yao::manual

This manual is for yao v4.5.0. It was almost entirely re-written from previous versions.

Written by Francois Rigaut on November 2009. Expand/Collapse all detailled comments.

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1. A session at a glance...

1.1 A basic yao session

... consist of a few steps:

1. Craft up a parameter file describing the system you want to model, say `"mysystem.par"`
2. Start yorick/yao
3. `aoread,"mysystem.par"`
4. `aoinit,some keywords...`
5. `aoloop,some keywords...`
6. `go`

Let us now enter into some details.

1.2 The Basics

Is yorick installed ? All set up as per the installation instructions ? Then go to the `examples` directory of the yao distribution; this might be in different locations depending on how you installed yao. To determine where is it is, run the command `find_examples_path()` within yao. Type the following at the unix prompt:

```
poliahu:~ $ yorick -i yao.i
 Copyright (c) 2005.  The Regents of the University of California.
 All rights reserved.  Yorick 2.1.05x ready.  For help type 'help'
 Yao version 4.5.0, Last modified 2009oct23
>
```

You get the yorick and yao welcome messages and the yorick prompt. Alternatively, you can start a normal yorick session and then include yao at any time by typing:

```
> #include "yao.i"
```

You can double check everything is normal by typing:

```
> info,aoread
func aoread(parfile)
```

if you get this message, you are in business. If not, fix your yorick installation. Click here to show/hide notes on Yorick.

- At this point it might be worth to mention that yorick, in its basic mode, does not have line recall or line editing capabilities. You can get that very easily into emacs, by installing yorick.el and yorick-auto.el in your emacs file/directory (if you installed yorick with the debian/ubuntu package manager, yorick.el should already be installed). See the instructions on top of yorick-#.#/emacs/yorick.el on how to do that. It's not complicated,

and worth every second you invest in this 5mn installation. An alternative, that I personally use, is to run yorick within rlwrap, a wrapper of readline. rlwrap provides command recall, filename completion, main command completion, and history from session to session. Just install rlwrap and define yorick as an alias:

```
alias yorick='rlwrap -s 2000 -c -f ~/.yorick/yorick.commands yorick'
```

or something equivalent. See the rlwrap man pages for more details.

- Soon, you will need to know more about yorick and its syntax. The yorick manual is in `Y_HOME/doc/yorick.pdf`. A short help is at `Y_HOME/doc/refs.pdf` (`Y_HOME`, as well as `Y_SITE` and `Y_USER`, are yorick variables, get them at the yorick prompt).

The first thing to do is to **create phase screens** (to simulate turbulence). Type

```
> create_phase_screens,2048,256,prefix="screen"
```

This will create N (N=long dimension/short dimension, 8 in that case) phase screens of dimension 2048x256 suitable for use by **yao**. It is advised to choose dimensions that are powers of 2. Depending on your platform and CPU, it may take some time (1mn or so), as this routine is absolutely not optimized. This is a one shot run. You will not need to do that everytime you run **yao**, as you can, and are encouraged, to use the same phase screens. You may need to run it once more to create larger phase screens if the need arises, but that's about it. The phase screens (screen1.fits to screen8.fits in the example above) will be created in the current working directory. Move them somewhere convenient (I have them in `Y_USER/data=.yorick/data` in my case). You will need to edit the **yao** parameter files to reflect the path and names of these phase screens if you put it somewhere different or used a different name (look for "atm.screen" in the parfile).

Next, we will try to run "sh6x6", which is a simple 6x6 Shack-Hartmann example. After you have edited the "sh6x6.par" file (in the `examples` directory) and modified the path and filename of the newly created phase screens, if needed, type:

```
> aoread,"sh6x6.par"
Yao, Version 4.5.0, 2009oct23
Checking parameters ...
No field stop defined for wfs 1. Setting to 'square'
wfs(1).fssize has not been set, will be forced to subap FoV
dm(1).coupling set to 0.200000
dm(1).iffile set to sh6x6-if1.fits
dm(2).iffile set to sh6x6-if2.fits
OK
>
```

What `aoread()` does is (a) read, or rather include, the parameter file, which will fill the various structures containing the definitions of the WFS, DM, loop, etc... and (b) go through a simple check of the parameters to see if anything is missing or if there are incompatible assigments, in which case it will print out an error message (hopefully understandable). Otherwise, it prints out informational messages or warnings.

Then we need to initialize the system. `aoinit()` will do that for us. It will initialize all the arrays (pupil, etc), initialize the system pupil, the various WFS, DM, etc. It will then compute the interaction matrix, invert it and finally plot (if requested) a graphical system configuration. The amount of information you get during the `aoinit` is set by `sim.verbose`. The default verbose in `sh6x6.par` is 0, which means you get no feedback at all except for warnings and error messages. Let's set `sim.verbose` to 1 and run `aoinit()`:

```
> sim.verbose=1
> aoinit,disp=1,clean=1
Checking parameters ...
OK

> INITIALIZING PHASE SCREENS
Reading phase screen "~/.yorick/data/screen1.fits"
Reading phase screen "~/.yorick/data/screen2.fits"
Reading phase screen "~/.yorick/data/screen3.fits"
Reading phase screen "~/.yorick/data/screen4.fits"

> INITIALIZING SENSOR GEOMETRY
Kernel FWHM for the iMat calibration = 0.364983
Pre-computing Kernels for the SH WFS
 WFS# |       Pixel sizes         | Subap. size | Number of pixels | #photons
      | Desired  Quantum  Actual  | Max  Actual | Desired   Actual | /sub/iter
```

```
 1      0.20000  0.03182  0.19093   2.04  1.91    10x10      10x10   70735.5
NGS#1 flux varies between 42795 and 70736 photon/subap/it

> Initializing DM influence functions
  >> Computing Influence functions for mirror # 1

Creating Influence function for actuator #1 2 3 4 5 6 7 8 9 10 11 12
13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
36 37 38 39 40 41 42 43 44 45 46 47 48 49

  >> Storing influence functions in sh6x6-if1.fits... Done
  >> Computing Influence functions for mirror # 2

  >> Storing influence functions in sh6x6-if2.fits... Done

> DOING INTERACTION MATRIX
  DM #1: # of valid actuators: 45. (I got rid of 4 actuators after iMat)
  >> valid I.F. stored in sh6x6-if1.fits
Computing valid to extrap. matrix for DM#1

> INITIALIZING MODAL GAINS
I did not find simulModeGains.fits or it did not have the right
   number of elements (should be 47), so I have generated
   a modal gain vector with ones in it.


> INTERACTION AND COMMAND MATRICES
 >> Preparing SVD and computing command matrice
Smallests 2 normalized eigenvalues = 0.014315    1.62232e-07
4 modes discarded in the inversion

Summary:
Mirror #1, stackarray, 45 actuators, conjugated @ 0 m
Mirror #2, tiptilt, 2 actuators, conjugated @ 0 m
WFS # 1, hartmann (meth. 2), 32 subap., offaxis (+0.0",+0.0"), noise enabled
D/r0 (500nm) = 42.4; 5000 iterations
>
```

