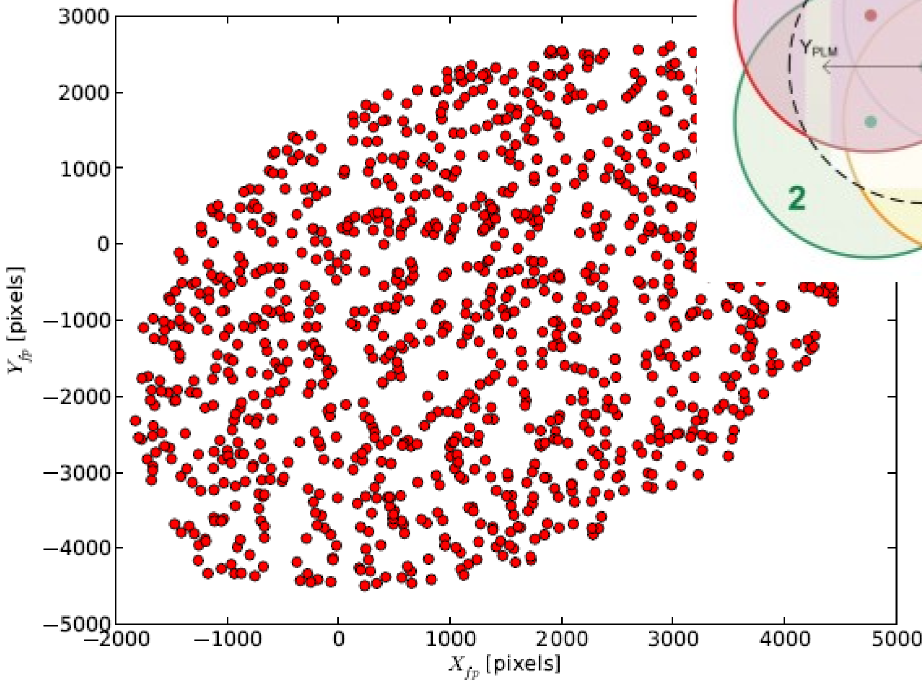
3) **Correlated noise induced by satellite jitter**

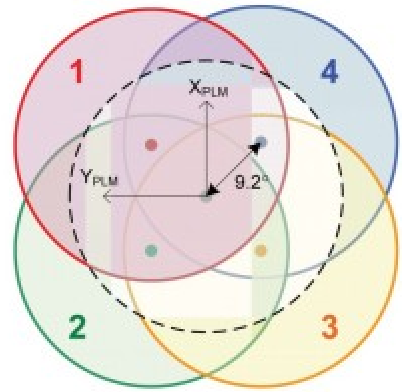
4) Long-term drift

Correlated noise and satellite jitter

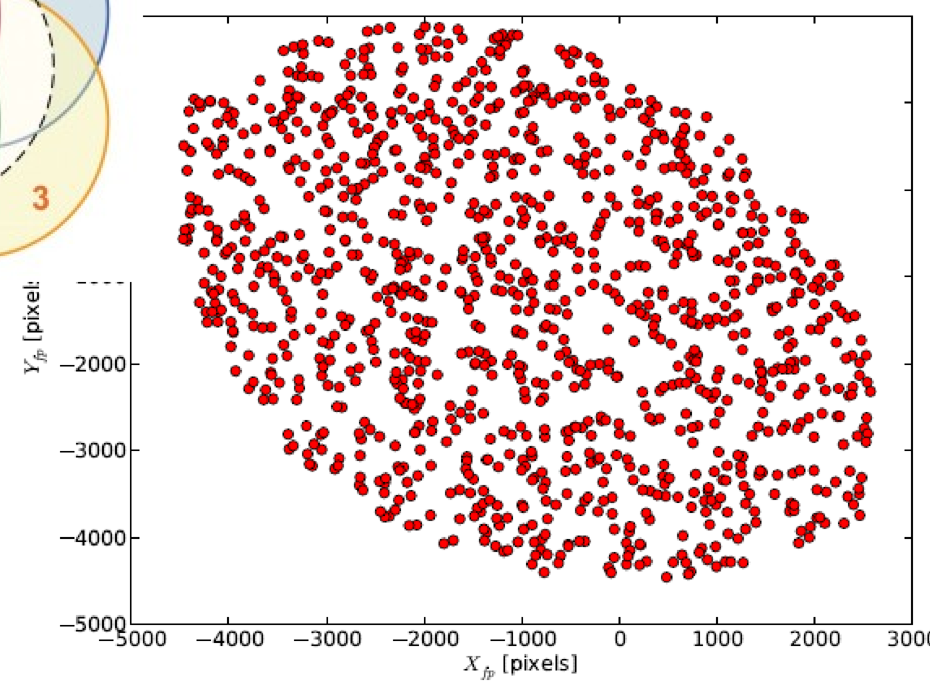
- Two telescopes simulated with PIS
- About 1200 imagettes centred arround targets common to the 2 telescopes

