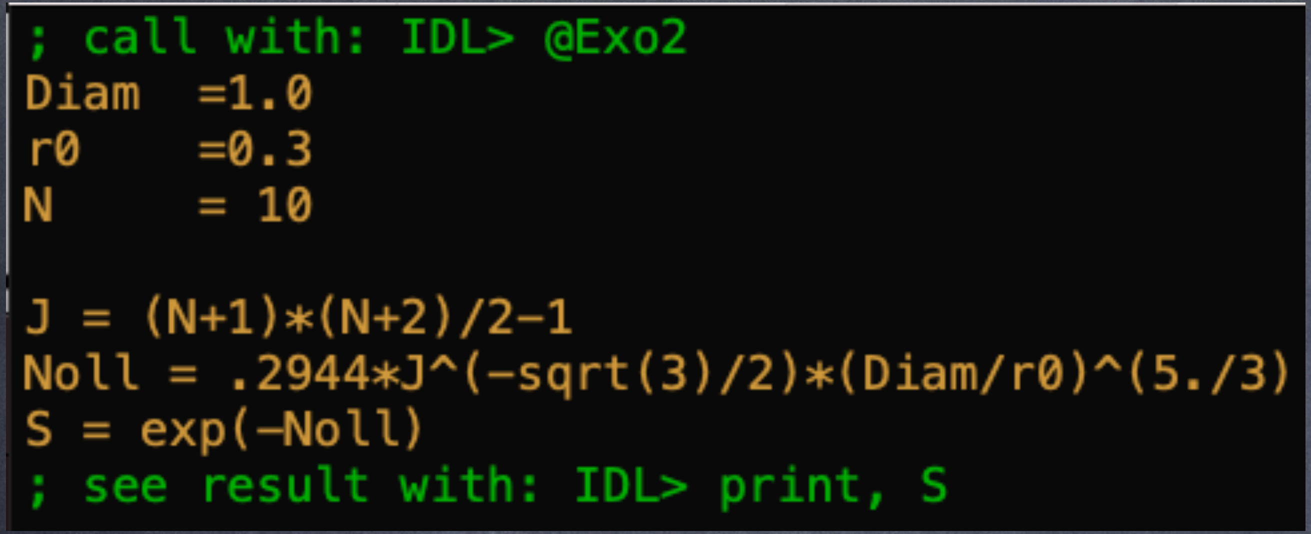
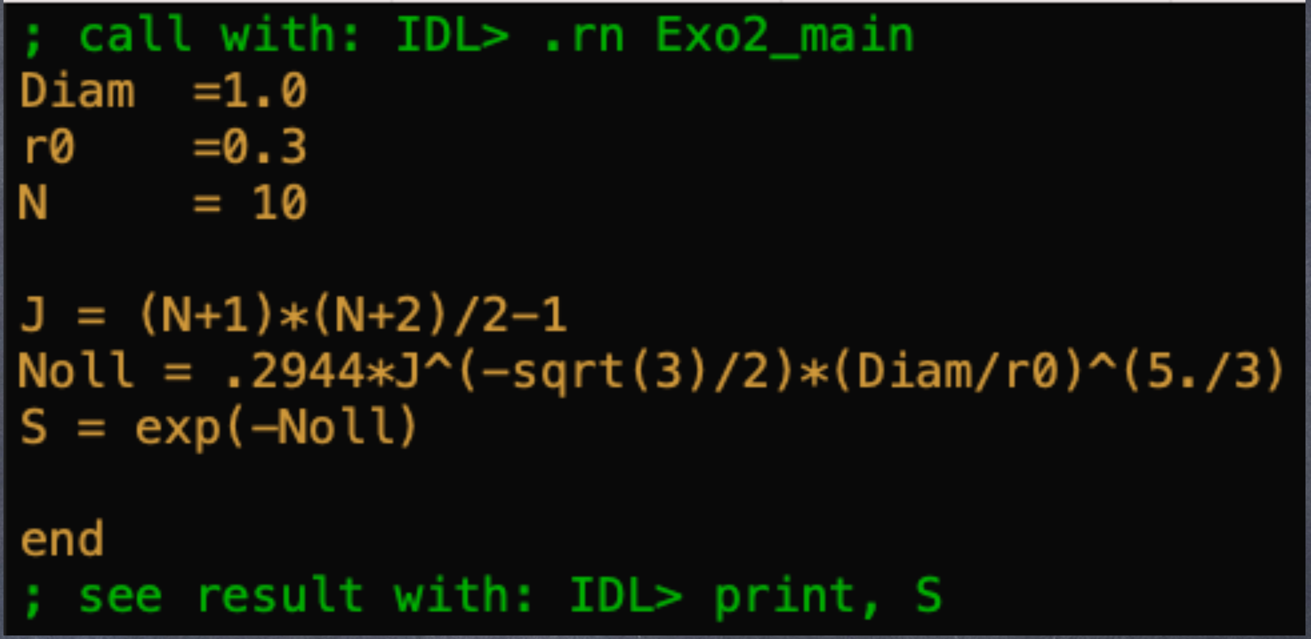
(IDL: 4 kind of routines/scripts)



```
; call with: IDL> @Exo2
Diam   =1.0
r0     =0.3
N      = 10

J = (N+1)*(N+2)/2-1
Noll = .2944*J^(-sqrt(3)/2)*(Diam/r0)^(5./3)
S = exp(-Noll)
; see result with: IDL> print, S
```

batch: all variables are accessible.

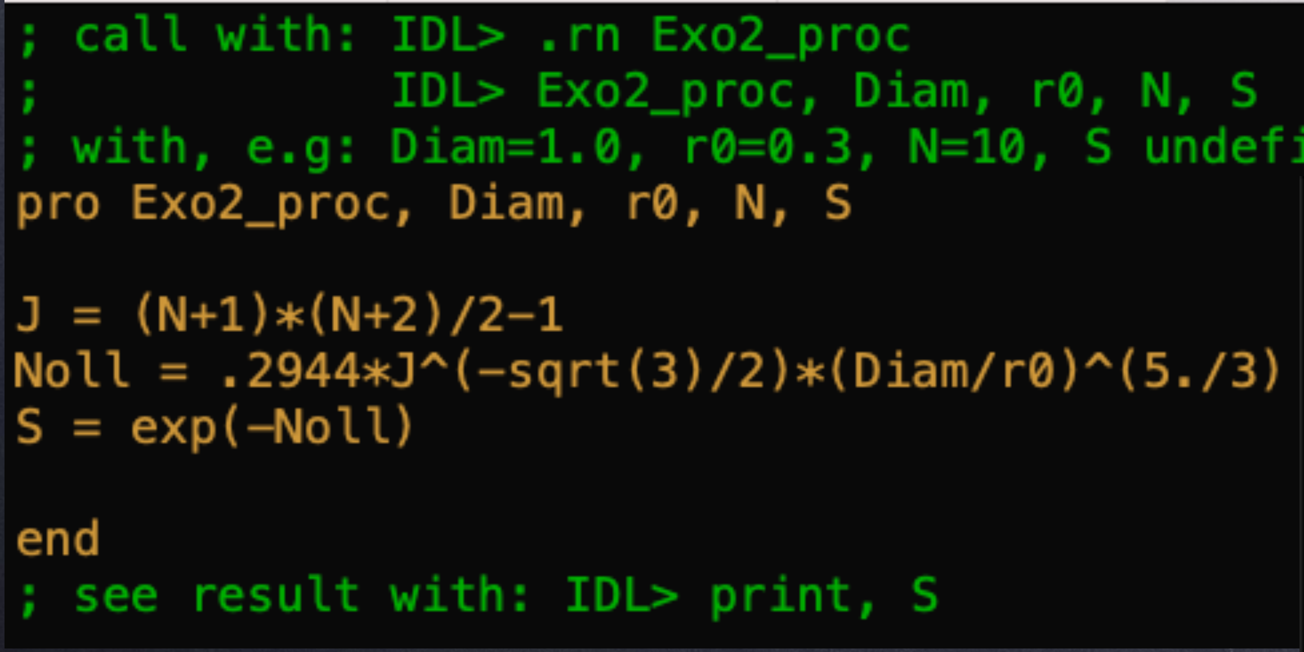


```
; call with: IDL> .rn Exo2_main
Diam   =1.0
r0     =0.3
N      = 10

J = (N+1)*(N+2)/2-1
Noll = .2944*J^(-sqrt(3)/2)*(Diam/r0)^(5./3)
S = exp(-Noll)

end
; see result with: IDL> print, S
```

main: idem (« .r » : run ; « .rn » : run new).

