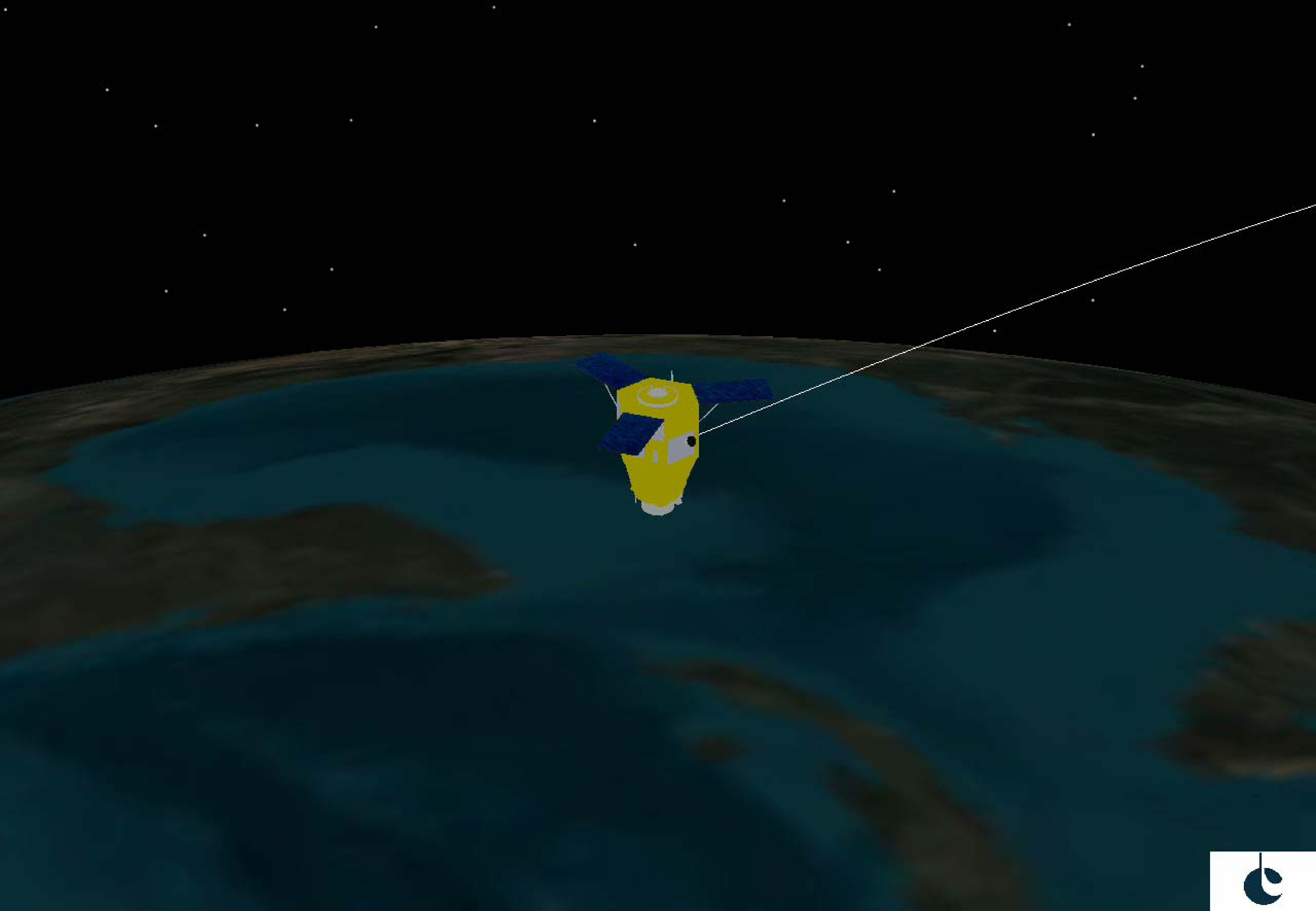
CNES
CENTRE NATIONAL D'ÉTUDES SPATIALES

Star-based Calibration Techniques for PLEIADES-HR Satellites

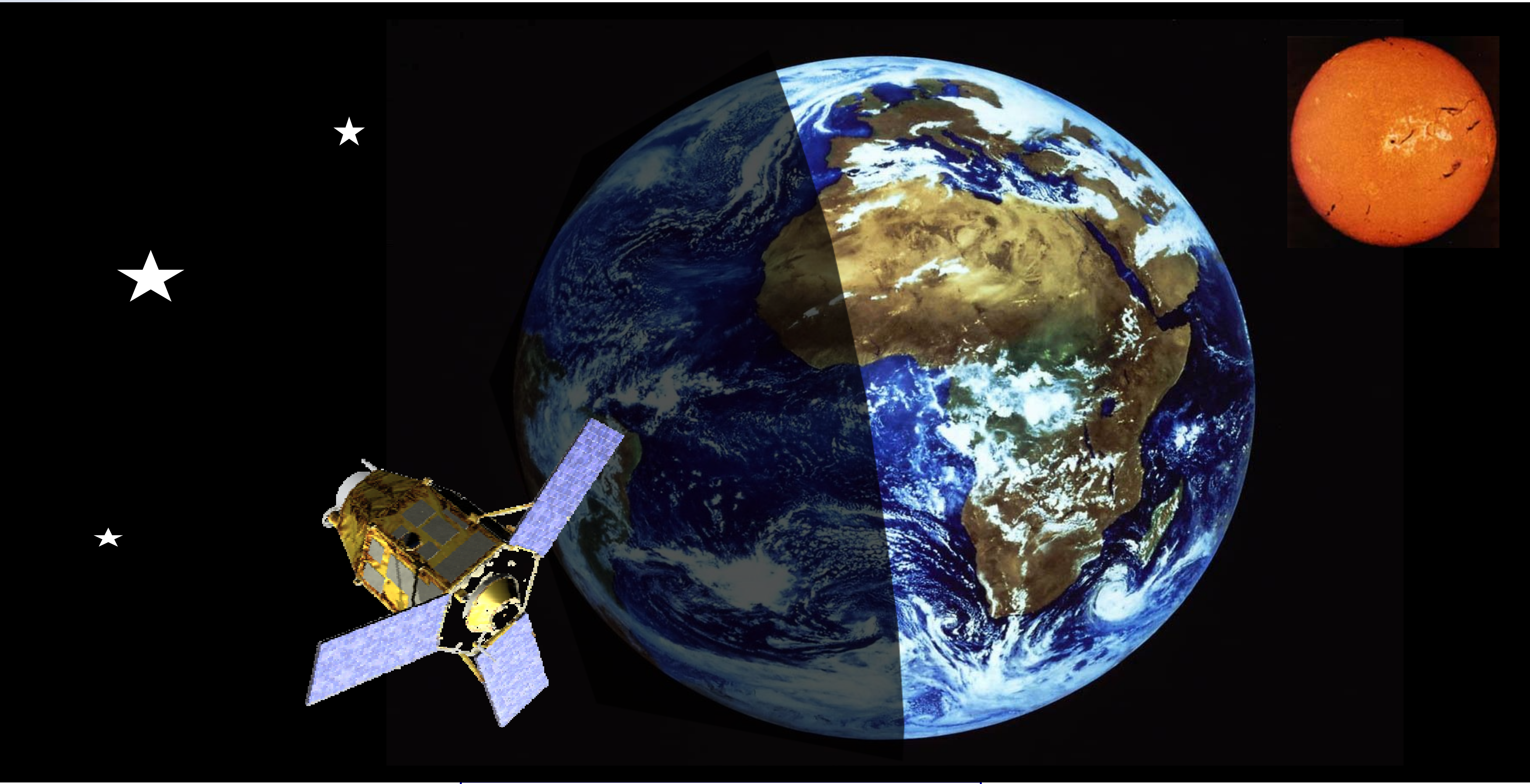
CALCON 2009

Sébastien FOUREST – Laurent LEBEGUE



Using the stars…

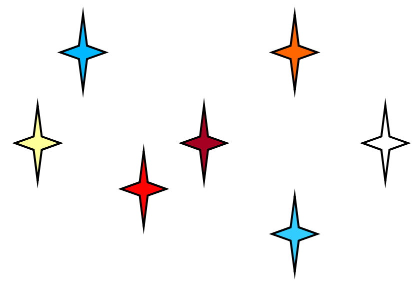
- Operational interests : cloud free scenes, eclipse orbit, …

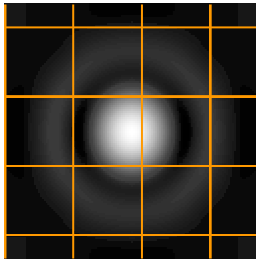


cnes

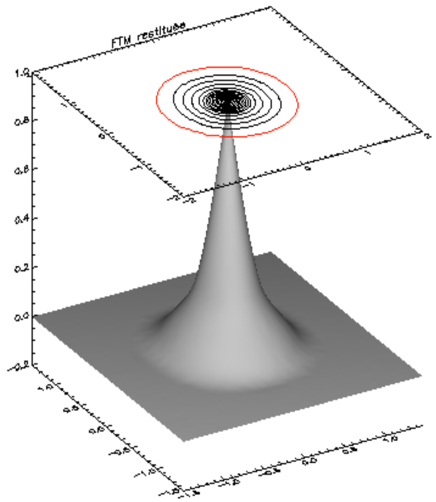
Outline

- Choosing the right stars





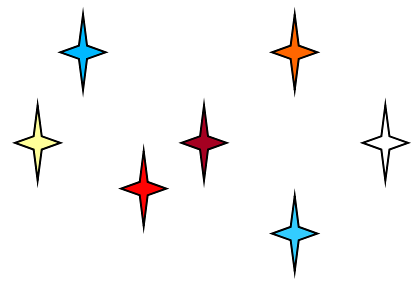
- Centering the star in the sampling grid



- MTF measurement
- Other applications

Outline

- Choosing the right stars



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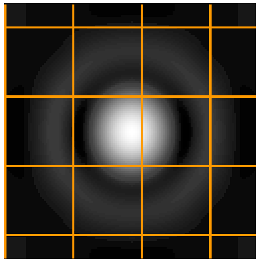
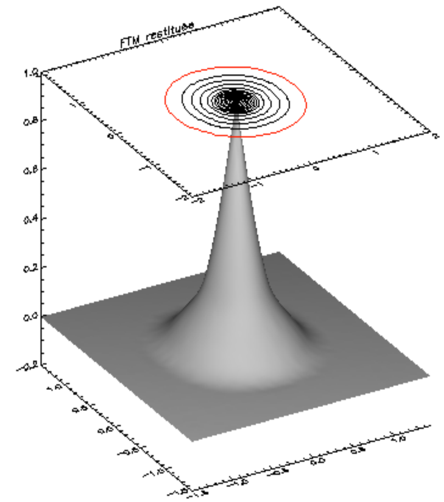


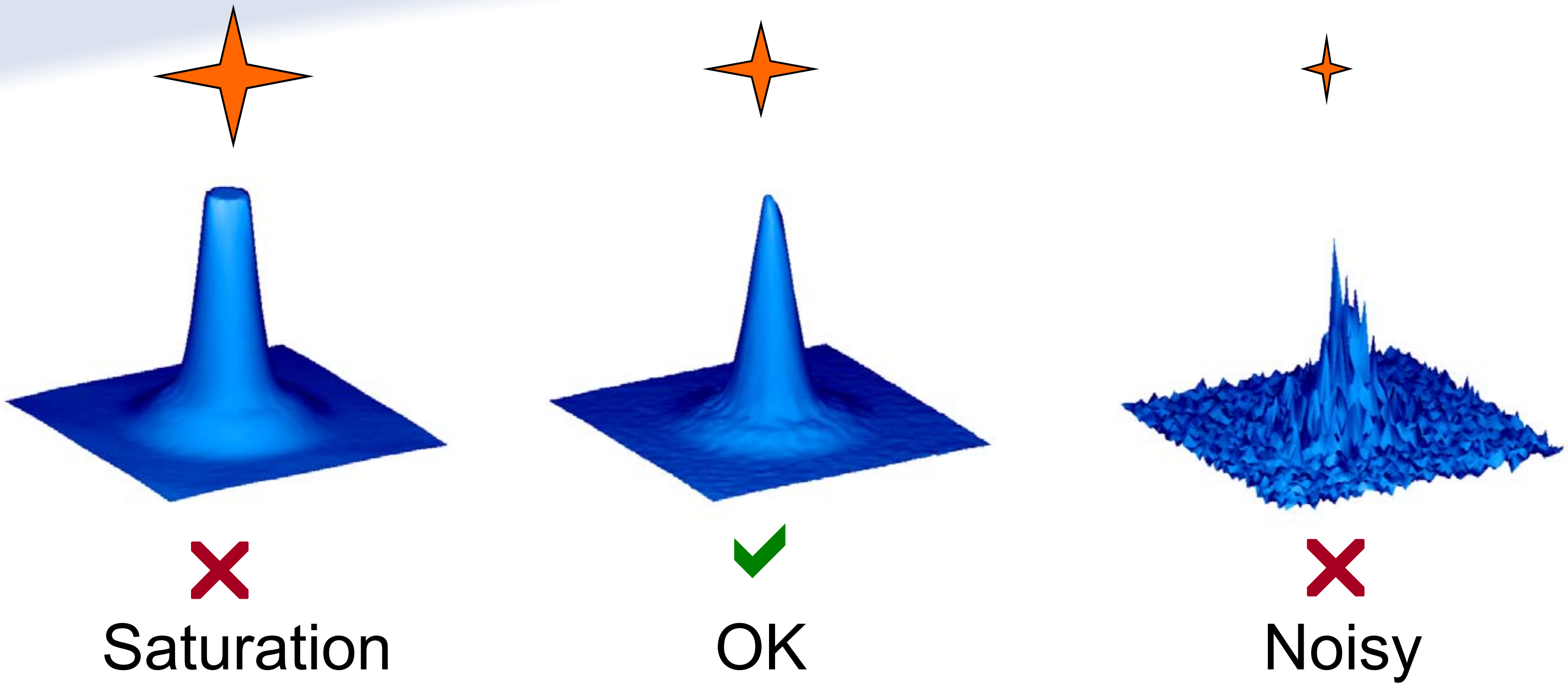
- MTF measurement



- Other applications

Choosing the right stars

magnitude range

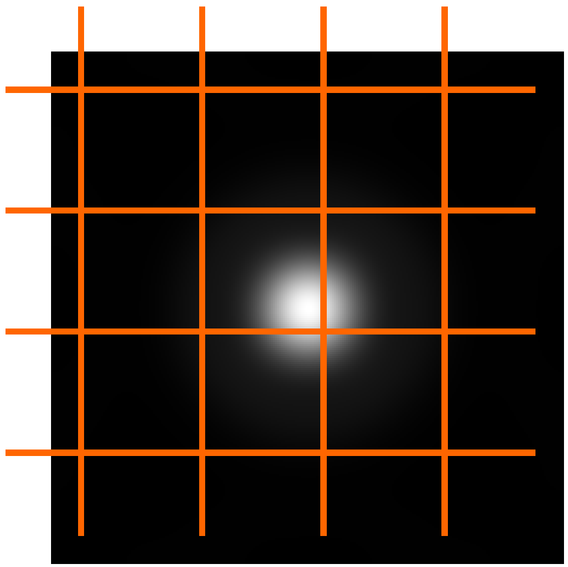


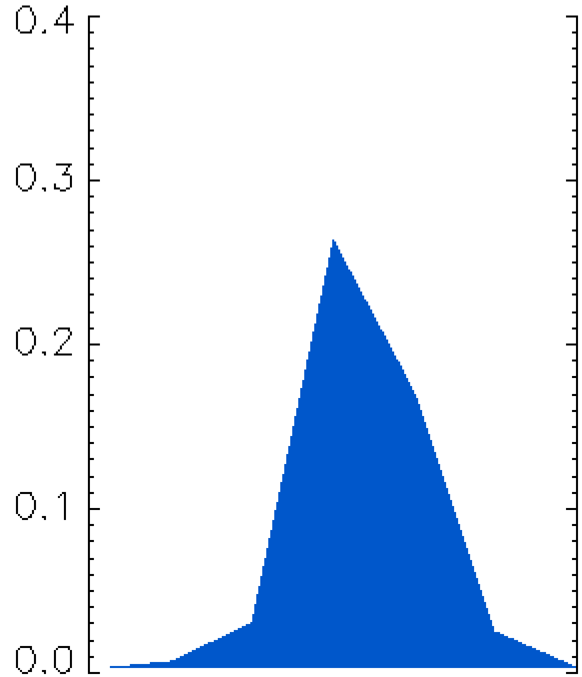
$$R = \left(\frac{f}{dx}\right)^2 .I_0 .2.512^{-Mag}$$

$$L_2 < R < L_{\max}$$

Choosing the right stars

magnitude range





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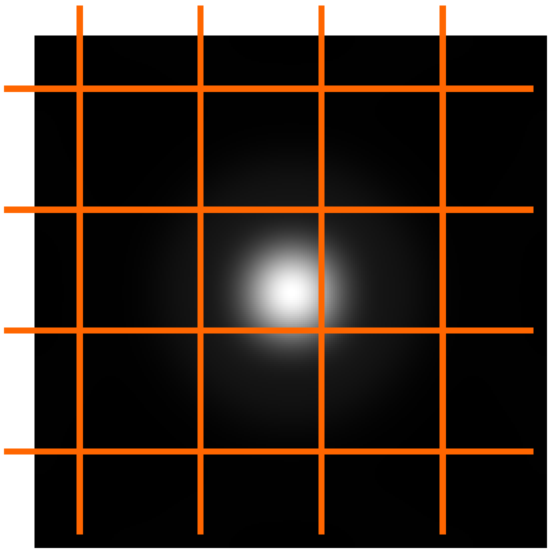

