

# Images & turbulence - 24

```

[IDL> restore, 'PSF_r0=10cm_L0=10m_lambda=500nm.sav'
[IDL> help
% At $MAIN$
CUBE_PSF      FLOAT      = Array[128, 128, 100]
I             INT        =      100
Compiled Procedures:
  $MAIN$

Compiled Functions:
  COMPUTE_RMS DIST      MAKEPUP      MAKE_PSF      WFCUBE2      WFGENERATION      WFIMG2

[IDL> window, XS=512, YS=512, /FREE
[IDL> for i=0,99 do tvscl, rebin(cube_PSF[*,*], 512, 512, /SAMPLE)

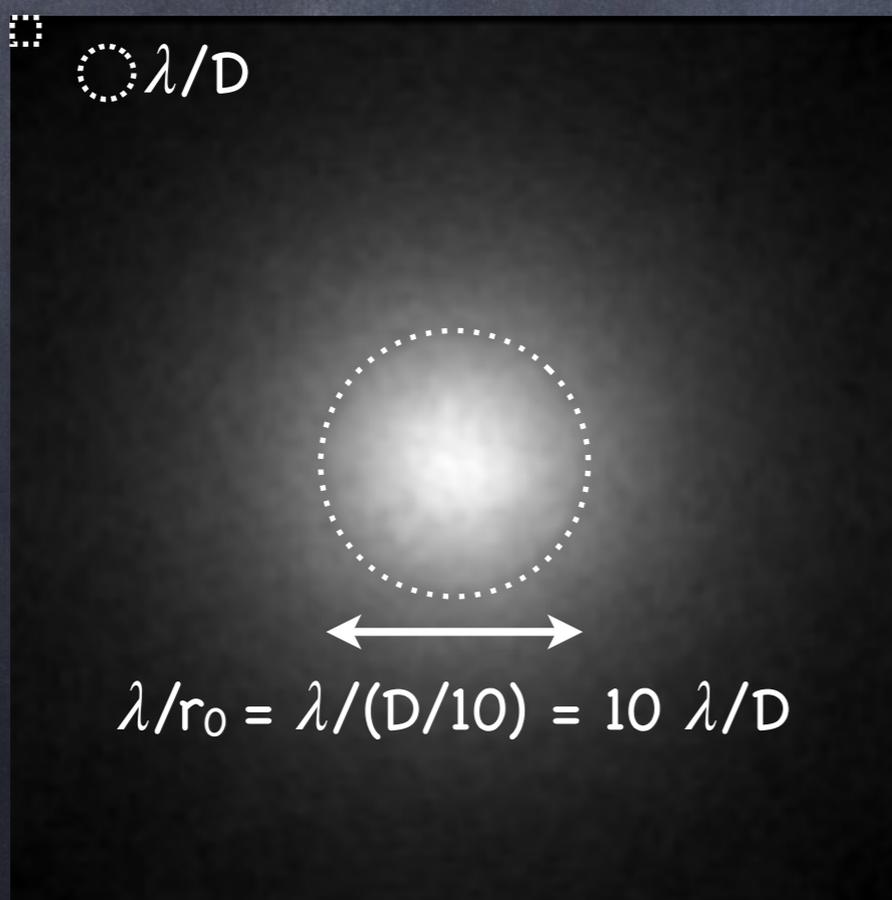
```

```

[IDL> longexp=total(cube_PSF,3)
[IDL> tvscl, rebin(longexp, 512, 512, /SAMPLE)^.1

