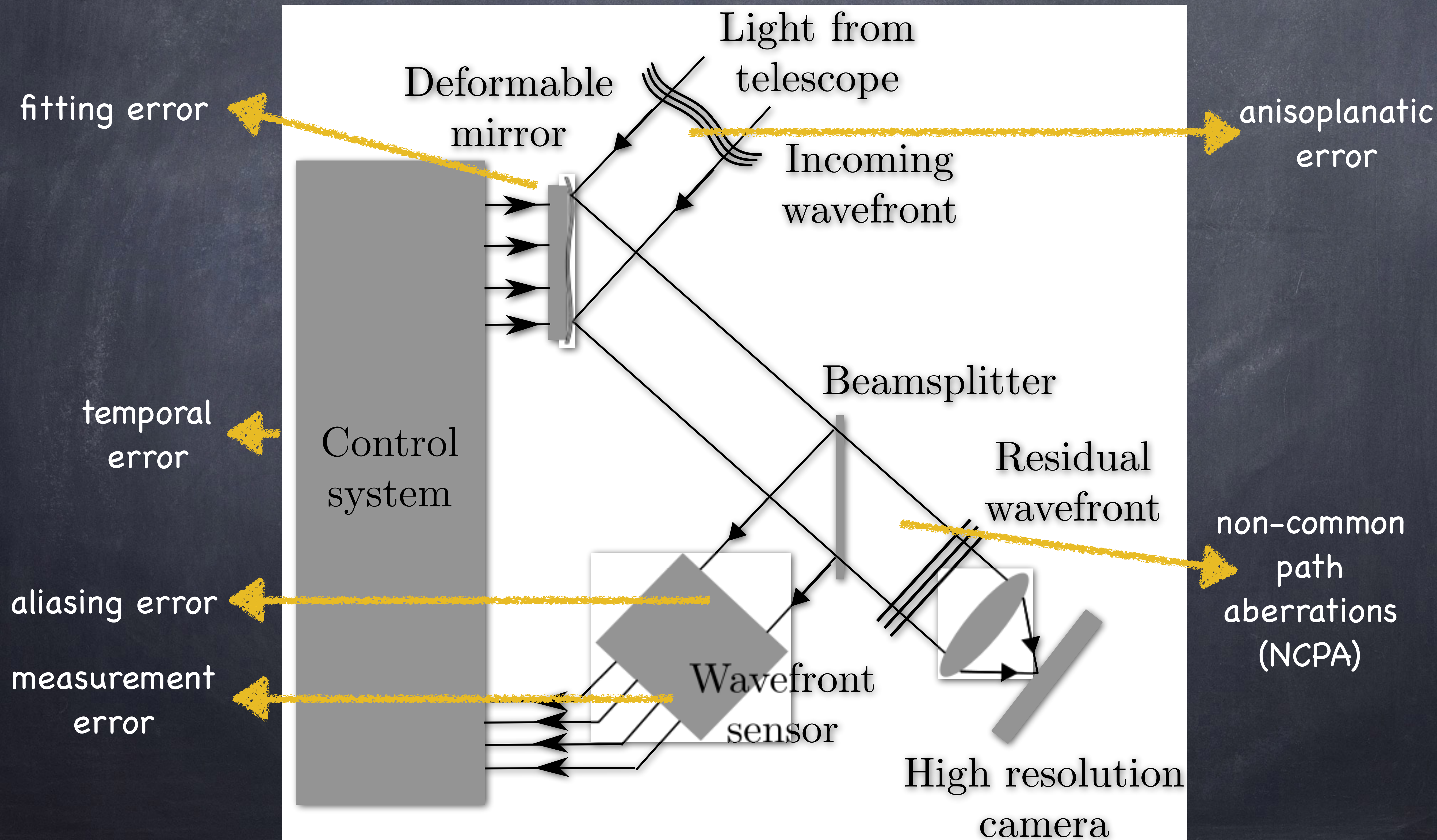
Post-AO error budget & PSF morphology - 1

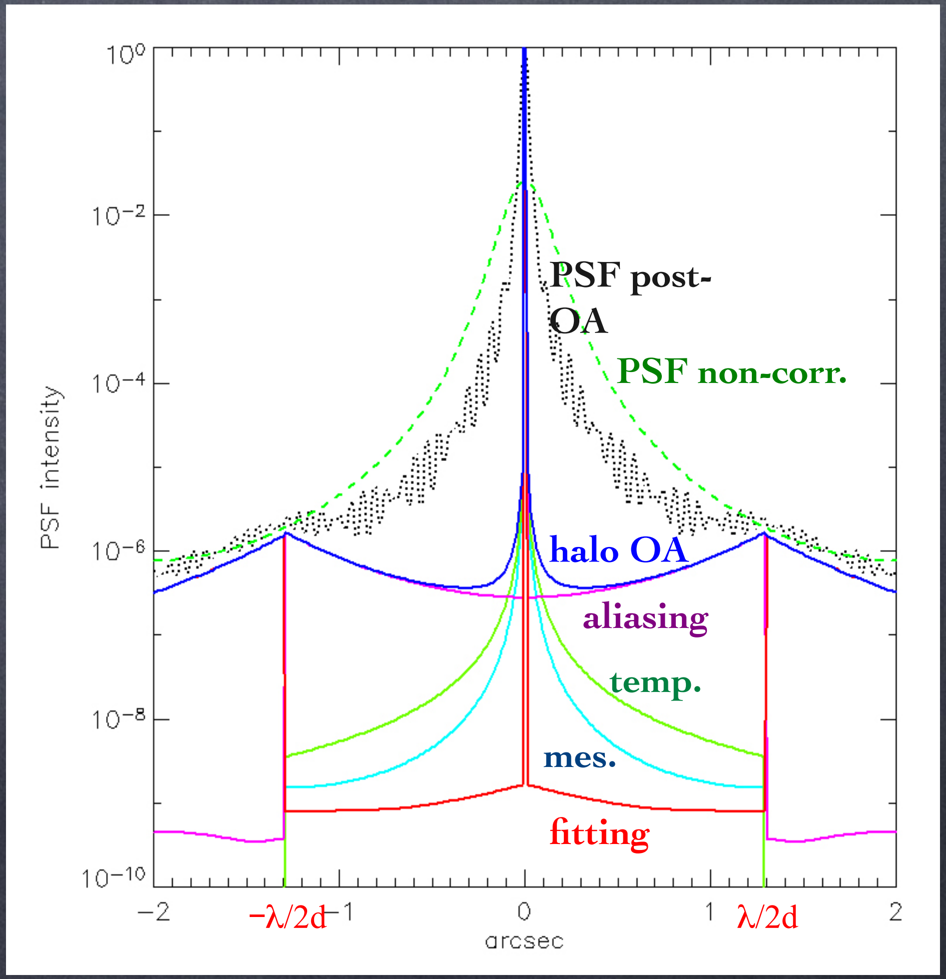


Post-AO error budget & PSF morphology - 2

$$\sigma^2_{\text{post-AO}} = \sigma^2_{\text{atm.}} + \sigma^2_{\text{AO syst.}} + \sigma^2_{\text{others}}$$