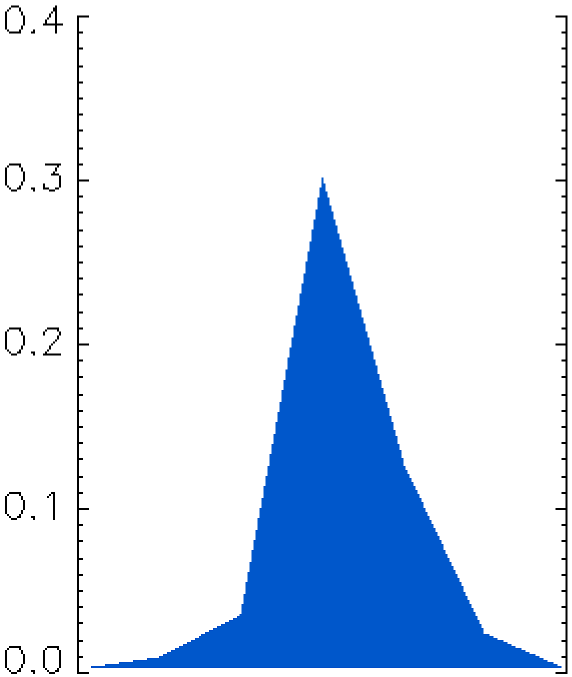

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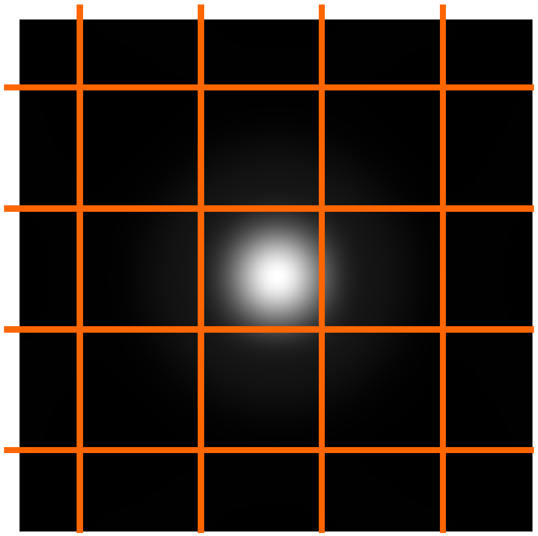

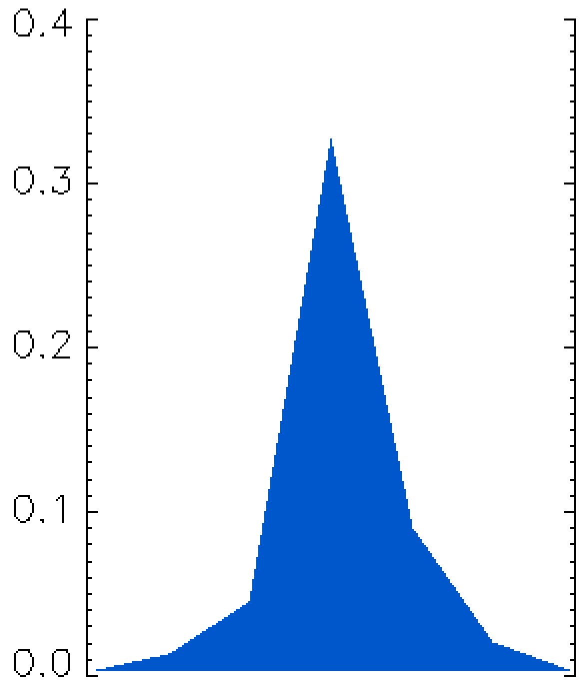

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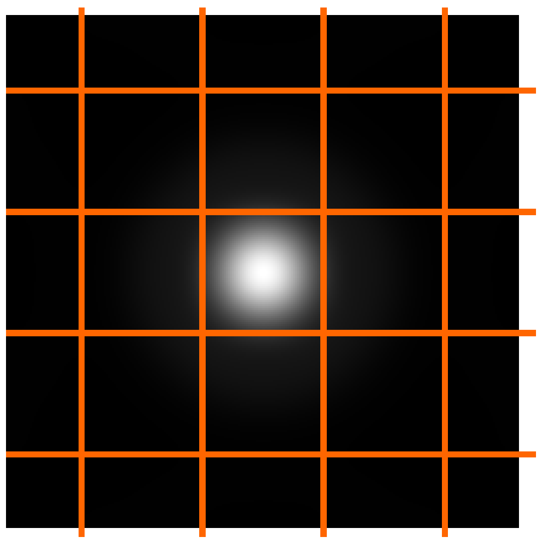

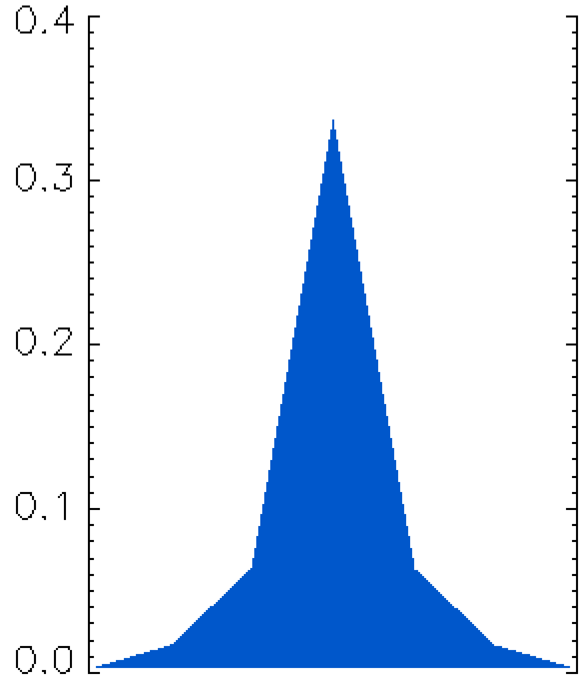

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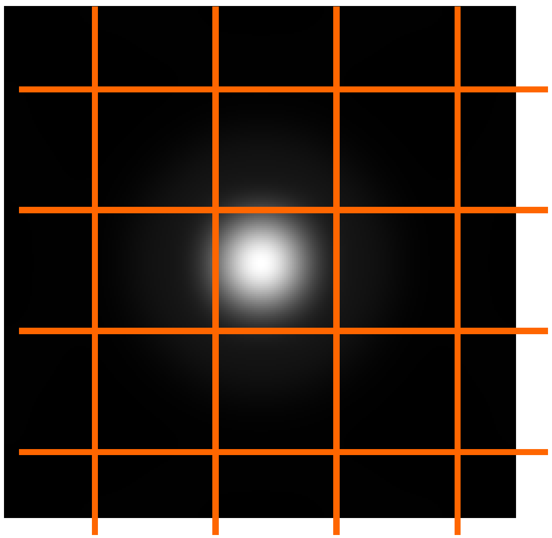

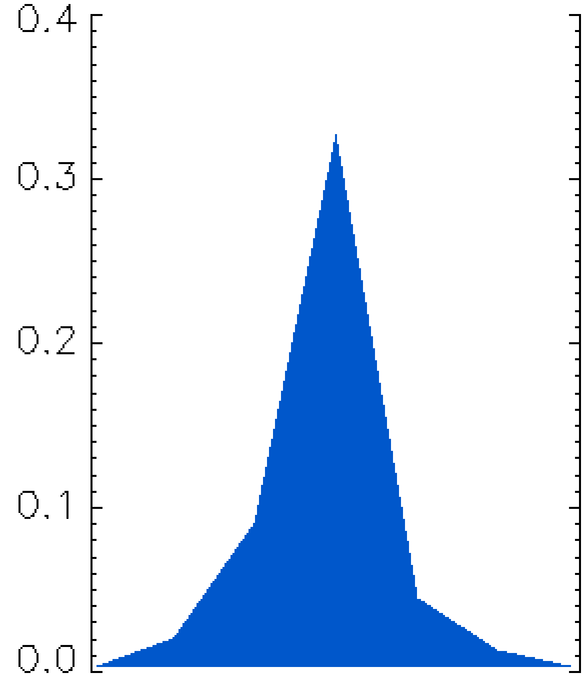

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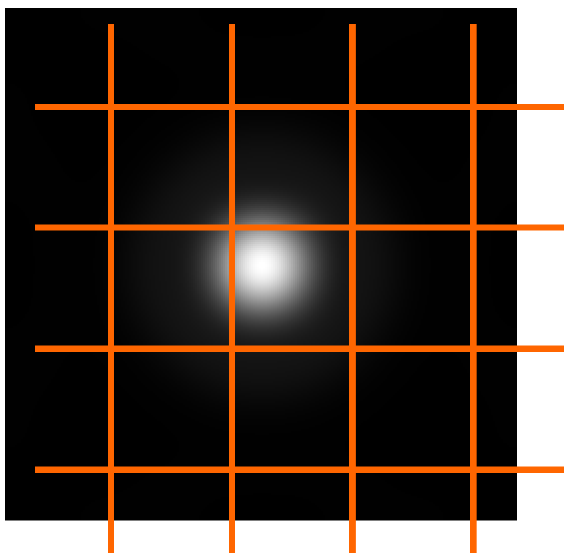

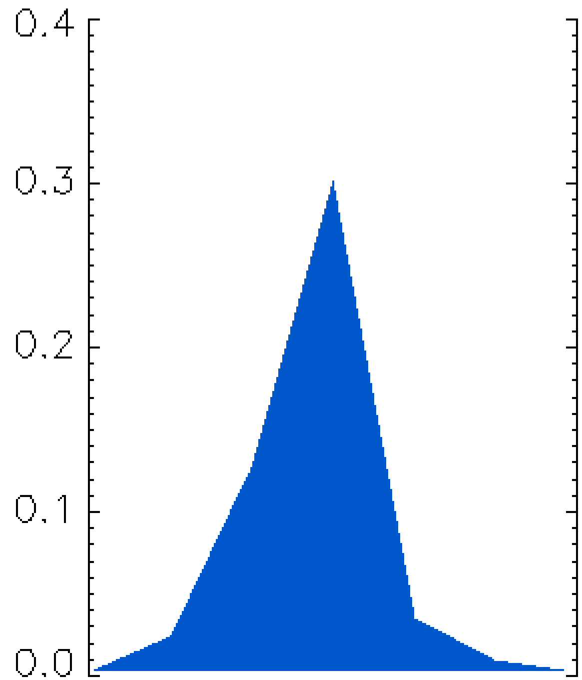

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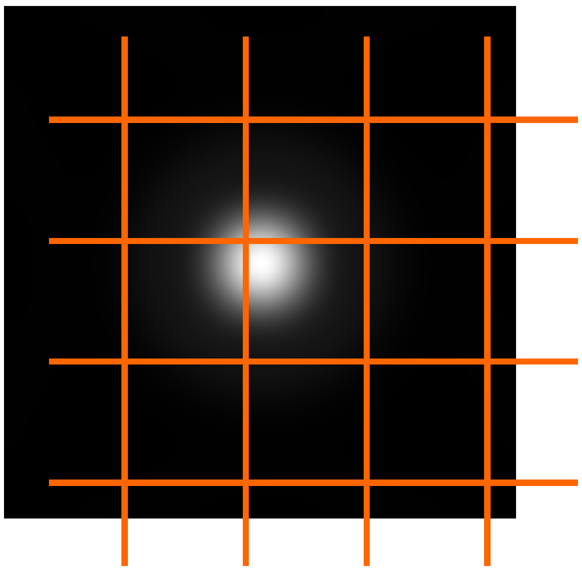

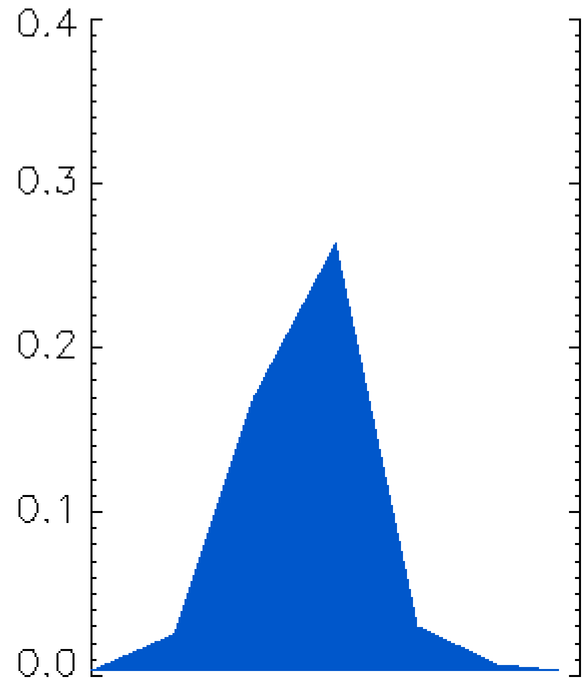

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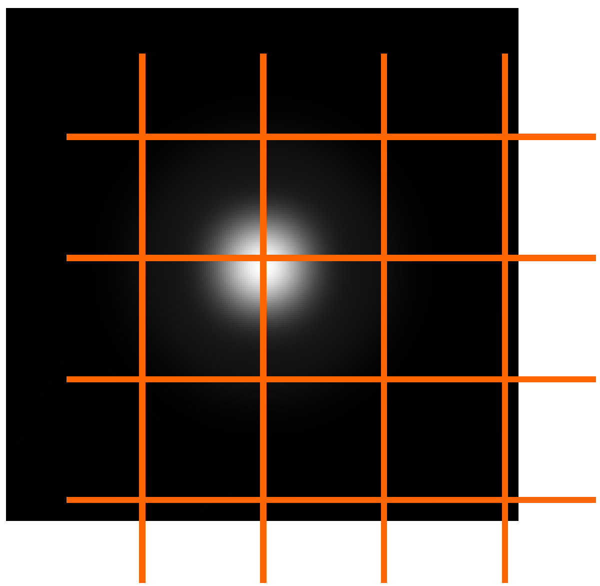
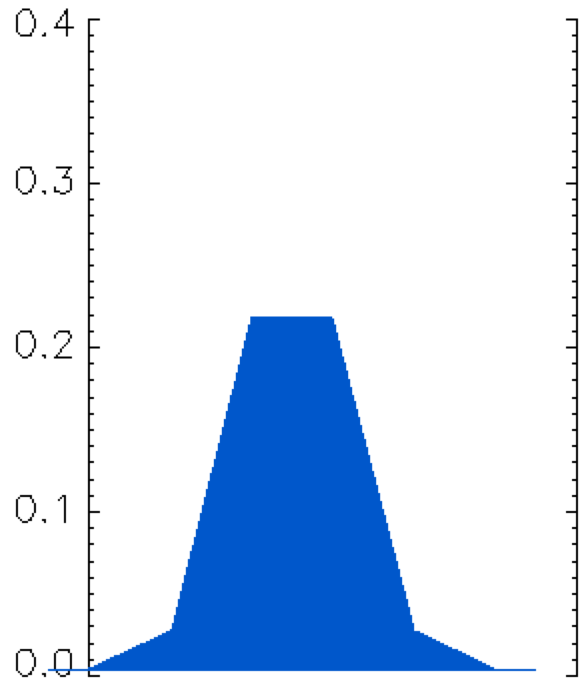
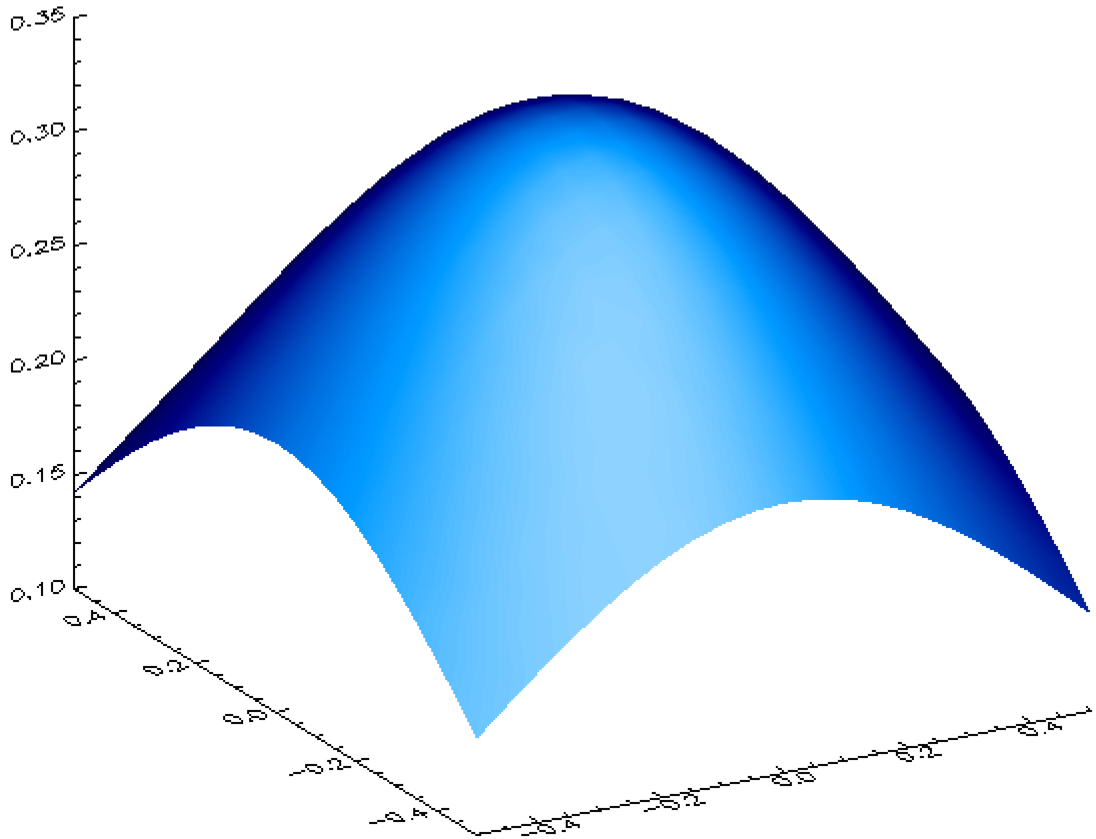




