

Centroid measurements in a Shack-Hartmann Wavefront Sensor

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Why such a study?

- The SOAR Adaptive Optics system
(SOAR = SOuthern Astronomical Research – 4m telescope)



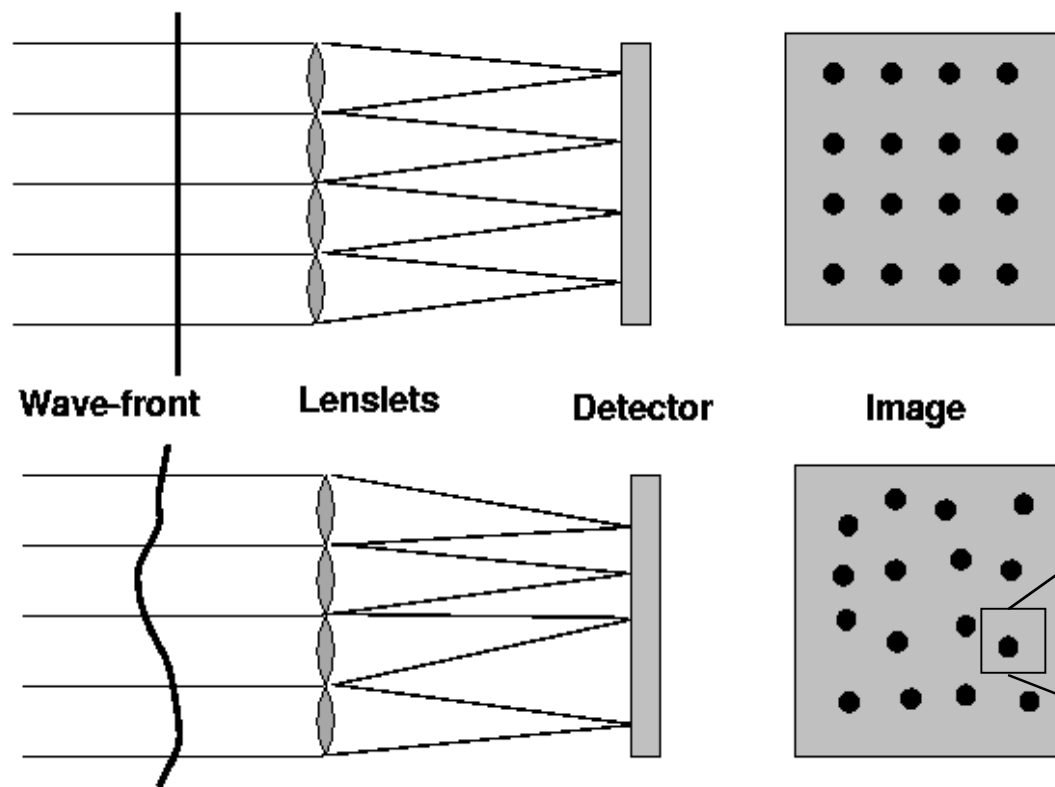
High
Angular
Resolution



AO
(WFS)

- No clear or complete research on the tools used to calculate a centroid

The Shack-Hartmann wavefront sensor principle



Need to know
as **accurately**
as possible the
centroids.

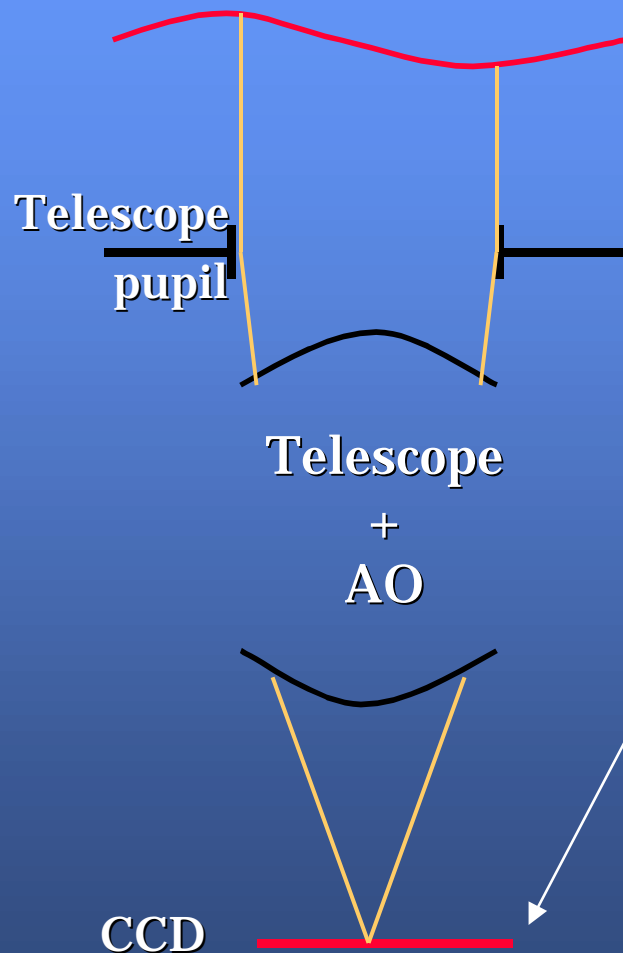
$$C_x = \frac{\sum_{x=0}^N \sum_{y=0}^N I_{x,y} \times x}{\sum_{x=0}^N \sum_{y=0}^N I_{x,y}}$$