At this point you have initialized everything. The `aoinit()` keyword `clean` indicates that you want to start from scratch, and ignore any influence function or interaction/command matrix files on your disk. The `disp=1` is to get some graphical feedback. You are now ready to run the loop:

```
> loop.niter = 1000
> aoloop,disp=10
NGS#1 flux varies between 42795 and 70736 photon/subap/it

> Starting loop with 1000 iterations
> go
 Iter#  Inst.Strehl  Long expo.Strehl  Time Left
     1  0.000        0.000             00:00:18.8
    51  0.407        0.393             00:00:15.1
   101  0.412        0.410             00:00:13.7
   [...]
   901  0.647        0.504             00:00:01.4
   951  0.546        0.507             00:00:00.7
Saving results in /home/frigaut/yorick-2.1/share/yao/examples/sh6x6.res (ps,imav.fits)...
time(1-2) =  9.49 ms  (WF sensing)
time(2-3) =  0.03 ms  (Reset and measurement history handling)
time(3-4) =  0.01 ms  (cMat multiplication)
time(4-5) =  1.85 ms  (DM shape computation)
time(5-6) =  1.44 ms  (Target PSFs estimation)
time(6-7) =  1.53 ms  (Displays)
time(7-8) =  0.05 ms  (Circular buffers, end-of-loop printouts)
Finished on 00:26:30
69.040800 iterations/second in average

         lambda   XPos   YPos  FWHM[mas]  Strehl  E50d[mas]  #modes comp.
Star# 1    1.65    0.0    0.0       44.1   0.507      172.0         35.1
Field Avg  1.65                      44.1   0.507      172.0
Field rms                             0.0   0.000        0.0
>
```

You have ran 1000 iterations (`loop.niter` in `sh6x6.par` is larger so we changed it before starting the loop in the example above to keep your demo time reasonable). `disp=10` in the call means "*do your displays every 10 iterations*". Depending on your graphic card, displays can be pretty expensive (time), thus it helps to display less frequently.

At any time, while the loop is running, you have access to the yorick prompt. You can type regular commands, but the most useful are:

- `stop` which will pause the execution of the loop,
- `cont` which will resume the loop where it paused,
- `reset` which will reset commands and dm shape,
- `restart` which will restart from iteration 1.

at the completion of the requested number of iterations, `go()` will automatically call the function `after_loop()`, which outputs a number of things as shown above (starting from "Saving results..."): Some statistics on execution time and number of iterations per seconds, and the Strehl, FWHM, etc, on every "target" for which positions were specified in the parameter file. You can call `after_loop()` by hand at any time also, and you can call it multiple times.

The resulting average images have been saved on disk ("sh6x6-imav.fits"), together with a small postscript file ("sh6x6.ps") that contains some graphics. Strehl, FWHM and 50 percent encircled energy are available as extern variables under the name strehl, fwhm and e50 (the averaged PSFs are also available, together with the history of DM commands, DM errors and WFS measurements if the keyword `savecb=` has been set):

```
> strehl
[[0.434317]]
```

These variables contains the values for all the images (here there is only one, but there can be an arbitrary number of positions and wavelengths at which you want to estimate the performance). This can be useful in script, as detailled below.

Finally, note that you can have access to some documentation on each function by typing `help,function_name`, e.g:

```
> help, aoinit
 /* DOCUMENT aoinit(disp=,clean=,forcemat=,svd=,dpi=,keepdmconfig=)
    Second function of the ao serie.
    Initialize everything in preparation for the loop (aoloop).
    Follows a call to aoread, parfile.

    disp         = set to display stuff
    clean        = if set, aoinit will start fresh. *Nothing* is kept from
[...]
```

Tip: sometimes the document section of a function is not up to date. You can get a peek on the actual function API by using info:

```
> info, aoinit
func aoinit(disp=,clean=,forcemat=,svd=,dpi=,keepdmconfig=)
```

2. The Parameter File

Here is an example of a parameter file (parfile). Comments below.

```
// YAO parameter file
//-------------------------------
sim.name           = "SH6x6 w/ TT mirror and WFS, full diffraction WFS";
sim.pupildiam      = 120;
sim.debug          = 0;
sim.verbose        = 0;

//-------------------------------
atm.dr0at05mic     = 42.44;  // this is r0=0.166 at 550 nm
atm.screen         = &(Y_USER+"data/screen"+["1","2","3","4"]+".fits");
atm.layerfrac      = &([0.4,0.2,0.3,0.1]);
atm.layerspeed     = &([11.,20,29,35]);
```

```
atm.layeralt       = &([0.,400,6000,9000]);
atm.winddir        = &([0,0,0,0]);

//--------------------------------
nwfs               = 1; // number of WFSs (>1 if e.g. mcao)
wfs                = array(wfss,nwfs);

wfs(1).type        = "hartmann";
wfs(1).lambda      = 0.65;
wfs(1).gspos       = [0.,0.];
wfs(1).gsalt       = 0.;
wfs(1).gsmag       = 5.;
wfs(1).shmethod    = 2;
wfs(1).shnxsub     = 6;
wfs(1).pixsize     = 0.2;
wfs(1).npixels     = 10;
wfs(1).noise       = 1;
wfs(1).ron         = 3.5;
wfs(1).shthreshold = 0.;
wfs(1).nintegcycles= 1;

//--------------------------------
ndm                = 2;
dm                 = array(dms,ndm);

n  =1;
dm(n).type         = "stackarray";
dm(n).iffile       = "";
dm(n).nxact        = 7;
dm(n).pitch        = 20;
dm(n).alt          = 0.;
dm(n).unitpervolt  = 0.01;
dm(n).push4imat    = 100;

n  =2;
dm(n).type         = "tiptilt";
dm(n).iffile       = "";
dm(n).alt          = 0.;
dm(n).unitpervolt  = 0.0005;
dm(n).push4imat    = 400;

//--------------------------------
mat.condition      = &([15.]);
mat.file           = "";

//--------------------------------
tel.diam           = 7.9;
tel.cobs           = 0.1125;

//--------------------------------
target.lambda      = &([1.65]);
target.xposition   = &([0.]);
target.yposition   = &([0]);
target.dispzoom    = &([1.]);

//--------------------------------
gs.zeropoint       = 1e11;

//--------------------------------
loop.gain          = 0.6;
loop.framedelay    = 1;
loop.niter         = 5000;
loop.ittime        = 2e-3;
loop.startskip     = 10;
loop.skipevery     = 10000;
loop.skipby        = 10000;
loop.modalgainfile = "simulModeGains.fits";

//--------------------------------
```

The parfile defines entirely your system. As you see, it is made of several (9) subsections, in which the 9 main yao structures are filled. All of the structure members are listed in the yao structure section, together with a short explanation of each parameters (structure member). How to combine these parameters to get yao to do what you

want is explained in the controlling features section below.

Several comments:

- A parfile, and the one above in particular, does not have to include **all** parameters. Only a few are mandatory for each elements (WFS, DM) and the rest have reasonable defaults.
- The parfile is in fact a yorick include file, and those are yorick statements you see in there. So you can make use of yorick loops, etc (see for example mcao2-bench.par on how the wfs structure is filled).
- Because they can have variable length, and be dynamically re-defined, many structure members are actually pointers (to vectors or arrays). A pointer in yorick is assigned with the symbol `&` so that `&a` is the pointer to the quantity `a`. The notation

```
atm.layerfrac = &([0.4,0.2,0.3,0.1]);
```

  is a shorthand for

```
a=[0.4,0.2,0.3,0.1];
atm.layerfrac = &a;
```

  If you forget the & sign, it should generate an error.
- There are about 20 parfiles in the example directory (remember? `find_examples_path()` will tell you where this directory is). Browse through these examples. It is recommended to actually start from one of these, preferably one that is close to the system you want to simulate, and adapt it to your needs, rather than starting from scratch.
- Once you are done, save the parfile and, in the same directory, start yao and go through the sequence of `aoread(), aoinit(), aoloop()` and `go()` as shown in section 1.