Choosing the right stars
magnitude range



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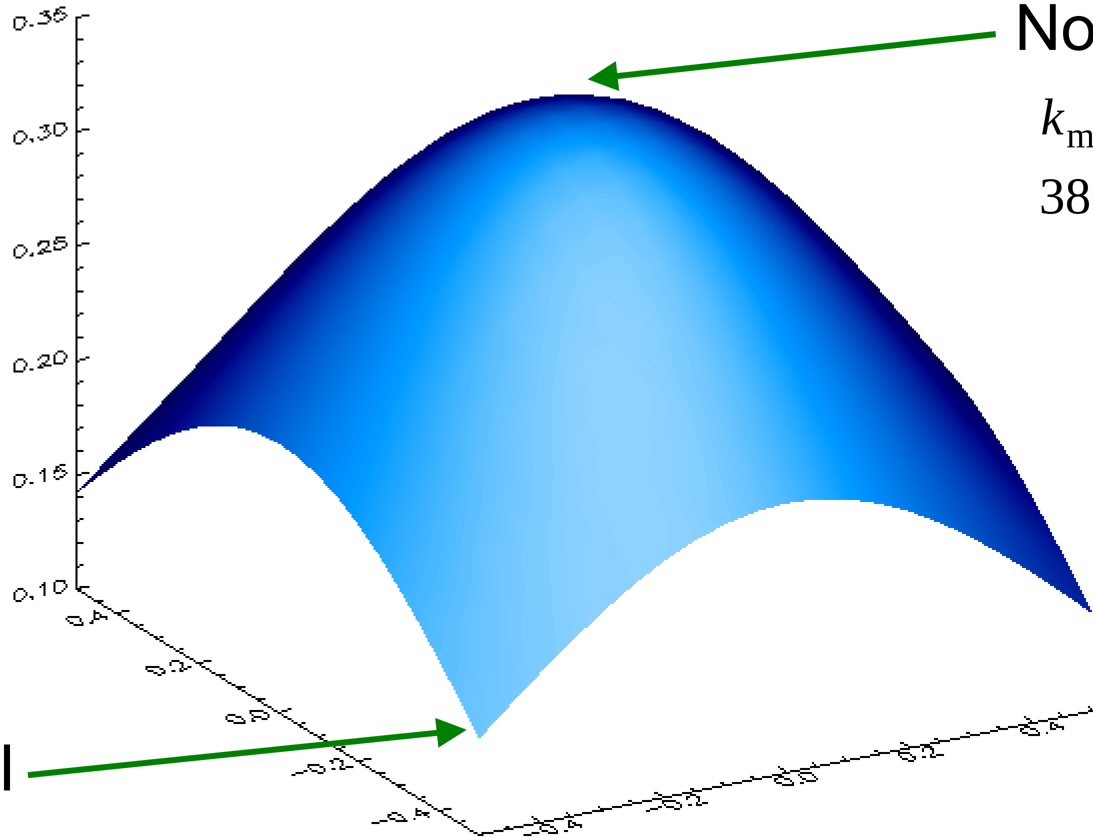


No saturation

$$k_{\max} * R < L_{\max}$$

$$380W / m^2 / sr / \mu m$$

Enough signal

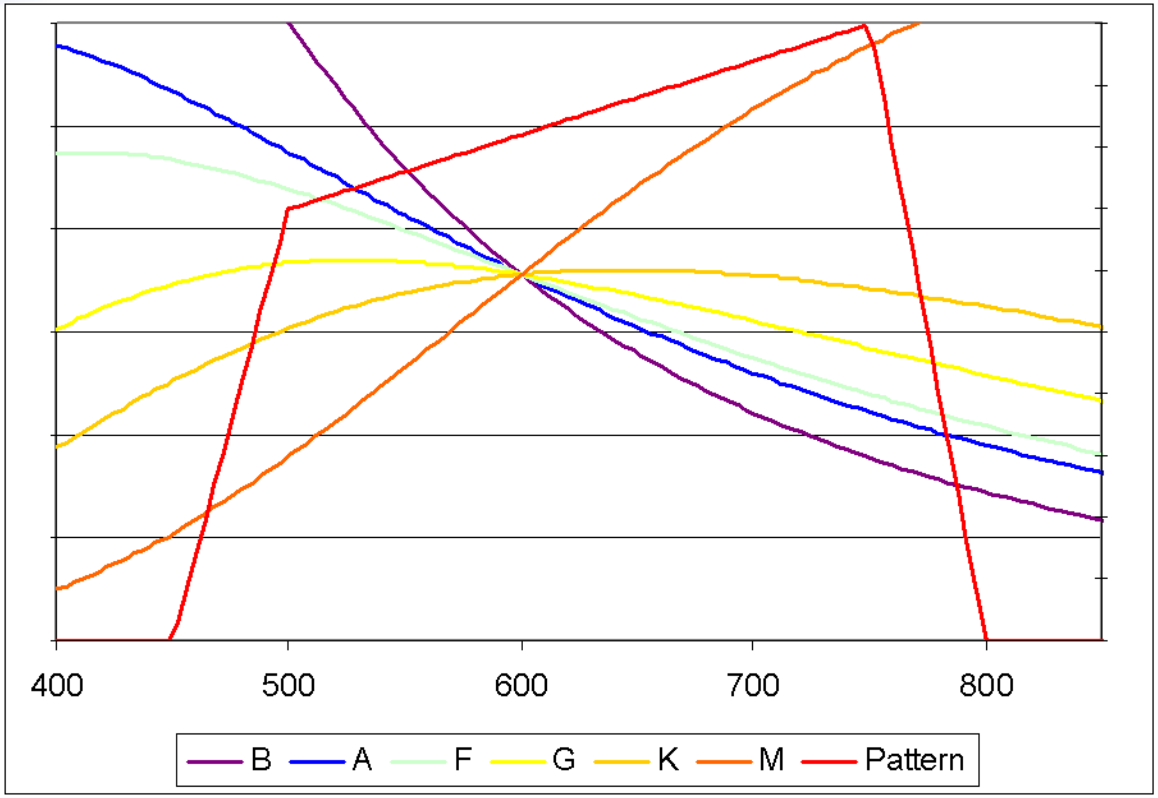
$$k_{\min} * R > L_2$$

$$100W / m^2 / sr / \mu m$$

$$mag \in [3.66 ; 2.44]$$

Choosing the right stars

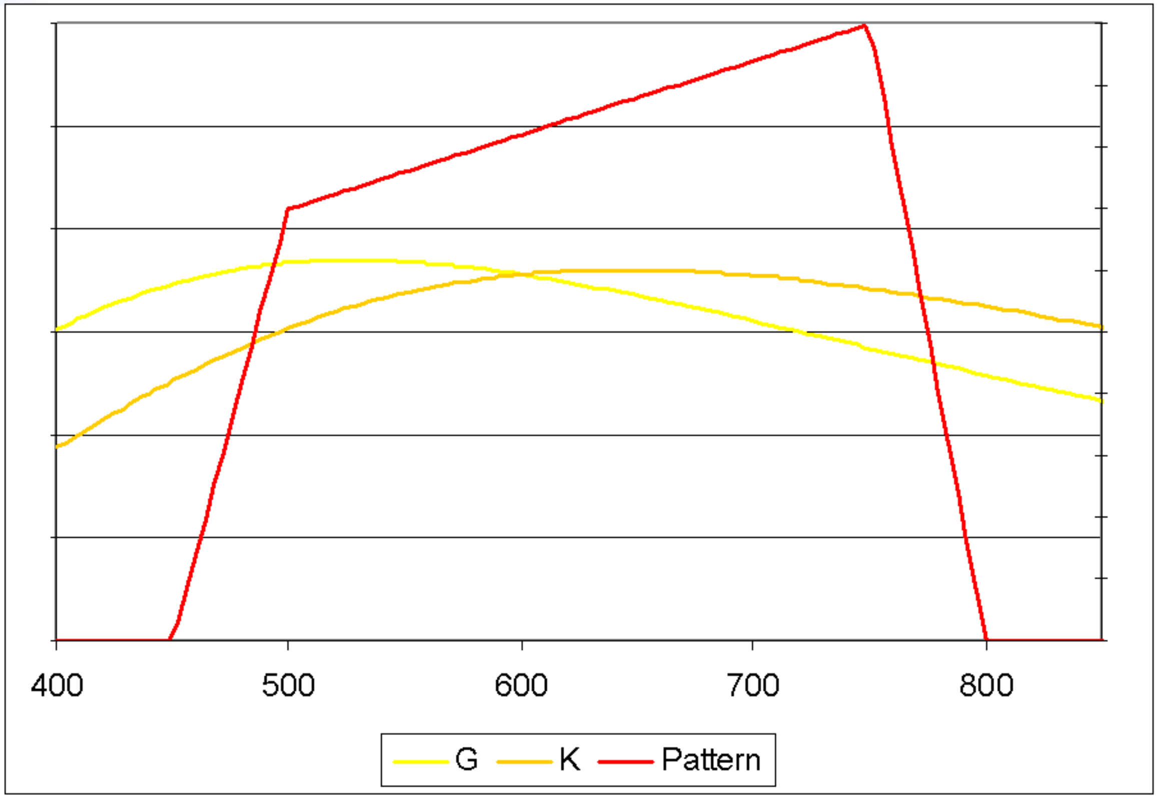
spectral range



Class	temperature	color	Class	temperature	color
B	10 000 - 25 000 K	Blue-white	G	5 000 - 6 000 K	Yellow (the Sun)
A	7 500 - 10 000 K	White	K	3 500 - 5 000 K	Yellow – Orange
F	6 000 - 7 500 K	Yellow – white	M	< 3 500 K	Red