$$\sigma^2_{\text{atm.}} = \sigma^2_{\text{aniso.}} + \ldots$$

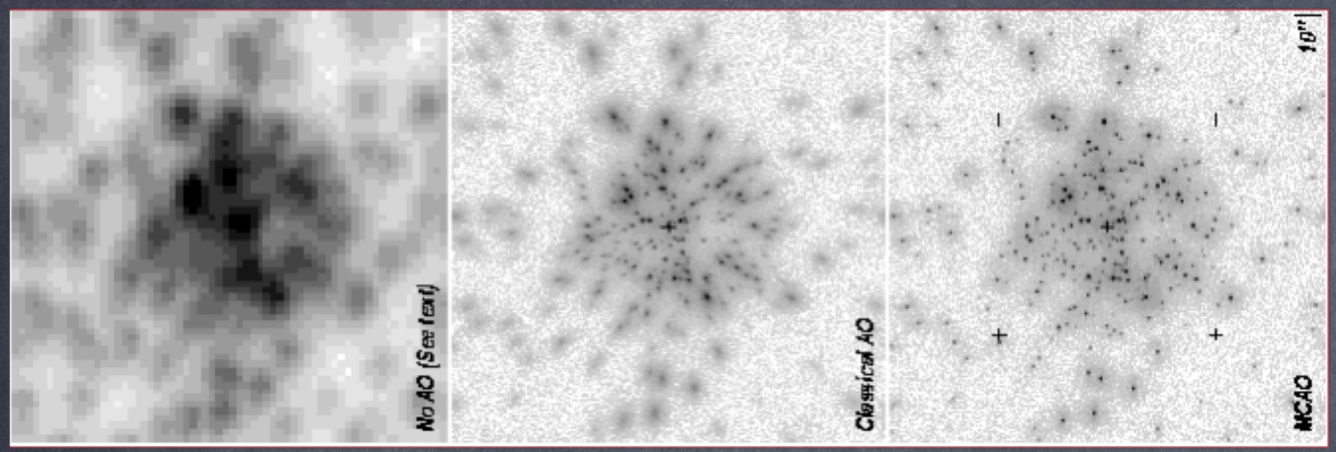
$$\sigma^2_{\text{others}} = \sigma^2_{\text{NCPA}} + \ldots$$



$$\sigma^2_{\text{AO syst.}} = \sigma^2_{\text{fitt.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{temp.}} + \ldots$$

Anisoplanatic error - 1

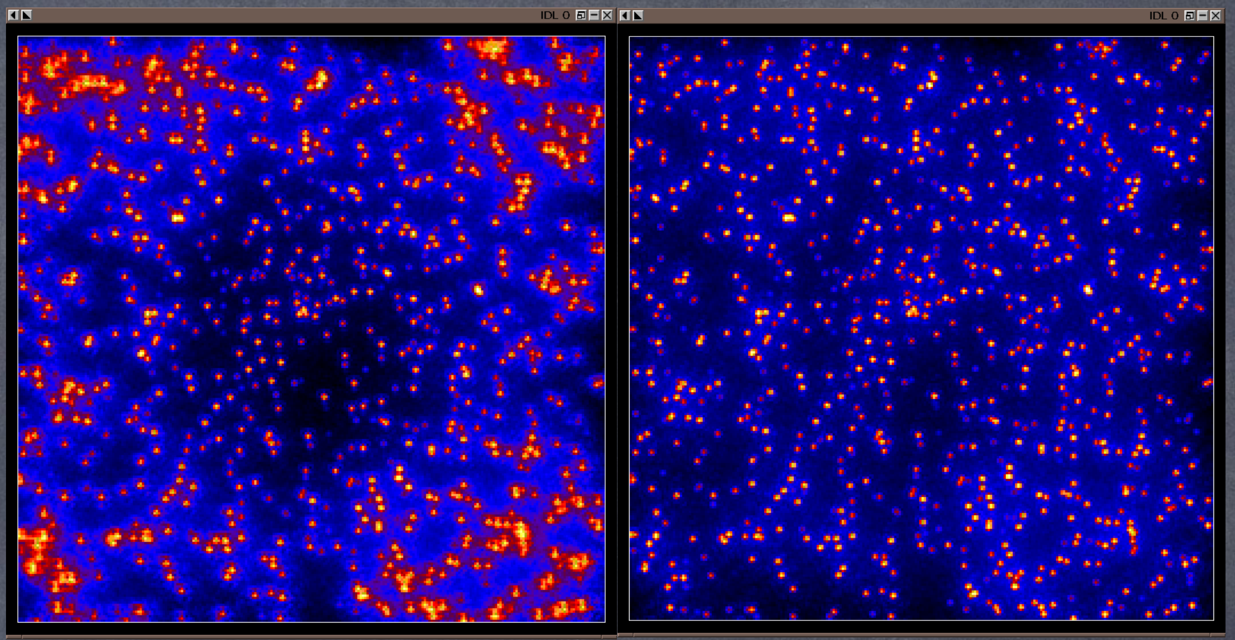
165”



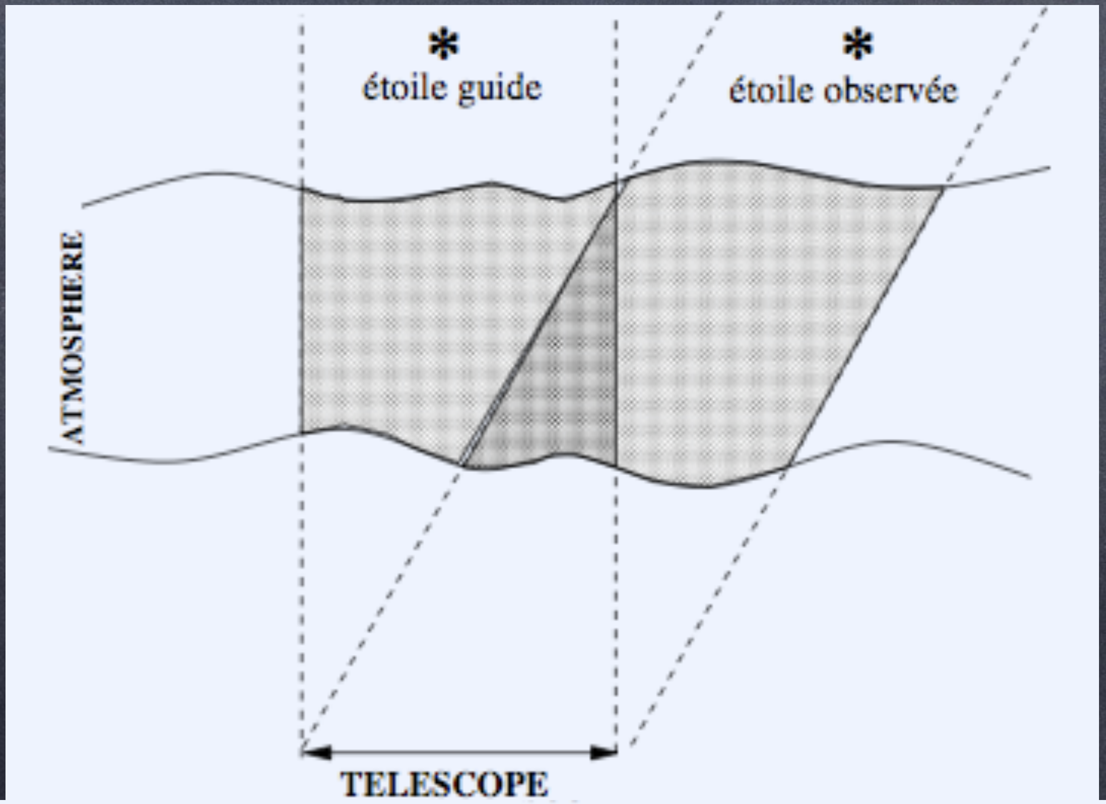
No AO

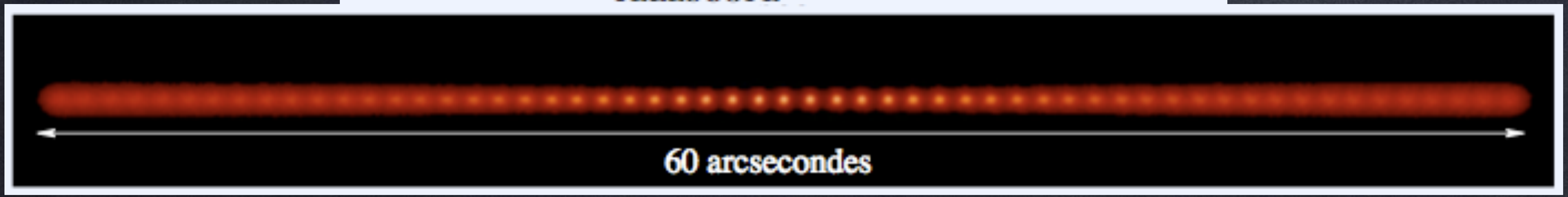
classical AO
(1 DM, 1 NGS)