3. Controlling Features

3.1 Overall Geometry

In yao, you have to define the AO system you want to simulate. It starts by defining an entrance aperture (the system pupil). This is done through 2 parameters: the physical pupil size (e.g. diameter) in real world units, meters. And because yao is a monte-carlo code, that uses arrays to generate phases and PSFs, we will need a pupil array and thus a pupil diameter in pixel.

```
sim.pupildiam  <- this is the pupil diameter in pixel (unitless)
tel.diam       <- this is the telescope diameter in meters
```

yao also uses arrays to store the deformable mirror influence functions, etc. Generally speaking, there are two types of variable and arrays: the one referring to quantities in the **near field** (pupil plane or close to it, e.g. altitude layers) and the one referring to quantities in the **far field** (Shack-Hartmann WFS spots, PSF image, observed object, etc...).

The figure on the right illustrates how you can set up a Shack-Hartmann + Stackarray deformable mirror (allegedly the most common type of AO system to date). I will review all these parameters in sections below, but what I want to emphasize here is the following:

- The pupil is defined on a pixel array
- The WFS has to be defined (at least SHWFS) to span an area commensurate with the pupil (see below). However, it is possible to slightly oversize, downsize or even shift the WFS w.r.t. the pupil, if needed.
- The DM actuator positions and span also has to be defined to span an area commensurate with the pupil and WFS (see below). For a stackarray mirror, for instance, you typically want to have the DM pitch equal to the

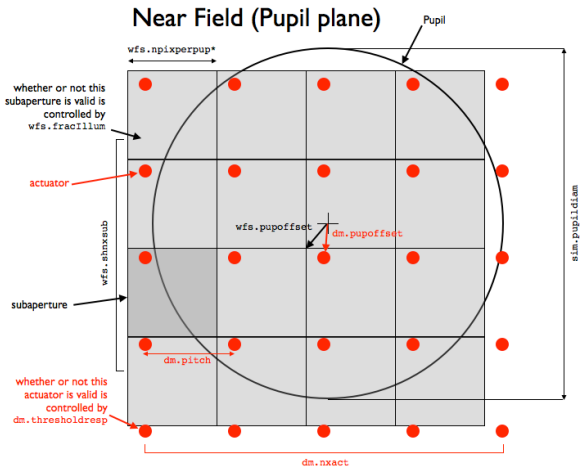


Figure 1: Typical geometry of a system (WFS and DM)

subaperture size (it doesn't have to be, but it is often the case). As for the WFS, you have the possibility to mismatch WFS and DMs by choosing a different pitch, or shifting the DM to induce misregistration.

3.1.1 Field of view considerations

The size of the pupil is actually quite important. By property of the Fourier transform, the field of view in the far field will be defined by the sampling in the near field, following the relation:

```
FoV = lambda/ps
```

where `ps = tel.diam/sim.pupildiam` is the pixel size in meter in the near field. So, for instance,

tel.diam [m]	sim.pupildiam [pixels]	FoV @650nm [']	FoV @1.65microns [']	Comment
8	128	2.14	5.44	
30	256	1.14	2.90	Probably too low
30	512	2.28	5.80	

Choose the field of view according to your application. But because eventually you will want to run simulations in presence of turbulence, **I generally advise to take at least 2 points per r0** (near field), and preferably 3. For `r0 = 16 cm`, that means a sampling of 8 cm (resp 5.33 cm), and for a 8-m telescope that would translate into 100 points (resp 150) across the pupil (`sim.pupildiam = 100`). If this is not done, you will likely end up with aliasing in the SHWFS subaperture images (probably less so in the final image if it is estimated in the Near Infrared and the WFS works in the visible). This is bad and will bias your results. You have been warned.

3.2 Pupil

Historically, yao was developed assuming circular pupils. So in any case, as said above, you will have to define `sim.pupildiam` and `tel.diam`. If another pupil shape is desired, it can be defined through a call to a user defined function `user_pupil()`. Click here to show/hide an example.

```
func make_square_pupil(void)
{
  extern ipupil, pupil;

  ipupil = array(0.0f,[2,sim._size,sim._size]);
  ipupil(sim._cent-sim.pupildiam/2+1:sim._cent+sim.pupildiam/2,
         sim._cent-sim.pupildiam/2+1:sim._cent+sim.pupildiam/2) = 1.0f;
  pupil = ipupil;
}
user_pupil = make_square_pupil;
```

This function needs to (re)define `ipupil` (used for the WFS) and `pupil` (used for the PSF or for CWFS) to override the default circular pupil definition (so ipupil and pupil needs to be in extern in your function). Both arrays have to have dimension = `sim._size * sim._size`. The yao parameters that can be used to define the pupil arrays are

- `sim._size`: size of the primary near field arrays used by yao: pupil, phase, etc...
- `sim._cent`: where the pupil center should be located in the pupil arrays. This could be `sim._size/2+1` (on a pixel) or `sim._size/2+0.5` (in between the 4 central pixels of the array), depending of your WFS configuration (see below).

A SH WFS geometry has some consequences on the centering of the pupil (`sim._cent`): if the number of subapertures in the telescope diameter (`sh.shnxsub`) is even, then obviously the center of the pupil will have to be within the 4 central subapertures, and because the subapertures size is defined as an integer number of pixels, this means the pupil has to be center in between 4 pixels. Conversely, if `wfs.shnxsub` is odd, **and** `wfs.npixpersub` is odd too, then the pupil has to be centered on a pixel (`sim._cent = sim/_size/2+1`). This is all handled automatically by the shwfs initialization function, but mentioned here for completeness as it is needed within user_pupil().

3.3 Wavefront Sensors

3.3.1 Shack-Hartmann WFS

Set `wfs.type="hartmann"`. The only other mandatory parameters to define are `wfs.shnxsub, wfs.npixpersub, wfs.npixels, wfs.pixsize and wfs.lambda`. Below I expand on these parameters.

3.3.1.1 Near Field

The **near field parameters** that need to be defined are:

- `wfs.shnxsub`: The number of subapertures in the aperture diameter
- `wfs.npixpersub`: The number of pixels across one subaperture, in the near field.

For a "normal" system, we want `wfs.shnxsub * wfs.npixpersub = sim.pupildiam`. But as said above, you can make npixpersub larger or smaller if you want to investigate the effect of subapertures larger or smaller than ideal. Also, by setting `wfs.pupoffset` [meter], you can investigate the effect of misregistration of the WFS w.r.t the entrance pupil (Show/Hide details).