Telescope group 1





Telescope group 4

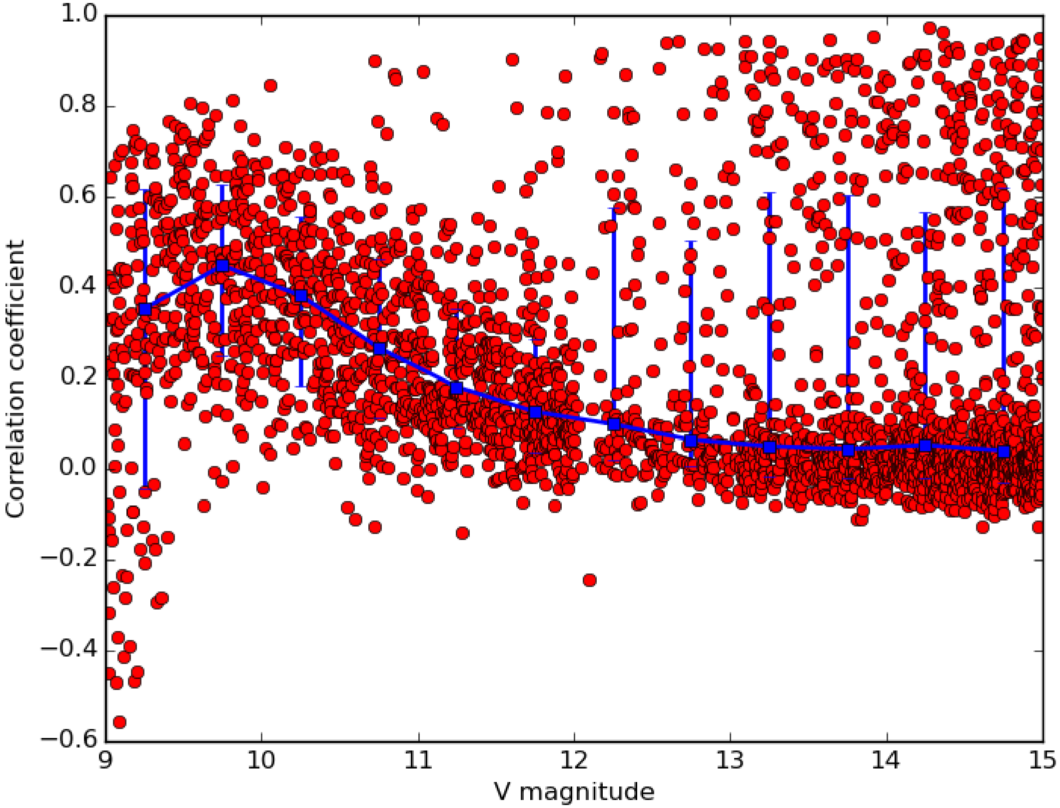


Correlated noise and satellite jitter

Correlation coefficient :