```

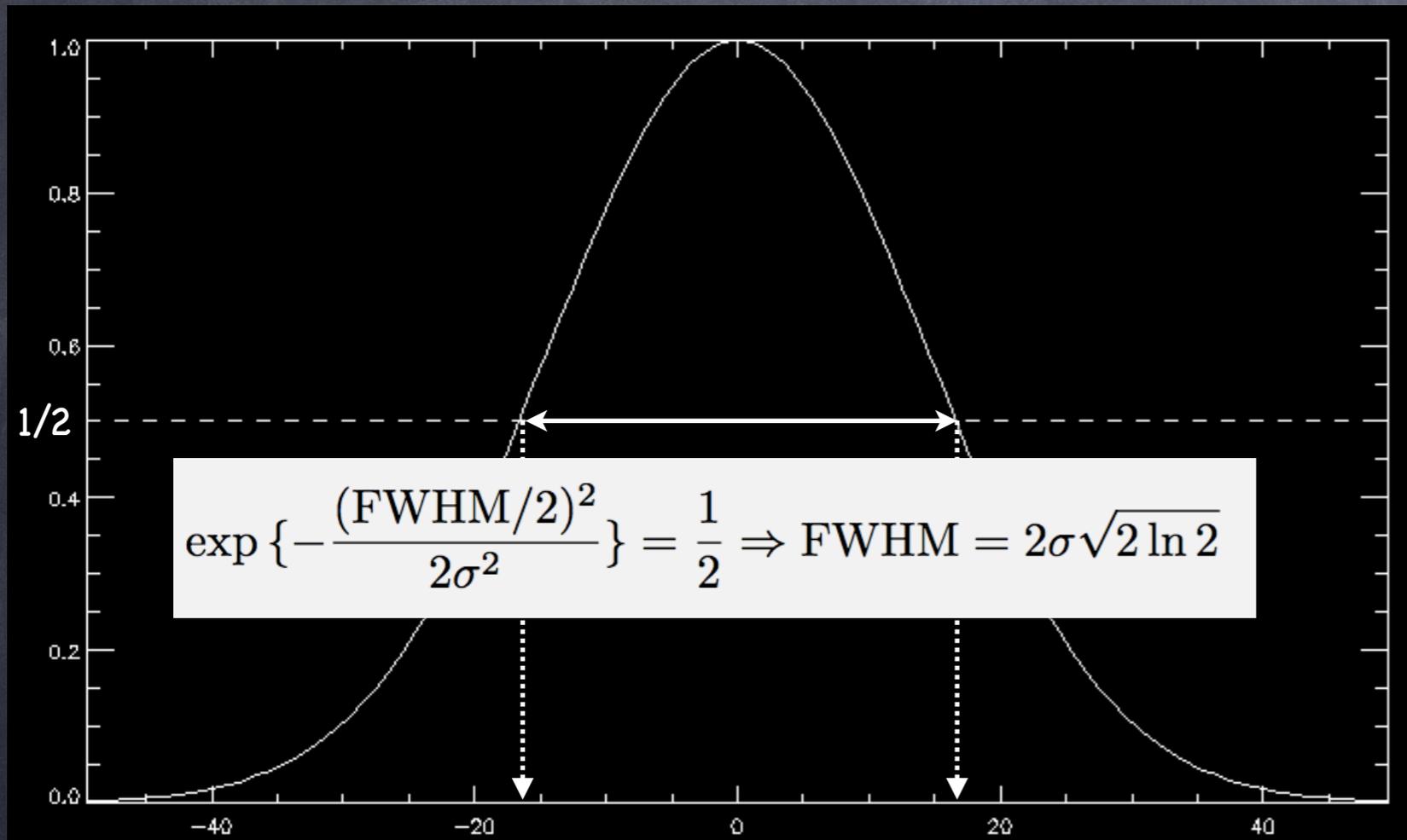
$$\lambda/L = 1/2 \lambda/D$$



## image formation:

- 1- cube of instantaneous PSFs (500nm & band H)
- 2- long-exposure PSF

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## image formation:

- 1- cube of instantaneous PSFs (500nm & band H)
- 2- long-exposure PSFs
- 3- fit with gaussian and compare FWHM vs.  $\lambda/r_0$  (seeing), also in function of the outerscale  $L_0$ .

-> Also read Martinez...

```
[IDL> res=gauss2dfit(longexp,a)
% Program caused arithmetic error: Floating underflow
[IDL> print, 2*((a[2]+a[3])/2)*sqrt(2*log(2))
      15.9637
IDL> █
```

In this example, the FWHM is  $\approx 16$ px and, since we have here:  $1\text{px}=(\lambda/D)/2$ , we have hence:  $\text{FWHM}\approx 8 (\lambda/D)$  [i.e.  $8*0.1''\approx 0.8''$  here (@500nm)]

# Images & turbulence - 26

## On the Difference between Seeing and Image Quality: When the Turbulence Outer Scale Enters the Game

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We attempt to clarify the frequent confusion between seeing and image quality for large telescopes. The full width at half maximum of a stellar image is commonly considered to be equal to the atmospheric seeing. However the outer scale of the turbulence, which corresponds to a reduction in the low frequency content of the phase perturbation spectrum, plays a significant role in the improvement of image quality at the focus of a telescope. The image quality is therefore different (and in some cases by a large factor) from the atmospheric seeing that can be measured by dedicated seeing monitors, such as a differential image motion monitor.

of telescope diameters and wavelengths. We show that this dependence is efficiently predicated by a simple approximate formula introduced in the literature in 2002. The practical consequences for operation of large telescopes are discussed and an application to on-sky data is presented.