What am I doing ?

Simulation of distorted wavefront (by the atmosphere)
Here = Simple spot Gaussian
(I_0, c_x, c_y, σ_s)

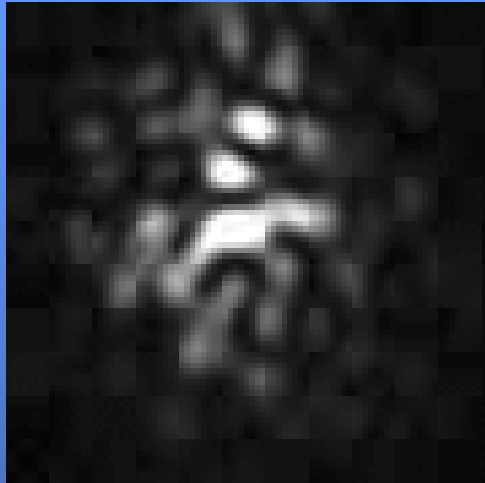
Simulation of the CCD
Centroiding for one subaperture

- true centroid (C_{true})
- measured centroid (C_{meas})



$$\text{Error}^2 \text{ rms} = \langle (C_{meas} - C_{true})^2 \rangle_{1000iter}$$

Problems



- sampling
- photon noise
- readout noise
- atmospheric turbulence

⇒ The simple centroid formula is not enough to find the center of the spot.

Tools: Thresholding Windowing
Others ...



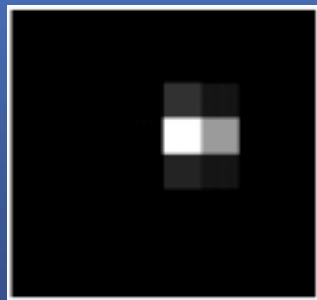
Computation

Gaussian spot: $(I_0, c_x, c_y, \sigma_s)$

$$I(x, y) = I_0 \frac{1}{2\pi\sigma_s^2} \exp\left(-\frac{(x - c_x)^2}{\sigma_s^2}\right) \exp\left(-\frac{(y - c_y)^2}{\sigma_s^2}\right)$$