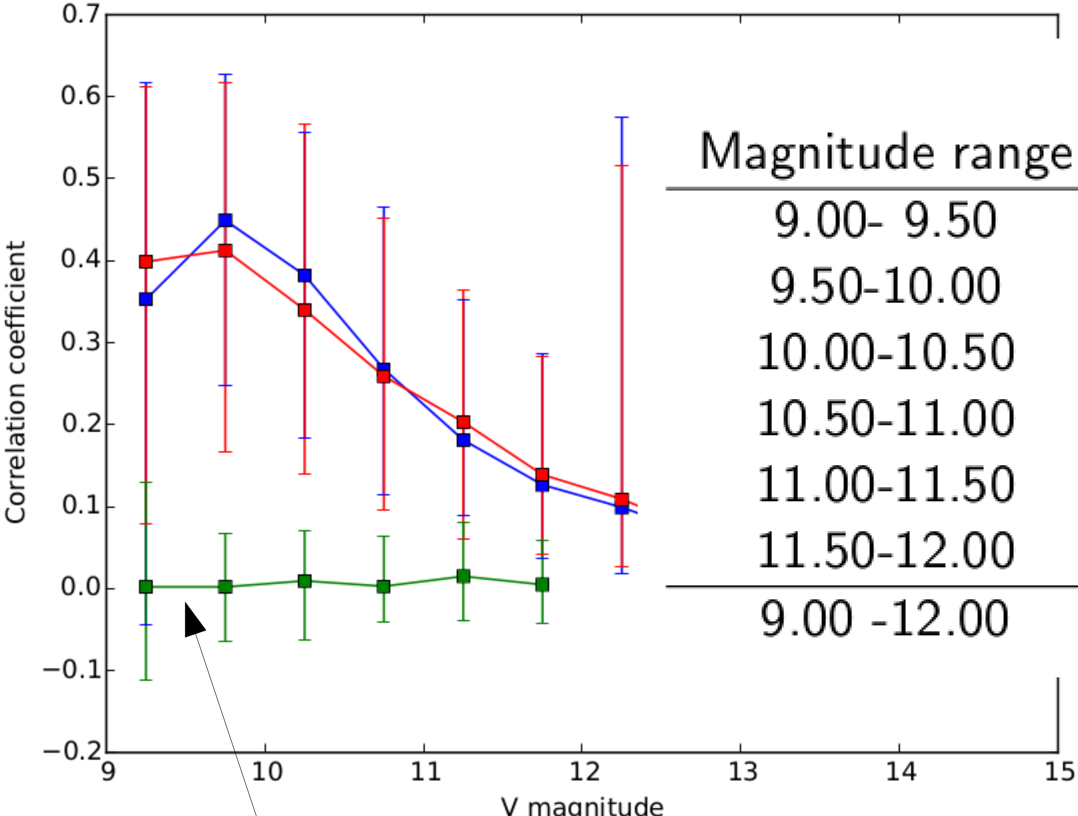
$$c_{X,Y} = \frac{\overline{\left(f_X - \overline{f_X}\right)\,\left(f_Y - \overline{f_Y}\right)}}{\left(Var(f_X)\,Var(f_Y)\right)^{1/2}}$$

- High level of correlation
- Strong dispersion
- Correlation coefficient decreases with increasing magnitude because of the decrease of the relative contribution of the jitter noise



→ « *Estimation of the correlated noise induced by the satellite Jitter*», PLATO-LESIA-PDC-TN-012

Correlated noise and satellite jitter



Magnitude range	$c_{A',B'}$ 16 %	50 %	84 %
9.00- 9.50	-0.112	$0.002^{+0.02}_{-0.01}$	0.129
9.50-10.00	-0.065	$0.002^{+0.01}_{-0.02}$	0.067
10.00-10.50	-0.062	$0.009^{+0.01}_{-0.01}$	0.071
10.50-11.00	-0.041	$0.003^{+0.01}_{-0.01}$	0.064
11.00-11.50	-0.039	$0.015^{+0.01}_{-0.01}$	0.081
11.50-12.00	-0.042	$0.005^{+0.01}_{-0.01}$	0.060
9.00 -12.00	-0.0548	$0.0057^{+0.004}_{-0.004}$	0.0723

Correlation coefficient ***after*** jitter correction

Correlated noise and satellite jitter

Noise-to-Signal Ratio (NSR) with correlated noise :

$$NSR = \frac{1}{\overline{y}} \left(\sum_{i \neq j} \mathcal{C}_{i,j} \, \sigma_i \sigma_j + \sum_i \sigma_i^2 \right)^{1/2}$$

$$NSR = NSR_0 \sqrt{1 + (N-1)\,\mathcal{C}}$$

correcting factor

NSR for un-correlated noise

C = 0.006
and
N = 32 telescopes

correcting factor **f ~ 10 %** (5 % for N = 8)