MCAO
(2 DM, 5 NGS)

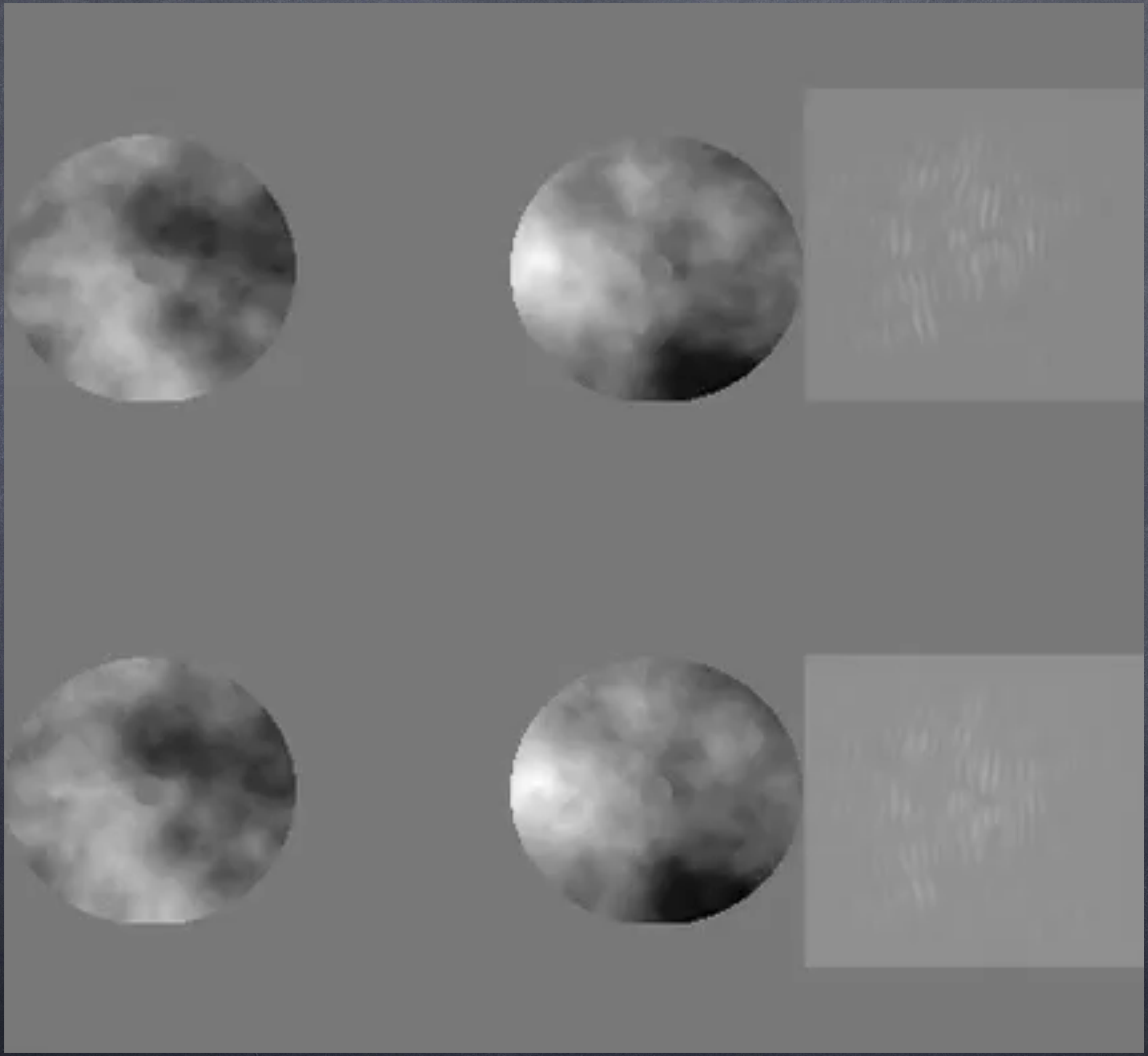


(bande J, champ de 1’, simu. B.Ellerbroek, Gemini Obs.)