Image parameters

Study parameters

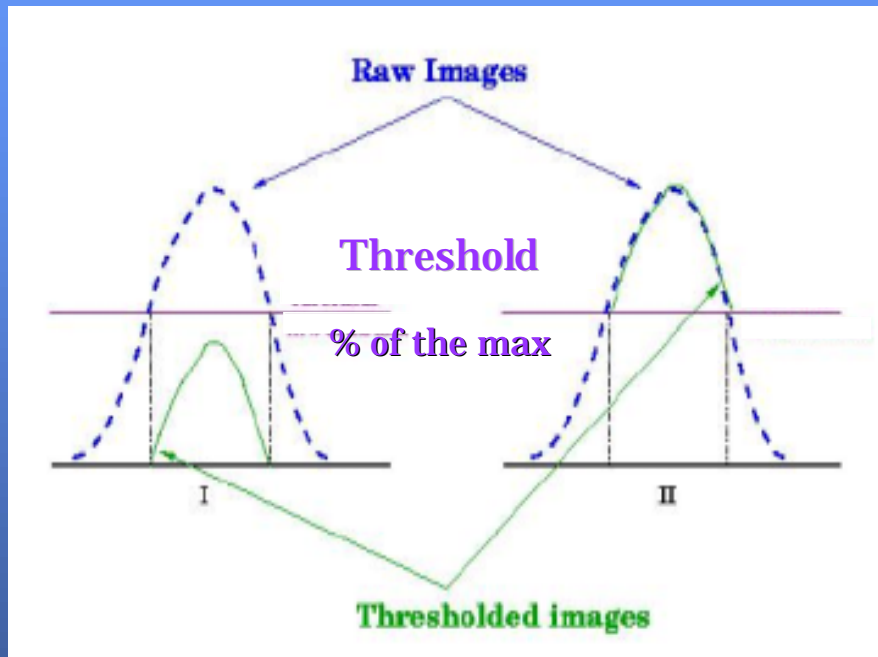


Spot rms size

8 pixels CCD

- $1/P = \text{SAMPLING}$ (size of the rms spot in CCD pixels)
- Number of CCD pixels
- Number of photons per spot: nph
- Readout noise: nr

Common methods

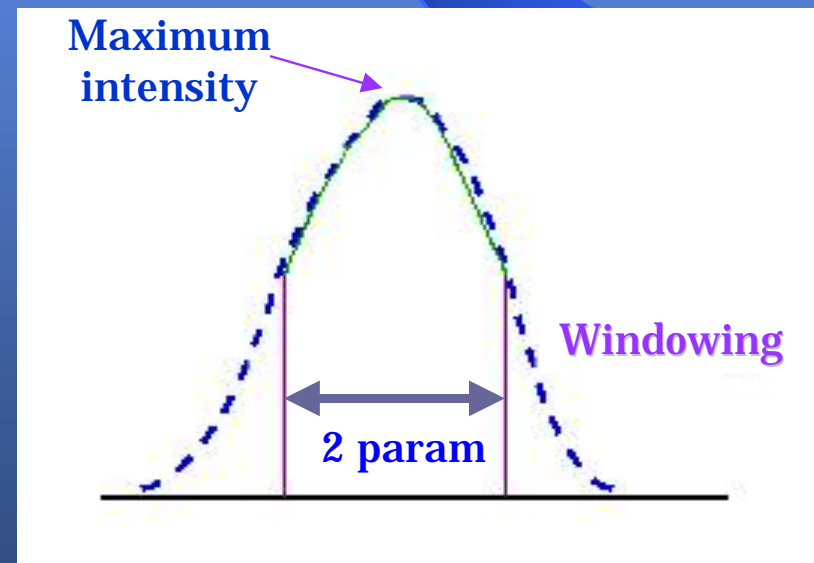


Thresholding

Method I better
Param = % of the max

Windowing

Param = radius of the window in pixels



Gaussian Fitting

- The detector image



+

- rms size of the Gaussian known

IDL procedure
“curvefit”

(Cxmeas; Cymeas)
coordinates of the
center

Physical bounds

- ***Photonic limit***

$$\sigma_{ph} = \sigma_s / \sqrt{nph}$$

The error rms measured will be expressed in σ_{ph} units

- ***Lower limit = Cramer-Rao bound***

Minimum error corresponding to a given physical system

Kim.A. Winick, JOSA, Vol.3, p1809-1815, 1986

- ***Upper limit = spot rms size***

$$\sigma_{err} < \sigma_s$$



Normalized error:

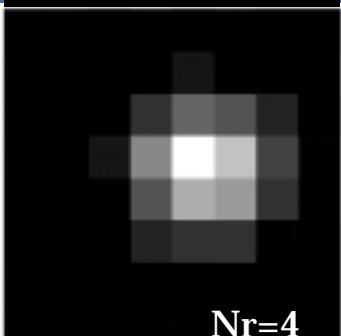
$$\frac{\sigma_{err}}{\sigma_{ph}} < \sqrt{nph}$$