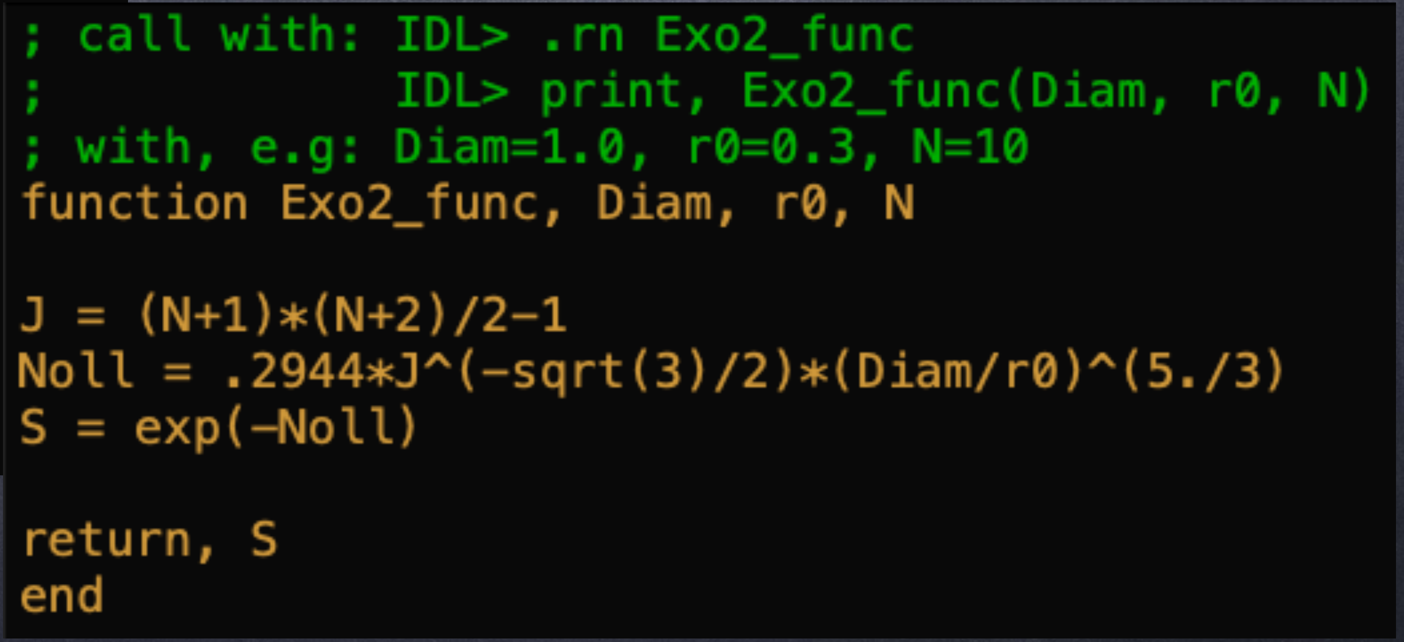


```
; call with: IDL> .rn Exo2_proc
;             IDL> Exo2_proc, Diam, r0, N, S
; with, e.g: Diam=1.0, r0=0.3, N=10, S undefined
pro Exo2_proc, Diam, r0, N, S

J = (N+1)*(N+2)/2-1
Noll = .2944*J^(-sqrt(3)/2)*(Diam/r0)^(5./3)
S = exp(-Noll)

end
; see result with: IDL> print, S
```

procedure: (input/output) parameters are accessible, but variables defined within the procedure are not.



```
; call with: IDL> .rn Exo2_func
;             IDL> print, Exo2_func(Diam, r0, N)
; with, e.g: Diam=1.0, r0=0.3, N=10
function Exo2_func, Diam, r0, N

J = (N+1)*(N+2)/2-1
Noll = .2944*J^(-sqrt(3)/2)*(Diam/r0)^(5./3)
S = exp(-Noll)

return, S
end
```

function: no output parameters, inside variables not accessible, result of the function returned.

(IDL: other useful remarks)

- IDL help is called with: `IDL>> ?`
- ‘?’ opens with a defined browser the file ‘idl.htm’, which can be also found directly here: **/usr/local/harris/idl89/help/online_help/Subsystems/idl/idl.htm**
- Or also with the help of the unix command ‘find’:

  ```
  linux>> cd /
  linux>> find . -name idl.htm
  ```

- See also (for routines which are part of a third library):

  ```
  IDL>> doc_library, ‘routine_name’
  ```

- Return to main level of programming after a crash: `retall`
- Details on a variable xxx: `idl> help, xxx`

  (all variables: `idl> help`)
- Close last opened window: `idl> wdelete`

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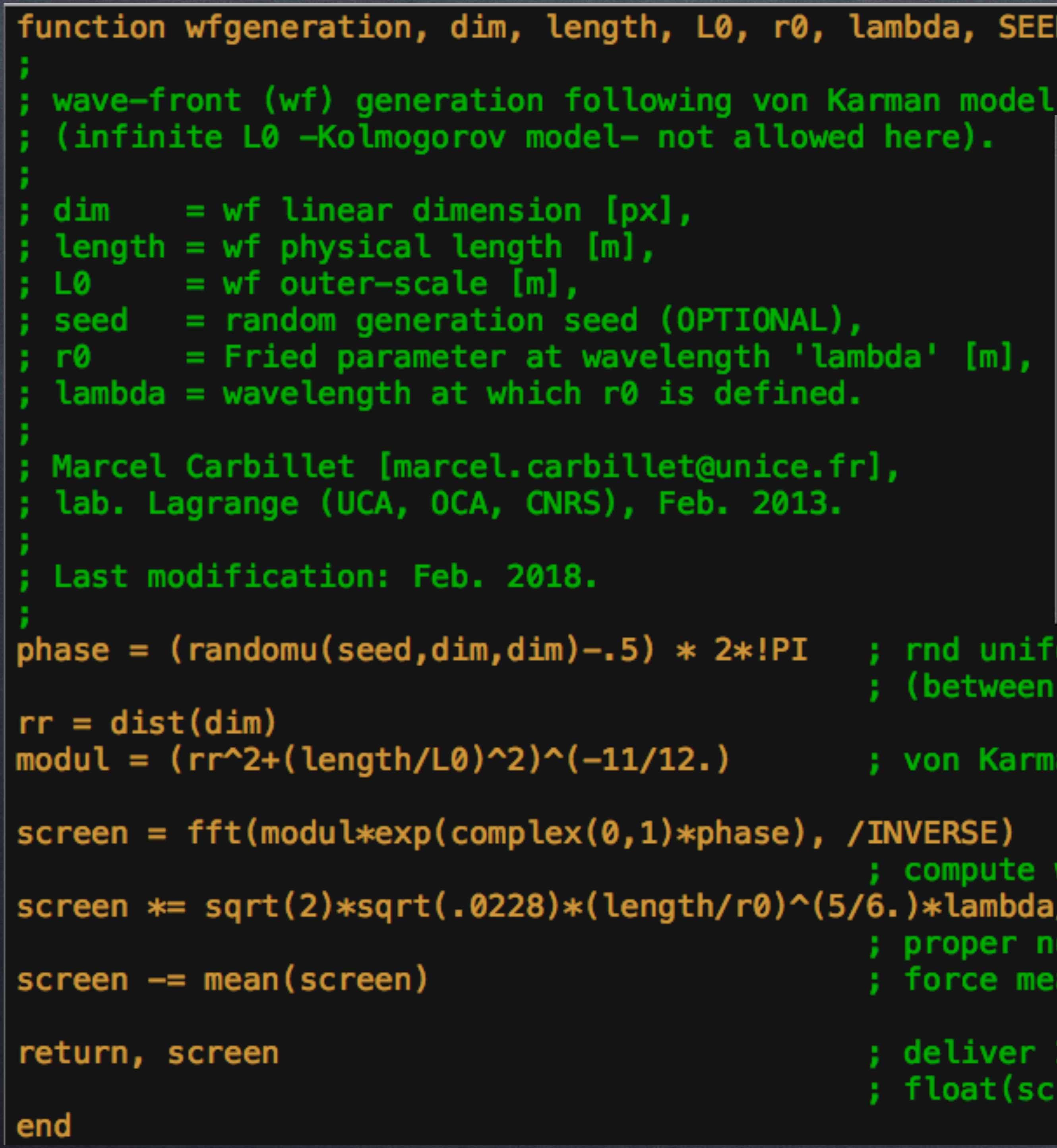
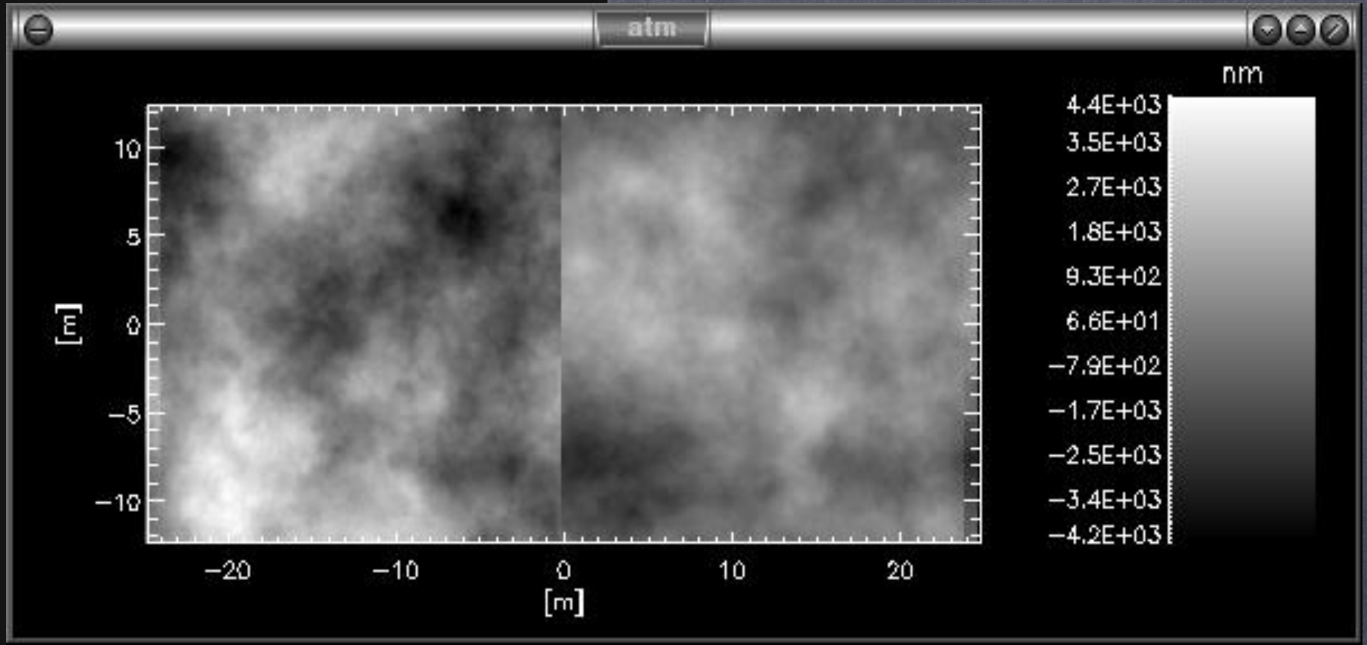
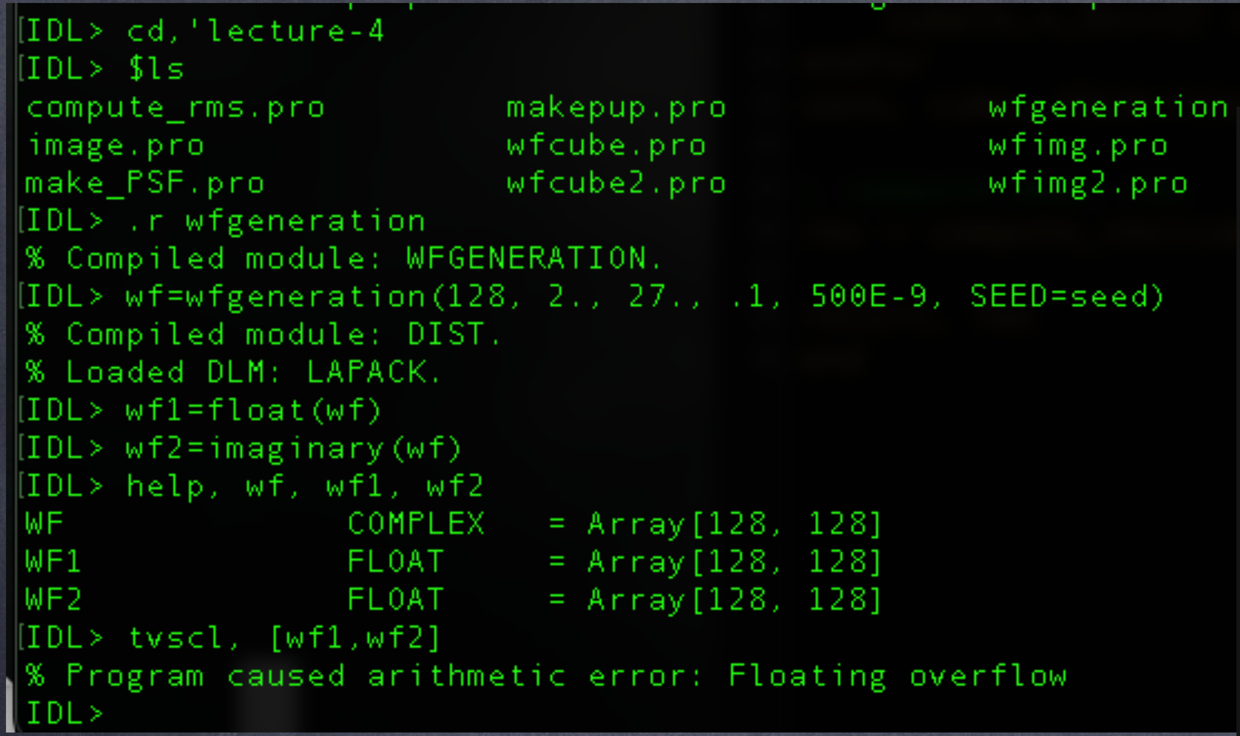


```
function wfgeneration, dim, length, L0, r0, lambda, SEED=seed
;
; wave-front (wf) generation following von Karman model
; (infinite L0 -Kolmogorov model- not allowed here).
;
; dim    = wf linear dimension [px],
; length = wf physical length [m],
; L0     = wf outer-scale [m],
; seed   = random generation seed (OPTIONAL),
; r0     = Fried parameter at wavelength 'lambda' [m],
; lambda = wavelength at which r0 is defined.
;
; Marcel Carbillet [marcel.carbillet@unice.fr],
; lab. Lagrange (UCA, OCA, CNRS), Feb. 2013.
;
; Last modification: Feb. 2018.
;
phase = (randomu(seed,dim,dim)-.5) * 2*!PI    ; rnd uniformly distributed phase
                                              ; (between -PI and +PI)
rr = dist(dim)
modul = (rr^2+(length/L0)^2)^(-11/12.)        ; von Karman model

screen = fft(modul*exp(complex(0,1)*phase), /INVERSE)
                                              ; compute wf
screen *= sqrt(2)*sqrt(.0228)*(length/r0)^(5/6.)*lambda/(2*!PI)
                                              ; proper normalization of wf
screen -= mean(screen)                        ; force mean to zero

return, screen                                ; deliver 2 independent wf:
                                              ; float(screen) & imaginary(screen)
end
```