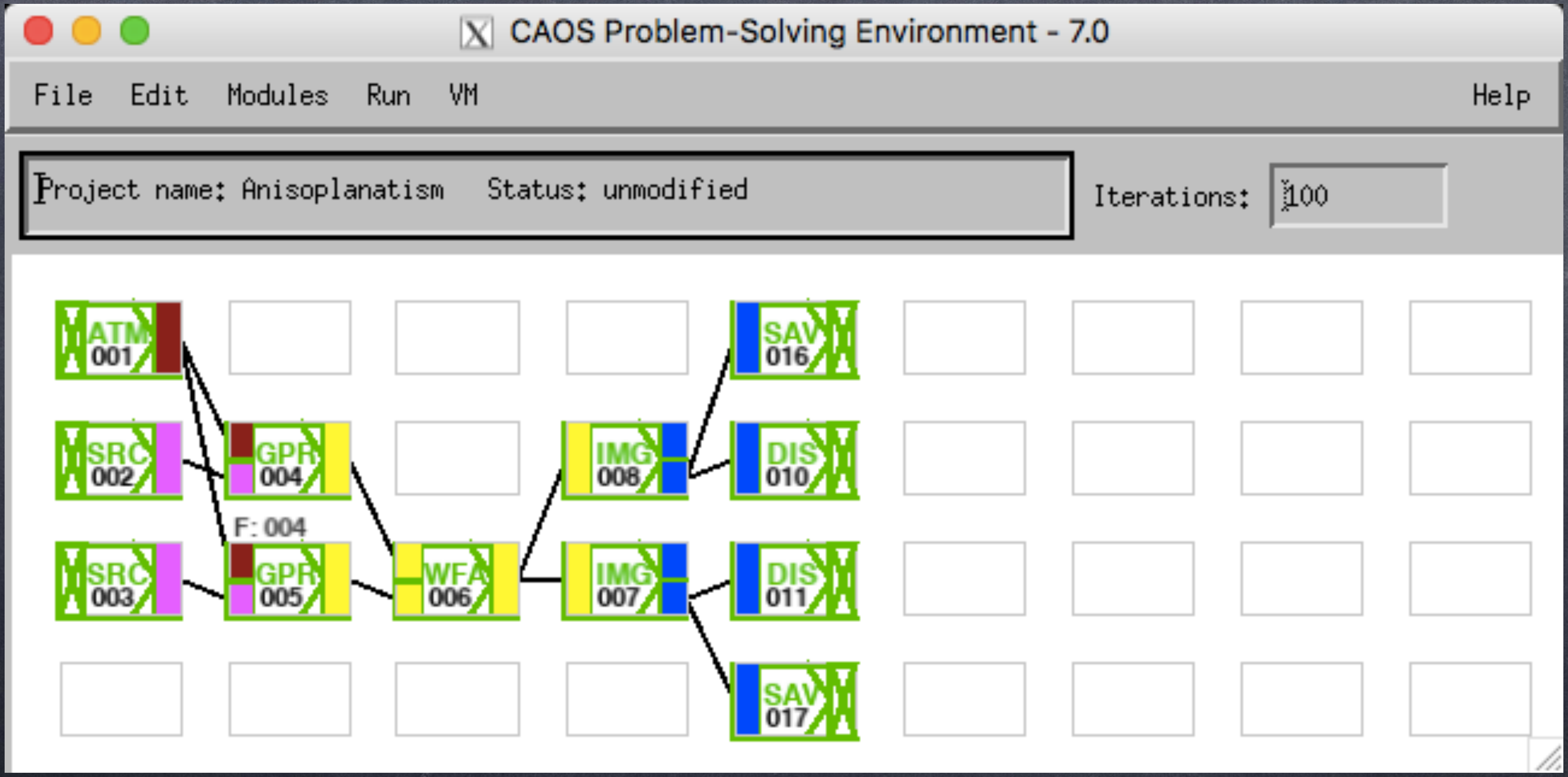


Anisoplanatic error - 2



Anisoplanatic error - 3

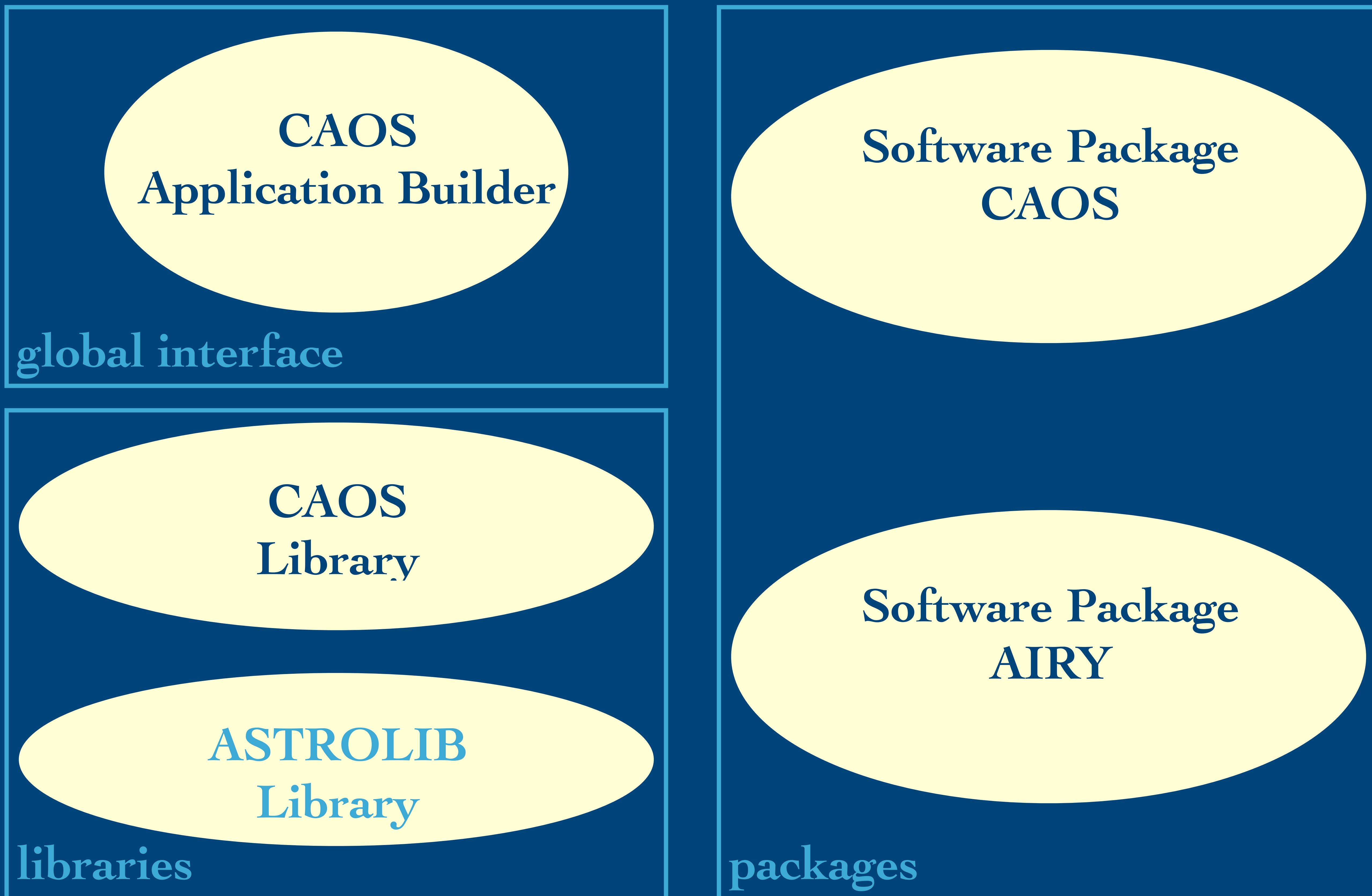
Numerical tool used for this study: CAOS
(CAOS Problem-Solving Environment + Software Package CAOS + Example project ``Anisoplanatism"...)



The CAOS “PSE”…

- CAOS means Code for *Adaptive Optics* Systems.
- “PSE” means Problem-Solving Environment.
- It is written in IDL, and based on a modular structure.
- It is composed of a global interface (the CAOS Application Builder), a library of utility routines (the CAOS Library), and some scientific packages (the Software Packages).
- a Software Package is a set of modules dedicated to a given scientific subject (AO, imaging, whatever).