But **large uncertainties** on the determination of C :
- low statistic
- still ideal jitter correction

→ « *Estimation of the correlated noise induced by the satellite Jitter*», PLATO-LESIA-PDC-TN-012

PLATO noise specifications for asteroseismology (N and F cameras)

T.Appourchaux[1], F.Baudin[1], M.-J.Goupil[2], R.Samadi[2], T.Morel[3], A.Robin[4]

1) Institut d'Astrophysique Spatiale, Orsay, France

2) Observatoire de Paris-Meudon, France

3) Institut d'Astrophysique et de Géophysique, Liège, Belgium

4) Observatoire de Besançon

Goal of the specification

- Typical flow down approach, i.e. from Science specifications to instrumental specifications
- Need to know the Radius, Mass and Age to 1%, 2% and 10% for thousands of stars of the P1 sample.
- Goal: what is the specification on the noise background in the power spectrum?

Assumptions for S/N for PLATO (I)

- Application to P1 sample only (worst case): dwarfs and sub-giants later than spectral type F5
- For P1, we have to derive stellar masses, radii and age for thousands of stars
- Radius, mass and age needs precise mode frequencies measured to better than 0.2 μHz
- Mode frequency precision given by Libbecht (1992) as:

$$\sigma_\nu^2 = f(\beta)\,\frac{\Gamma}{4\pi T}\,, \qquad (2)$$

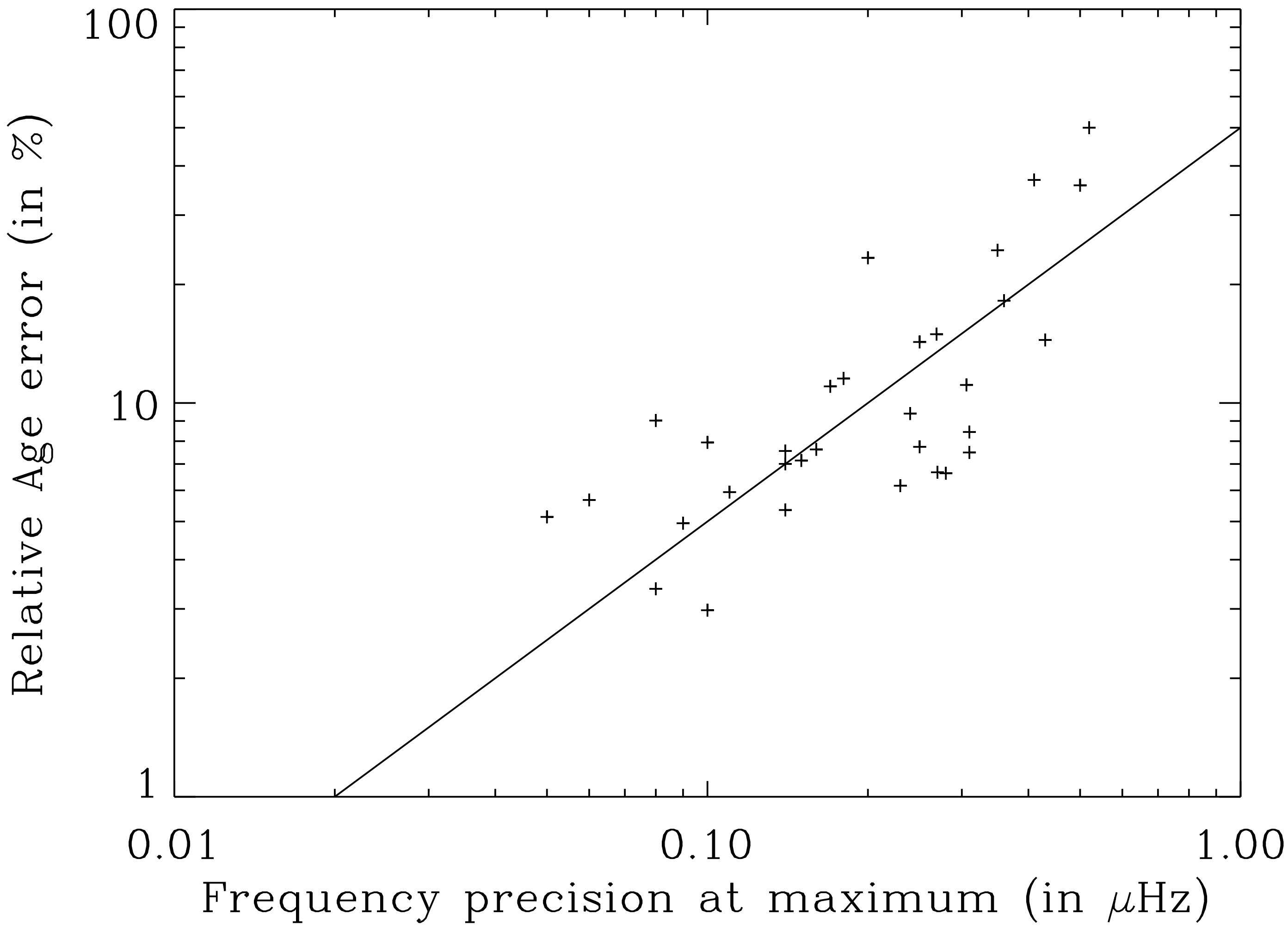
where $\beta = B/A$ is the inverse signal-to-noise ratio and