Comparison results

True image

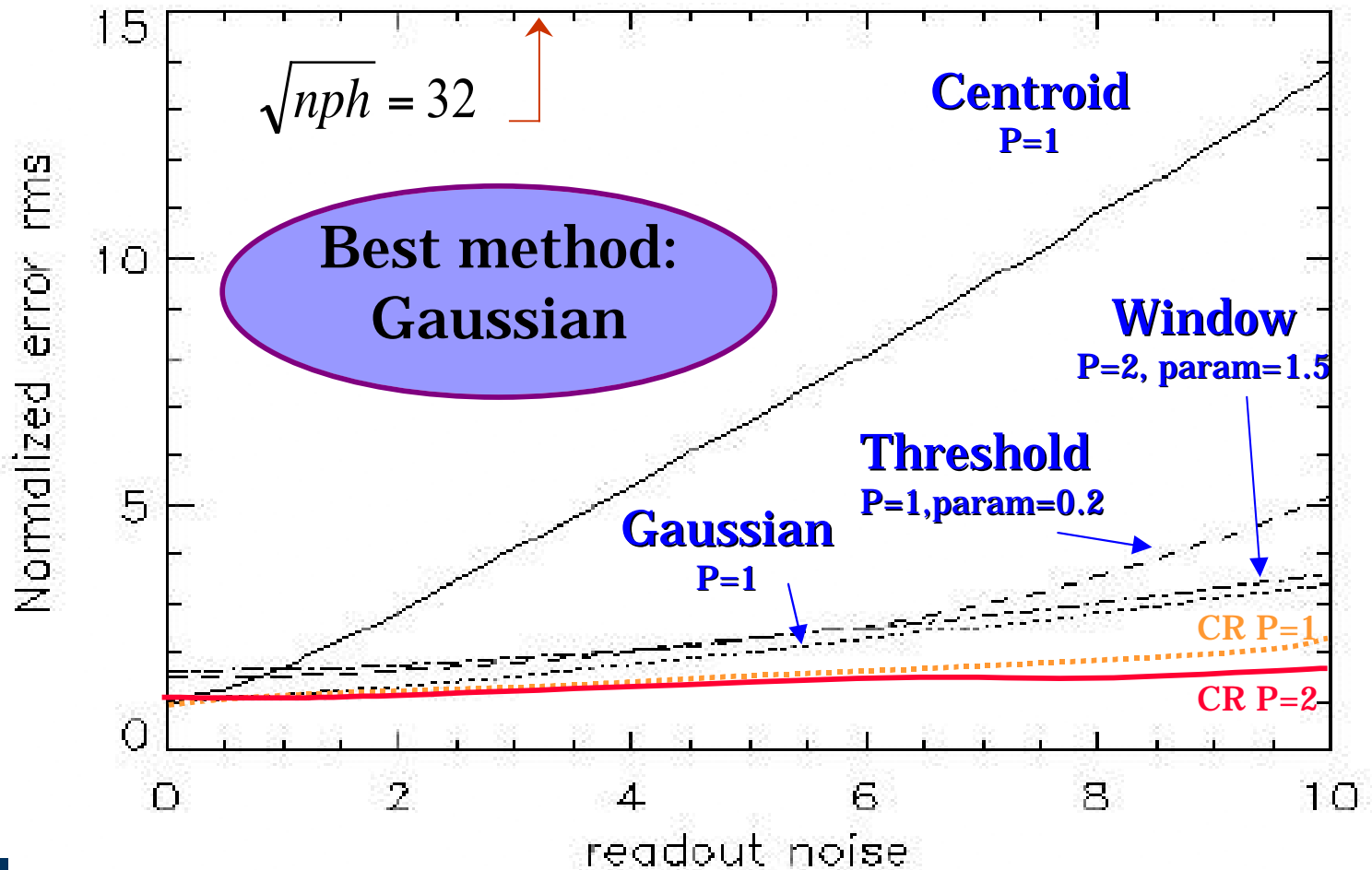


Image on the detector



RMS spot size =
1 CCD pixel

Error rms; $nph = 1000$