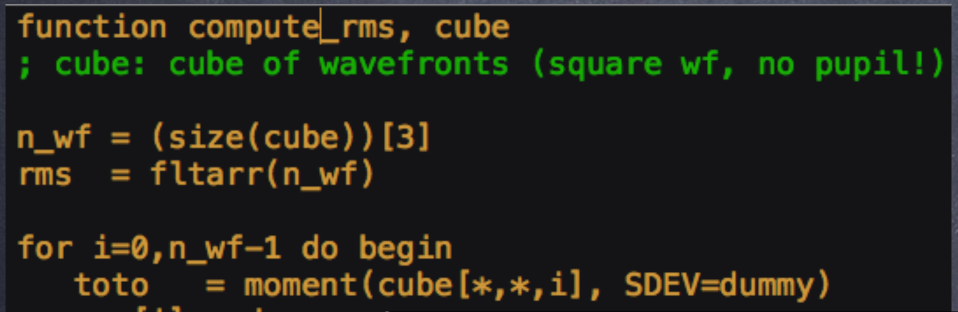


wf generation:
generate a cube of statistically independent wf (typically 100)...
=> compute mean *rms* for different [r_0 , L_0]

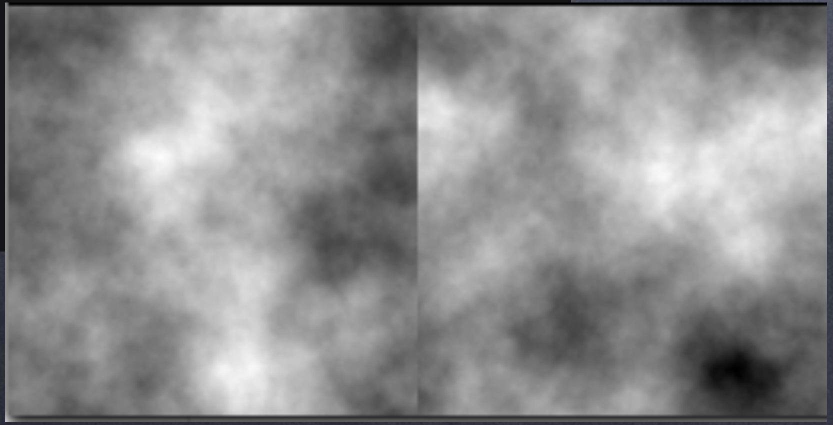
Images & turbulence - 18

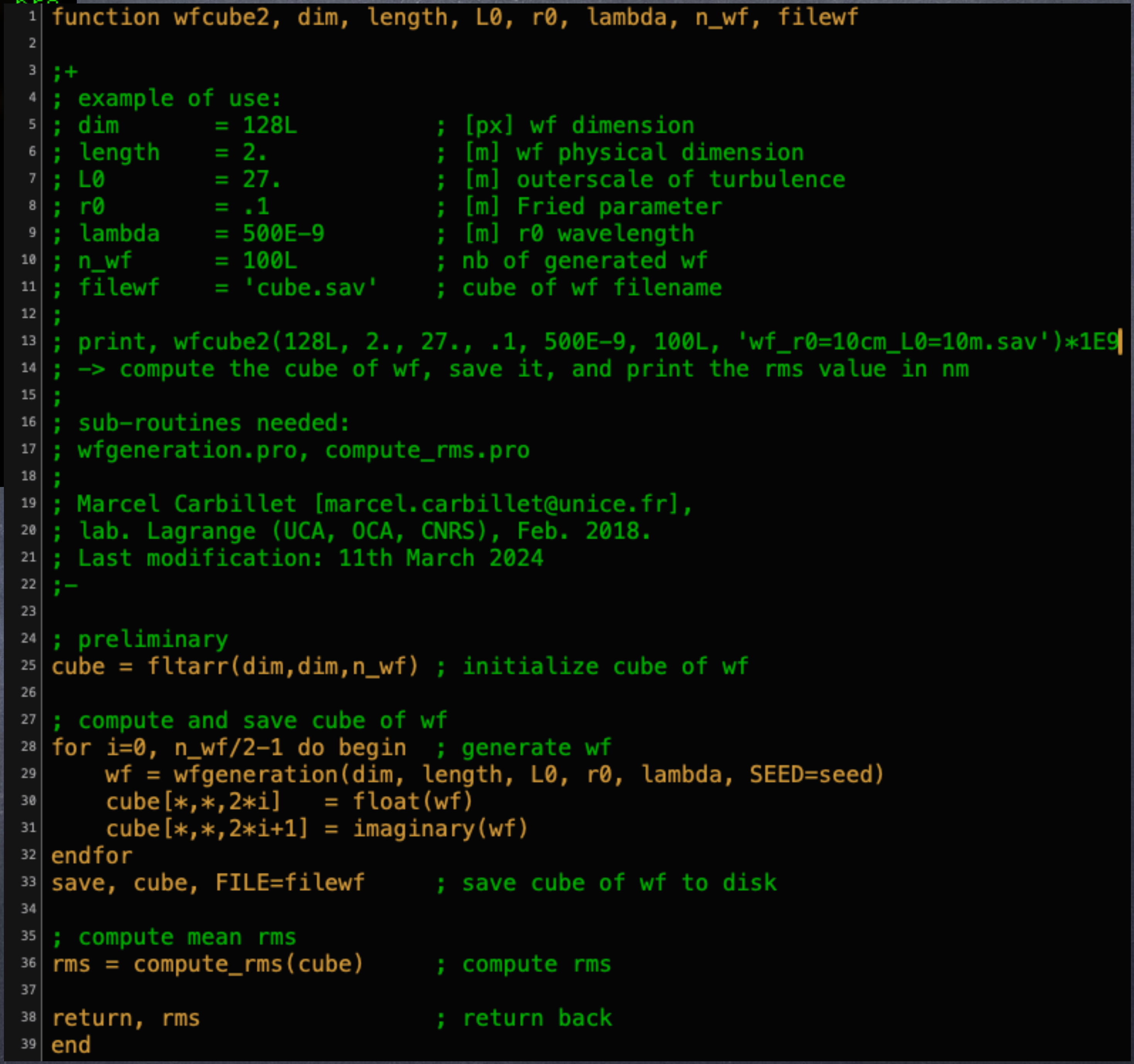


```
IDL> cd,'lecture-4
IDL> $ls
compute_rms.pro          makepup.pro            wfgeneration.pro
image.pro                wfcube.pro             wfimg.pro
make_PSF.pro             wfcube2.pro            wfimg2.pro
IDL> .r wfgeneration
% Compiled module: WFGENERATION.
IDL> wf=wfgeneration(128, 2., 27., .1, 500E-9, SEED=seed)
% Compiled module: DIST.
% Loaded DLM: LAPACK.
IDL> wf1=float(wf)
IDL> wf2=imaginary(wf)
IDL> help, wf, wf1, wf2
WF              COMPLEX   = Array[128, 128]
WF1             FLOAT     = Array[128, 128]
WF2             FLOAT     = Array[128, 128]
IDL> tvscl, [wf1,wf2]
% Program caused arithmetic error: Floating overflow
IDL>
```