$$f(\beta) = (1+\beta)^{1/2}[(1+\beta)^{1/2} + \beta^{1/2}]^3\ .$$

where Γ is the mode linewidth, *T* is the observing time, *B/A* is the inverse signal-to-noise ratio in the power spectrum (*B/A* is now termed *B/H*)

- For a 2-year observing, a mode linewidth of 1 μHz, a S/N of 1, the mode frequency precision is better than 0.2 μHz

A naive derivation of age error

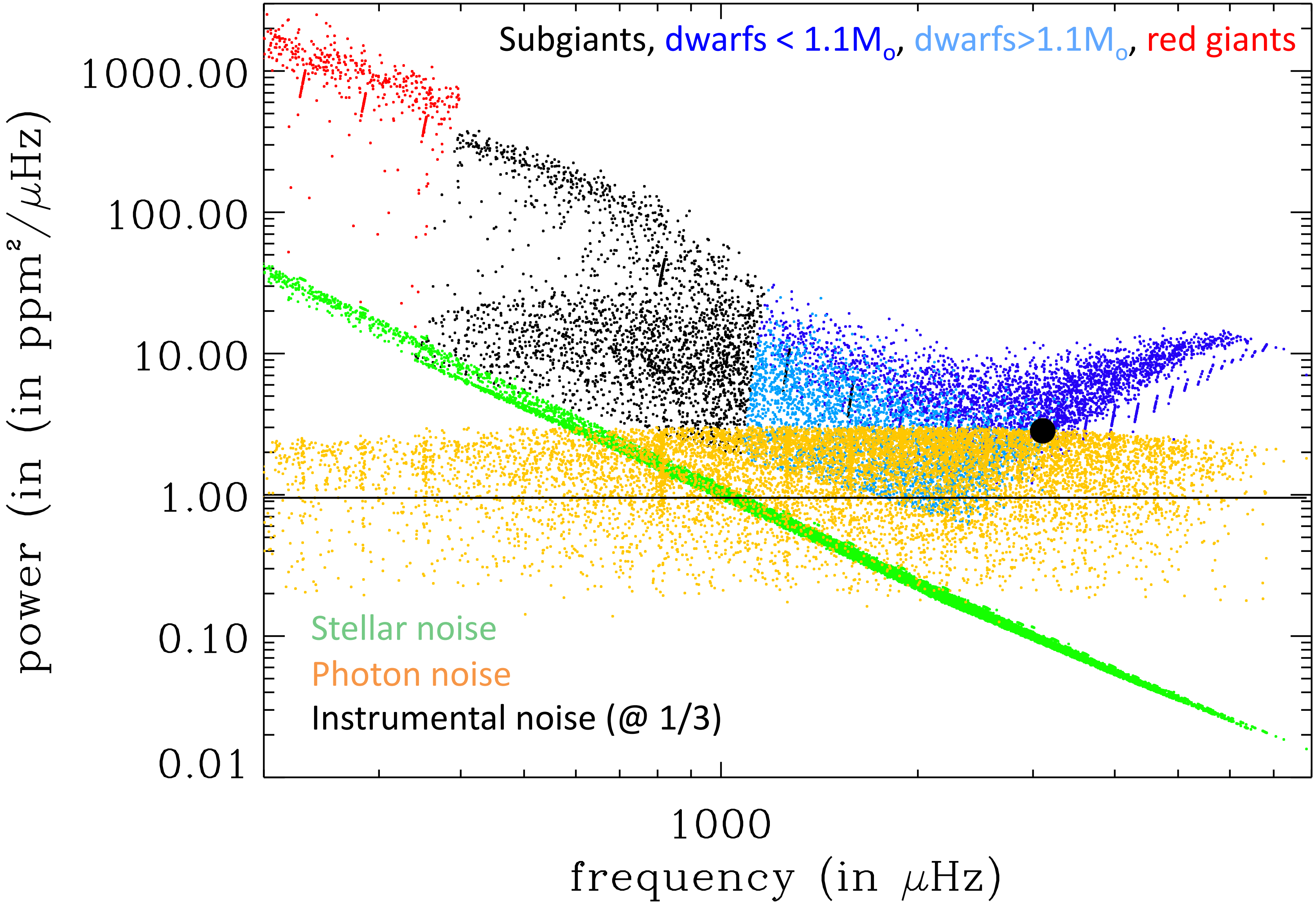


After Metcalfe et al (2014) and
Appourchaux et al (2012)

Assumptions for S/N for PLATO (II)

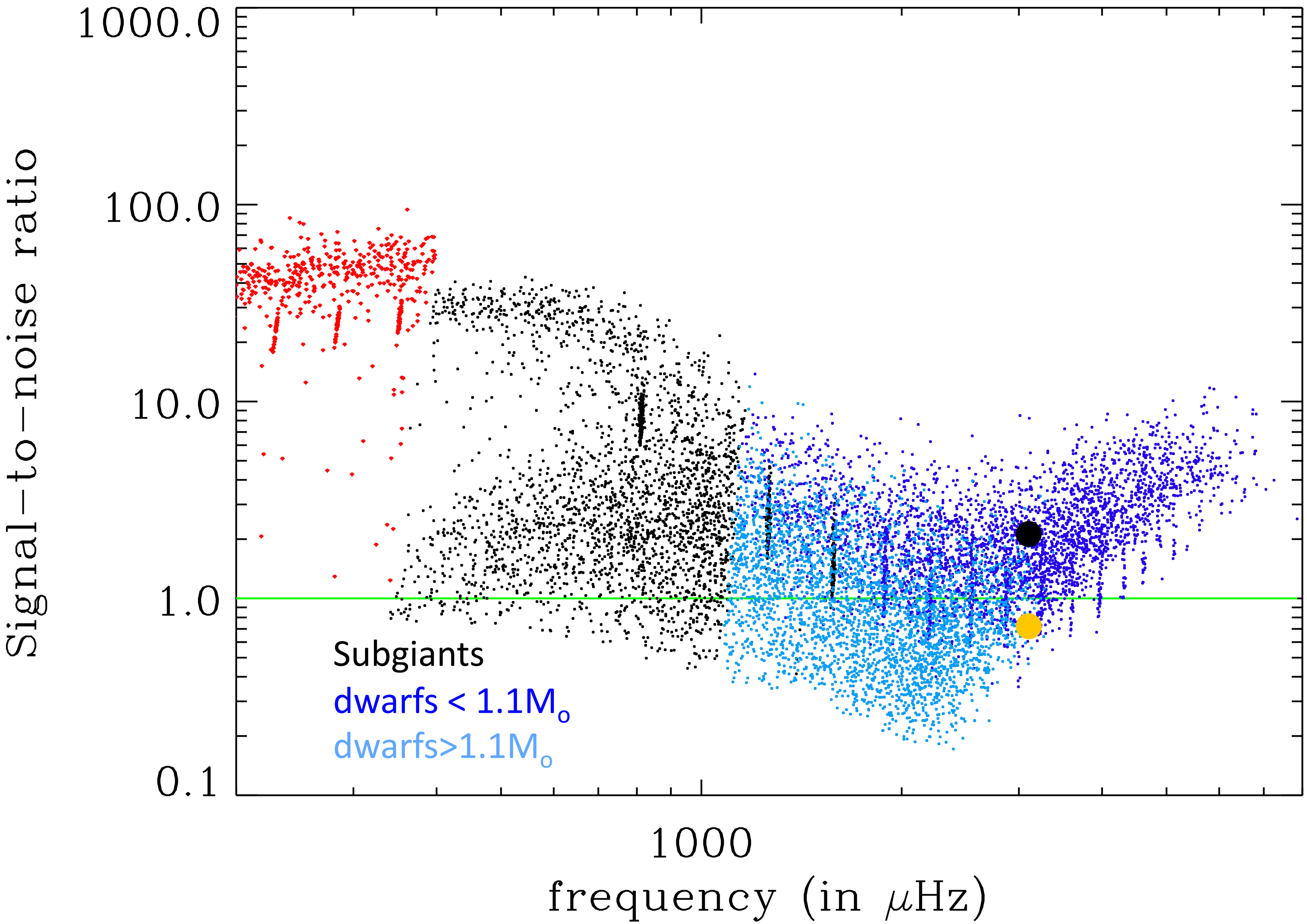
- Mode height (H) derived from:
  - Mode amplitude A from Corsaro et al (2013)
  - Mode linewidth Γ from Appourchaux et al (2012) for solar-like stars and from Corsaro et al (2013) for red giants
  - Both at frequency of maximum power
- Background noise (B) derived from the sum of:
  - Granulation noise from Kallinger et al (2014)
  - Photon noise from PLATO-DLR-MIS-LI-002 (28.2 ppm in one hour for m_V=11 @ 6000K)
  - Instrumental noise specified at 1/9 of the photon noise in power (tests performed at 1/9, 1/3 and 1 of the photon noise)
- Simulation of the P1 from the Robin et al (2003) model comprising about 28000 simulated stars
- S/N calibrated with an independent calculation based on the work of Appourchaux et al (2012)