Choosing the right stars

spectral range

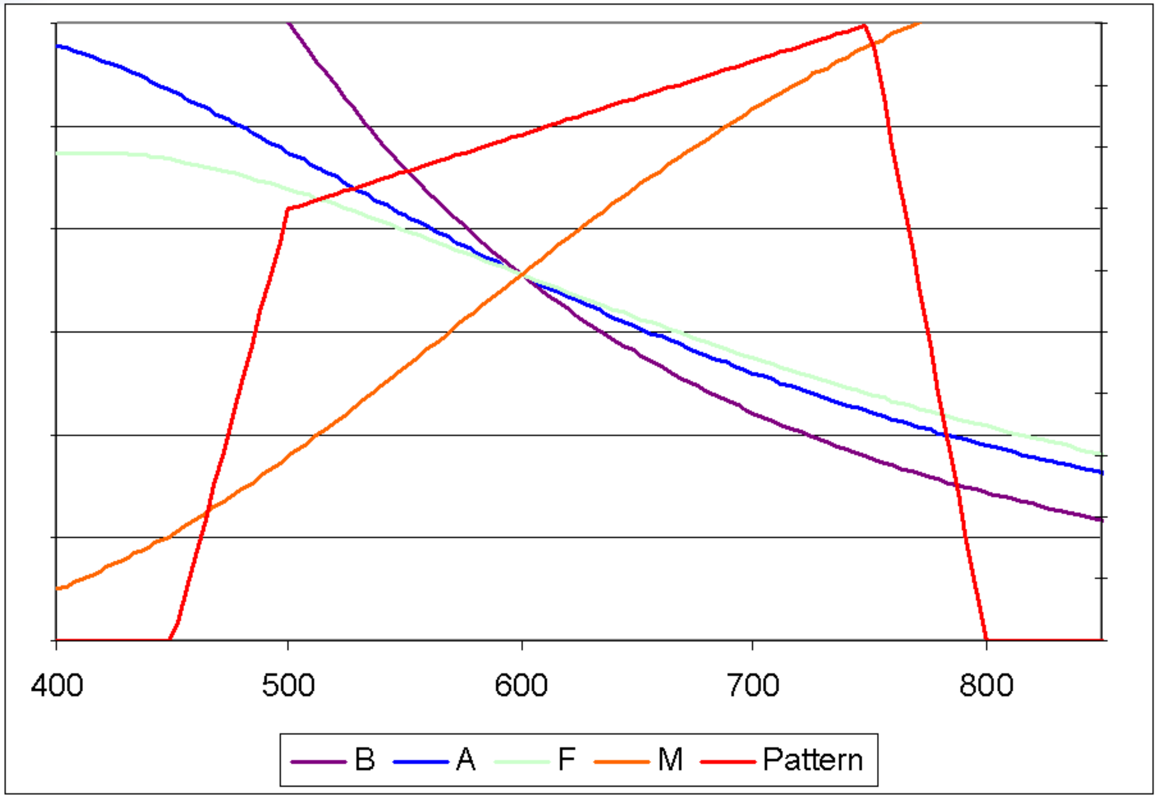


Classes G8 → K3 : uniform spectrum

40 stars compliant with magnitude constraints

Choosing the right stars

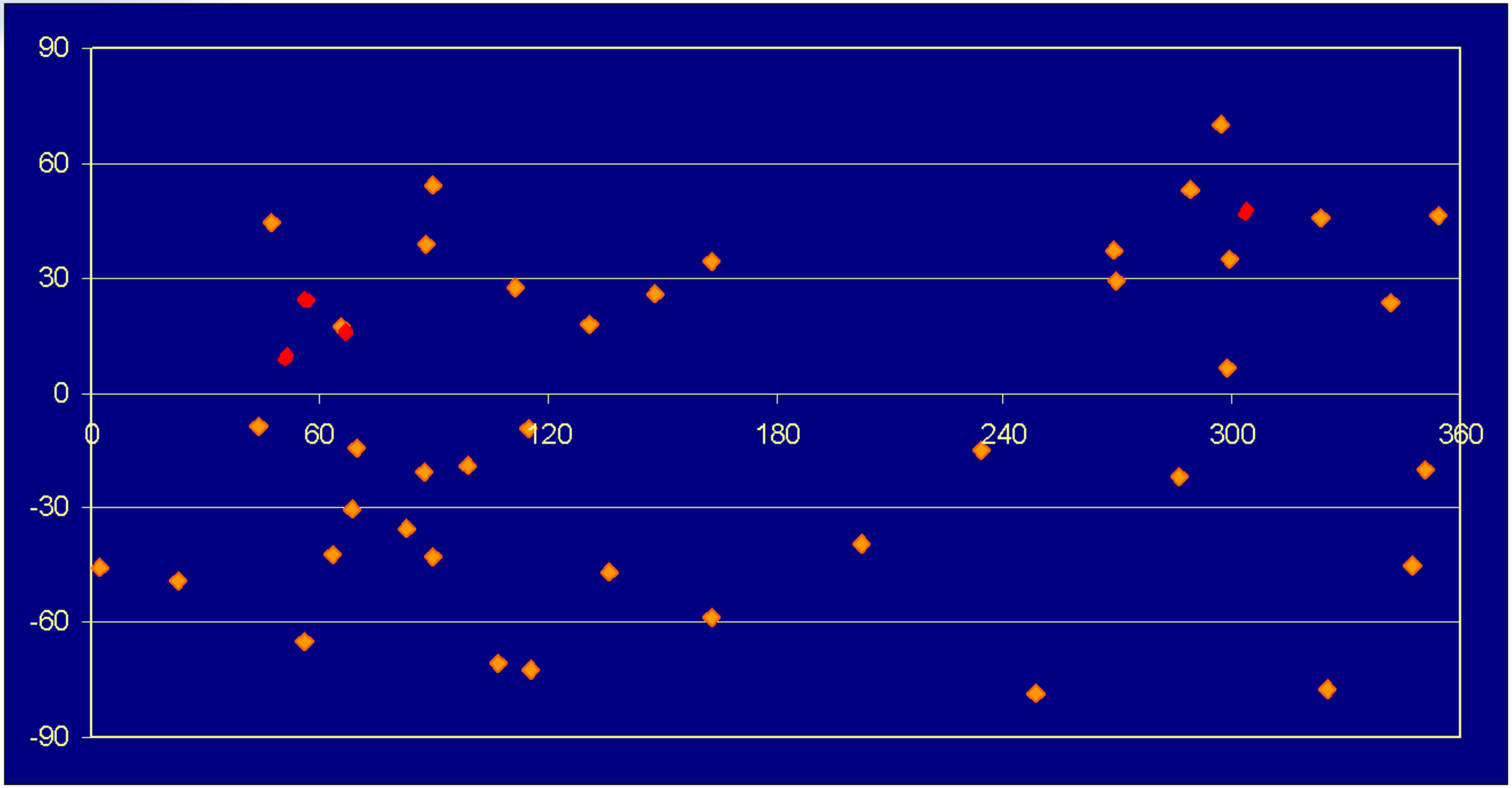
spectral range



Other classes : spectral dependencies study

Area of particular interest in the sky

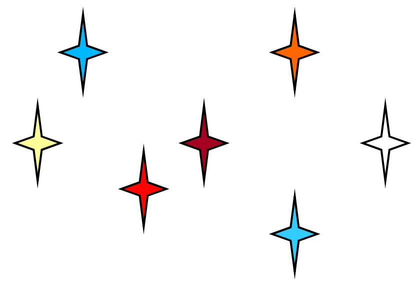
Choosing the right stars



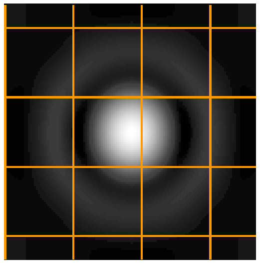
The exploitable sky

Outline

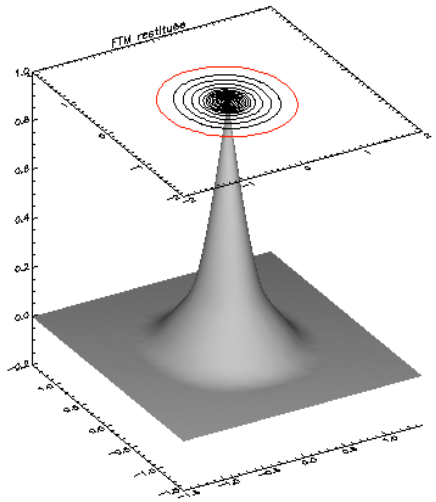
- Choosing the right stars



- **Centering the star in the sampling grid**



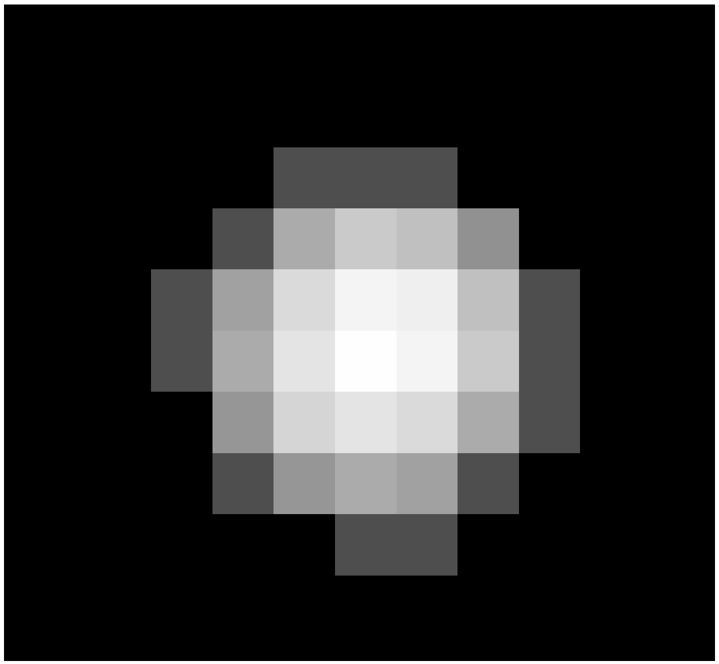
- MTF measurement



- Other applications

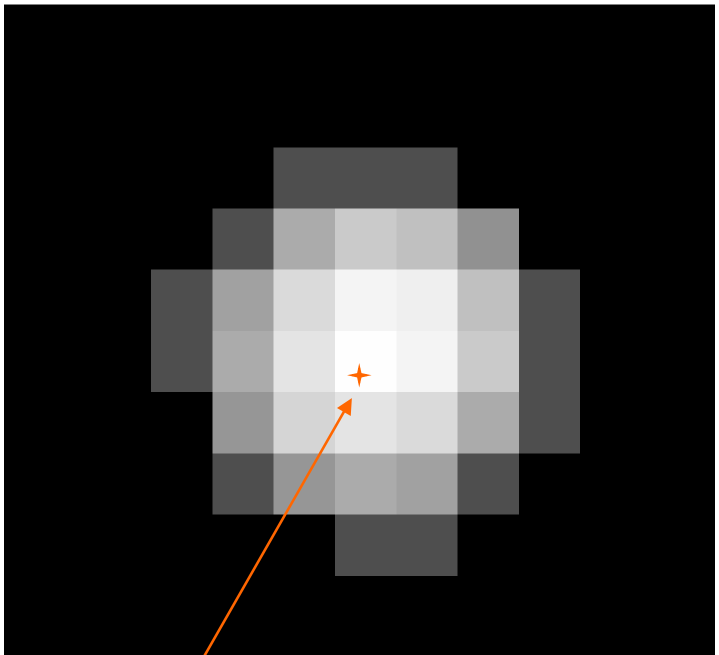
Centering in the sampling grid

principle



- Where was the star ?

Centering in the sampling grid
principle

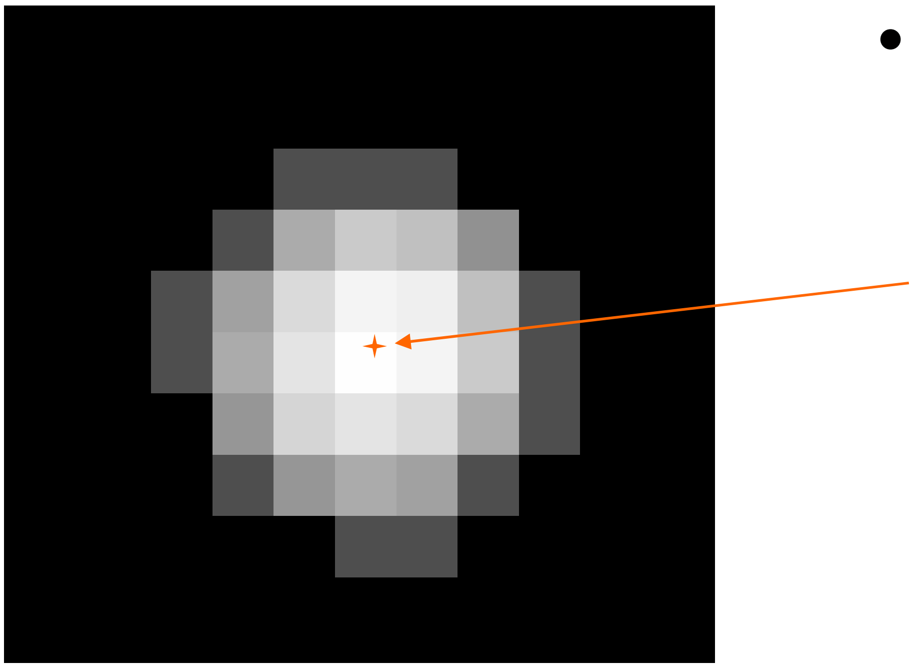


Here ?

- Where was the star ?

Centering in the sampling grid

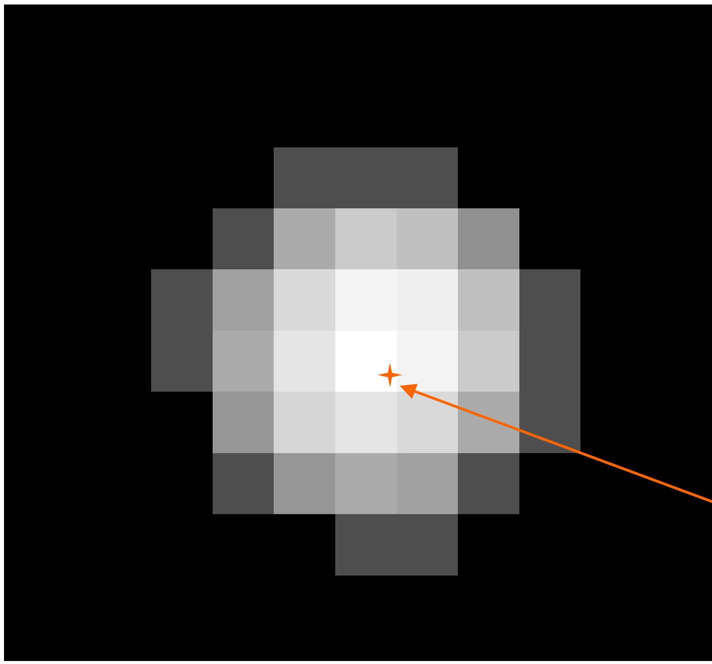
principle



- Where was the star ?

Centering in the sampling grid

principle



- Where was the star ?

Here ?

Centering in the sampling grid

Basic methods

■ **Basic methods :**

- **Maximum pixel : accuracy = 0.5px**

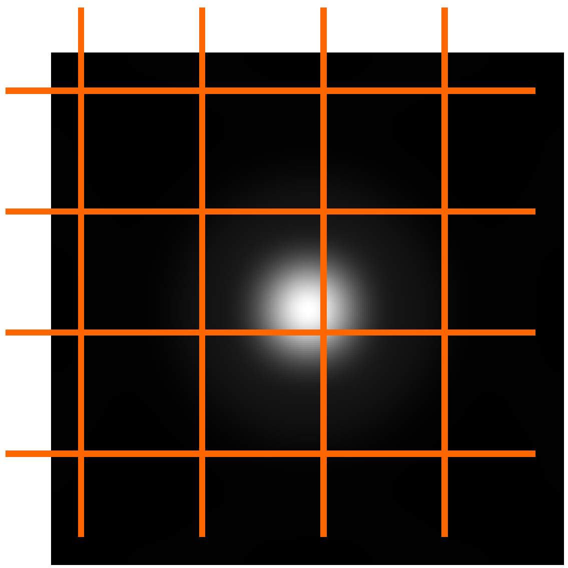
- **Barycentre : accuracy = 0.25px**

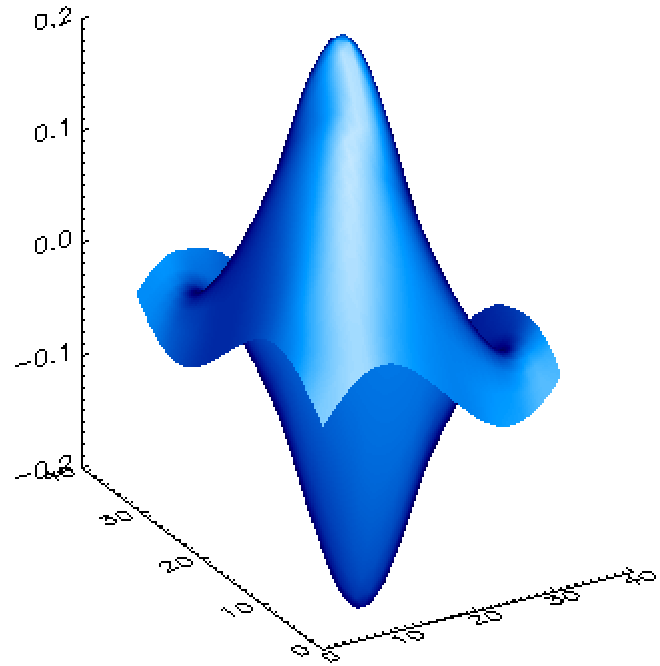
$$OC = \left(\sum r_{i,j}.OM_{i,j}\right) \Big/ \sum r_{i,j}$$

- **Search for the real Fourier Transform…**

Centering in the sampling grid

Real FT

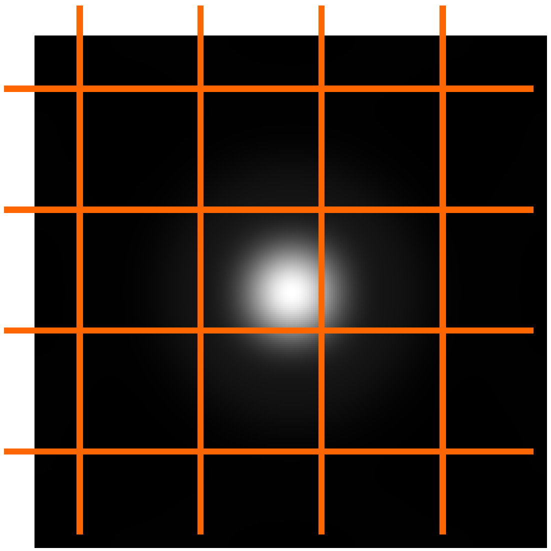


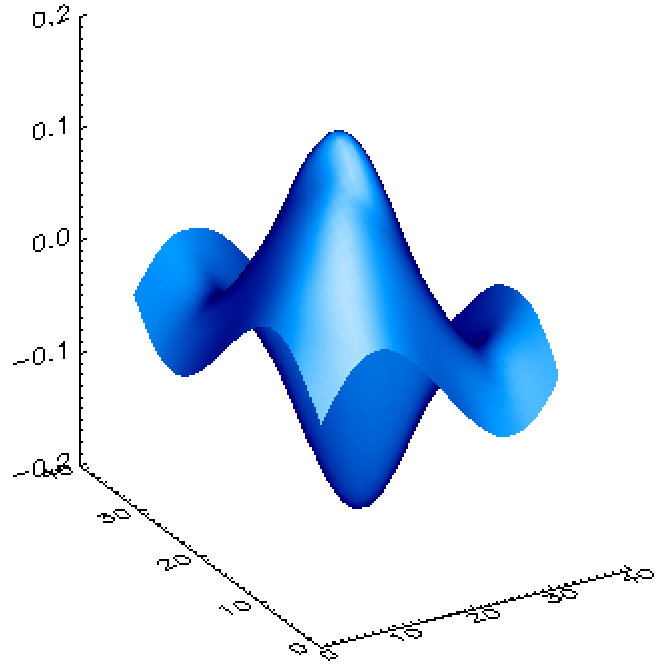


Imaginary part of the Fourier transform

Centering in the sampling grid

Real FT





Imaginary part of the Fourier transform

Centering in the sampling grid

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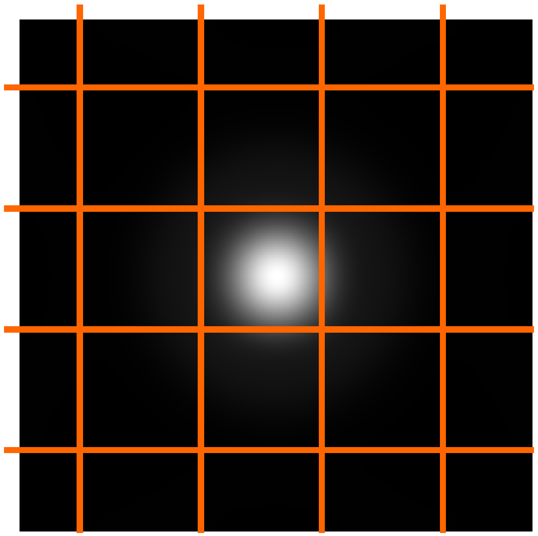
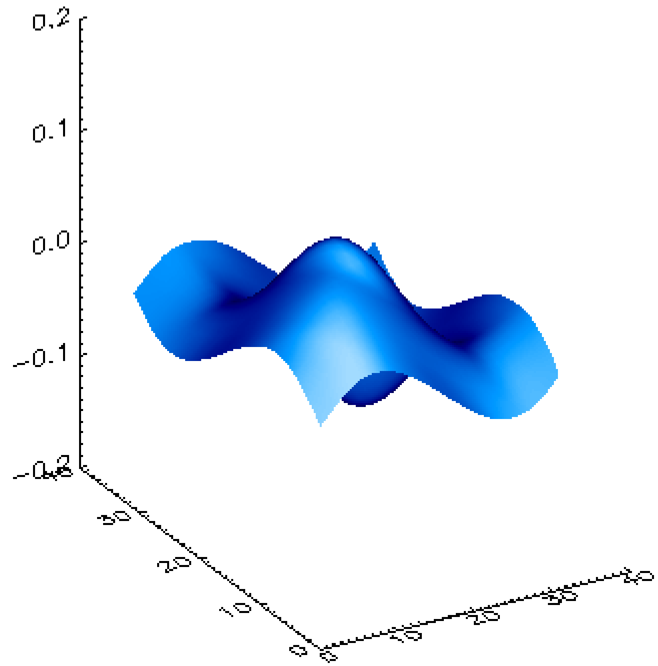
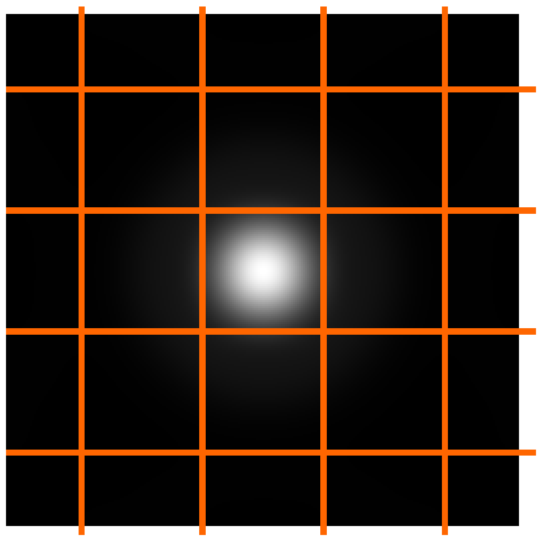