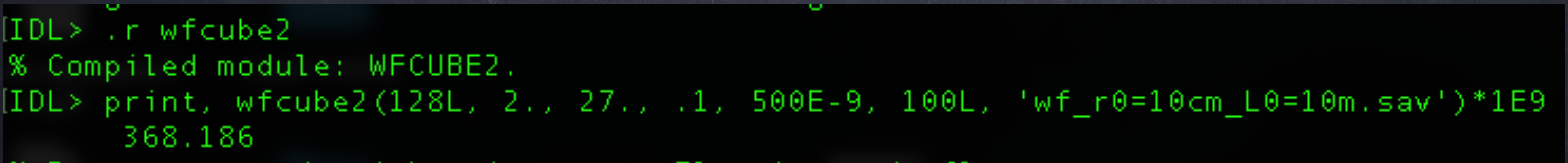


```
function compute_rms, cube
; cube: cube of wavefronts (square wf, no pupil!)

n_wf = (size(cube))[3]
rms  = fltarr(n_wf)

for i=0,n_wf-1 do begin
   toto   = moment(cube[*,*,i], SDEV=dummy)
   rms[i] = dummy
endfor

rms_moy = mean(rms)

return, rms_moy
end
```

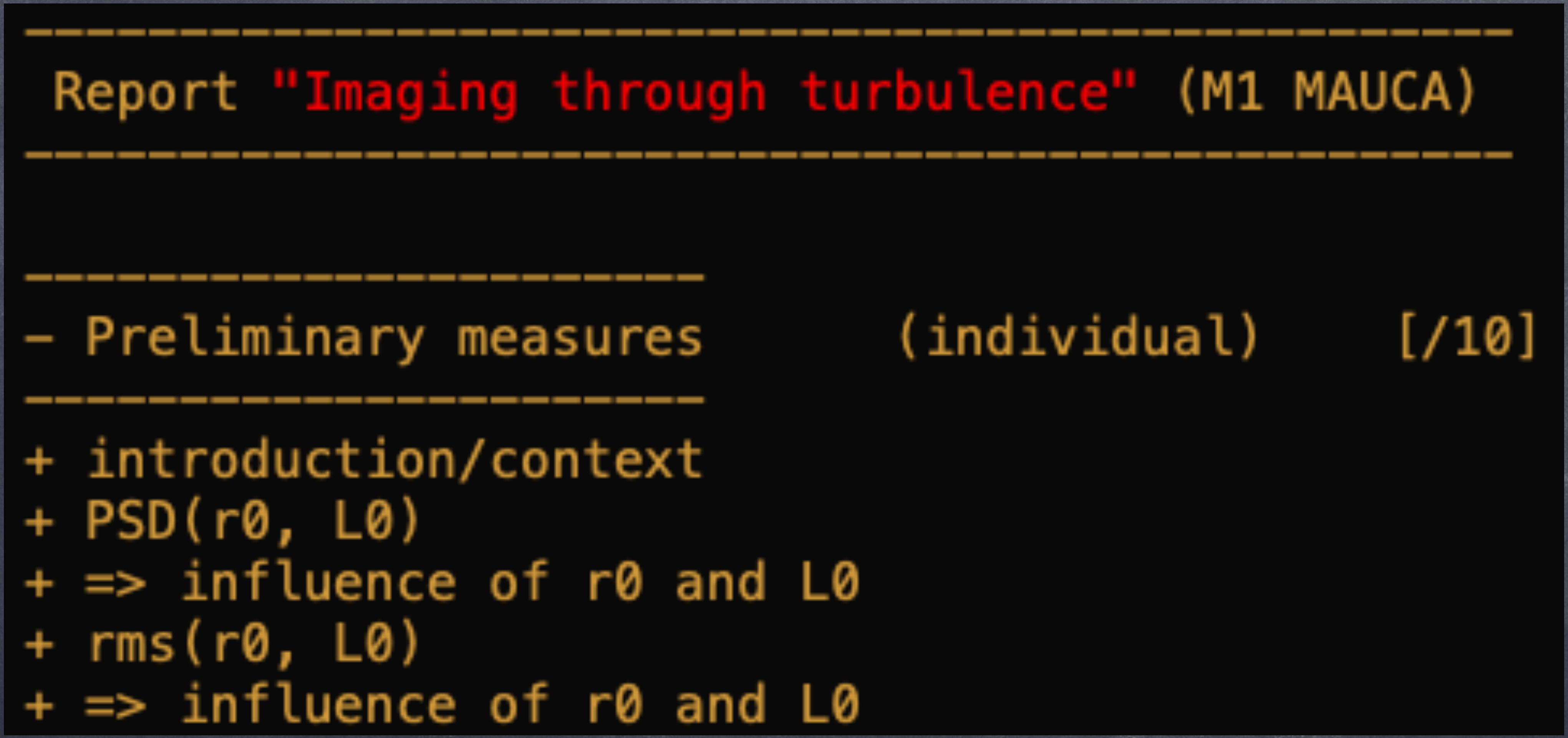




```
function wfcube2, dim, length, L0, r0, lambda, n_wf, filewf

;+
; example of use:
; dim       = 128L          ; [px] wf dimension
; length    = 2.            ; [m] wf physical dimension
; L0        = 27.           ; [m] outerscale of turbulence
; r0        = .1            ; [m] Fried parameter
; lambda    = 500E-9        ; [m] r0 wavelength
; n_wf      = 100L          ; nb of generated wf
; filewf    = 'cube.sav'    ; cube of wf filename
;
; print, wfcube2(128L, 2., 27., .1, 500E-9, 100L, 'wf_r0=10cm_L0=10m.sav')*1E9
; -> compute the cube of wf, save it, and print the rms value in nm
;
; sub-routines needed:
; wfgeneration.pro, compute_rms.pro
;
; Marcel Carbillet [marcel.carbillet@unice.fr],
; lab. Lagrange (UCA, OCA, CNRS), Feb. 2018.
; Last modification: 11th March 2024
;-

; preliminary
cube = fltarr(dim,dim,n_wf) ; initialize cube of wf

; compute and save cube of wf
for i=0, n_wf/2-1 do begin  ; generate wf
    wf = wfgeneration(dim, length, L0, r0, lambda, SEED=seed)
    cube[*,*,2*i]   = float(wf)
    cube[*,*,2*i+1] = imaginary(wf)
endfor
save, cube, FILE=filewf     ; save cube of wf to disk

; compute mean rms
rms = compute_rms(cube)     ; compute rms

return, rms                 ; return back
end
```



```
IDL> .r wfcube2
% Compiled module: WFCUBE2.
IDL> print, wfcube2(128L, 2., 27., .1, 500E-9, 100L, 'wf_r0=10cm_L0=10m.sav')*1E9
      368.186
```



```
------------------------------------------------
 Report "Imaging through turbulence" (M1 MAUCA)
------------------------------------------------


----------------------
- Preliminary measures      (individual)    [/10]
----------------------
+ introduction/context
+ PSD(r0, L0)
+ => influence of r0 and L0
+ rms(r0, L0)
+ => influence of r0 and L0
```

(more to come...)