### Background and definitions

In practice the resolution of ground-based telescopes is limited by the atmospheric turbulence, called “seeing”. It is traditionally characterised by the Fried parameter ( $r_0$ ) – the diameter of a telescope such that its diffraction-limited resolution equals the seeing resolution. The well-known Kolmogorov turbulence model describes the shape of the atmospheric long-exposure point spread function (PSF), and many other phenomena, by this single parameter  $r_0$ . This model predicts the dependence<sup>1</sup> of the PSF FWHM (denoted  $\epsilon_0$ ) on wavelength ( $\lambda$ ) and inversely on the Fried parameter,  $r_0$ , where  $r_0$  depends on wavelength (to

A finite  $L_0$  reduces the variance of the low order modes of the turbulence, and in particular decreases the image motion (the tip-tilt). The result is a decrease of the FWHM of the PSF. In the von Kàrmàn model,  $r_0$  describes the high frequency asymptotic behaviour of the spectrum where  $L_0$  has no effect, and thus  $r_0$  loses its sense of an equivalent wavefront coherence diameter. The differential image motion monitors (DIMM; Sarazin & Roddier, 1990) are devices that are commonly used to measure the seeing at astronomical sites. The DIMM delivers an estimate of  $r_0$  based on measuring wavefront distortions at scales of  $\sim 0.1$  m, where  $L_0$  has no effect. By contrast, the absolute image motion and long-exposure PSFs are affected by large-scale distortions and depend on  $L_0$ . In this context the Kolmogorov expression for  $\epsilon_0$ <sup>1</sup> is therefore no longer valid.

Proving the von Kàrmàn model experimentally would be a difficult and eventually futile goal as large-scale wavefront perturbations are anything but stationary. However, the increasing number of esti-

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Logbook "Imaging through turbulence" (M1 MAUCA)

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- Preliminary measures

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+ introduction/context

+ PSD( $r_0$ ,  $L_0$ )

+ => influence of  $r_0$  and  $L_0$

+ rms( $r_0$ ,  $L_0$ )

+ => influence of  $r_0$  and  $L_0$

+ FWHM( $r_0$  or  $\lambda \Rightarrow r_0$ ,  $L_0$ )

+ => influence of  $r_0$  and  $L_0$

+ => comparison with the "seeing"  $\lambda/r_0$

(more to come...)

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-> Detector noises:

- At first: *photon noise* (or *shot noise*), poissonian, actually a transformation of the image.

$$p(n) = \frac{N^n e^{-N}}{n!}, \text{ with : } N = \frac{L\Delta t}{h\nu}, L = \text{luminosity}, \Delta t = \text{time exp.}$$

$p(n)$  = probability to detect  $n$  photons when  $N$  are expected

For large  $N$ : ~gaussian...

$$p(n) \simeq \exp\left(-\frac{(n - N)^2}{2N}\right)$$

# Images & turbulence - 28

-> Detector noises:

- At first: *photon noise* (or *shot noise*), poissonian, actually a transformation of the image.
- At last: *read-out noise (RON)*, gaussian with zero mean and rms  $\sigma_e$  [e-/px], additive noise.
- In between: *dark current noise*, *amplification noise* & *exotic dark current noise* in the case of EMCCDs, noise due to the *calibration of the flat field*, '*salt & pepper*' noise ('hot' and 'cold' pixels), etc.

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```
;; Photon noise (Poisson)
if keyword_set(PHOT_NOISE) then begin
  idx=where((image GT 0.) AND (image LT 1E8),c)
  if (c NE 0) then for i=01,c-11 do $
    noisy_image[idx[i]]=randomn(seed_pn,POISSON=image[idx[i]],/DOUBLE)
  endif
endif

;; Additive dark-current noise (Poisson)
if keyword_set(SIGMA_DARK) then begin
  if not(keyword_set(DELTA_T)) then begin
    message, "dark-current noise calculation does need a time exposure value!!"
  endif else noisy_image+=randomn(seed_dark,npx,nty,POISSON=sigma_dark*delta_t,/DOUBLE)
endif

;; EMCCD noises
;; Additive exotic (time-exposure-independent) dark-current noise (Poisson)
if keyword_set(EXODARK) then noisy_image+=randomn(seed_xd,npx,nty,POISSON=exodark,/DOUBLE)

;; Additive main EMCCD noise (Gamma)
if keyword_set(GAIN_L3CCD) then begin
  idx=where(image GT 0, c)
  if (c NE 0) then for i=01,c-11 do $
    noisy_image[idx[i]]+=gain_l3ccd*randomn(seed_l3ccd,GAMMA=image[idx[i]],/DOUBLE)
  ; noisy_image=long(temporary(noisy_image))
endif

;; Flat-field calibration residuals
if keyword_set(FFOFFSET) then begin
  ffres=randomn(seed_ff,npx,nty)*ffoffset+1.
  idx = where(ffres LE 0., c)
  if (c NE 0) then ffres[idx]=1. ; Put possible<=0 ff values to 1.
  noisy_image*=ffres
endif