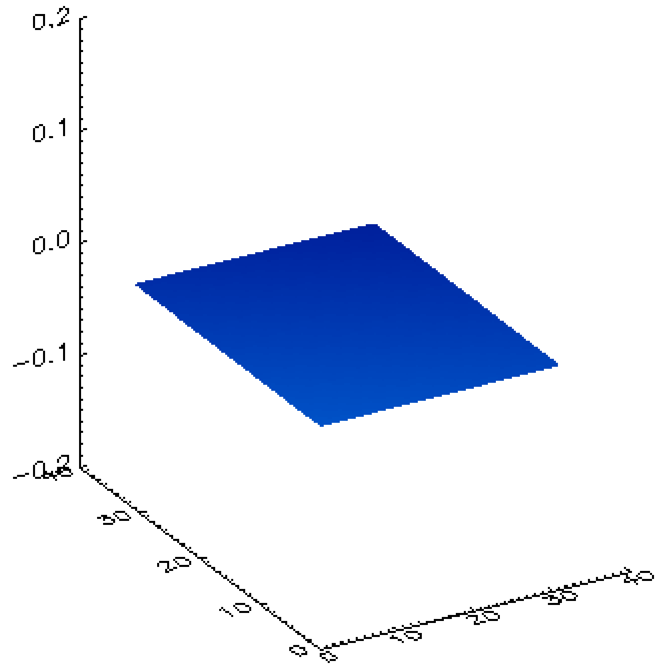


Imaginary part of the Fourier transform

Centering in the sampling grid

Real FT

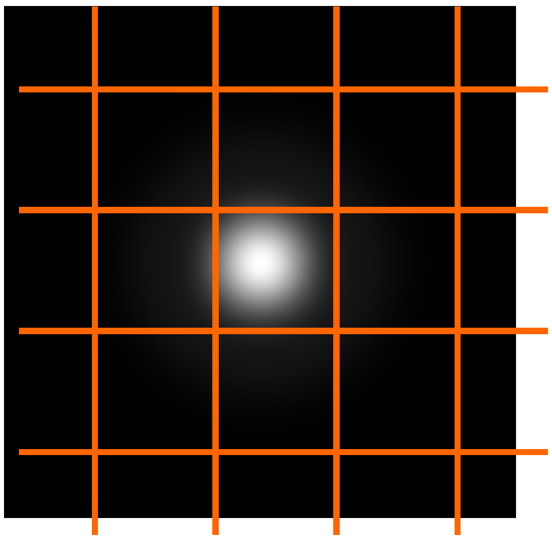


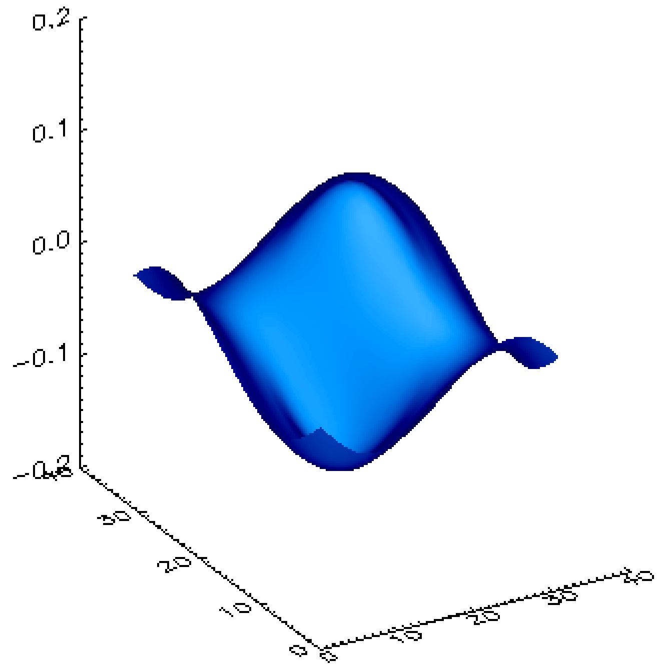


Imaginary part of the Fourier transform

Centering in the sampling grid

Real FT





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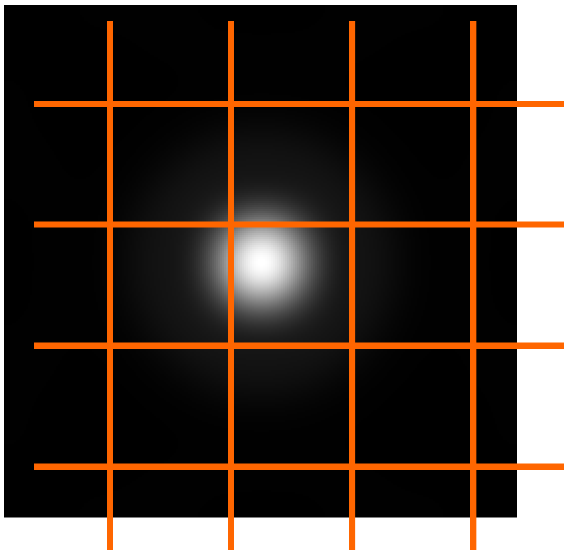
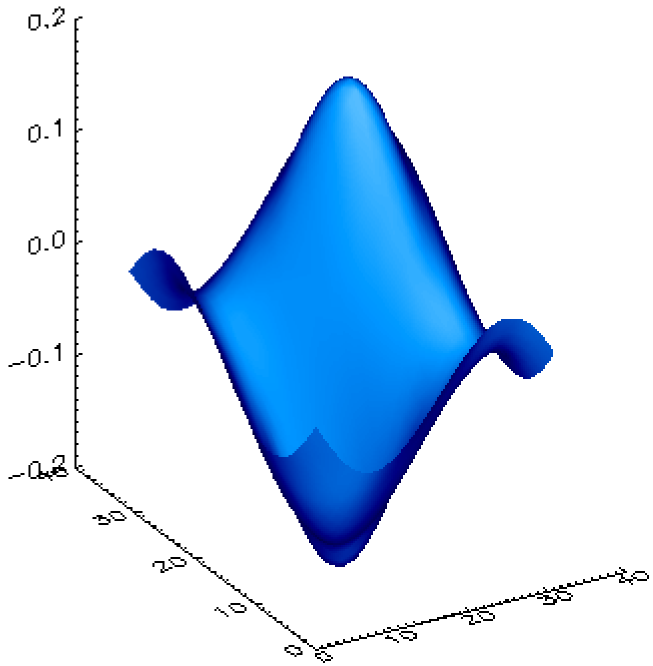
Real FT





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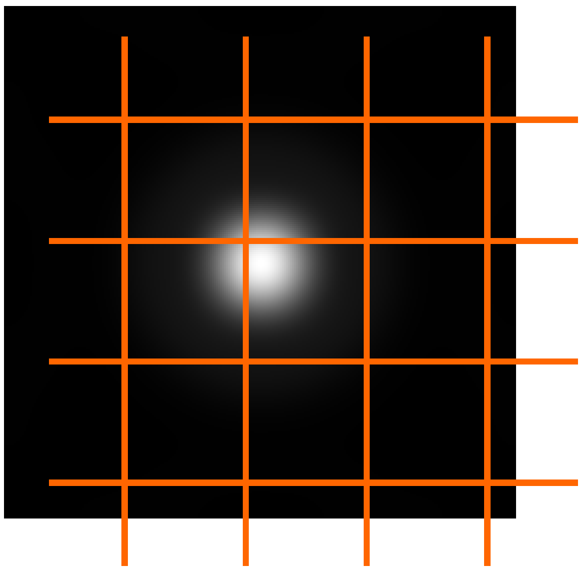
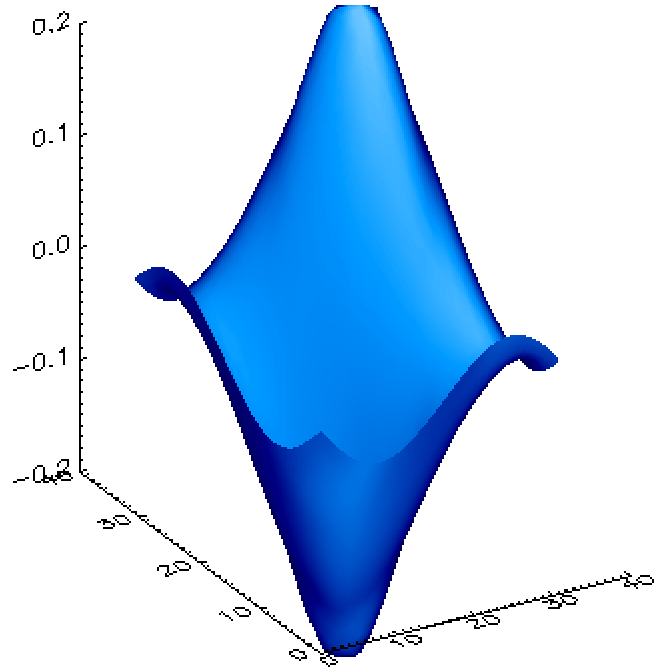
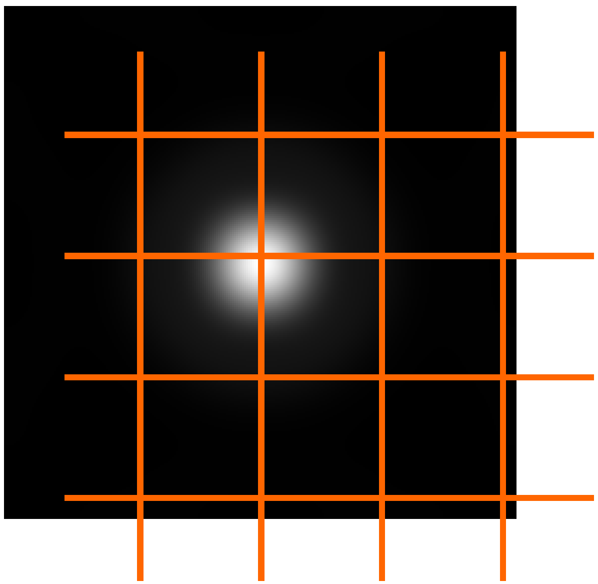


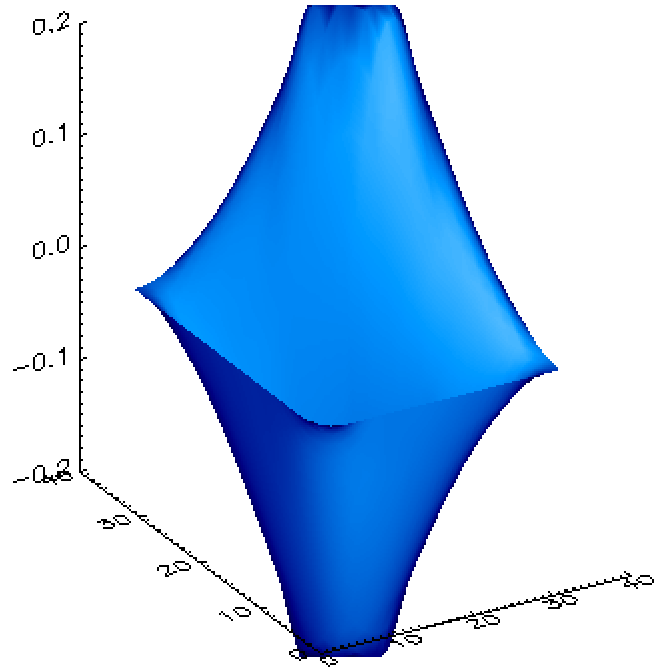


Imaginary part of the Fourier transform

Centering in the sampling grid

Real FT





Imaginary part of the Fourier transform

Centering in the sampling grid

Real FT

→Looking for the phase ramp that cancel the Fourier transform :

$$(dx, dy)\ ?\ FT * \varphi_{ramp}(dx, dy) \equiv 0$$

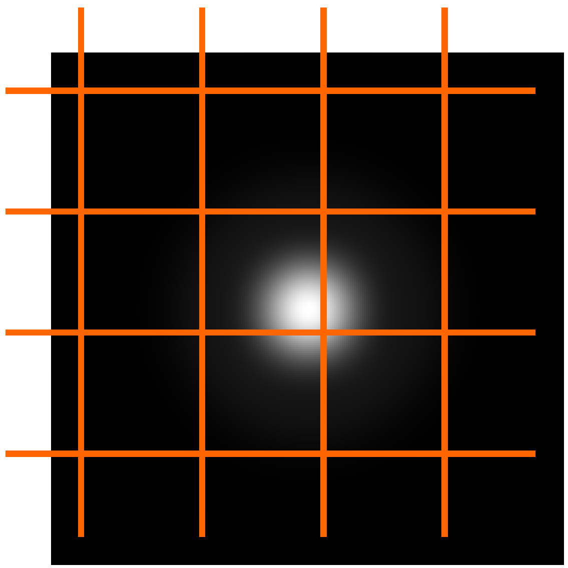
→Problem : aliased images

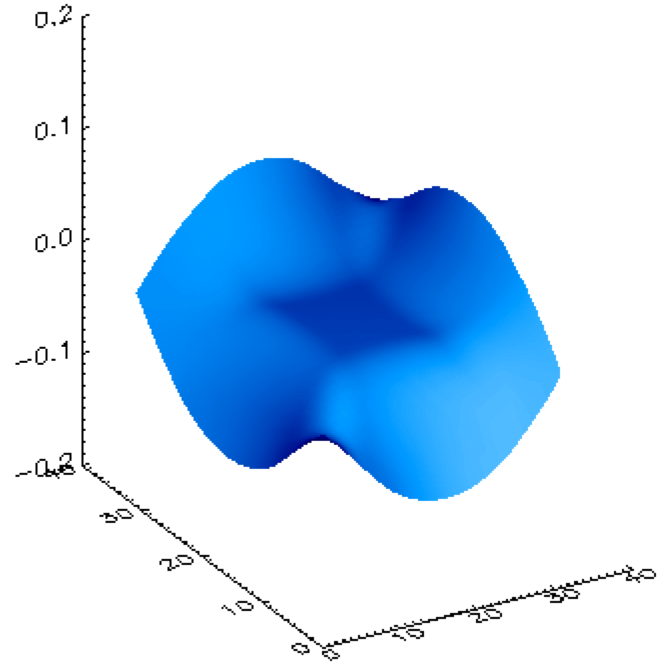
$$\varphi_{ramp}^{-1} \circ sampling \circ \varphi_{ramp}(MTF) \neq realTF$$

Can be avoided as long as aliasing is low, ie $MTF_{fs} \approx 0$

Centering in the sampling grid

Real FT

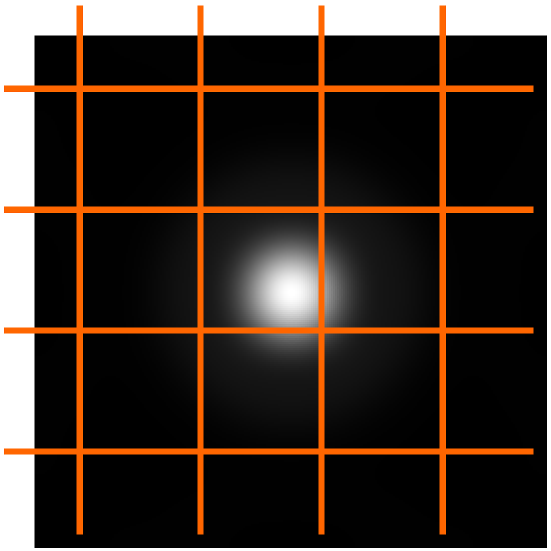


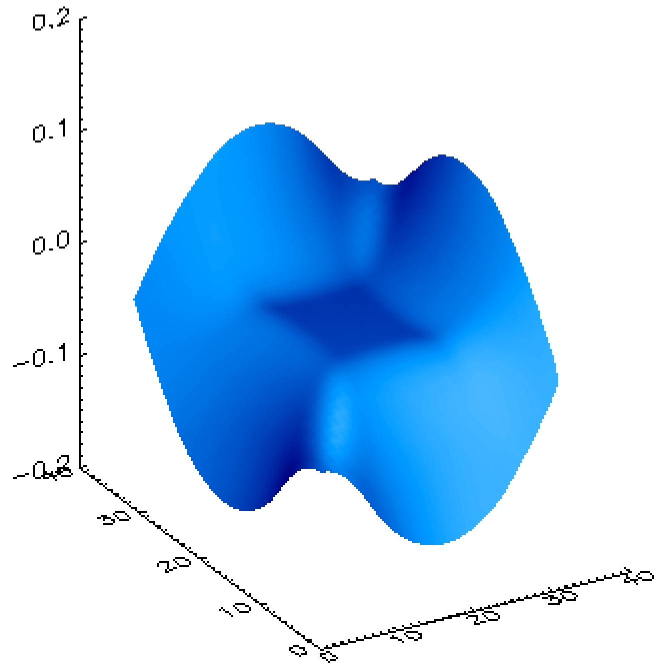


Imaginary part of the Fourier transform
Multiplied by the appropriate phase ramp

Centering in the sampling grid

Real FT





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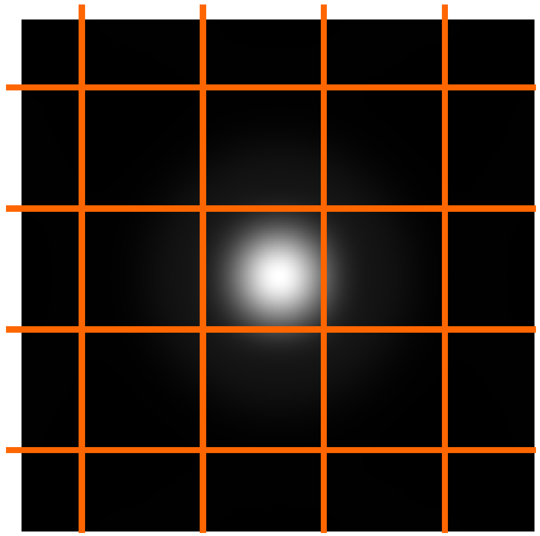