For instance, I have this AO system mounted at Nasmyth and the derotator is not very well aligned, and shifts the pupil image on the lenslet array by 3% of the overall pupil diameter (say in X). There are 2 ways to simulate this: I can either re-define the pupil (using `user_pupil()` as above) or I can use the pupoffset parameter:

```
wfs.pupoffset = [0.03*tel.diam,0.];
```

Of course, make sure tel.diam is defined in your parfile before this instruction (or put an explicit numerical value). Depending on what you want, you will have to also offset the DM (or not) using dm.pupoffset (same units).

3.3.1.2 Far Field

The **far field parameters** to define for a SHWFS are:

- `wfs.npixels`: The number of (CCD) pixel per subaperture in the far field
- `wfs.pixsize`: The SHWFS (CCD) pixel size, in arcsec.

So that of course, the subaperture field of view will be `wfs.npixels * wfs.pixsize`. The whole discussion about sampling above of course applies here too, and field of view can not be arbitrary large. The pixel size is also constrained by FFT properties, and yao will round the pixel size you have selected to the nearest possible value (this should be printed out on screen during `aoinit` if `sim.verbose>=1`).

3.3.1.3 Field Stops

Since v4.5.0, yao can handle field stops (before also, but not in the same easy fashion), defined using the parameters `wfs.fstop, wfs.fssize and wfs.fsoffset`. You have the choice between no field stop (`wfs.fstop="none"`), or a square or round field stop (`wfs.fstop="square" or "round"`). If needed, you can use your own defined geometry by setting `wfs.fsname` to the name of a fits file that contains the image of a field stop (show/hide how). The default is to use a square field stop of size equal to the subaperture field of view (i.e. optimal).

If you elect to do that, I advise you to first run the `aoinit()` without this parameter, but with some field stop defined (`wfs.fstop and wfs.fssize`). When aoinit is done, look at the array `*wfs(ns)._submask`. This is the field stop that has been computed with the fstop and fssize parameters. Note that this mask is applied in the C shwfs() routine on an image of the subaperture spots that has a different sampling than the one you requested with `wfs.npixsize`, so that the pixel size in `*wfs(ns)._submask` is actually `wfs.npixsize/wfs._rebinfactor`. You can start with `*wfs(ns)._submask` and create your own field stop image, save it into a fits file, set `wfs.fsname` and re-start `aoinit()`. Note that the field stop image can be real, i.e. represent partially transparent material.

3.3.1.4 Subaperture Coupling

Since v4.5.0, yao correctly includes **coupling between neighbor subapertures**: In a real system, if there is no field stop, the spot image of a subaperture can wander into a neighbor subaperture and wreak havoc the slope estimation. yao now correctly handle this behavior: all subaperture images are computed, then added to an image that will include all spots. When all spots have been computed, each spot image is extracted and the spot position is estimated from there (center of gravity, soon to come weighted CoG, etc...).

3.3.1.5 Graphic configuration

When the correct debug setting is selected (`sim.debug>=1`), `aoinit()` will display a SHWFS far field graphic configuration diagram as shown on the right (click on it to enlarge). Reported on it are:

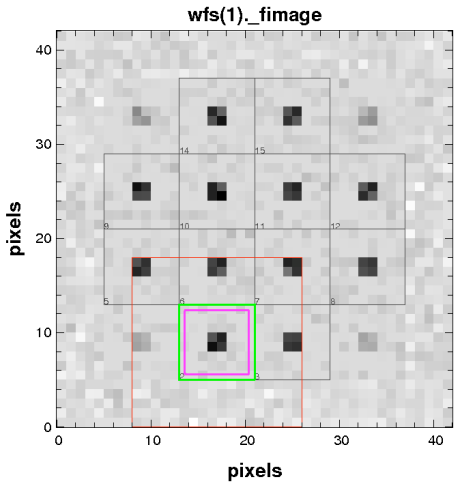


Figure 2: Shack-Hartmann focal plane features

- The SHWFS image. This image is accesible to the user in `*wfs._fimage`, if the need arises. This image includes the spots from **all subapertures**, including the ones which are not "valid" (because their fractional flux is lower than `wfs.fracIllum`). The valid subaperture spots are indicated by the thin grey squares.
- For one spot, the diagram plots :
  - the subaperture effective field of view (green square),
  - the total field of view spanned by this subaperture (see discussion on field of view above), in which the spot can wander (red square) and
  - the outline of the field stop (in magenta).

3.3.2 Curvature WFS

Set `wfs.type="curvature"`. The only other mandatory parameters to define are `wfs.l, wfs.nsubperring and wfs.lambda`:

- `wfs.l` is the extra focal distance in an F/60 beam. The first curvature system for astronomy, the UH13, had a WFS input beam of F/60 (on the membrane mirror), and thus use to define extra focal distance in a F/60 beam. I wrote aosimul, the precursor to yao, to model PUEO, the curvature system for the CFHT, which was largely based on UH13. So from then on, to have a common ground, I (and other people) used to quote extra focal distances in a F/60 beam. It is easy to make the conversion to another F ratio, but yao only handles these units.
  Note that the extra-focal image is computed as the Fresnel diffraction of the pupil complex amplitude, using the following algorithm:
  - Fourier Transform the pupil complex amplitude
  - add a quadratic (focus) term with amplitude *alpha*
  - Fourier transform back

  What you get after that is a defocused pupil image. This has limitations. For instance, it is not possible to compute an image too close to focus, as this would imply alpha = ∞. Of course, this depends of the sampling in the near field, but typically, one can cover reasonable extra focal distances of 5-10cm up (typical systems like PUEO use 15-20cm depending on the seeing, NICI on Gemini uses 40cm).

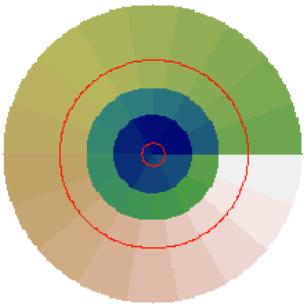


Figure 3: CWFS Subaperture map

- `wfs.nsubperring`: typically, to date, most of the curvature WFS for astronomy were based on a polar design: rings of subapertures. `wfs.nsubperring` is a pointer to a long vector that contains the number of subaperture per ring: the first element is the number of subapertures in the first ring, the second element the number of subaperture in the second ring, etc.. so that `wfs.nsubperring` could look like `&([6,12,18])` for a system with 3 rings of with 6, 12 and 18 subapertures (the & is because `wfs.nsubperring` is a pointer). yao automatically computes the inner and outer radius of each ring so that every subaperture receives the same amount of light. The user can modify this behavior by setting `wfs.rint` and `wfs.rout` to speficy the inner and outer radius of each ring. (show/hide details). The subapertures are defined on an array, that is, each pixels of an array of the same size as ipupil belongs to one and only one subaperture. After an `aoinit()`, you can get a view of the subaperture number map (figure 3) by calling:

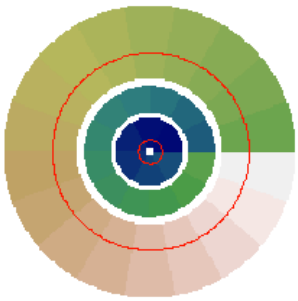


Figure 4: CWFS, effect of rint and rout

```
// call again the subap init function:
subs = make_curv_wfs_subs(ns,sim._size,sim.pupildiam,cobs=tel.cobs);
// build the one image where pixel value = subaperture number
submap = (subs*(indgen(wfs(ns)._nsub)(-,-,)))(,,sum);
// display it:
fma; pli submap;
```