Comparison results

True image

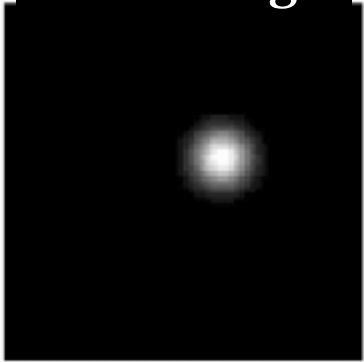
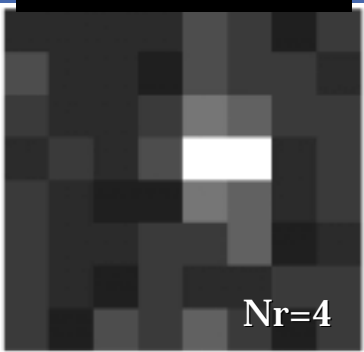
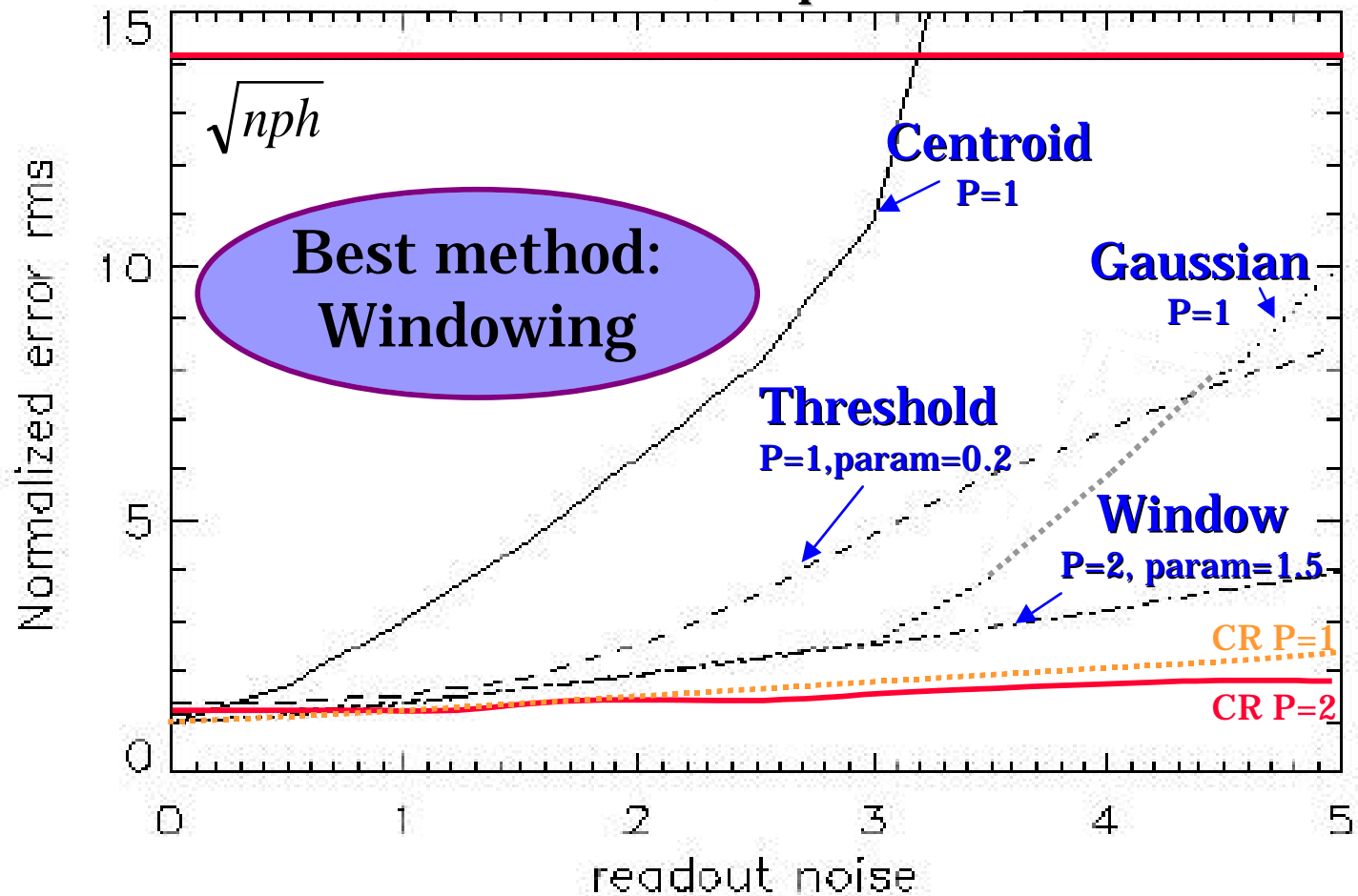