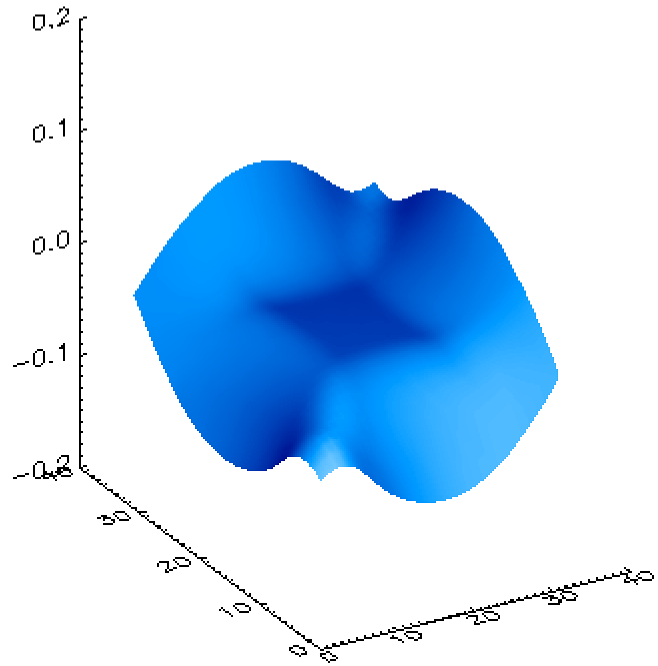

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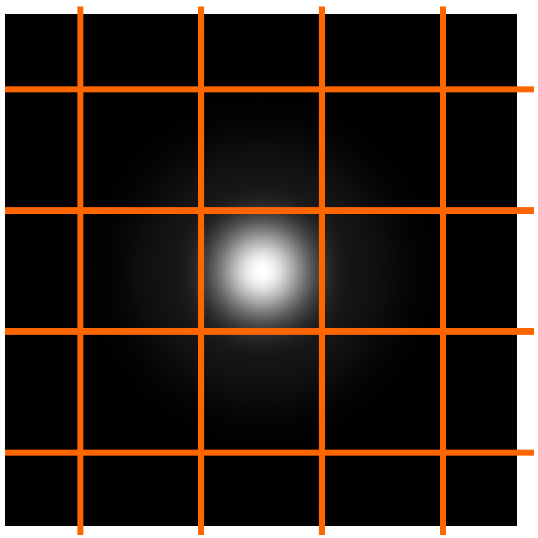

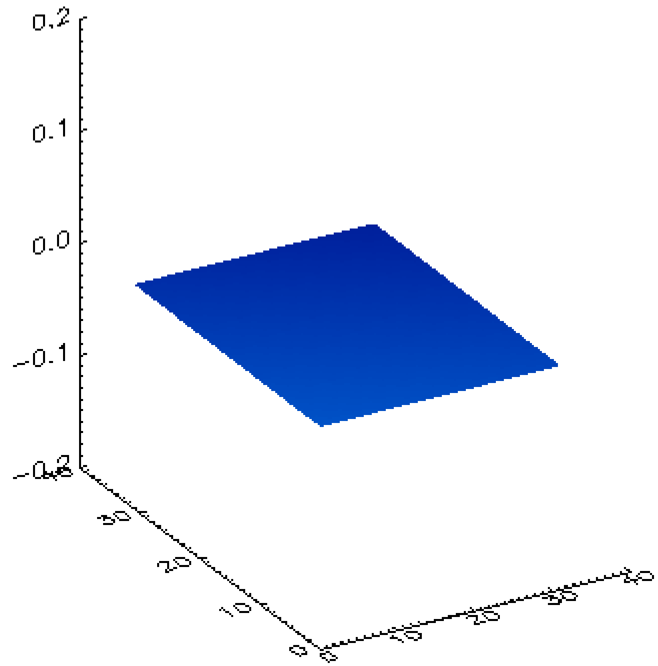

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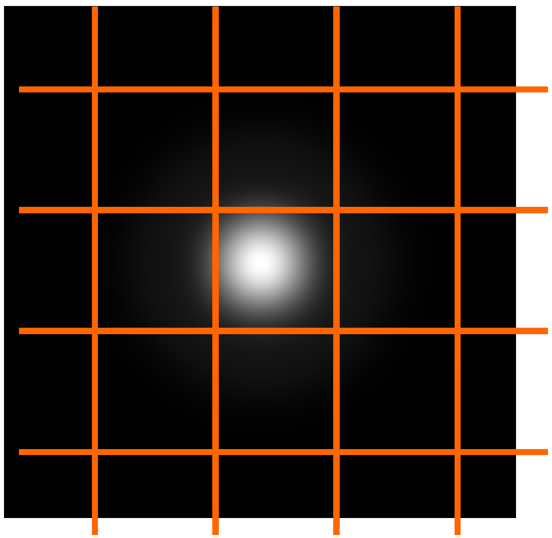

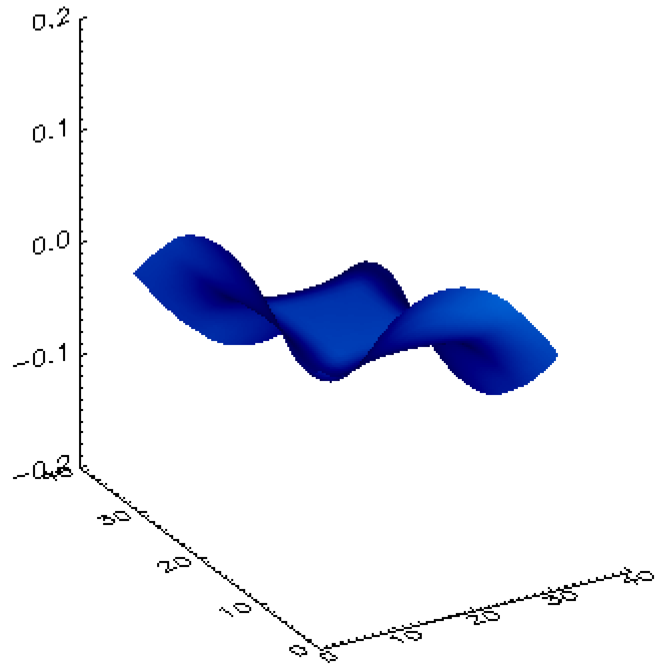

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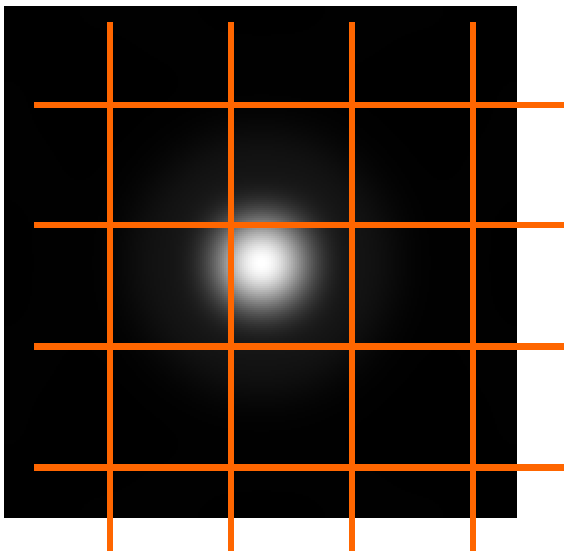

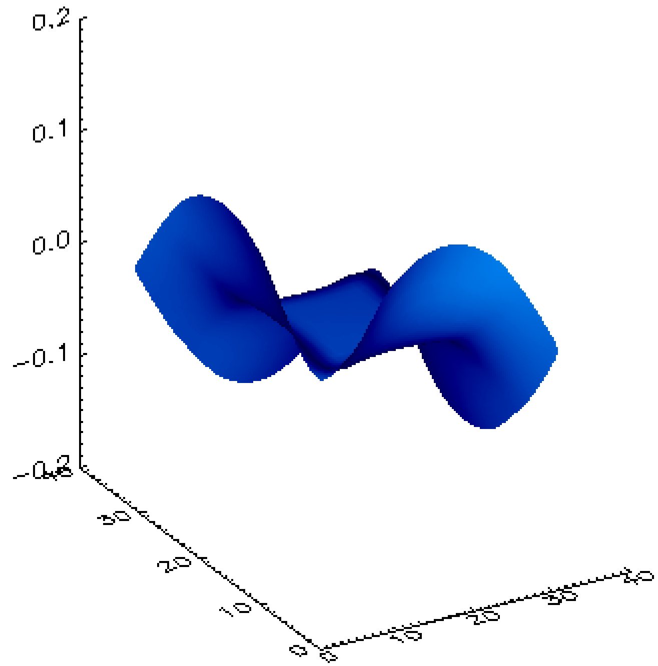

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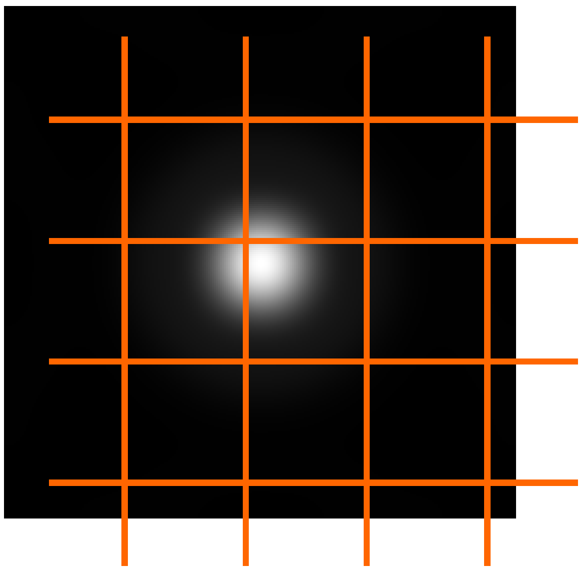
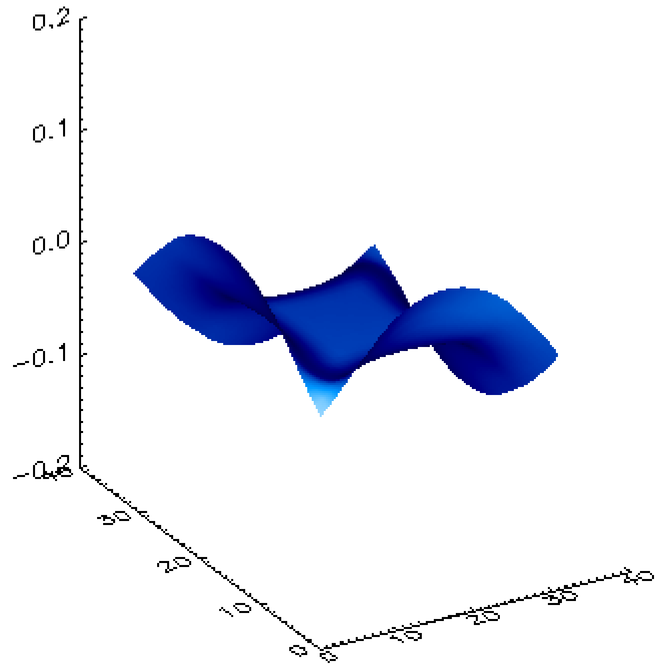
Centering in the sampling grid

Real FT

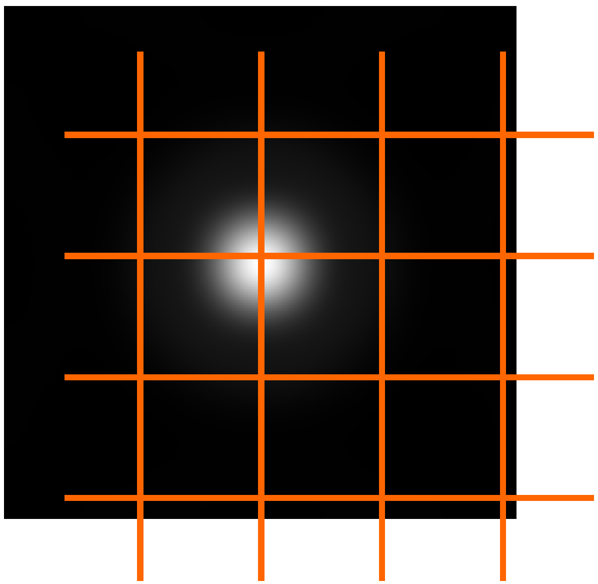


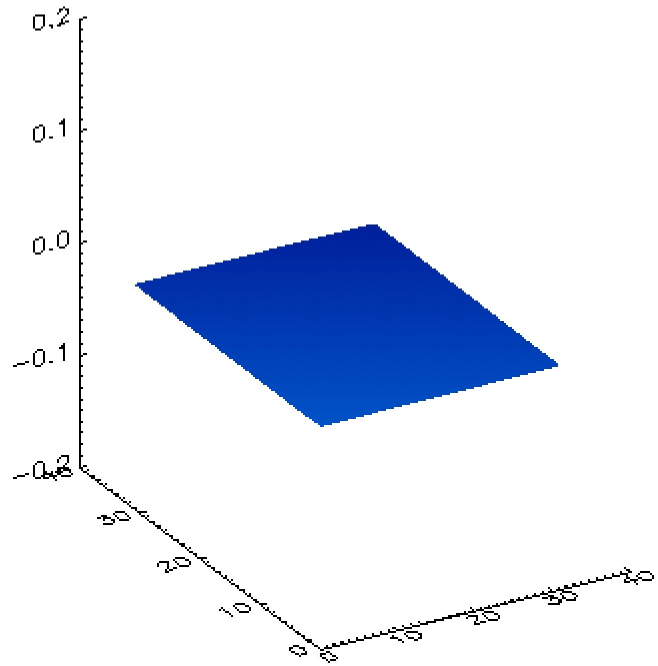


Imaginary part of the Fourier transform
Multiplied by the appropriate phase ramp

Centering in the sampling grid

Real FT





Imaginary part of the Fourier transform
Multiplied by the appropriate phase ramp

Centering in the sampling grid

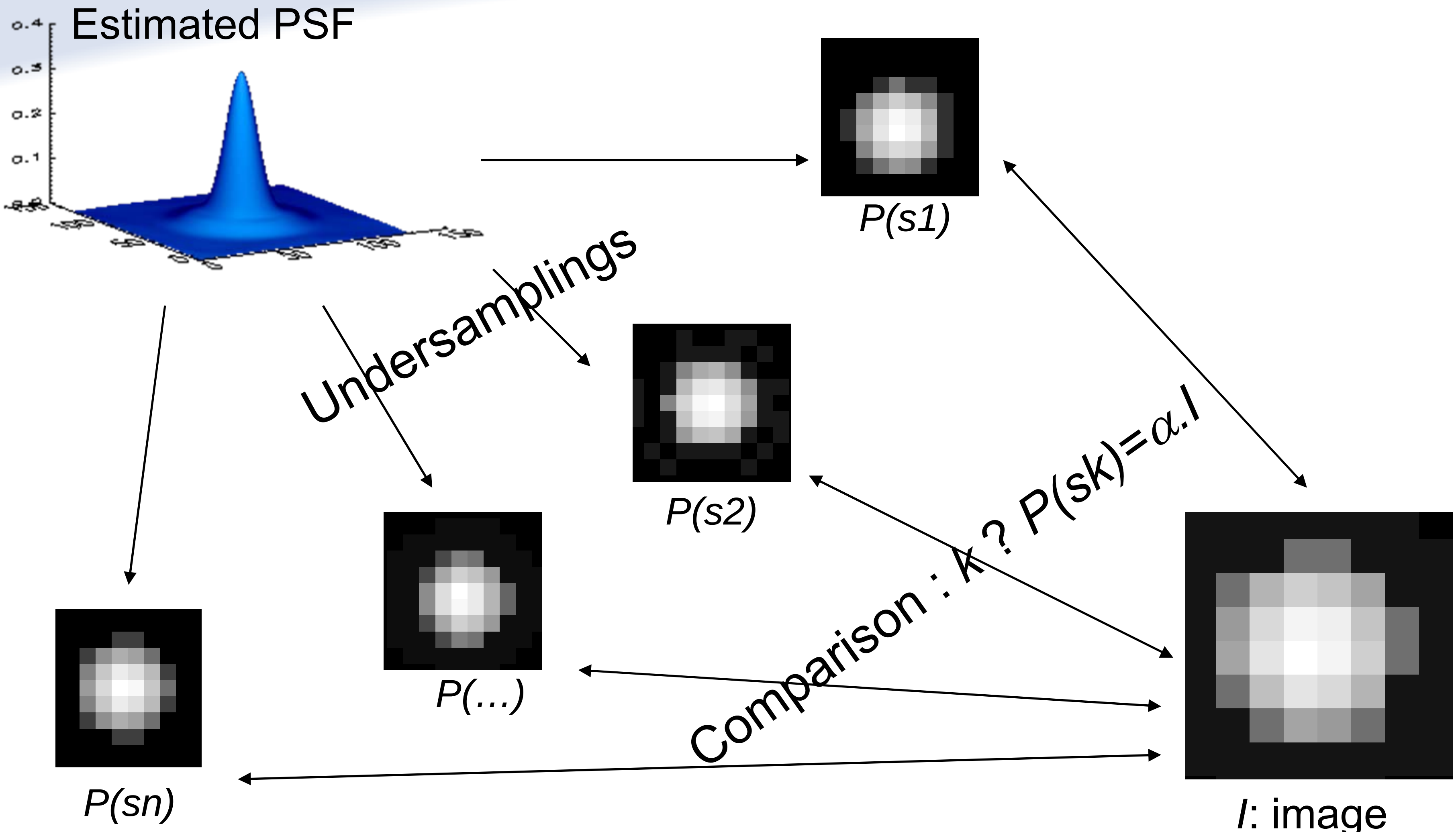
Real FT

Restrain the cancellation of the Fourier transform in the vicinity of low frequencies