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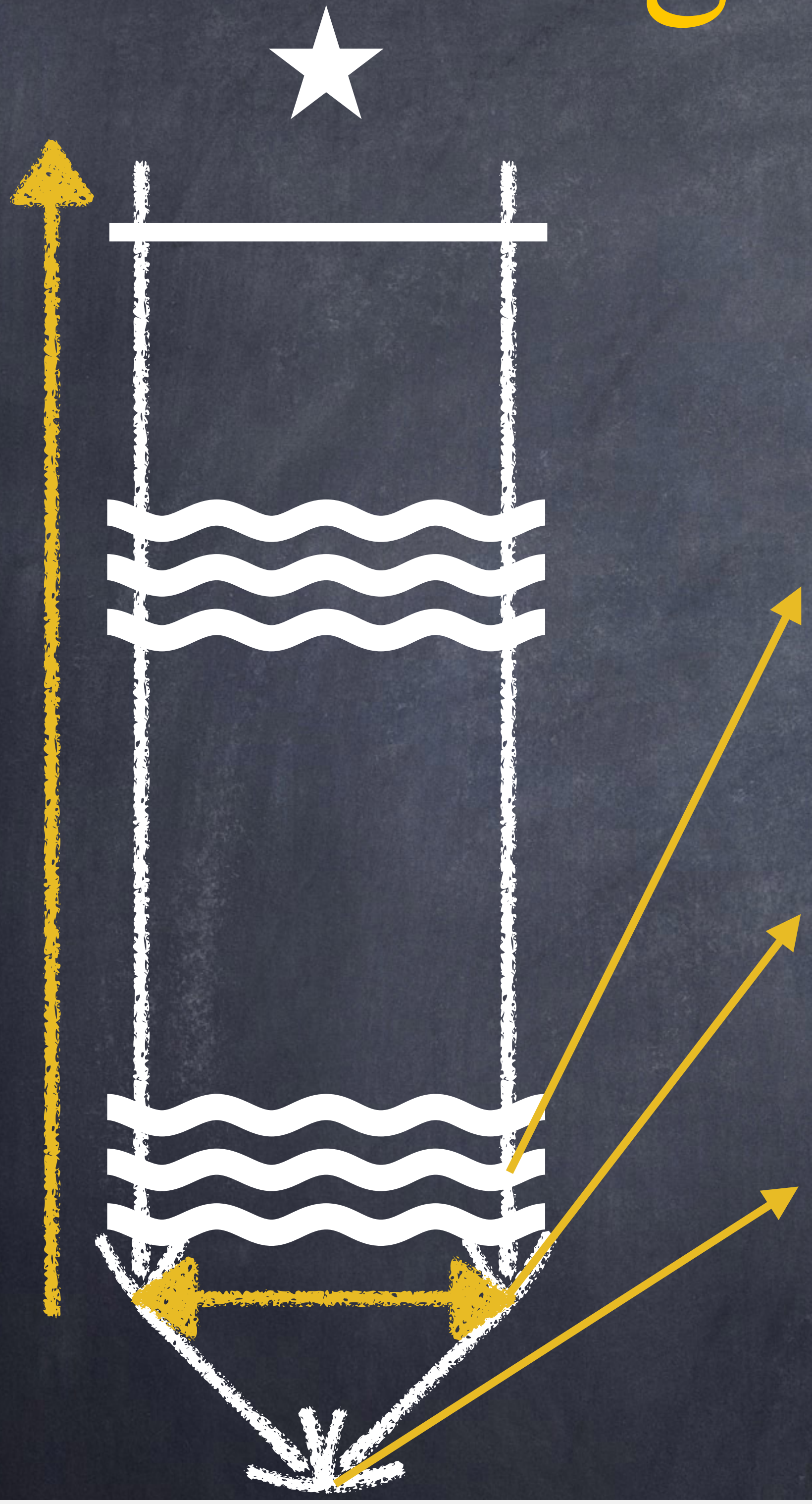

$$\Psi(\vec{r}) = A\ \exp\left(\imath\Phi(\vec{r})\right)$$

$$P(\vec{r}) \Rightarrow A\ P(\vec{r})\ \exp\left(\imath\Phi(\vec{r})P(\vec{r})\right)$$

$$S_\lambda(\vec{\alpha}) \propto \|FT\{A\ P(\vec{r})\ \exp\left(\imath\Phi(\vec{r})P(\vec{r})\right)\}\|^2$$

$$A = 1 \text{ and } \Phi(\vec{r}) = \frac{2\pi}{\lambda}\delta(\vec{r}) \Rightarrow S_\lambda(\vec{\alpha}) \propto \|FT\{P(\vec{r})\ \exp\left(\imath\frac{2\pi}{\lambda}\delta(\vec{r})P(\vec{r})\right)\}\|^2$$

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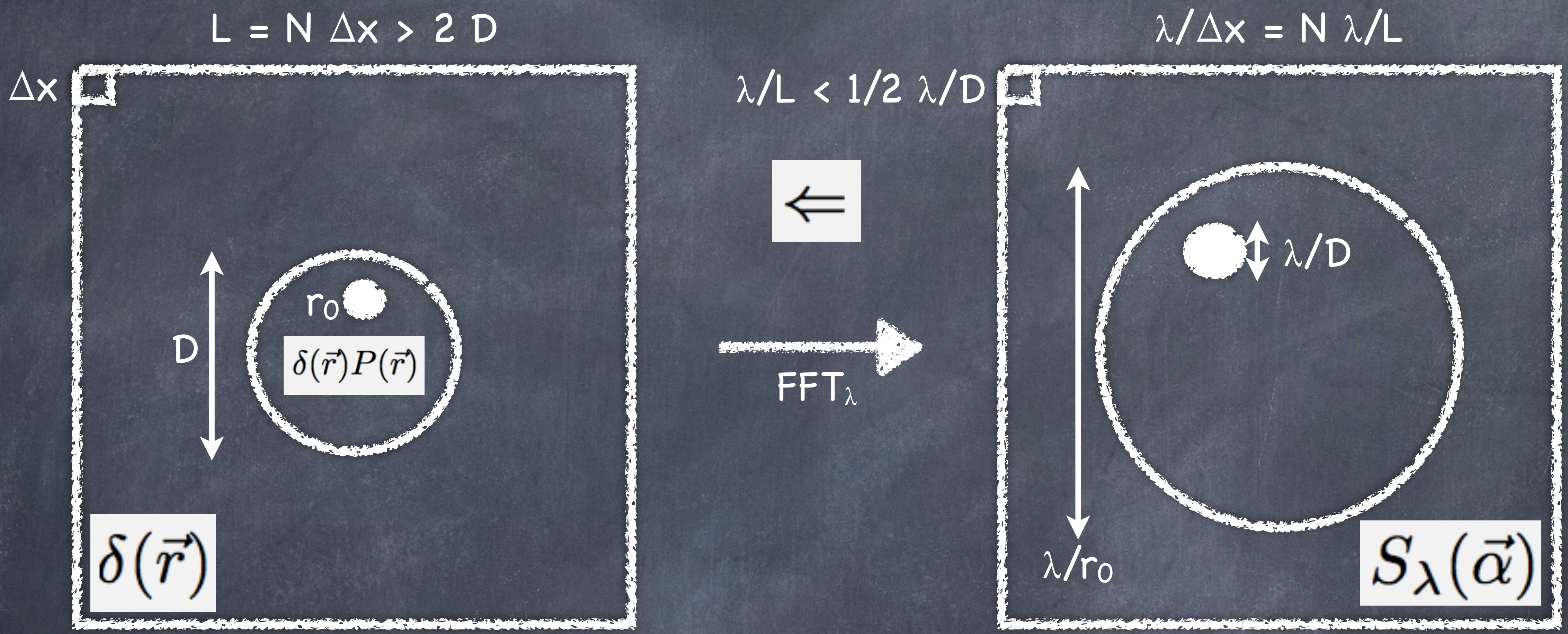

Shannon (=Nyquist) criterium

=> the image pixel λ/L must be at most half the resolution element (resel!) λ/D (in other words : one must have AT LEAST 2 image pixels per λ/D)

=> the simulated wavefronts must be at least twice the telescope diameter ($L>2D$)

In addition

- λ/r_0 should be smaller than $\lambda/\Delta x$ (=> N large enough)