`wfs.rint and wfs.rout` can modify this behavior and let the user impose his/her own inner and outer radius for each ring. Just set `wfs.rint` and `wfs.rout` to the *N* ring inner radius (in fraction of pupil radius), e.g.

```
  wfs.rint = &([0.2,0.6,0.9]);
  wfs.rout = &([0.55,0.85,1.5]);
```

to produce something like on figure 4 (the red line is the pupil outline). This comes handy to take into account dead zones between rings due to glue, etc... We will see later that the same can be done for curvature DM. You can also rotate rings using `wfs.angleoffset`, which points to a float vector of same dimension as `wfs.nsubperring`, containing the angle offset per ring. For instance in the figure 4 case, if I wanted to have the external ring rotated 90 degrees CCW so that the green/white subaperture edge is at 12:00 o'clock, I would use `wfs.angleoffset = &float([0,0,90.])`

3.3.3 Zernike WFS

Set `wfs.type="zernike"`. The only other mandatory parameter is `wfs.nzer`, which, as its name says, define the number of zernike in the WFS. Note that this include piston, so `wfs.nzer=11` would include up to spherical (included). Important note: The Zernike are the **Noll Zernike** (see Noll 1976), which are not the standard Zernike, but the one used most commonly in AO. Normalization??

3.3.4 User defined WFS

Set `wfs.type="name_of_your_function"`.

Users can define their own WFS, to be integrated into the yao flow. The API are relatively straighforward:

```
func user_wfs_func(ipupil,phase,ns,init=)
```

where

- ipupil and phase are the pupil and phase (size `sim._size`),
- `ns` is the WFS number (as defined in the parfile), and
- init is just a flag set the first time this function is called (in `aoinit()`) that allow the user function to make some initializations, if needed.

The function should **return** a measurement vector (show/hide example).

This is the simplest and dumbest example: a WFS that return the absolute piston of the input phase (I know...)

```
func piston_wfs(pup,phase,ns,init=)
{
  if (init) {
    /* do whatever you need to do and keep possible
       init variable in extern
       here we don't need to init anything. */
  }
  return avg(phase(where(pup)));
}
```

3.3.5 Photometry and noise

Photometry and noise are only relevant (and implemented) for Shack-Hartmann and Curvature WFS.

All the photometry is controlled with the `wfs.gsmag, wfs.skymag` and `wfs.zeropoint`. `wfs.zeropoint` is defined in photons/second/full_aperture (incident on the telescope aperture, i.e. after crossing the atmosphere). Note that this depends on the telescope diameter (may be it was a bad choice to define it like that, but now it's done). It is simple enough to convert known photometric zero point to yao zeropoint. The number of photons available for WFSing is derived from this zeropoint and the above mentioned magnitude following regular equations (see also `wfs.optthroughput`).

yao doesn't have a concept of ADU. Or rather, I am assuming one electron/ADU across the board. So the signal in in electrons, and the noise is also in electrons.

3.4 Deformable Mirrors

The deformable mirrors are entirely and solely defined through their influence functions (shape and location). During the `aoinit()` phase, yao calls DM influence function definition functions, for each DM in the parameter file. Once computed, the influence functions are stored in the dm structure (`*dm._def`) and saved on disk for future runs (`name-if#.fits` files). Note that if you have a set of commands, you can get the DM surface by calling

```
surf = compute_dm_shape(nm,command_ptr);
```

where command_ptr is a pointer to a float vector containing the DM commands (e.g. `command_ptr = &(float(indgen(dm._nact)))`).

3.4.1 Stackarray (PZT,SAM,Piezo) DM

Set `dm.type="stackarray"`. The only other mandatory parameters for stackarrays are `dm.pitch` and `dm.nxact`.

3.4.1.1 Dimensioning

`dm.nxact` sets the number of actuators in the diameter of the DM (along the X or Y axis). This includes extrapolated/slaved actuators/guard rings.

`dm.pitch` sets the pitch (i.e. interactuator distance) in near field *pixels*.

Note that you have to dimension the stackarray DM according to your base system definition (`sim.pupildiam`). If you set `sim.pupildiam=60` and `dm.nxact=7` and you do not desire an extra ring of actuator, then you should set `dm.pitch=10` to span the entire pupil diameter (7 actuators, 6 spaces between actuators...).

3.4.1.2 Influence functions

This was the first type of DM implemented in yao. With time, we have implemented several type of influence functions. By default, it uses a functional form which was first derived by J.-P. Gaffard of then CGE (now CILAS) to fit ZIGO measurements of CGE DM's real influence functions. It is possible to use newer (but not necessarily better) forms by setting `dm.irexp`:

`dm.irexp`	functional form
0	Old, adhoc functional form fitted on actual ZIGO data
1	exp(-(d/irfact)^1.5)
2	sinc*gaussian

irfact is set through `dm.irfact`.

3.4.1.3 Actuator Coupling

You can set the inter-actuator coupling with `dm.coupling`. `dm.coupling=0.3` means 30% coupling between an actuator and its nearest neighbor. Typical value are 0.1-0.4. The almost universal consensus nowadays is to use coupling values of about 0.3.

3.4.1.4 Saving RAM & Disk with dm.elt

Stackarray mirrors have very local influence functions. Therefore, for large number of actuators, most of the surface of the DM is zero. It is thus a big waste of RAM and disk (these influence functions take a lot of space). Enabling dm.elt will save most of this space back: only a small subsection of the whole DM surface is kept, surrounding the actuator. The coordinates of this subimage is kept, and used later by `comp_dm_shape()` to compute the correct DM shape. The call to `comp_dm_shape()` is transparent. Depending on the value of `dm.elt` for the current DM, `comp_dm_shape()` will call the relevant C routine. In fact, there is no compromise in setting `dm.elt`, but its benefit really only show up for large stackarray DM (dm.nxact≥10).

3.4.1.5 Extrapolated/Slaved actuators

The idea in yao is to define all of your stackarray mirror in your parameter file, then run `aoinit()` and calibrate the iMat, then select which actuators are controlled and which are extrapolated based on the WFS sensitivity to it. Use `dm.thresholdresp` to select this threshold. This is a fractional number, so 0 would filter all actuators and 1 would retain them all. 0.5 would retain all actuator which measurement *max response* is larger than the max response of all actuators. Note that if you set `dm.thresholdresp` to a negative value, `aoinit()` will enter an interactive mode into which you can test various values of `dm.thresholdresp` (Show/Hide example).