Accuracy = 0.04 pixel

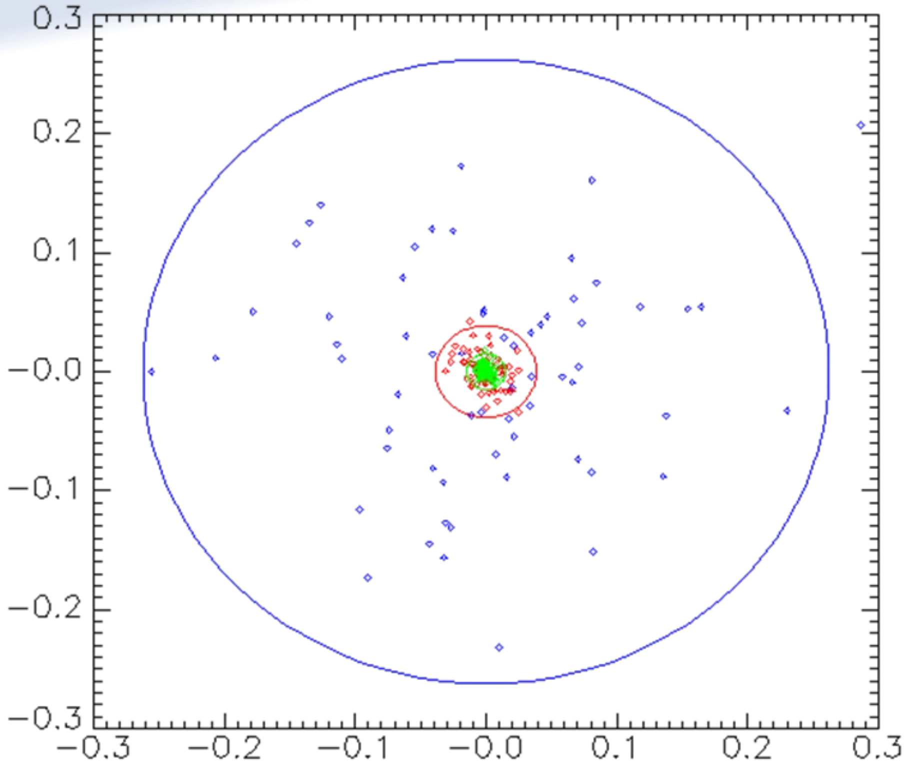
Centering in the sampling grid

PSF correlation



$$P(s_k)=\alpha.I \Leftrightarrow \left\|P(s_k)\cdot I\right\| = \left\|P(s_k)\right\|.\left\|I\right\|$$

Centering in the sampling grid



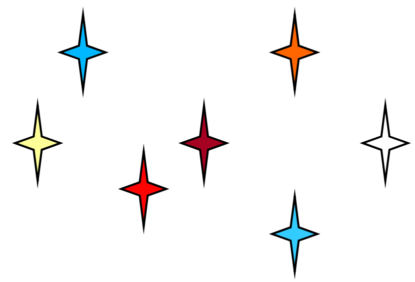
Barycentre: 0.25px

Real FT: 0.04px

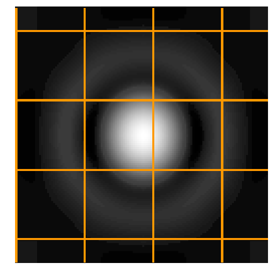
PSF correlation: 0.015px

Simulations from real PSF and random shifts

Outline

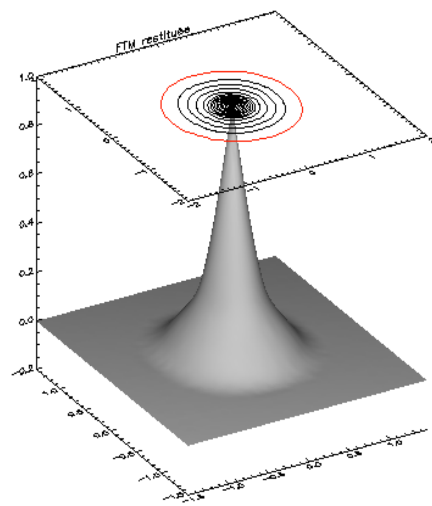


■Choosing the right stars



■Centering the star in the sampling grid

■MTF measurement



■Other applications

MTF measurement

Principle

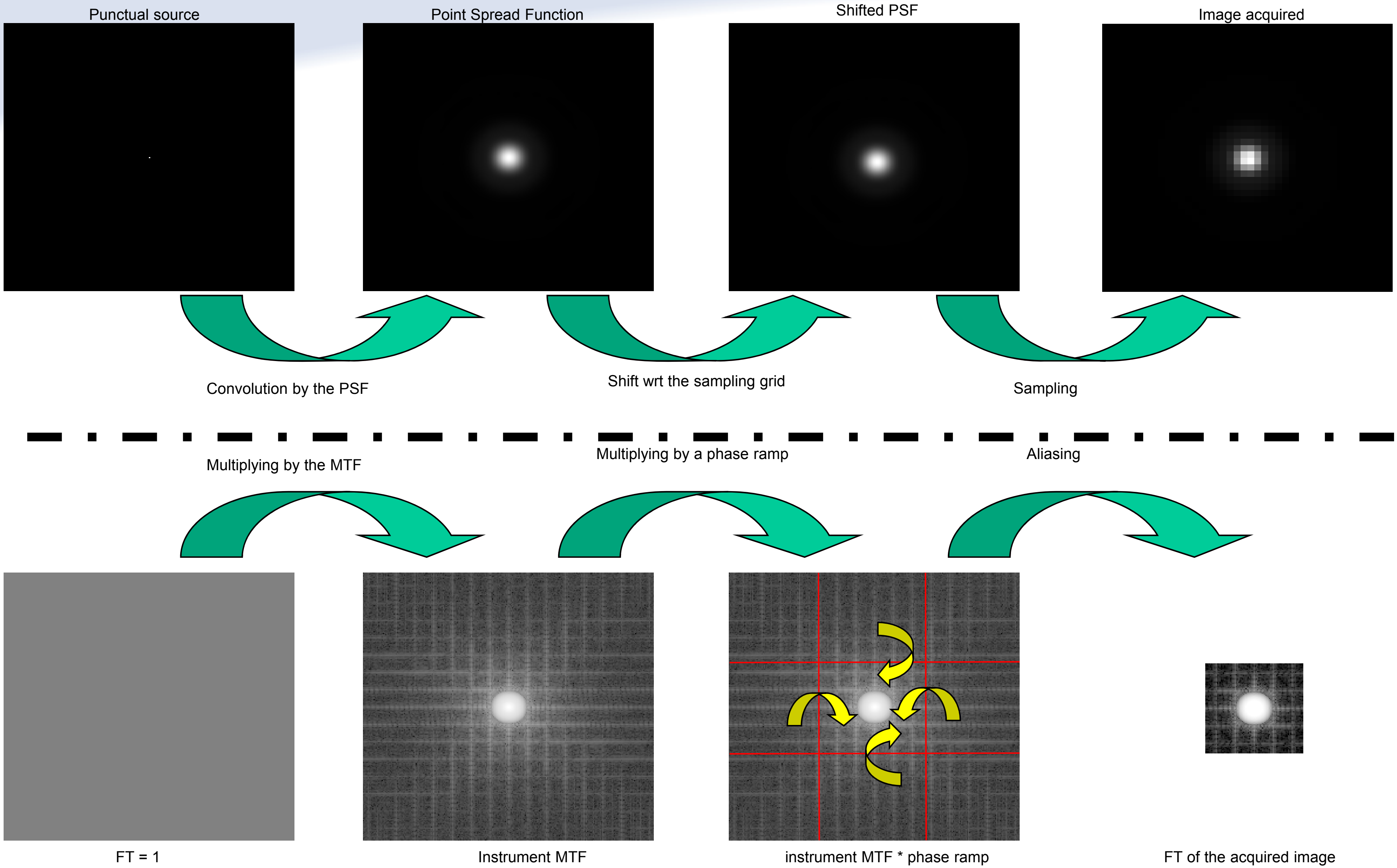
- PSF = image of a punctual source
- Randomly sampled PSF = images of stars

→ Interlacing the images leads to the PSF

Problem : irregular sampling…

Solution : known shifts + Fourier reasoning

MTF measurement



$$FT(star) = alias\left(MTF * \varphi_{ramp}(dx, dy)\right)$$

- dx and dy are known for each image
- Multiplying by a phase ramp is a linear operation
- Aliasing in the Fourier domain is a linear operation

→linear problem : $\begin{bmatrix} FT(star_1) \\ FT(star_2) \\ FT(star_n) \end{bmatrix} = [A].[MTF]$

Efficient resolution with a least squares algorithm

MTF measurement

Equations

Regularization

Known cut-off frequency:

$$MTF\left(f_x, f_y\right) = 0 \text{ if } \sqrt{\left(f_x^2 + f_y^2\right)} > f_{cutoff}$$

Still a linear constraint, can be included in the least squares equations with a variable weight

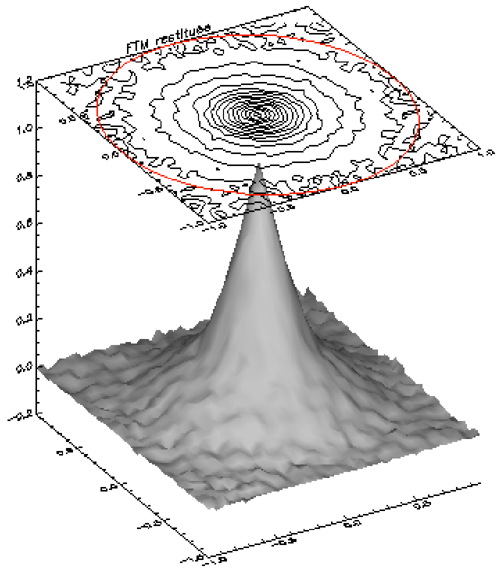
cnes

MTF measurement

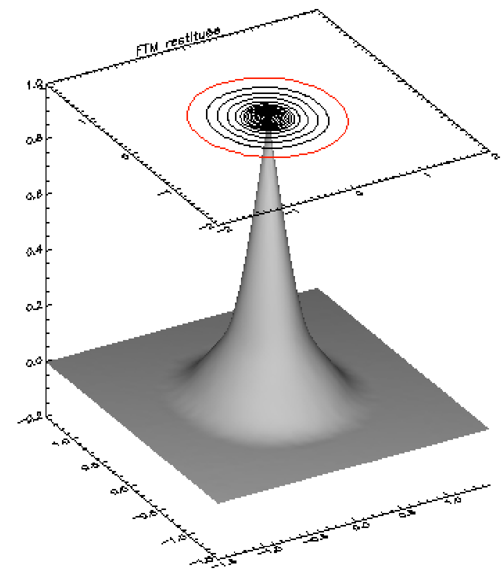
Results

Simulations include :

- Signal and obscurity noise
- Compression
- Micro-vibrations

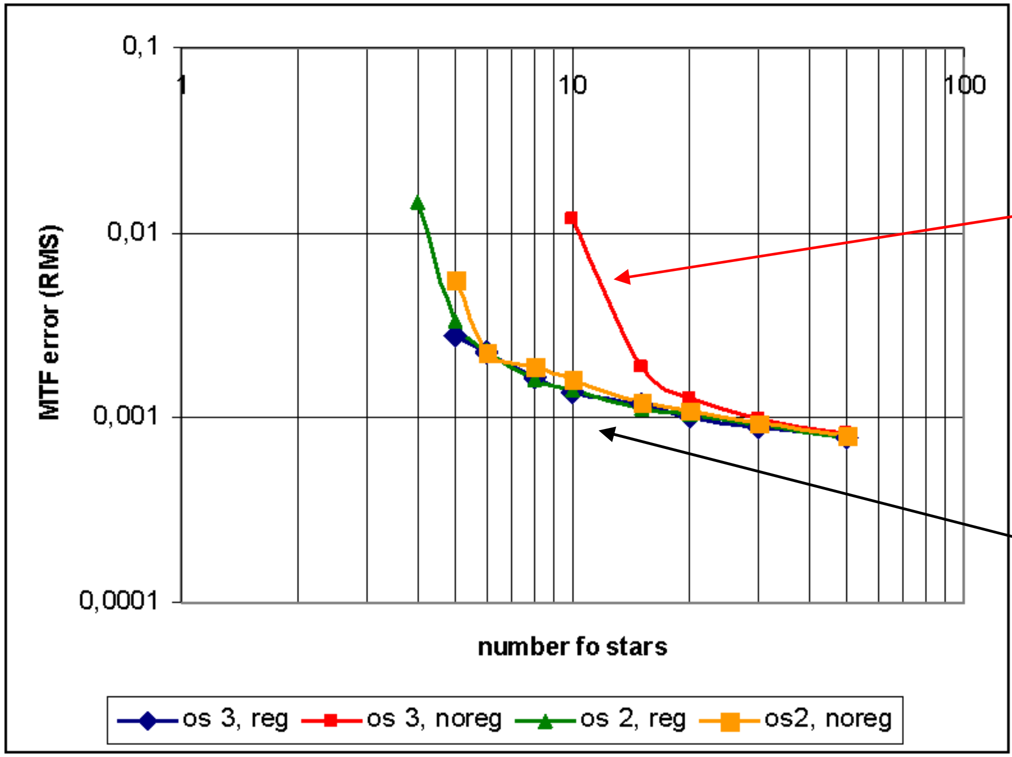


[$-f_s$; f_s] - 4 stars - no regularization



[$-3f_s/2$; $3f_s/2$] - 5 stars - regularization

MTF error (RMS) vs. number of stars used in computation



No regularization, oversampling 3:

>15 stars needed

Other cases:

>6 stars needed

Assessment of MTF with an oversampling of 2 or 3, with or without regularization

MTF measurement

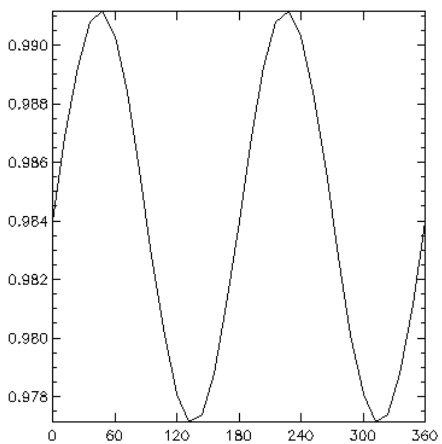
Results

Injected micro-vibrations :

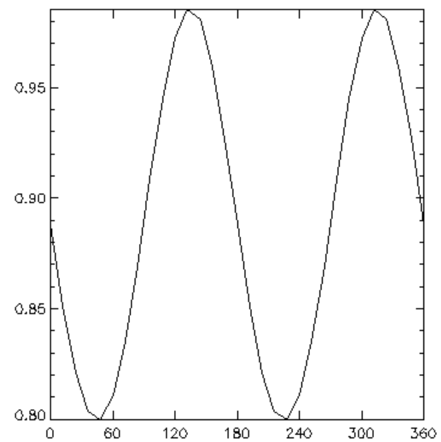
75Hz, 0.2px

350, 0.35px

FTM drop wrt direction in the image

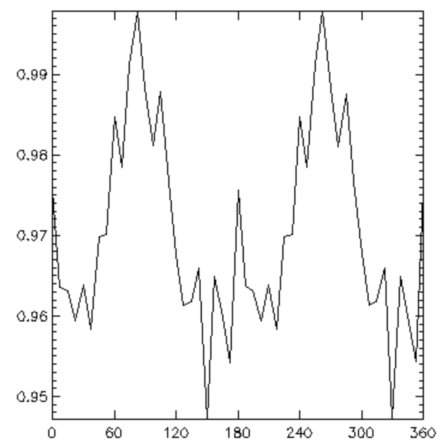


[0.978 ; 0.990]

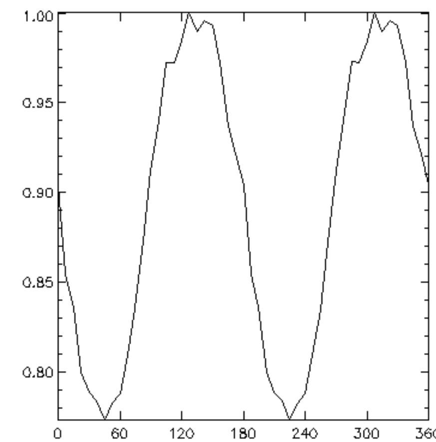


[0.80 ; 0.99]

Assessed drop from simulated stars measurements



No significant

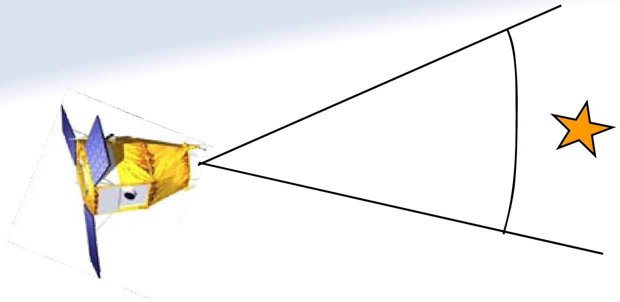


Good assessment

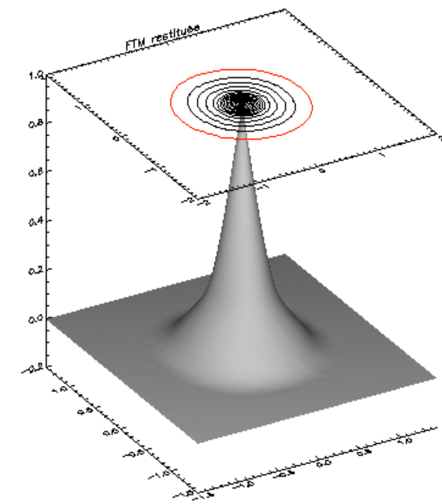
Ability to measure the system MTF

MTF measurement

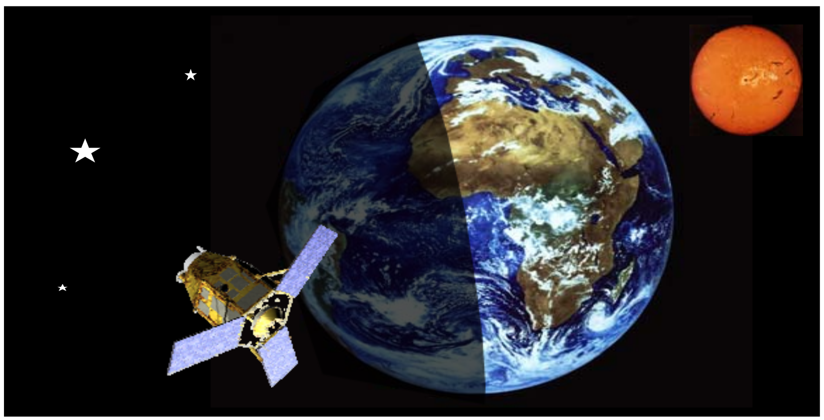
Operational aspects



Shooting 10 times the same star = 2 minutes



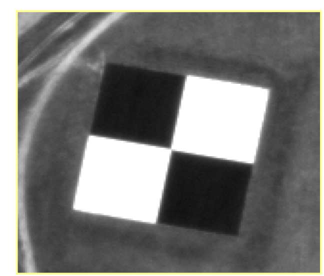
MTF measurement accuracy ≈ 10^{-3}



Dozens of stars accessible 15 times a day even during eclipses

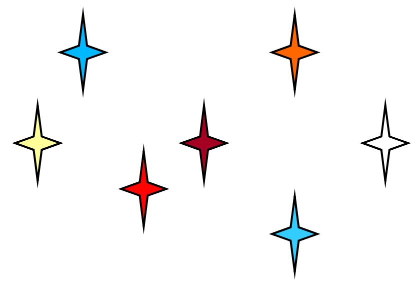
Sensitivities : thermal, seasonal, spectral,…