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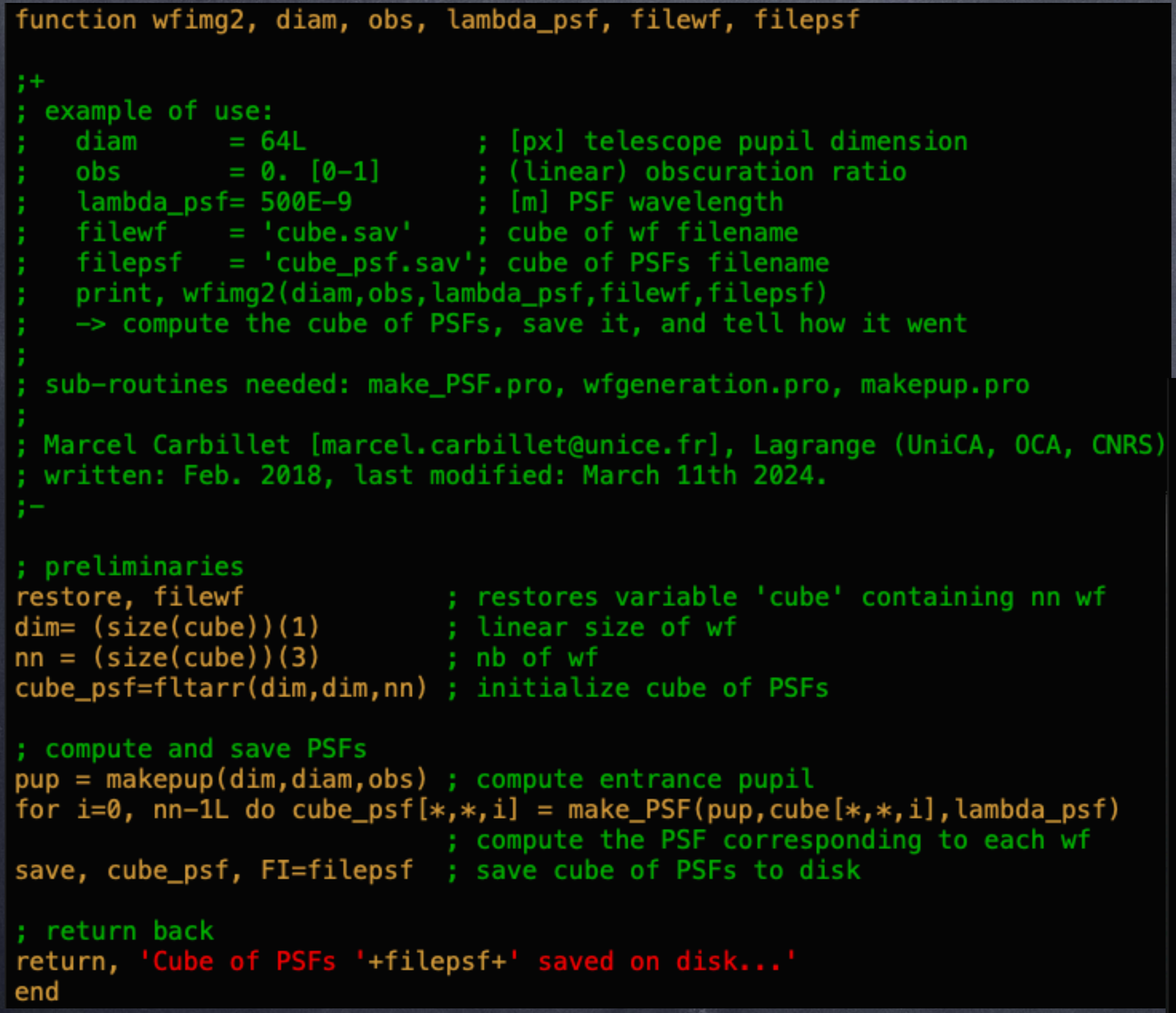
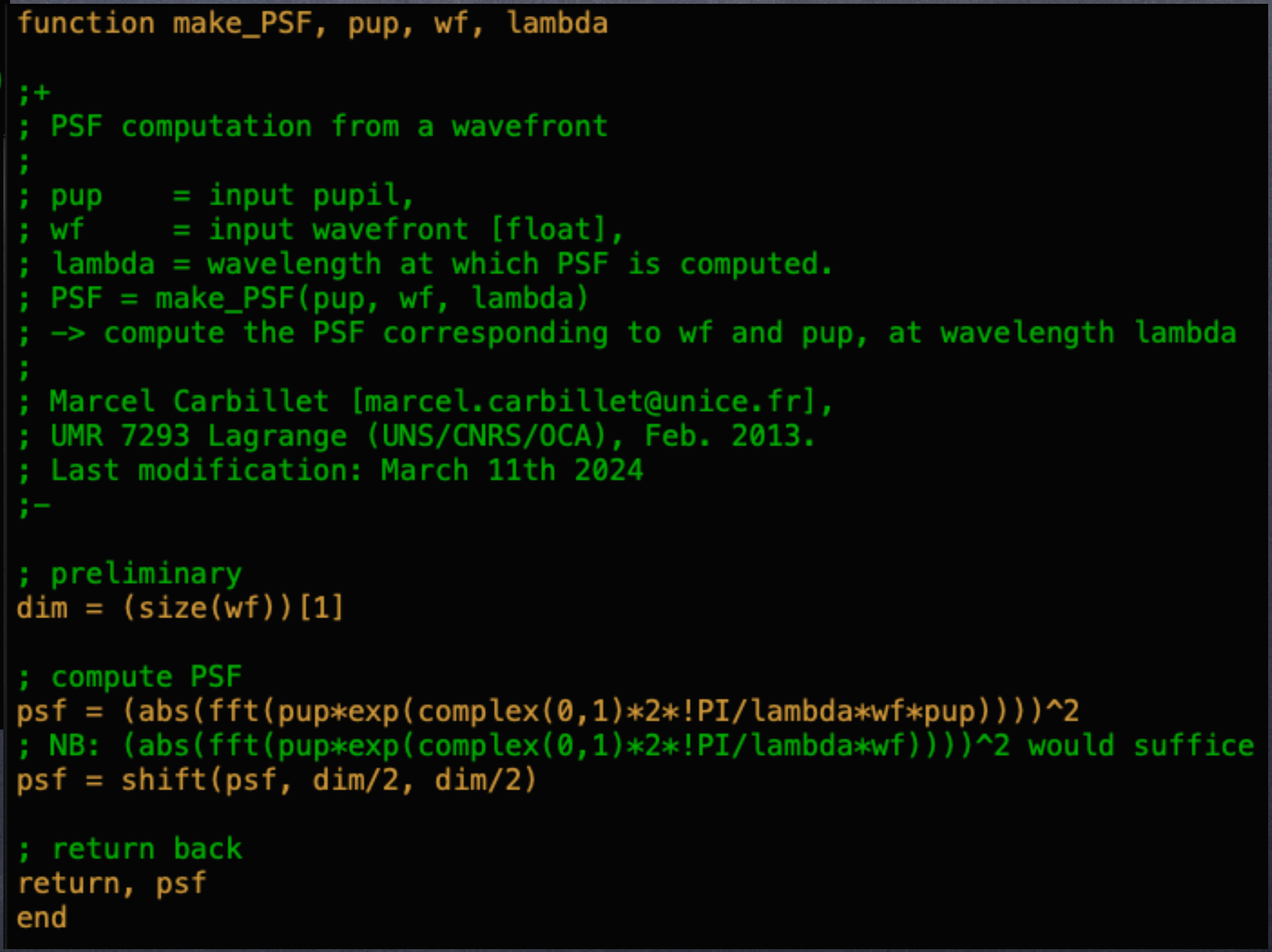
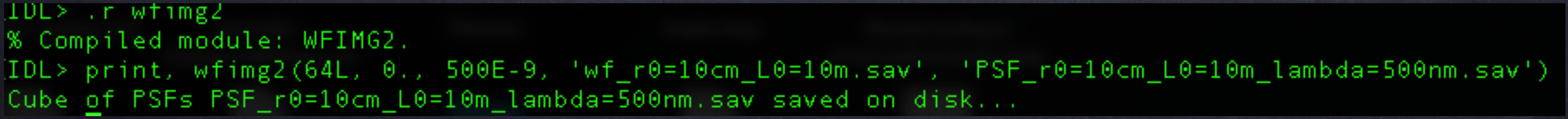


```
function wfimg2, diam, obs, lambda_psf, filewf, filepsf

;+
; example of use:
;   diam      = 64L             ; [px] telescope pupil dimension
;   obs       = 0. [0-1]        ; (linear) obscuration ratio
;   lambda_psf= 500E-9          ; [m] PSF wavelength
;   filewf    = 'cube.sav'      ; cube of wf filename
;   filepsf   = 'cube_psf.sav'; cube of PSFs filename
;   print, wfimg2(diam,obs,lambda_psf,filewf,filepsf)
;   -> compute the cube of PSFs, save it, and tell how it went
;
; sub-routines needed: make_PSF.pro, wfgeneration.pro, makepup.pro
;
; Marcel Carbillet [marcel.carbillet@unice.fr], Lagrange (UniCA, OCA, CNRS)
; written: Feb. 2018, last modified: March 11th 2024.
;-

; preliminaries
restore, filewf               ; restores variable 'cube' containing nn wf
dim= (size(cube))(1)          ; linear size of wf
nn = (size(cube))(3)          ; nb of wf
cube_psf=fltarr(dim,dim,nn) ; initialize cube of PSFs

; compute and save PSFs
pup = makepup(dim,diam,obs) ; compute entrance pupil
for i=0, nn-1L do cube_psf[*,*,i] = make_PSF(pup,cube[*,*,i],lambda_psf)
                              ; compute the PSF corresponding to each wf
save, cube_psf, FI=filepsf    ; save cube of PSFs to disk

; return back
return, 'Cube of PSFs '+filepsf+' saved on disk...'
end
```

image formation:
1- cube of instantaneous PSFs (500nm & H-band)



```
function make_PSF, pup, wf, lambda

;+
; PSF computation from a wavefront
;
; pup    = input pupil,
; wf     = input wavefront [float],
; lambda = wavelength at which PSF is computed.
; PSF = make_PSF(pup, wf, lambda)
; -> compute the PSF corresponding to wf and pup, at wavelength lambda
;
; Marcel Carbillet [marcel.carbillet@unice.fr],
; UMR 7293 Lagrange (UNS/CNRS/OCA), Feb. 2013.
; Last modification: March 11th 2024
;-

; preliminary
dim = (size(wf))[1]

; compute PSF
psf = (abs(fft(pup*exp(complex(0,1)*2*!PI/lambda*wf*pup))))^2
; NB: (abs(fft(pup*exp(complex(0,1)*2*!PI/lambda*wf))))^2 would suffice
psf = shift(psf, dim/2, dim/2)

; return back
return, psf
end
```



```
IDL> .r wfimg2
% Compiled module: WFIMG2.
IDL> print, wfimg2(64L, 0., 500E-9, 'wf_r0=10cm_L0=10m.sav', 'PSF_r0=10cm_L0=10m_lambda=500nm.sav')
Cube of PSFs PSF_r0=10cm_L0=10m_lambda=500nm.sav saved on disk...
```

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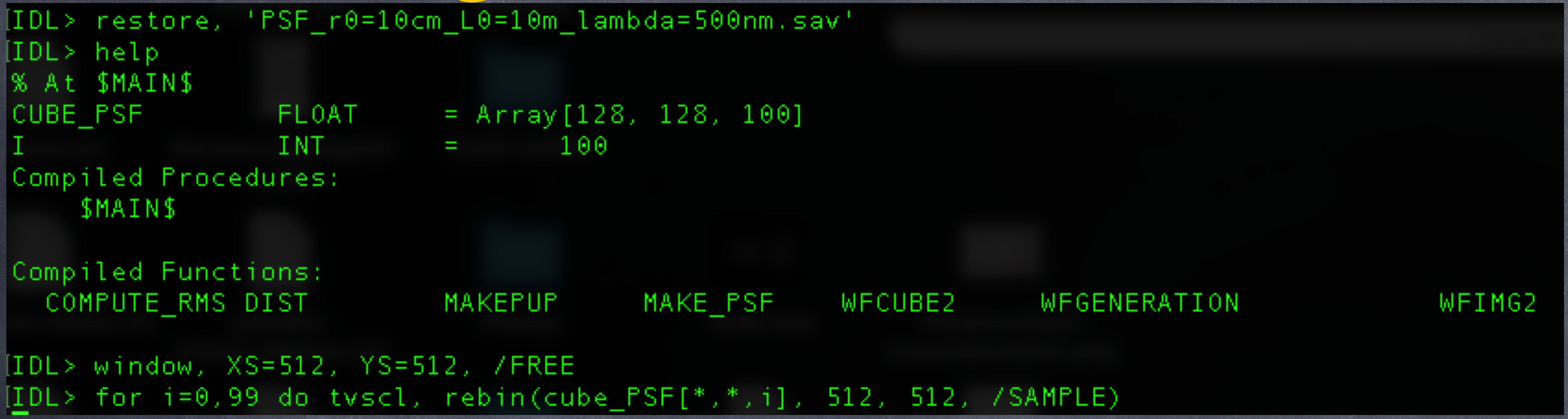
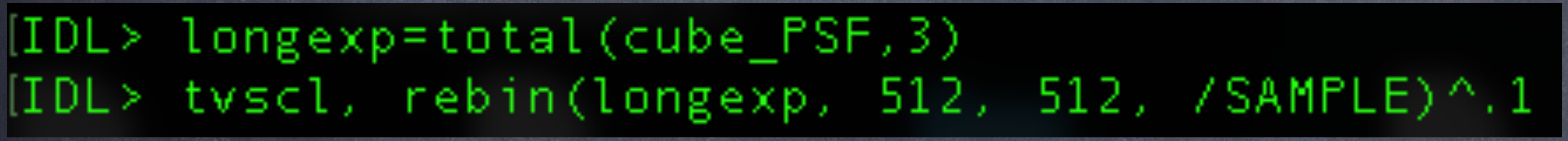


```
IDL> restore, 'PSF_r0=10cm_L0=10m_lambda=500nm.sav'
IDL> help
% At $MAIN$
CUBE_PSF        FLOAT     = Array[128, 128, 100]
I               INT       =      100
Compiled Procedures:
    $MAIN$

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[*,*,i], 512, 512, /SAMPLE)
```