CAOS Problem Solving Environment -1

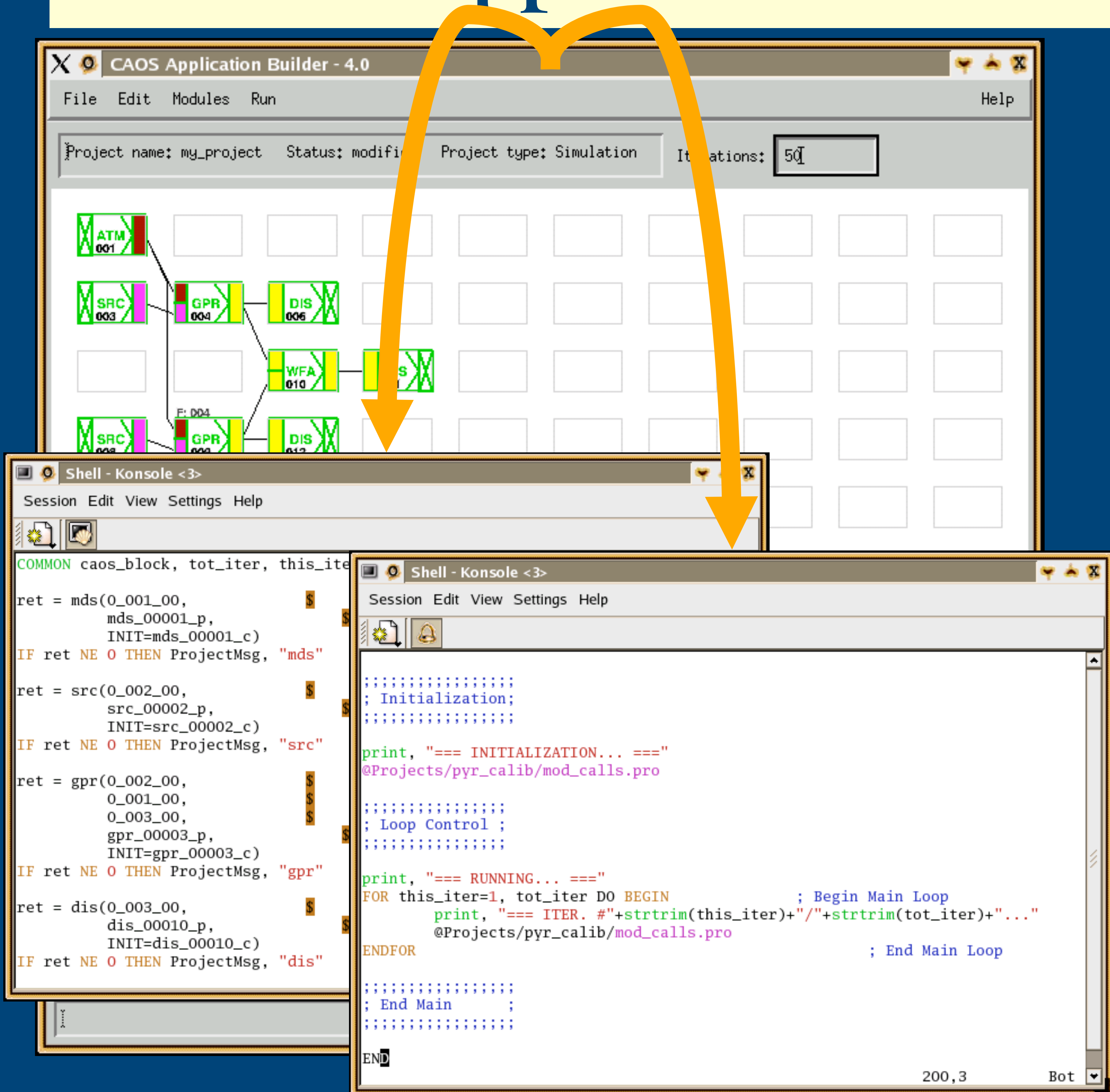


CAOS Problem Solving Environment -2

- caos_pse
  - appbuilder
  - library
  - packages
    - Soft. Pack. CAOS
    - Utilities
  - work_caos
    - admin. files
    - Projects
      - example projects
      - your own projects
    - other routines

somewhere else: astrolib, possibly some other library

CAOS Application Builder



It is the global user interface of the CAOS PSE: essentially a **worksheet** where the user can place small blocks, the modules, and connect them with data paths to form a **project.**

When the project is designed, it can be saved on disk, **generating the IDL code** which implements the simulation program.

The "virtual machine" feature of IDL permits in addition to have an IDL-licence-free version of a given project...

CAOS PSE: availability

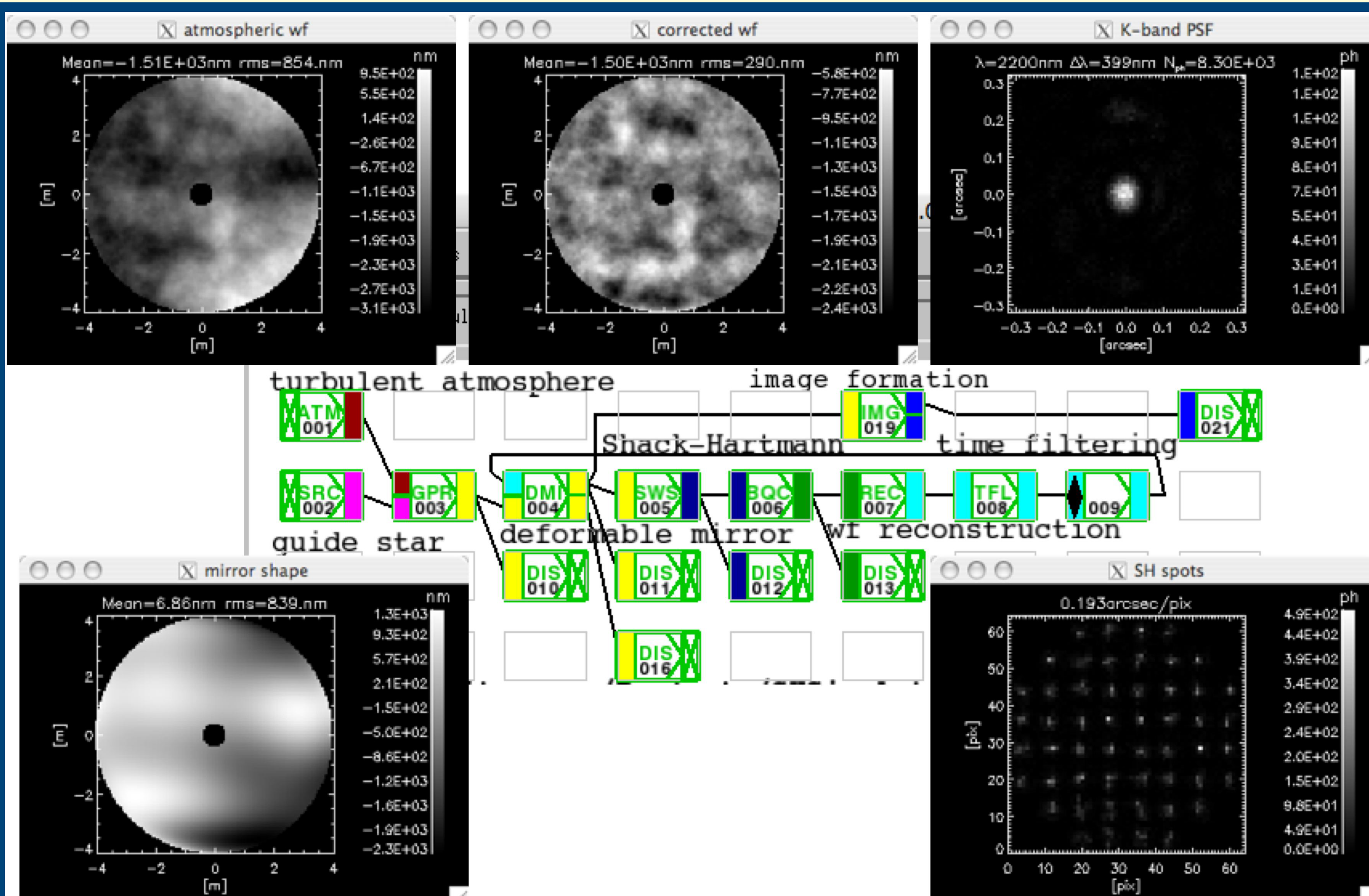
All (*public!*) parts of the CAOS PSE are available for download:

http://lagrange.oca.eu/caos/

Current status of the dedicated mailing-lists (as on February 2017):

- **Soft. Pack. CAOS: 101 subscribers,**
- **Soft. Pack. AIRY: 25 subscribers.**

End-to-end AO modeling with the Software Package CAOS - 1



End-to-end AO modeling with the Software Package CAOS - 2

Table 1. The 31 modules of the Software Package CAOS, version 7.0.