Very promising in comparison with existing methods

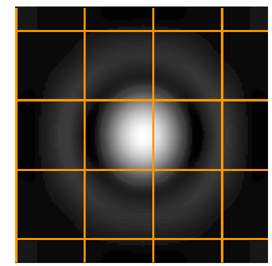


Outline

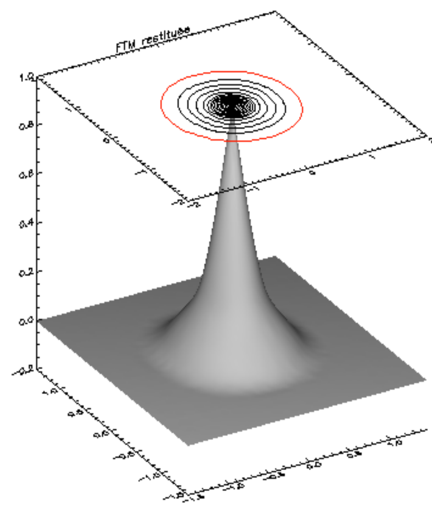
- Choosing the right stars



- Centering the star in the sampling grid

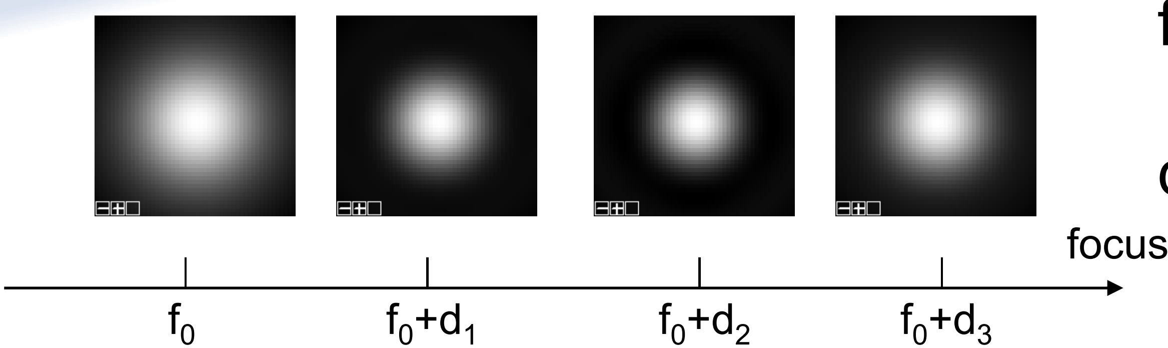


- MTF measurement



- **Other applications**

Other applications
Refocus

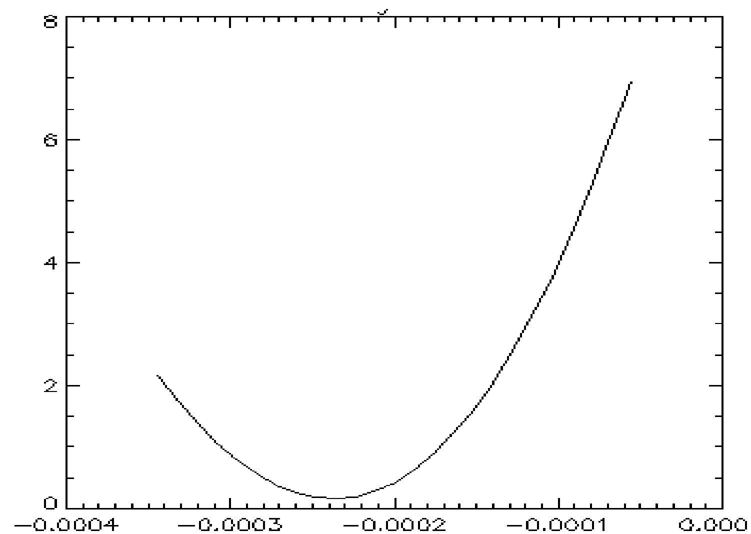


f_0 unknown

d_i known (focus mechanism)

Defocus = multiplication by a filter
→ Linear operation

One single least squares resolution with all the images and a guessed value for f_0

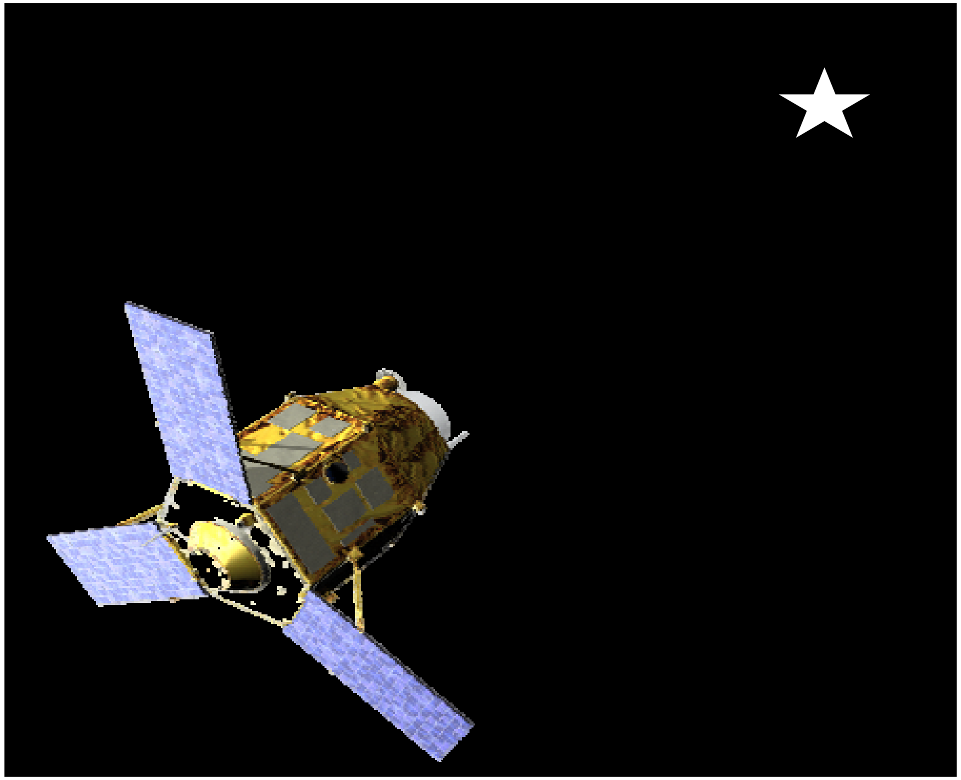


Least squares residuals vs. f_0

Other applications

Line of sight dynamic stability

- Using the stars
  - stationary in an inertial frame
  - If the sensor remains pointed at the star, it will create a bright column in the image whose straightness depends on the line-wise behaviour of the potential micro-vibrations



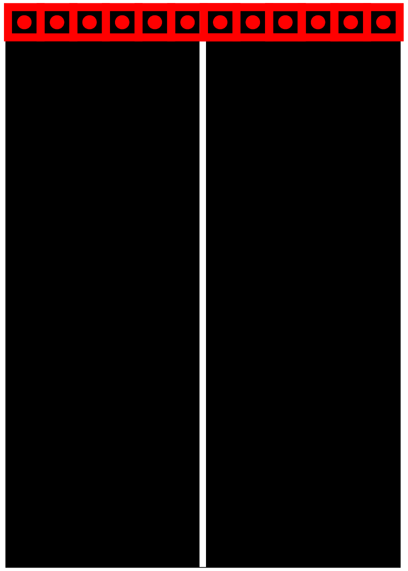


Image without microvibrations

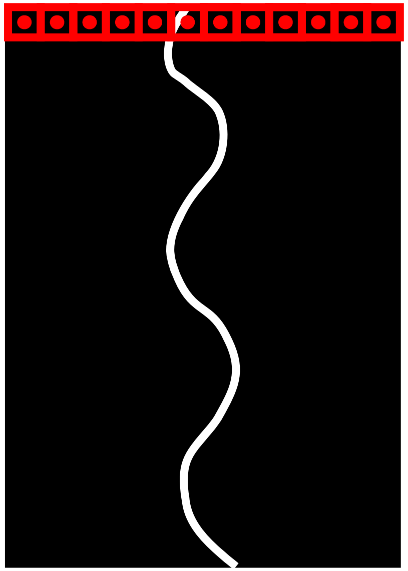
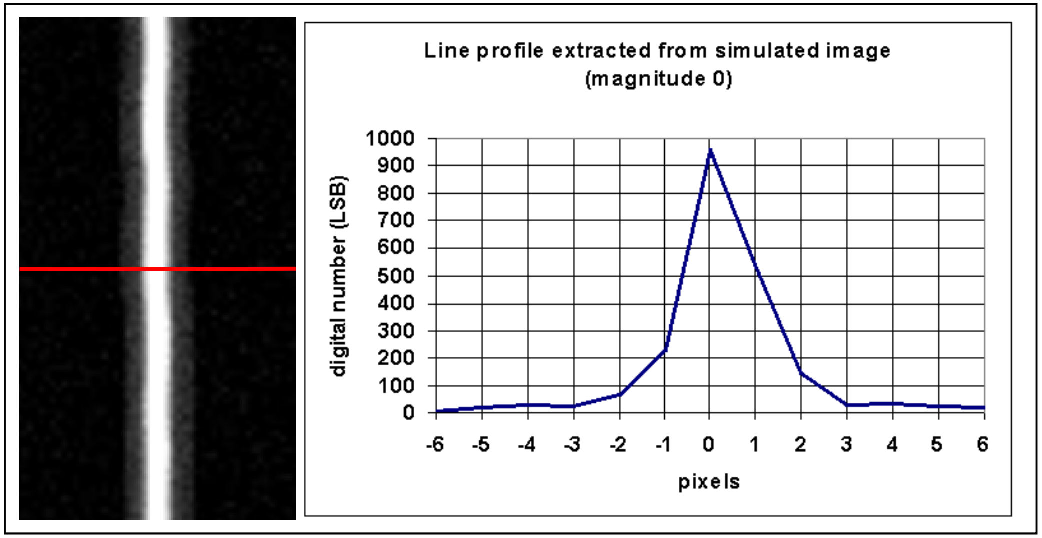


Image with microvibrations

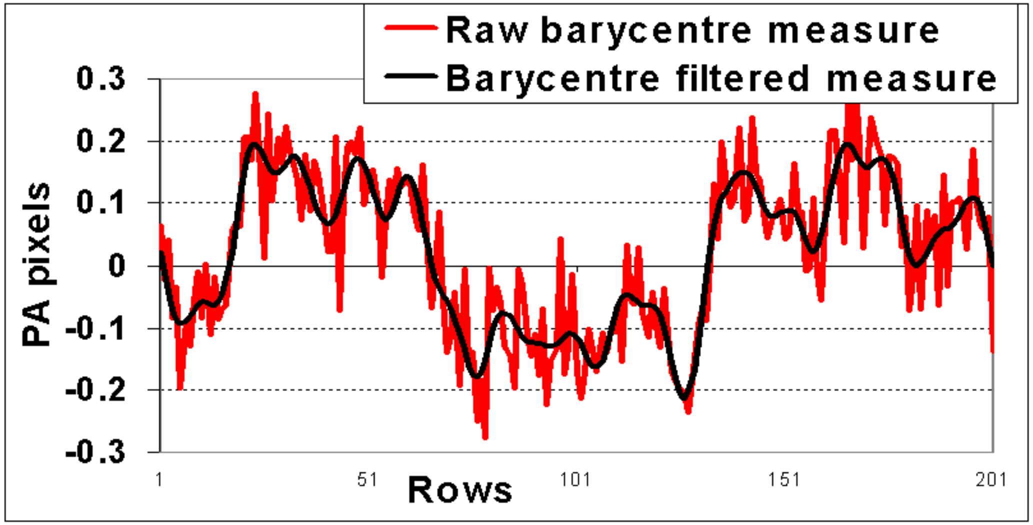
Other applications

Line of sight dynamic stability

- Image simulations
  - MTF 0.12 at nyquist frequency
  - SNR 150 at 100 W/m²/sr/µm
  - Compression 2.5 bits/pel
  - 13 lines TDI
  - Almost-inertial guidance
  - Disturbances characteristics



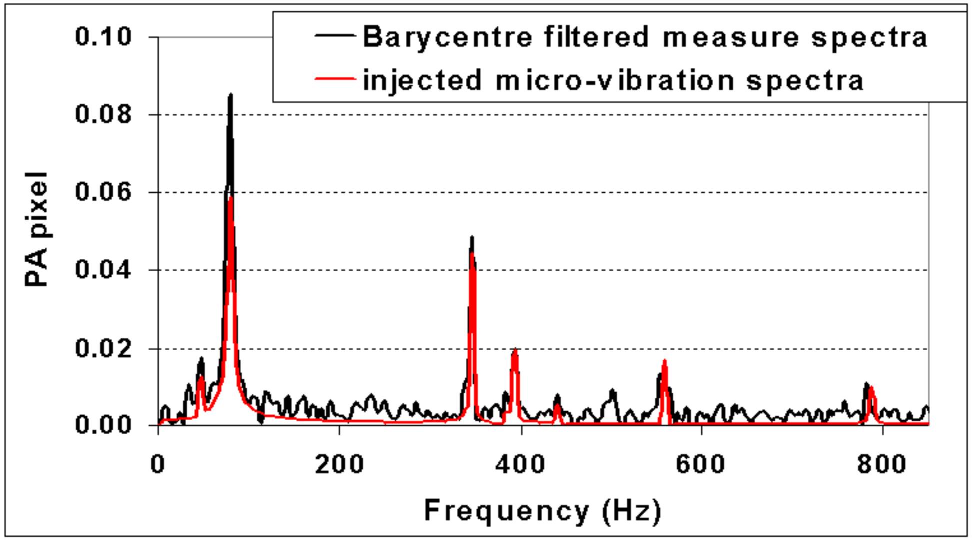
- Absolute position along the time is given by the barycentre measurement for each line
- … and low pass filtering [0..1000 Hz]



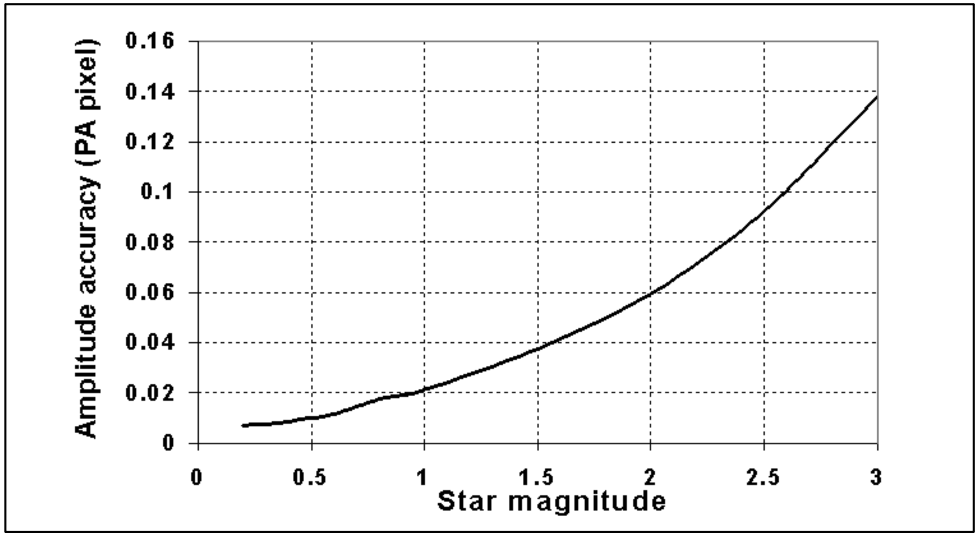
Other applications

Line of sight dynamic stability

- Measurement accuracy
  - Frequency until 800 Hz are observed



  - Amplitude accuracy depends on the star magnitude (SNR of illuminated pixels)
    - RMS deviation ~ 0.02 PA pixels for magnitude 1
    - RMS deviation ~ 0.10 PA pixels for magnitude 2.5



Conclusion

Brand new image calibration methods have been designed and are still studied thanks to Pleiades-HR satellite agility

These capabilities offer large operational benefits

New efficient algorithms lead to outstanding performances:

- ~10^{-3} for MTF
- ~30µm for refocus
- 0.02px for micro-vibrations

Next time : operational results !

Thank you for your attention !