Image on the detector



RMS spot size =
0.5 CCD pixel

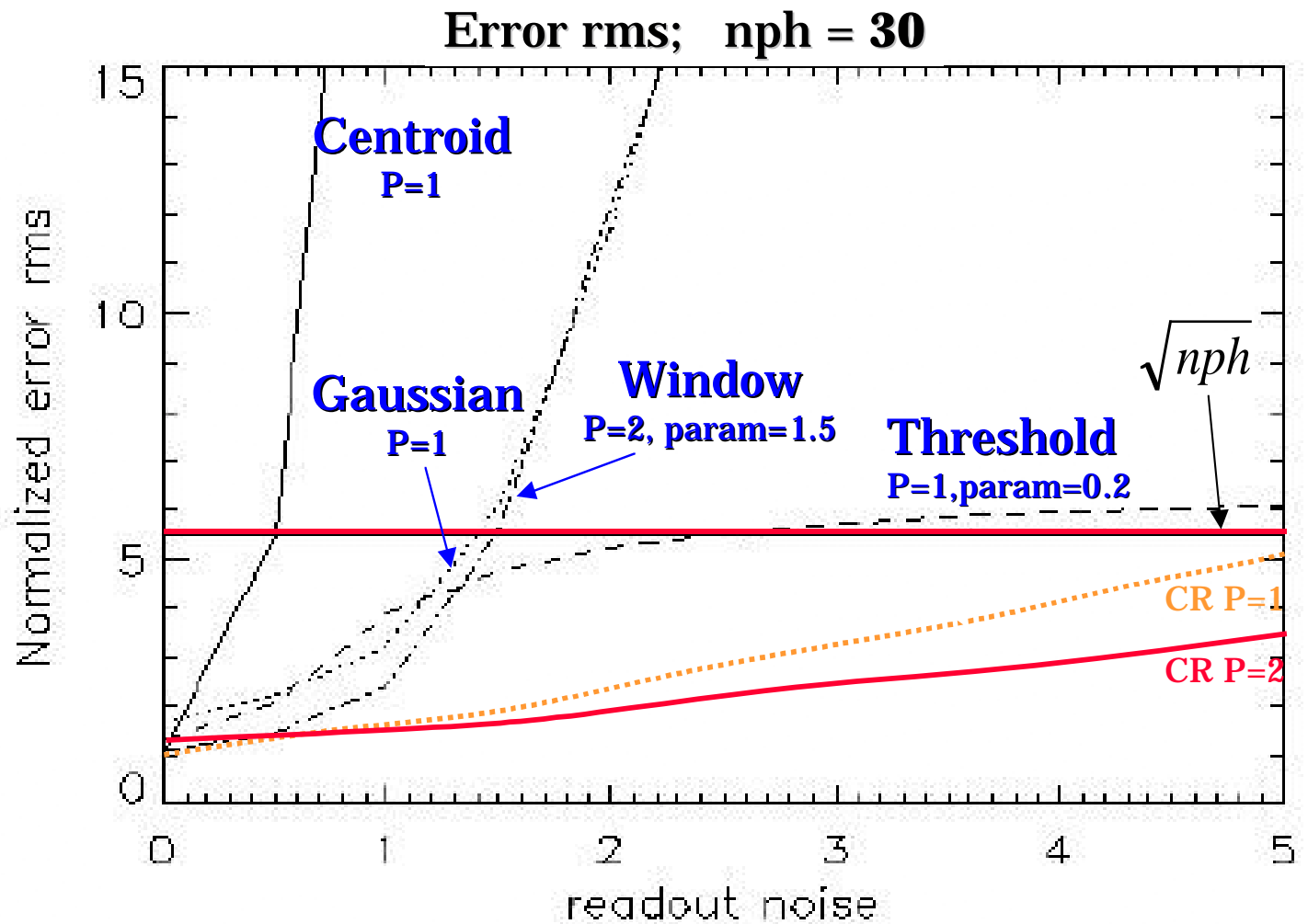
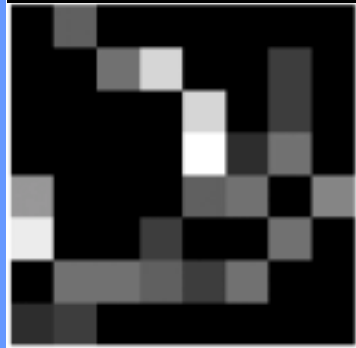
Error rms; $nph = 200$



Comparison results

Not reliable

Thresholded image



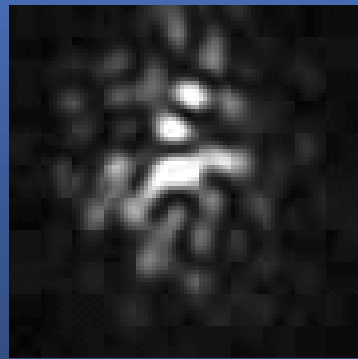
Conclusion

Best method depends on the number of photons and the readout noise !!