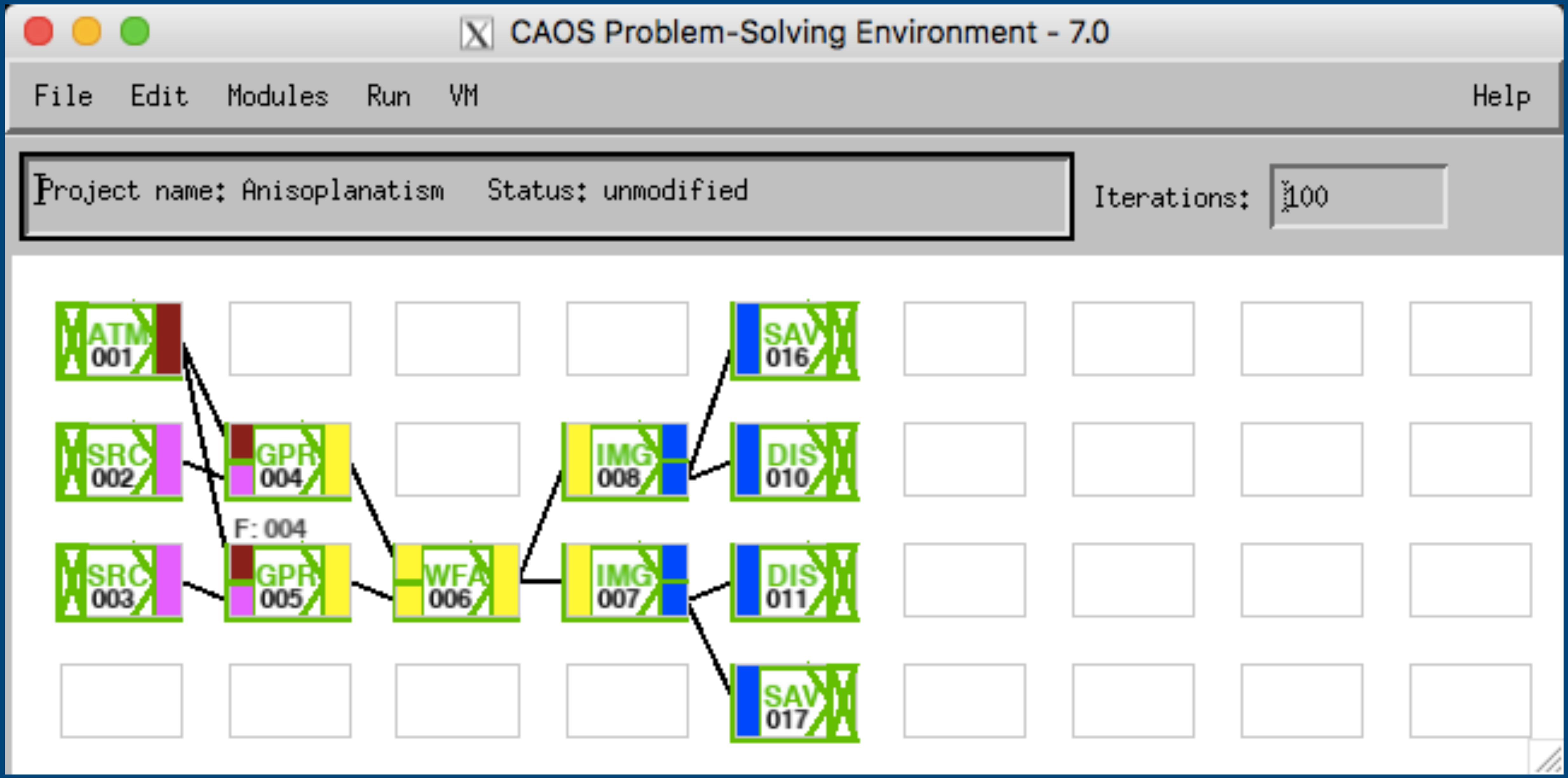
Module	Purpose
Optical turbulence & image formation	
ATM - ATMosphere building	-builds the turbulent atmosphere (FFT+subharmonics, Zernike) (see also utility PSG - Phase Screen Generation)
SRC - SouRCe definition	-characterizes the guide star/observed object
GPR - Geometrical PRopagator	-propagates light from source to telescope through atmosphere
IMG - IMaGing device	-forms an image of the observed object (+detector noises)
Wavefront sensing	
PYR - PYRamid wavefront sensor	-simulates the pyramid wavefront sensor
SLO - SLOpe computation	-computes the slopes from the pyramid signals
SWS - Shack-Hartman Wavefront Sensor	-simulates the Shack-Hartmann (SH) wavefront sensor
BQC - Barycentre/Quad-cell Centroiding	-compute the signals from the SH spots centroiding calculus
IWS - Ideal Wavefront Sensing	-applies "ideal" wavefront sensing (see text)
TCE - Tip-tilt CEntroiding	-computes and reconstructs tip-tilt
Wavefront reconstruction, control & correction	
REC - wavefront REConstruction	-reconstructs the wavefront
TFL - Time-FiLtering	-applies time-filtering after wavefront reconstruction
SSC - State-Space Control	-applies state-space control
DMI - Deformable MIrror	-simulates the behavior of a deformable mirror (DM)
TTM - Tip-Tilt Mirror	-simulates the behavior of a tip-tilt mirror
Calibration	
CFB - Calibration FiBer characterization	-defines a fiber to be used for calibration purpose
MDS - Mirror Deformation Sequencer	-generates a sequence of DM modes or influence functions
SCD - Save Calibration Data	-saves the calibration data (interaction matrix+set of deformates)
Wide-field AO	
AVE - signals AVEraging	-averages measurements from various wavefront sensors
COM - COMbine measurements	-combines measurements from various wavefront sensors
DMC - Deformable Mirror Conjugated	-corrects at different conjugated altitudes
Other modelling modules	
LAS - LASer characterization	-defines laser projector characteristics
NLS - Na-Layer Spot definition	-characterizes the Sodium-layer behavior
IBC - Interferometric Beam Combiner	-combines the light from two apertures
COR - COResonagraphic module	-simulates various coronagraphs (Lyot, Roddier&Roddier, FQPM)
AIC - Achromatic Interfero-Coronagraph	-simulates the Achromatic Interfero-Coronagraph
BSP - Beam SPlitter	-splits the light beam
Other utility modules	
WFA - WaveFront Adding	-adds or combines together wavefronts
ATA - ATmosphere Adding	-adds or combines together atmospheres
IMA - IMage Adding	-adds or combines together images
STF - STructure Function	-calculates the structure function and compares to theory

Imaging through the turbulent atmosphere: anisoplanatism ! - 1

Table 1. The 31 modules of the Software Package CAOS, version 7.0.

Module	Purpose
[illegible]	
ATM - ATMosphere building	-builds the turbulent atmosphere (FFT+subharmonics, Zernike) (see also utility PSG - Phase Screen Generation)
SRC - SouRCe definition	-characterizes the guide star/observed object
GPR - Geometrical PRopagator	-propagates light from source to telescope through atmosphere
IMG - IMaGing device	-forms an image of the observed object (+detector noises)
Wavefront sensing	
PYR - PYRamid wavefront sensor	-simulates the pyramid wavefront sensor
SLO - SLOpe computation	-computes the slopes from the pyramid signals
SWS - Shack-Hartman Wavefront Sensor	-simulates the Shack-Hartmann (SH) wavefront sensor
BQC - Barycentre/Quad-cell Centroiding	-compute the signals from the SH spots centroiding calculus
IWS - Ideal Wavefront Sensing	-applies "ideal" wavefront sensing (see text)
TCE - Tip-tilt CEntroiding	-computes and reconstructs tip-tilt
Wavefront reconstruction, control & correction	
REC - wavefront REConstruction	-reconstructs the wavefront
TFL - Time-FiLtering	-applies time-filtering after wavefront reconstruction
SSC - State-Space Control	-applies state-space control
DMI - Deformable MIrror	-simulates the behavior of a deformable mirror (DM)
TTM - Tip-Tilt Mirror	-simulates the behavior of a tip-tilt mirror
Calibration	
CFB - Calibration FiBer characterization	-defines a fiber to be used for calibration purpose
MDS - Mirror Deformation Sequencer	-generates a sequence of DM modes or influence functions
SCD - Save Calibration Data	-saves the calibration data (interaction matrix+set of deformates)
Wide-field AO	
AVE - signals AVEraging	-averages measurements from various wavefront sensors
COM - COMbine measurements	-combines measurements from various wavefront sensors
DMC - Deformable Mirror Conjugated	-corrects at different conjugated altitudes
Other modelling modules	
LAS - LASer characterization	-defines laser projector characteristics
NLS - Na-Layer Spot definition	-characterizes the Sodium-layer behavior
IBC - Interferometric Beam Combiner	-combines the light from two apertures
COR - CORonagraphic module	-simulates various coronagraphs (Lyot, Roddier&Roddier, FQPM)
AIC - Achromatic Interfero-Coronagraph	-simulates the Achromatic Interfero-Coronagraph
BSP - Beam SPlitter	-splits the light beam
Other utility modules	
WFA - WaveFront Adding	-adds or combines together wavefronts
[illegible]	[illegible]
IMA - IMage Adding	-adds or combines together images
STF - STructure Function	-calculates the structure function and compares to theory

Imaging through the turbulent atmosphere: anisoplanatism ! - 2



Install CAOS PSE + Soft. Pack. CAOS + Example project… - 1

http://lagrange.oca.eu/caos/

DOWNLOADS:

- Last version of the **CAOS PSE** (version 7.1): here.
- Last version of the **Software Package CAOS (version 7.0)**: here.
- Last version of the **Software Package AIRY (version 7.2)**: here.