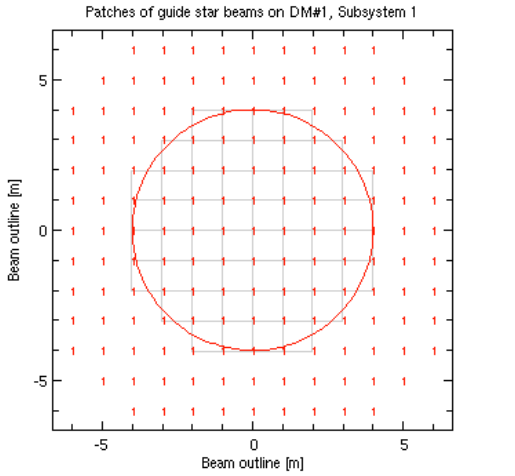
In this example, I have a SHWFS with 8x8 subapertures and a stackarray DM with 13x13 actuators. The relevant

parts of the parfile are as follow:

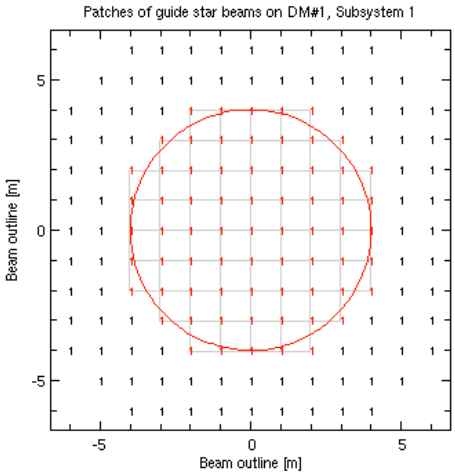
```
sim.pupildiam       = 256;

wfs                 = array(wfss,1);
wfs(1).type         = "hartmann";
wfs(1).shnxsub      = 8;
wfs(1).npixpersub   = 32;
wfs(1).lambda       = 0.65;
wfs(1).pixsize      = 0.25;
wfs(1).npixels      = 8;

dm                  = array(dms,1);
dm(1).type          = "stackarray";
dm(1).iffile        = "";
dm(1).nxact         = 13;
dm(1).pitch         = 32;
dm(1).alt           = 0.;
dm(1).thresholdresp = -0.1;
```



Configuration actuator/beams in a plane at altitude 0
Solid lines: Outline of this subsystem GS beams
Dotted line: Circle including outermost ray to specified science objects (at 0.0 arcsec off-center)
Numbers for stackarrays actuators: colored:controlled, BW: extrapolated
# of active actuators= 157, # of extrapolated actuators=0



Configuration actuator/beams in a plane at altitude 0
Solid lines: Outline of this subsystem GS beams
Dotted line: Circle including outermost ray to specified science objects (at 0.0 arcsec off-center)
Numbers for stackarrays actuators: colored:controlled, BW: extrapolated
# of active actuators= 157, # of extrapolated actuators=0

After doing the iMat calibration in `aoinit()`, and if `dm.thresholdresp<0`, you will be presented with the figure shown above on the left. Notice that all actuators are red, which means they are currently all valid. In the yorick console, yao will write the current number of valid actuators. Answer "y" and enter a new threshold (here I entered 0.5). The plot updates (see figure above on the right) and now shows valid actuator (still in red) and extrapolated actuators (now in foreground color -here black-). Once you are satisfied, answer "n" to "Again?" and yao will proceed.

```
DM #1: # of valid actuators: 157 Again ? y
Threshold (old = -0.100000) : 0.5
type return to continue...
DM #1: # of valid actuators: 69 Again ? n
  DM #1: # of valid actuators: 69. (I got rid of 88 actuators after iMat)
  >> valid I.F. stored in test-if1.fits
```

Once extrapolated actuators are selected, yao stores the valid influence functions and the extrapolated ones in 2 different files (e.g. `test-if1.fits` and `test-if1-ext.fits`). Influence functions are not recomputed in further calls to `aoinit()` unless the clean keyword is set (in which case `aoinit()` restart from scratch and recompute *everything*).

Normalization??

3.4.2 Bimorph (curvature) DM

Set `dm.type="bimorph"`. The other mandatory parameter is `dm.nelperring`.

`dm.nelperring`: This is similar to wfs.nsubperring (see here) and defines the number of electrodes per ring.

Now, most curvature mirror are a bit different from this simple design provided by defining `dm.nelperring`, in which there is no gap between rings. Many curvature DMs have for instance a large gap between the outer ring of electrodes (the one that create mostly boundary conditions) and the next inner electrode ring. To create more realistic DM electrode pattern, use `angleoffset`, `rint`, `rout`, `supportRadius` and `supportOffset`.

The general idea follows what has been exposed in the curvature WFS area above. With `rint` and `rout`, one can define the inner and outer radius of each ring of electrodes, expressed in fraction of the pupil radius. With `angleoffset`, one can define a global rotation per ring, and with the `support*` parameters, one can define the physical properties of the 3 DM support points.

That brings us to the next subject: how curvature DMs are modelled. Right now, what we do is solve the Poisson equation, imposing a given curvature over a given electrode and integrating twice to get the DM surface. Then, we impose that the three points defined as the support location go through the z=0 plane. It's that simple. It means that we do not currently support fancier support method like continuous support (e.g. by a rubber ring), 6 points support, etc..

3.4.3 Modal (Zernike, Karhuenen-Loeve) DM

Set `dm.type="zernike" or "kl"`. Other mandatory keywords are `dm.nzer` (for zernike) or `dm.nkl` (for KL), which specify the number of modes. Note that nzer will start and include piston, while nkl will not (there is formally no piston mode in the KL basis).

3.4.4 Segmented DM

Set `dm.type="segmented"`. The other mandatory keywords is `dm.nxseg`.

`dm.nxseg` is the number of segment in the long diameter (X axis).

`dm.fradius` stands for "filter radius". Segments are created over a wider area than the nxseg defined above. Only segments which distance to the (0,0) pupil coordinates is ≤ fradius will be kept. default dm.pitch*dm.nxseg/2.

3.4.5 User defined DM

Set `dm.type="name_of_your_function"` (as a string).

The API for the user provided DM function are as follow:

```
func make_my_dm(nm,disp=)
```

where nm is the DM number. Use the disp keyword to display whatever you need to display when this routine is called. The goal of this routine is to create maps of the influence functions. These maps have to be stored (thus this function has to create and fill) in the array *dm._def (dm._def is a pointer to the data). The proper way to do that is:

```
func make_my_dm(nm)
{
  extern dm;   // dm is extern (global)
  dim = dm(nm)._n2-dm(nm)._n1+1; // <- important
  def = array(float,[3,dim,dim,n_actuator]);
  for (i=1;i<=n_actuator;i++) def(,,i) = some_form; // <- fill it to your taste
  dm(nm)._def = &def;  // <- store influence functions
  dm(nm)._nact = n_actuator;  // <- important, number of actuators
}
```

Explanation: In this user supplied function, you have to define the influence functions (*dm._def) and, importantly, the number of actuators (dm._nact). Prior to the call to this function, `aoinit()` has defined `dm._n1` and `dm._n2`, which are the indices at which these influence function will go in the big `sim._size x sim._size` array used for FFT, etc. The influence functions are reduced in size to save RAM, as they can potentially take a lot of memory space. Normally, `dm._n1` and `dm._n2` are defined to include the pupil pixel diameter (`sim.pupildiam`) plus 4 pixels padding on each side if the DM altitude is zero (in the pupil), and are defined to span the entire sim._size array if the DM altitude is above ground (as there is no simple way to know where to stop exactly as this depends on the WFS and target locations). Note that `dm` is defined in extern as you are modifying its value.

3.4.6 Tip-Tilt Mirror

Set `dm.type="tiptilt"`.

This creates a regular tip-tilt mirror. The units in the command vector are arcsecs.