| nph/nr | Methods | Size of the spot | Param |
|--------------------------|------------------|-------------------------|---|
| high | Gaussian | 1 CCD pixel | * |
| Low (nph=200) | Windowing | 0.5 CCD pixel | window diameter = 3 CCD pixels |
| Very low | ?? | ?? | ?? |

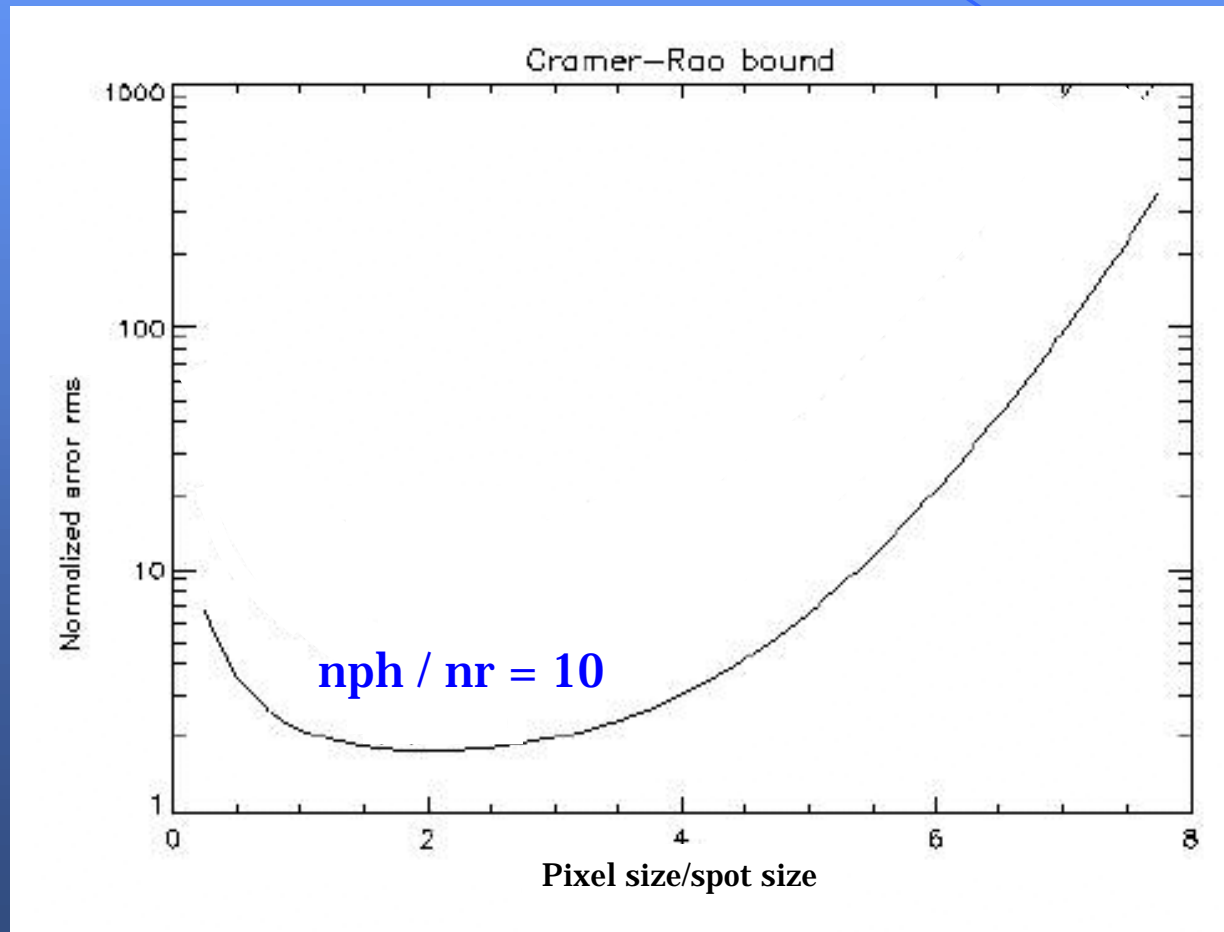
Plan

- Increase robustness at low number of photons
- Consider the spot structure resulting from the atmosphere



**Image obtained
with real phase
screens**

Cramer-Rao bound



From Winick
paper