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

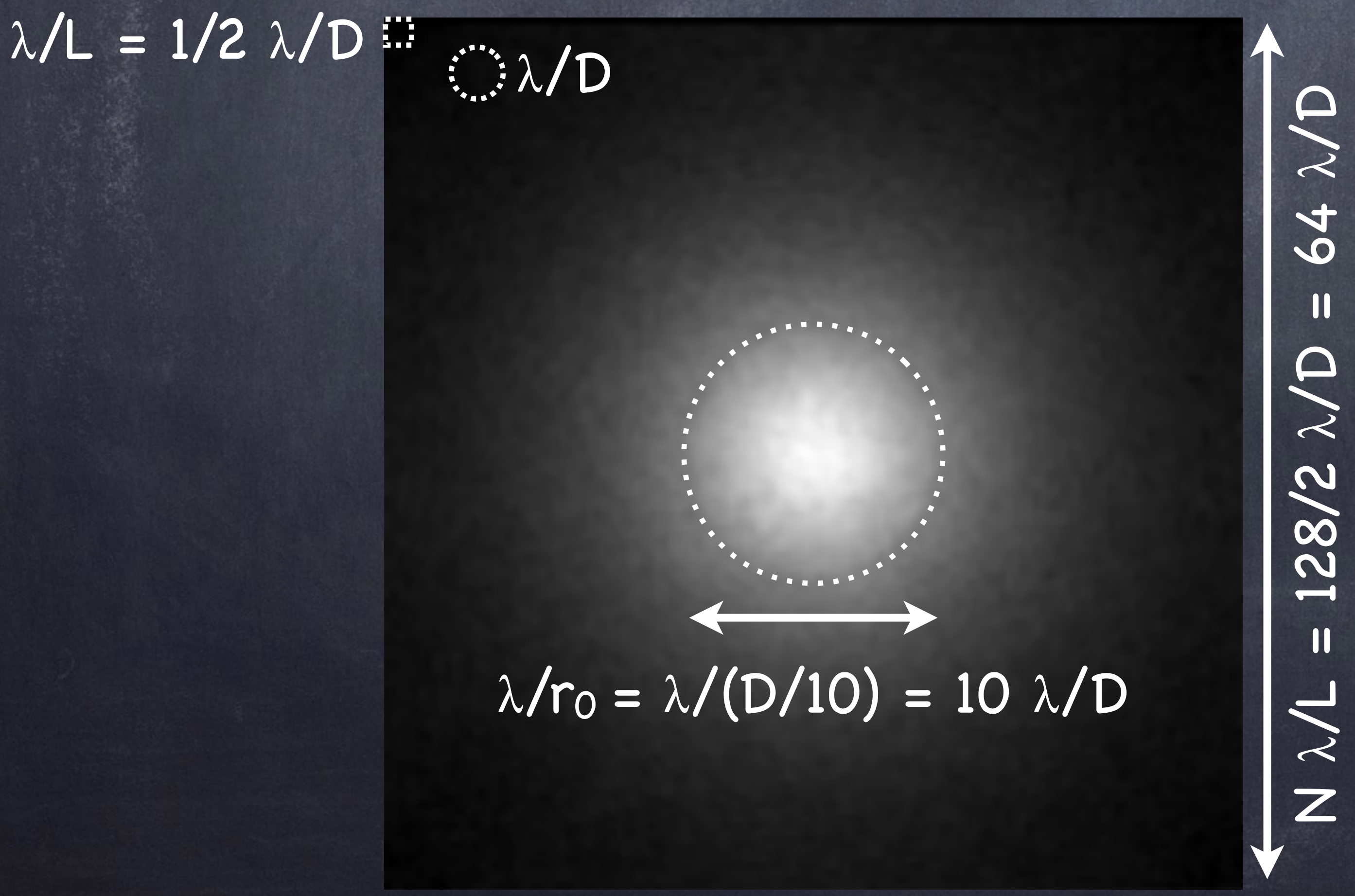


image formation:

1- cube of instantaneous PSFs (500nm & band H)

2- long-exposure PSF

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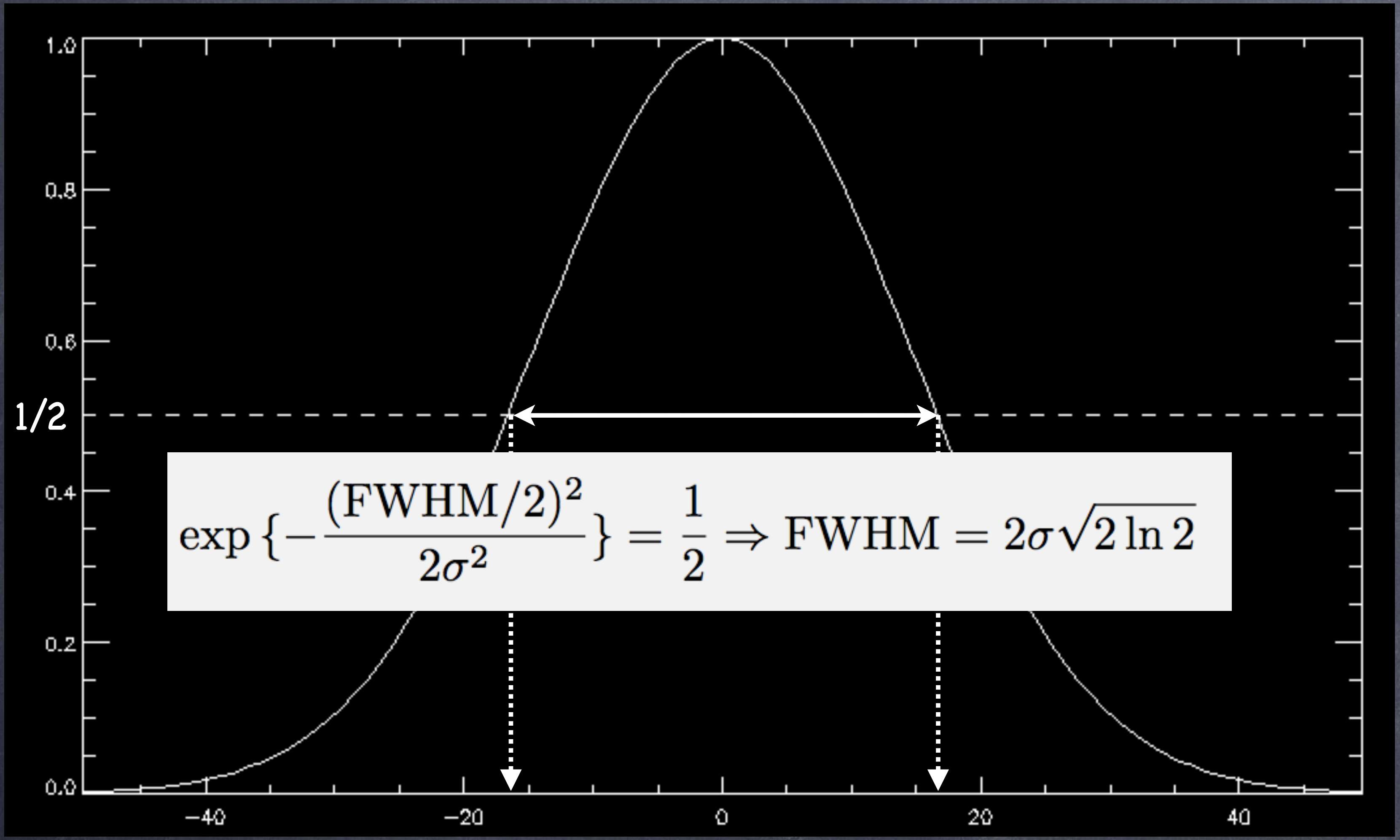


$$\exp\{-\frac{(\mathrm{FWHM}/2)^2}{2\sigma^2}\} = \frac{1}{2} \Rightarrow \mathrm{FWHM} = 2\sigma\sqrt{2\ln 2}$$

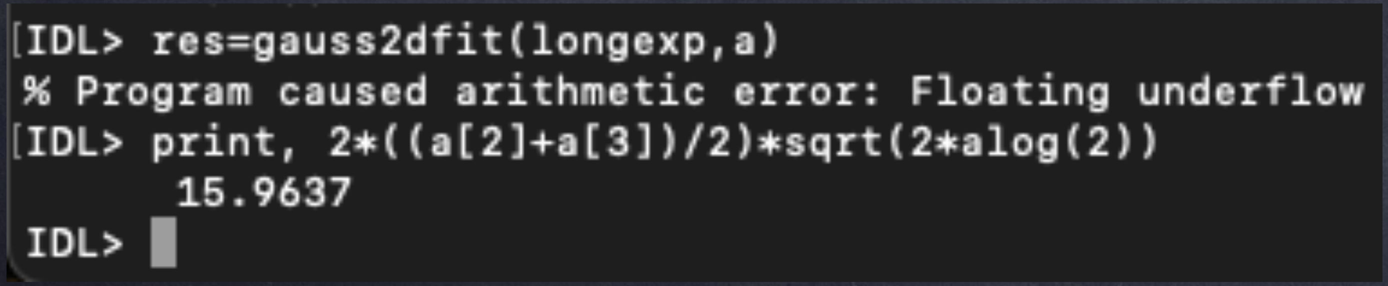
image formation:

1- cube of instantaneous PSFs (500nm & band H)

2- long-exposure PSFs

3- fit with gaussian and compare FWHM vs. λ/r_0 (seeing), also in function of the outerscale L_0.