3.4.7 Anisoplanatism "DM"

Set `dm.type="aniso"`.

This has been implemented because of the need in MCAO to control plate scale modes (also called anisoplanatism modes or quadratic modes). You will need to set `dm.alt` to the altitude of an existing DM of a regular type (e.g. stackarray) that will be responsible for the creation of the anisoplanatism modes (see mcao2-bench.par for an example of aniso DM).

3.4.8 Hysteresis and misregistration/offset

3.4.8.1 Hysteresis

Hysteresis is implemented at the top level so that it works for any kind of DM (during the AO loop only). The parameter `dm.hysteresis` is fairly self explanatory: `dm.hysteresis=0.1` means 10% hysteresis.

3.4.8.2 Misregistration

`dm.misreg` allow to induce DM misregistration (on the fly). `dm.misreg` is expressed in pixels, so you will have to do a small conversion to get it in other units, but this way, it works for any kind of DM. Note that `dm.misreg` can be fractional (fraction of a pixel). Because the size of the array containing the DM influence function is limited to save memory space, the misregistration using this parameter can only be of a few pixels (up to 4 I believe for a ground-conjugated DM). If you wish to induce more registration, use the parameter `dm.pupoffset` (see below).

3.4.8.3 Offsets

Yao v4.5.0 introduced a new kind of influence function offset parameter: `dm.pupoffset`. `dm.pupoffset` is entered in **meters** (a 2 elements vector which contains the x and the y offsets). Those are transversal offset of the influence functions in the near field. This functionality is implemented in the `compute_dm_shape()` function, so it is general and works for all types of DM. `dm.pupoffset` is intended for large offsets, and the influence functions are shifted by an integer number of pixels (the requested offset in meter, rounded to the nearest pixel, see `sim.pupildiam` and `tel.diam`). If you want finer control over the DM position, use `dm.misreg` (see above). `dm.pupoffset` is similar to `wfs.pupoffset` (see WFS section), but for the DMs.

3.5 Other Features

More to come (a note to myself).

- disjoint pupils
- loop parameters: framedelay, control law
- Normalization of various parameters and arrays
- Variables (aoinit or not aoinit?)
- Vibrations parametrization

4. Yao Structures

Comment on notation: `&float` = pointer to a float array/vector (idem for &long, &string, etc...). Define it as:

```
atm(1).layerfrac = &([0.5,0.2,0.3]);
```

I know, it seems weird, but there is a good reason to have done it like this.

sim structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
name	string	N/A	none	no	A name for this simulation run
pupildiam	long	pixels	none	yes	Pupil diameter
debug	long	N/A	0	no	Debug level
verbose	long	N/A	0	no	Verbose level

atm structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
dr0at05mic	float	Unitless	none	yes	Dr0 at 0.5 microns, at zenith
screen	&string	N/A	none	yes	Phase screen file names
layerfrac	&float	Unitless	none	yes	Layer fraction. Sum to one is insured in aoinit
layerspeed	&float	meter/sec	none	yes	Layer speed
layeralt	&float	meter	none	yes	Layer altitude, at Zenith
winddir	&long	Unitless	0	yes	Wind dir (not operational, use 0 for now)

wfs structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
type	string	N/A	none	yes	Valid types are "curvature", "hartmann", "pyramid", "zernike" or "user_function" where user_function is the name of a function defined by the user (see doc)
lambda	float	micron	none	yes	WFS wavelength in microns
subsystem	long	N/A	1	no	Subsystem this WFS belongs to
gsmag	float	Unitless	0	no	WFS guide star magnitude. For LGSs, see below
skymag	float	Unitless	0 (no sky)	no	WFS sky magnitude/arcsec^2. [0 means no sky]
noise	long	N/A	0	no	Enable noise (photon noise & read out noise)
ron	float	e-	0	no	Read out noise
darkcurrent	float	e-/s/pixel	0	no	Dark current
gspos(2)	float	arcsec	[0,0]	no	WFS guide star position [x,y]
gsalt	float	meter	0	no	WFS guide star altitude, at zenith. 0 for infinity.
gsdepth	float	meter	0	no	WFS guide star depth in meter, at zenith (e.g. Na layer thickness)
laserpower	float	Watt	0	See comment	WFS laser power projected on sky (Na laser only). Required when using lasers. Exclusive with gsmag i.e. define one OR the other
filtertilt	long	N/A	0	no	Filter TT on this sensor (0=no)
correctUpTT	long	N/A	0	no	Correct uplink tip-tilt (0=no)
uplinkgain	float	Unitless	0	no	Uplink TT loop gain
dispzoom	float	N/A	1.0	no	Zoom factor for the display, useful in multi-WFS configuration (typically around 1)
optthroughput	float	Unitless	1.0	no	Optical throughput to WFS
disjointpup	long	N/A	0	no	If set, the WFS#n will be filtered by an array disjointpup(,,n) that has to be defined by the user. see user_pupil(). Allow for GMT-type topology

Curvature WFS only keywords

l	float	meter	none	yes	Extra focal distance in a F/60 beam
nsubperring	&long	Unitless	none	yes	# of subapertures per ring. See doc

angleoffset	&float	degree	0	no	CCW Offset angle for first subaperture of ring. See doc
rint	&float	Unitless	See comment	no	Inner radius for each ring, in fraction of pupil radius
rout	&float	Unitless	See comment	no	Outer radius for each ring, in fraction of pupil radius
fieldstopdiam	float	arcsec	1.0	no	Diameter of field stop. Used **only** to compute sky contribution (with skymag)
Shack-Hartmann WFS only keywords					
shmethod	long	N/A	none	yes	1= Geometric, simple gradient average over subaperture. 2=Diffractive, full propagation
shnxsub	long	Unitless	none	yes	# of subapertures in telescope diameter
pixsize	float	arcsec	none	yes	Focal plane: Subaperture CCD pixel size in arcsec
npixels	int	Unitless	none	yes	Focal plane: Final # of pixels per subaperture
npixpersub	long	Unitless	none	no	Pupil plane: # of pixel in a subaperture (to force npixpersub and bypass constraint that pupildiam should be a multiple of this number e.g. to investigate lenslet larger than pupildiam
pupoffset(2)	float	meter	[0,0]	no	Pupil plane: Offset of the whole WFS subapertures w.r.t telescope aperture. Allow misregistration w.r.t telescope pupil and other funky configurations
shthreshold	float	e-	0	no	Threshold for the computation of the subaperture signal from CCD spots >= 0
biasrmserror	float	e-	0	no	rms error on WFS CCD bias in electron
flatrmserror	float	Unitless	0	no	rms error on WFS CCD flat, referenced to 1 (i.e. 0.1 mean 10% rms error). Typical value can be 0.01
fsname	string	N/A	none	no	Fits file with subaperture amplitude mask. It should have dimension 2^sdimpow2 square. Can be float or long.
fstop	string	N/A	"square"	no	Valid fiels stop type are "none", "square" or "round"
fssize	float	arcsec	sub. size	no	Side (square) or diameter (round) of field stop
fsoffset(2)	float	arcsec	[0,0]	no	Field stop offsets [x,y]
kernel	float	arcsec	See comment	no	FWHM in arcsec of WFS spot gaussian kernel. Default is computed as a function of D/r0 and only used during iMat calibration
nintegcycles	int	Unitless	1	no	# of iterations over which to integrate before delivering slopes
fracIllum	float	Unitless	0.5	no	Focal plane: Fraction of subaperture illuminated for the subaperture to be valid
LLTxy(2)	float	meter	[0,0]	no	Coordinates [x,y] of the laser projector, if any

centGainOpt	long	N/A	0	no	Centroid gain optimization flag. Only for LGS (correctupTT and filtertilt must also be set for this to work)
rayleighflag	int	N/A	0	no	Take rayleigh into account?
Zernike WFS only keywords					
nzer	int	Unitless	none	yes	Number of Zernike to be sensed. Starts at piston included.