CAOS Problem-Solving Environment (CAOS PSE) # version 7.1

- Installation instructions
- CAOS PSE 7.1 archive file

Install CAOS PSE + Soft. Pack. CAOS + Example project… - 2

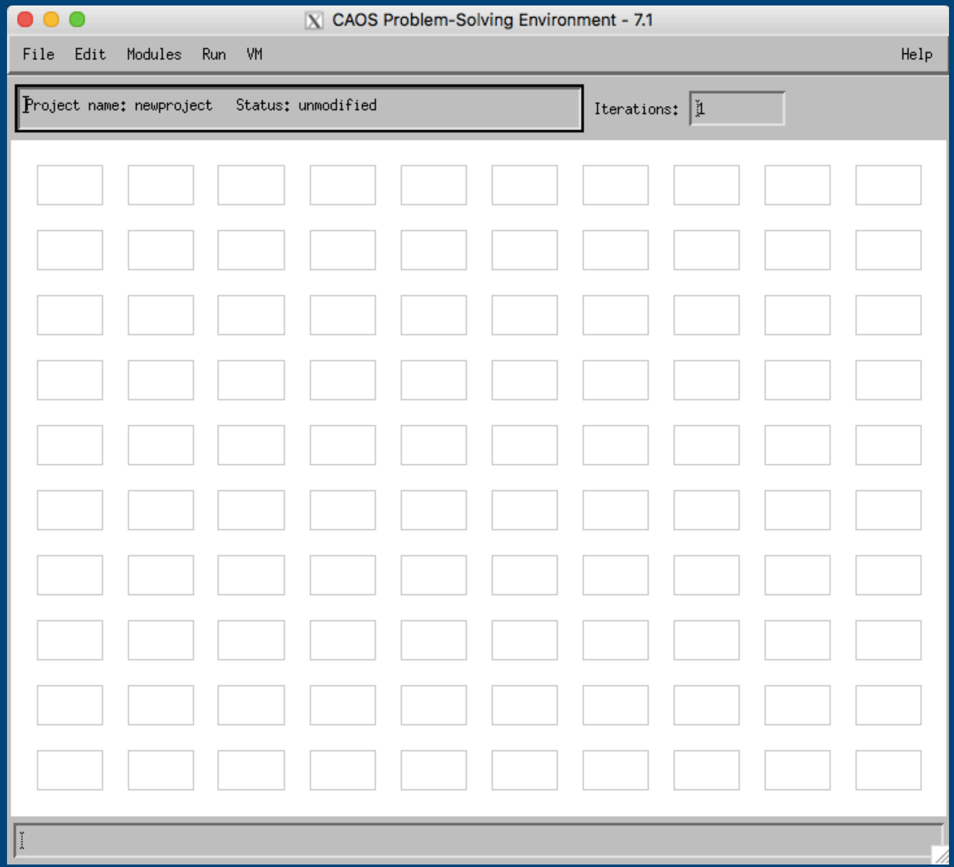
```
01-Click on "CAOS PSE 7.1 archive file" and unpack then the downloaded file
   caos_pse_7.1.tgz (with, e.g., "tar xvfz"). A directory called "caos_pse_7.1"
   will be created.
   Note that no Software Package is included, but the template one. The
   Software Packages (Soft.Pack.CAOS, Soft.Pack.AIRY) are obtainable from:
       http://lagrange.oca.eu/caos/

2a-UNIX/LINUX/MACOSX cases:
   Change directory to .../caos_pse/work_caos and:
   2a.1- Fix the paths in caos_env.sh (or .csh, depending on your shell).
   2a.2- Idem in caos_startup.pro.
```

```
03-UNIX/LINUX/MACOSX cases:
   Type "source caos_env.csh" (or .sh).
```

```
04-Launch IDL.
```

```
05-Type "worksheet" at the CAOS prompt in order to use the CAOS
   Application Builder.
```



Install CAOS PSE + Soft. Pack. CAOS + Example project… - 3

DOWNLOADS:

- Last version of the **CAOS PSE** (version 7.1): here.
- Last version of the **Software Package CAOS (version 7.0)**: here.
- Last version of the **Software Package AIRY (version 7.2)**: here.

Software Package CAOS
version 7.0

- Installation instructions
- Soft.Pack.CAOS 7.0 archive file
- Example projects using the Soft.Pack.CAOS 7.0

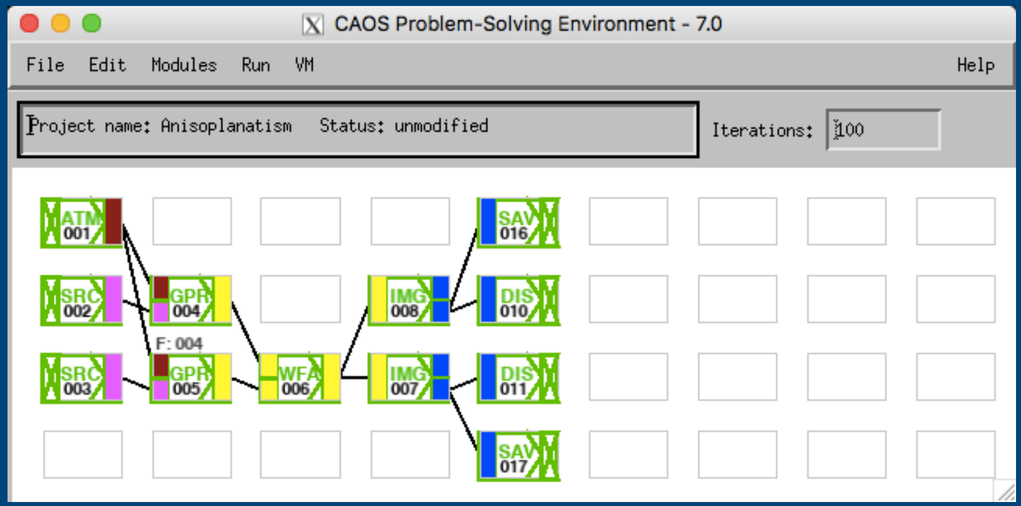
Install CAOS PSE + Soft. Pack. CAOS + Example project… - 4

```
02-Change directory to .../caos_pse/packages/, then click on the link
   "Soft.Pack.CAOS 7.0 archive file" and unpack the downloaded file
   CAOS_Software_Package_7.0.tgz (with, e.g., "tar xvfz").
   A directory called "CAOS_Software_Package_7.0" will then be created.
   Note that you will need to eliminate the .tar file when unpacking
   is concluded - in fact NO OTHER FILES than the set of modules
   (packages) have to be present in the "packages" directory.

03-Please note that some modules of this distribution also need the IDL
   Astronomy User's Library, commonly called "astrolib". This library
   is available from http://idlastro.gsfc.nasa.gov.

04-Change directory to .../work_caos/, then click on the link
   "Example projects using the Soft.Pack.CAOS 7.0" and unpack the
   downloaded file Projects.tgz, containing the directory "Projects"
   where some example projects can be found.

05-UNIX/LINUX/MACOSX cases:
   Type "source caos_env.csh" (or .sh).
```




```
07-Type "worksheet" at the CAOS prompt in order to use the CAOS
   Application Builder.

08-Type "@compile_all_CAOS_modules" in order to re-generate the
   default parameter files of the whole set of modules (upgrading so
   any possible pre-defined path).

09-You can find some examples in work_caos/Projects to play around with.
   Let open one example project from the worksheet ("File"->"Open Project").
```

Alternative to regular installation: copy CAOS PSE + Soft. Pack. CAOS + project "Anisoplanatism"

02-~~Change directory to .../caos_pse/packages/, then click on the link "Soft.Pack.CAOS 7.0 archive file" and unpack the downloaded file CAOS_Software_Package_7.0.tgz (with, e.g., "tar xvfz"). A directory called "CAOS_Software_Package_7.0" will then be created. Note that you will need to eliminate the .tar file when unpacking is concluded - in fact NO OTHER FILES than the set of modules (packages) have to be present in the "packages" directory.~~

→ >> cp -r ../marcel/caos_pse .