Simulation for PLATO P1



Simulation of S/N for PLATO P1

Fraction of stars above detection level=87%



Results for the P1 sample

Case	Photon noise	Instrumental noise	Stellar noise	$F_{R,M,Age}$ F	$F_{R,M,Age}$ G	$F_{R,M,Age}$ K	$F_{R,M,Age}$ Subgiants	$F_{R,M,Age}$ Giants
Ca	x	1/9	x	13.1%	14.1%	1.2%	14.7%	47.8%
Cb	x **N Cameras**	1/3	x	9.6%	13.7%	1.2%	14.2%	47.8%
Cc	x	1	x	3.4%	10.4%	1.2%	12.4%	47.8%
Ca	x	1/9	x	5.3%	7.1%	0.8%	10.3%	62.2%
Cb	x **F Cameras**	1/3	x	3.4%	6.2%	0.8%	9.4%	62.2%
Cc	x	1	x	0.5%	4.5%	0.8%	7.9%	61.6%

More than 4500 stars of F, G, K type

Summary

- For asteroseismology, the limit of 28.2 ppm per hour has to include **<u>all</u>** source of noise: instrumental, photon, stellar
- For the P1 sample simulated by the Robin et al model, an instrumental noise at 1/3 of the photon noise in power, we get stellar masses, radii and age for 87% of all stars, for 23% of all stars being either F, G or K stars
- For the P1 sample simulated by the Robin et al model, an instrumental noise at 1/9 of the photon noise in power, the percentages are increased by 4% (91%, 27% respectively).
- The nominal value of 1/9 is provided with a margin of a factor 3. (1/9 to 1/3 in power)
- Limitation of the study:
  - There are very few measurements of mode height above 3500 μHz which makes the predictive power very small for light stars.
  - Therefore the results for K stars is likely not to be trusted at all.
  - For G stars, about 6 stars out of 10 have a ν_{max} lower than 3500 μHz
  - All F stars have their ν_{max} lower than 3500 μHz
- Document available: PLATO-IAS-SCI-AN-001 V3.2, March 12, 2015