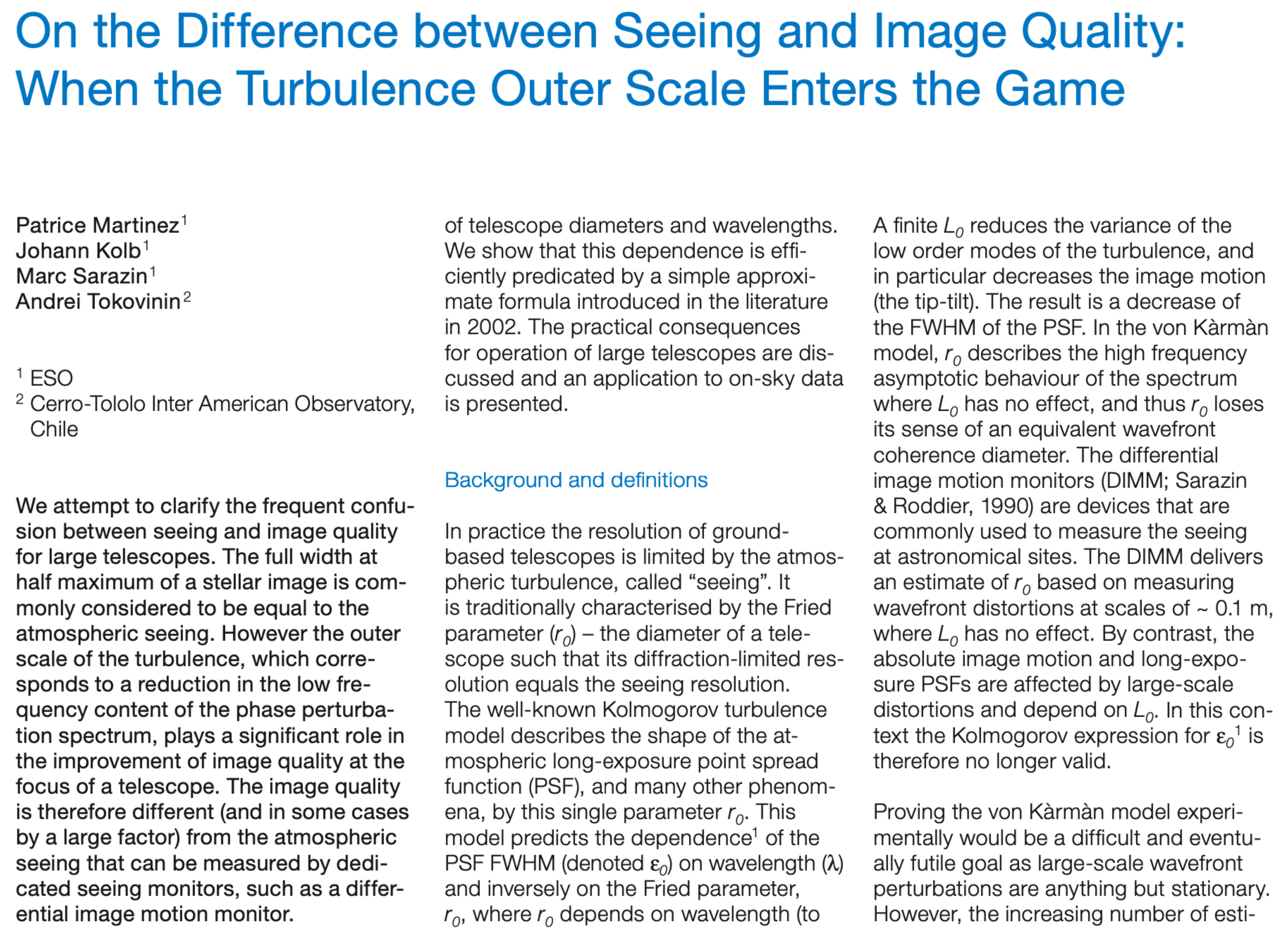
-> Also read Martinez...



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

In this example, the FWHM is ≈16px and, since we have here: 1px=(λ/D)/2, we have hence: FWHM≈8 (λ/D) [i.e. 8*0.1″≈0″8 here (@500nm)]

Images & turbulence - 23+



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

Patrice Martinez[1]
Johann Kolb[1]
Marc Sarazin[1]
Andrei Tokovinin[2]

[1] ESO
[2] Cerro-Tololo Inter American Observatory, Chile

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.

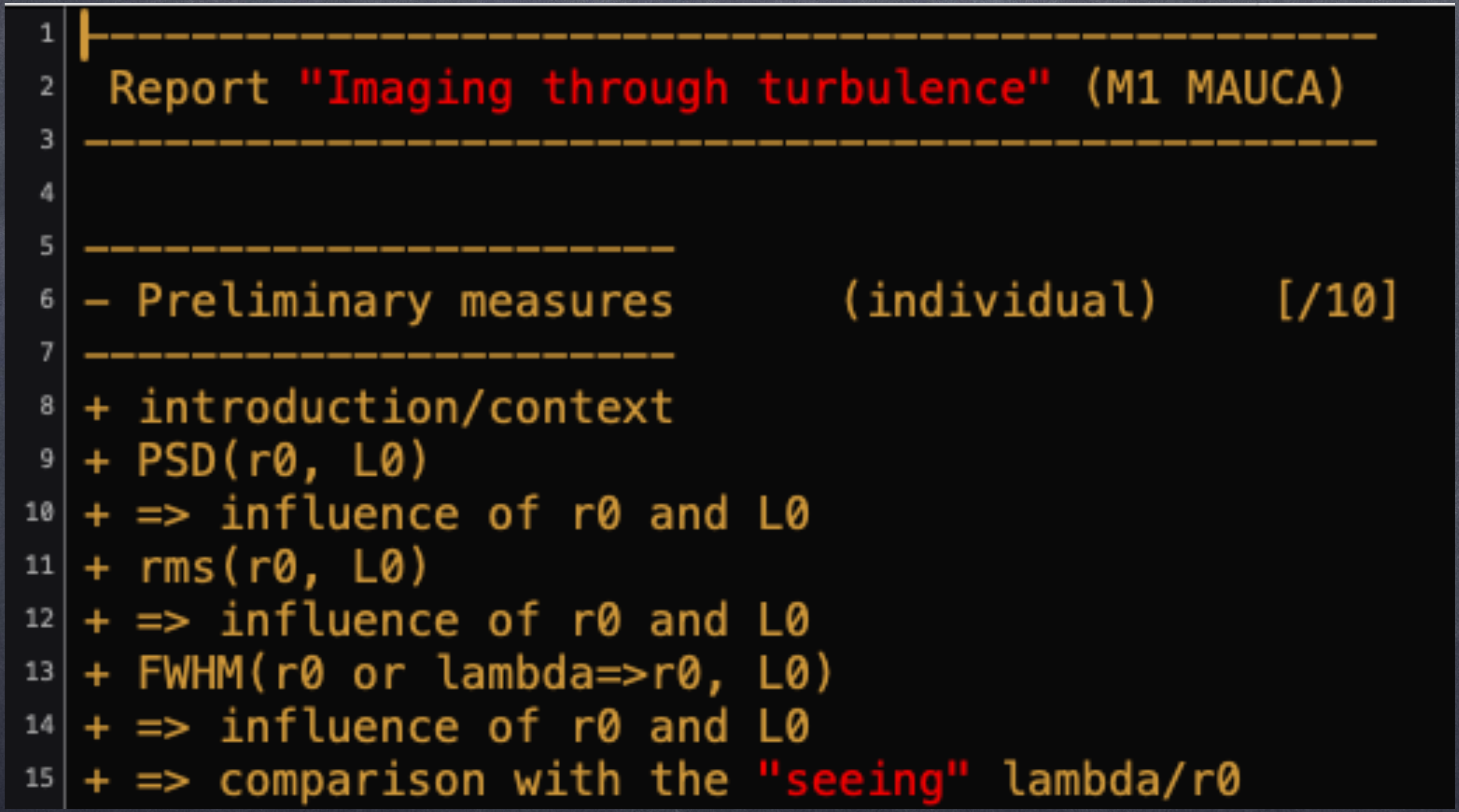
of telescope diameters and wavelengths. We show that this dependence is efficiently predicated by a simple approximate formula introduced in the literature in 2002. The practical consequences for operation of large telescopes are discussed and an application to on-sky data is presented.

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[1] of the PSF FWHM (denoted ε_0) on wavelength (λ) 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 ~ 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 ε_0[1] 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-



```
------------------------------------------------
 Report "Imaging through turbulence" (M1 MAUCA)
------------------------------------------------


----------------------
- Preliminary measures      (individual)    [/10]
----------------------
+ introduction/context
+ PSD(r0, L0)
+ => influence of r0 and L0
+ rms(r0, L0)
+ => influence of r0 and L0
+ FWHM(r0 or lambda=>r0, L0)
+ => influence of r0 and L0
+ => comparison with the "seeing" lambda/r0
```

(more to come…)