03-~~Please note that some modules of this distribution also need the IDL Astronomy User's Library, commonly called "astrolib". This library is available from http://idlastro.gsfc.nasa.gov.~~

→ >> cp -r ../marcel/astrolib .

04-Change directory to .../work_caos/, ~~then click on the link "Example projects using the Soft.Pack.CAOS 7.0" and unpack the downloaded file Projects.tgz, containing the directory "Projects" where some example projects can be found.~~

→ … and adapt caos_env.sh & caos_startup.pro

05-UNIX/LINUX/MACOSX cases:
Type "source caos_env.csh" (or .sh).

→ then type 'IDL'…

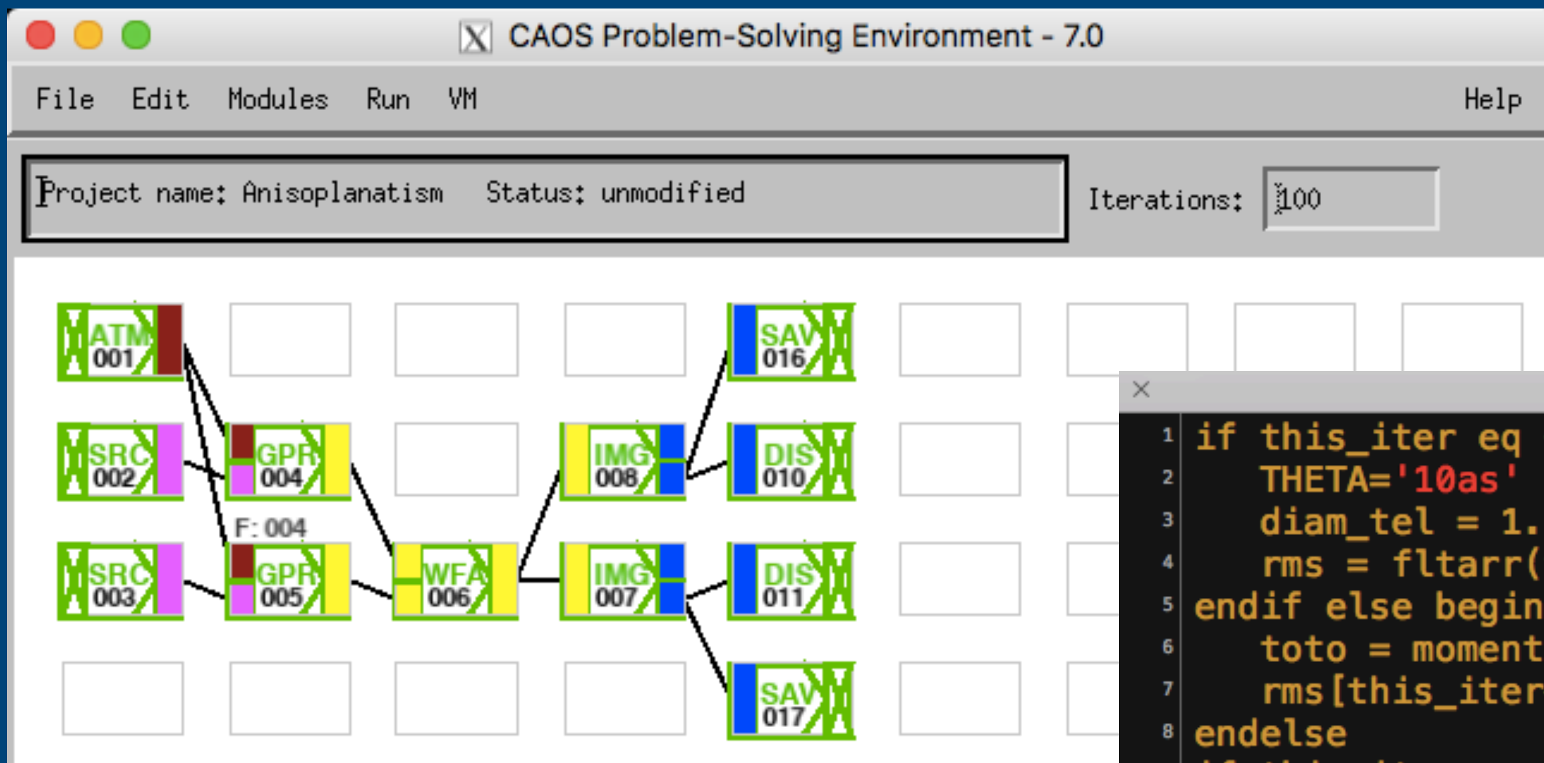
07-Type "worksheet" at the CAOS prompt in order to use the CAOS Application Builder.

08-Type "@compile_all_CAOS_modules" in order to re-generate the default parameter files of the whole set of modules (upgrading so any possible pre-defined path).

09-~~You can find some examples in work_caos/Projects to play around with. Let open one example project from the worksheet ("File"->"Open Project").~~

→ open project "Anisoplanatism"…

Modify project "Anisoplanatism"



modif_mod_calls.pro

```
if this_iter eq 0 then begin
   THETA='10as'
   diam_tel = 1.
   rms = fltarr(tot_iter)
endif else begin
   toto = moment(o_006_00.screen, SDEV=dummy)
   rms[this_iter-1] = dummy
endelse
if this_iter eq tot_iter then begin
   save, rms, FILE='Projects/Anisoplanatism/rms_'+THETA+'.sav'
   print, "rms moyen en sortie = ", mean(rms)*1E9, " [nm]"

   PSF_H = o_007_00.image
   LAMBDA = o_007_00.lambda
   RES = o_007_00.resolution
   toto  = gauss2dfit(PSF_H,a) & sig = (a[3]+a[2])/2.
   fwhm = 2*sig*sqrt(2*alog(2))*RES
   print, "FWHM en H = ", fwhm, ' ["] = ', $
          fwhm/(LAMBDA/diam_tel*!RADEG*3600), " [lambda/D]"

   PSF_500 = o_008_00.image
   LAMBDA = o_008_00.lambda
   RES = o_008_00.resolution
   toto  = gauss2dfit(PSF_500,a) & sig = (a[3]+a[2])/2.
   fwhm = 2*sig*sqrt(2*alog(2))*RES
   print, "FWHM à 500nm = ", fwhm, ' ["] = ', $
          fwhm/(LAMBDA/diam_tel*!RADEG*3600), " [lambda/D]"
endif
```

add the following code ``by hand" at the end of the file ``mod_calls.pro"...
(copy it from file ``modif_mod_calls.pro")

run the simulation project:
.r ./Projects/Anisoplanatism/project.pro

(Another useful metrics: the Strehl ratio)

$$S = \frac{I_{\text{post AO}}[0,0]}{I_{\text{perfect}}[0,0]}$$

where *I[0,0]* is the intensity of the PSF at the optical center of the field (K. Strehl, Zeit. Instrumenkde 22, 213 (1902)).

$$S \simeq \exp\{-\sigma^2_{\text{post AO}}\}$$

in the framework of the Maréchal's approximation, where the variance (in radians²) is supposed to be small enough...