;; Additive read-out noise (Gaussian)
if keyword_set(SIGMA_RON) then $
  noisy_image+=randomn(seed_ron,npx,nty,/NORMAL,/DOUBLE)*sigma_ron

;; Force to zero negative values
if keyword_set(POSITIVE) then begin
  idx=where(noisy_image LT 0, c)
  if (c GT 0) then noisy_image[idx]=0.
endif
```

CALLING SEQUENCE

```
noisy_image = addnoise(input_image,
  PHOT_NOISE=phot_noise,
  DELTA_T=delta_t,
  EXODARK=exodark,
  GAIN_L3CCD=gain_l3ccd,
  FFOFFSET=ffoffset,
  SIGMA_RON=sigma_ron,
  POSITIVE=positive,
  OUT_TYPE=out_type
)
```

img formation w/noise:

- 1- 'add' photon noise on one short-exp. PSF (in function of N...),
- 2- long-exp. PSF (100N photons!),
- 3- 'add' photon noise on the long-exp. PSF,
- 4- compare long-exp. & short-exp. noisy images (and 'clean' images).

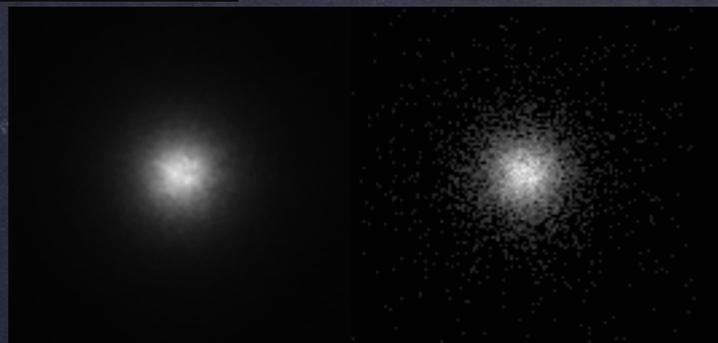
# Images & turbulence - 30

```
[IDL> restore, 'PSF_r0=10cm_L0=10m_lambda=500nm.sav'  
[IDL> help  
% At $MAIN$  
CUBE_PSF          FLOAT      = Array[128, 128, 100]  
SHORTEXP          DOUBLE     = Array[128, 128]  
Compiled Procedures:  
  $MAIN$  
  
Compiled Functions:  
  
[IDL> shortexp=cube_PSF[*,*,0]  
[IDL> total(shortexp)  
      0.19702147  
[IDL> shortexp=shortexp/total(shortexp)*100.  
[IDL> total(shortexp)  
      99.999664  
[IDL> .r addnoise  
% Compiled module: ADDNOISE.  
[IDL> shortnoisy=addnoise(shortexp, /PHOT_NOISE)
```

img formation w/noise:

- 1- 'add' photon noise on one short-exp. PSF (in function of N...),
- 2- long-exp. PSF (100N photons!),
- 3- 'add' photon noise on the long-exp. PSF,
- 4- compare long-exp. & short-exp. noisy images (and 'clean' images).

```
[IDL> tvscl, [shortexp,shortnoisy]^0.5  
[IDL> longexp=total(cube,3)  
[IDL> longexp=longexp/total(longexp)*100.*100L  
[IDL> longnoisy=addnoise(longexp, /PHOT_NOISE)  
[IDL> tvscl, [longexp,longnoisy]^0.5
```



-> Possibly also compare with the stacked (noisy) image...

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- Preliminary measures  
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- + introduction/context
- + PSD( $r_0$ ,  $L_0$ )
- +  $\Rightarrow$  influence of  $r_0$  and  $L_0$
- + rms( $r_0$ ,  $L_0$ )
- +  $\Rightarrow$  influence of  $r_0$  and  $L_0$
- + FWHM( $r_0$  or  $\lambda \Rightarrow r_0$ ,  $L_0$ )
- +  $\Rightarrow$  influence of  $r_0$  and  $L_0$
- +  $\Rightarrow$  comparison with the "seeing"  $\lambda/r_0$
- + noisy images
- + any personal deepening on the subject ?

(more to come...)

# Adaptive optics - 0

(Credit: Markus Feldt, Max Planck Institut für Astronomie – Heidelberg, 2025)

→ [https://www2.mpia-hd.mpg.de/homes/feldt/post/02\\_adaptive\\_optics/](https://www2.mpia-hd.mpg.de/homes/feldt/post/02_adaptive_optics/)

# Adaptive optics - 1

# Adaptive optics - 2