dm structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
type	string	N/A	none	yes	Valid types are "bimorph", "stackarray" "tiptilt", "zernike", "kl", "segmented", "aniso" or "user_function", where user_function is the name of a function provided by the user
pitch	long	pixel	none	yes	Actuator pitch (pixel). stackarray/segmented only
subsystem	long	N/A	1	no	Subsystem this DM belongs to
iffile	string	N/A	""	no	Influence function file name. Leave it alone.
alt	float	meter	0	no	Conjugation altitude, at zenith
hyst	float	Unitless	0	no	DM actuator hysteresis (0. to 1.)
push4imat	float	Volt	20	no	Voltage to apply for iMat calibration. Note: the default is not OK for many configs. Change at will
thresholdresp	float	Unitless	0.3	no	Normalized response threshold (in WFS signal) below which an actuator will not be kept as valid
unitpervolt	float	mic/Volt	0.01	no	Influence function sensitivity in unit/volt. Stackarray: micron/Volt, Tip-tilt: arcsec/Volt.
maxvolt	float	Volt	none	no	Saturation voltage (- and +) in Volt. None if not set
gain	float	Unitless	1.0	no	Loop gain for this DM (total = this times loop.gain)
misreg(2)	float	pixel	[0,0]	no	DM misregistration [x,y]
xflip	long	N/A	0	no	Flip DM left/right (0=no)
yflip	long	N/A	0	no	Flip DM up/down (0=no)
pupoffset(2)	float	meter	[0,0]	no	Global offset of whole actuator pattern w.r.t pupil
disjointpup	long	M/A	0	no	If set, dm(n) will be filtered by an array disjointpup(,,n) that has to be defined by the user. See user_pupil(). Allow for GMT-type topology.
Stackarray-only (SAM, PZT) keywords					
nxact	long	Unitless	none	yes	Number of actuator in pupil diameter
elt	long	N/A	0	no	ELT mode: allow to save huge amount of RAM and time for the computation of the DM shape. No drawback
coupling	float	Unitless	0.2	no	Influence function coupling coefficient

ecmatfile	string	N/A	none	no	Valid to extrapolated projection matrix (extrap_com)
noextrap	long	N/A	0	no	Set to disable use of extrapolated actuators
pitchMargin	float	Unitless	1.44	no	Margin to include more corner actuators when creating inf.functions optional [1.44]
irexp	long	N/A	0	no	Use original functional form (irexp=0) or exp(-(d/irfact)^1.5) model (irexp=1) or sinc*gaussian (irexp=2)
irfact	float	Unitless	1.0	no	use when irexp=1 (see above)
Bimorph-only keywords					
nelperring	&long	Unitless	none	yes	Number of electrodes per ring, e.g &([6,12,18])
angleoffset	&float	degree	0	no	Offset angle for first electrode in ring
rint	&float	Unitless	See comment	no	Inner radius for each ring, see doc
rout	&float	Unitless	See comment	no	Outer radius for each ring, see doc
supportRadius	float	Unitless	2.2	no	Radius of DM 3 support points, normalized in pupil radius
supportOffset	float	dgree	90	no	Angle offset of first support point
Zernike DM-only keywords					
nzer	long	Unitless	none	yes	Number of Zernike modes, including piston???
Karhuenen-Loeve DM-only keywords					
nkl	long	Unitless	none	yes	Number of Karhuenen-Loeve modes, including piston???
Segmented DM-only keywords					
nxseg	long	Unitless	none	yes	Number of segments in long axis (X)
fradius	float	pixel	See comment	no	Segments are created over a wider area than the nxseg defined above. Only segments which distance to the (0,0) pupil coordinates is <= fradius will be kept. default dm.pitch*dm.nxseg/2.

mat structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
condition	&float	Unitless	none	yes	Condition numbers for SVD, per subsystem.
file	string	N/A	none	???	iMat and cMat filename. Leave it alone.

tel structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
diam	float	meter	none	yes	Telescope diameter
cobs	float	Unitless	0.	no	Central obstruction / telescope diameter ratio
Tip vibration parameters					

tipvib_white_rms	float	arcsec	0.	no	rms of vibration white noise
tipvib_1overf_rms	float	arcsec	0.	no	rms of vibration 1/f noise (from 1 Hz to cutoff)
tipvib_peaks	&float	Hz	0	no	positions of vibration peak in PSD
tipvib_peaks_rms	&float	arcsec	0	no	rms of each vibration peaks (defined above)
tipvib_peaks_width	&float	Hz	1freq bin	no	width of each vibration peaks (default 1 freq bin)

tilt vibration parameters

tiltvib_white_rms	float	arcsec	0.	no	rms of vibration white noise
tiltvib_1overf_rms	float	arcsec	0.	no	rms of vibration 1/f noise (from 1 Hz to cutoff)
tiltvib_peaks	&float	Hz	0	no	positions of vibration peak in PSD
tiltvib_peaks_rms	&float	arcsec	0	no	rms of each vibration peaks (defined above)
tiltvib_peaks_width	&float	Hz	1freq bin	no	width of each vibration peaks (default 1 freq bin)

target structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
lambda	&float	micron	none	yes	Image wavelengths in micron
xposition	&float	arcsec	none	yes	"Targets" X positions in the field of view
yposition	&float	arcsec	none	yes	"Targets" Y positions in the field of view
dispzoom	&float	Unitless	1.	no	Display zoom, useful for multi-targets. Typically around 1

gs structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
zeropoint	float	See comment	none	yes	Photometric zero point (#photons@pupil/s/full_aper, mag0 star).
zenithangle	float	degree	0	no	Zenith angle. The zenith angle is used to compute: r0 off-zenith, atmopheric turbulence layer altitude, LGS altitude and thickness of Na Layer, LGS brighness note that dm altitude is unchanged
lgsreturnperwatt	float	phot/cm2/s	22.	no	Sodium LGS return in photons/Watt /cm2/s at entrance pupil, at zenith. Modified by gs.zenithangle. Basically, you have to fold in this the sodium density and your model of return

loop structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
niter	long	Unitless	none	yes	Total number of iterations
ittime	float	second	none	yes	Iteration time (sampling time)
gain	float	Unitless	0	See comment	Loop gain. Optional, but important!
leak	float	Unitless	0	no	Leak term (0 means no leak)

gainho	&float	Unitless	0	no	Higher order gains (starting at 2nd order, up to 10th)
leakho	&float	Unitless	0	no	Higher order leaks (starting at 2nd order, up to 10th)
framedelay	long	frames	0	no	Loop delay (# of frames). Regular CCD 1 frame integration -> framedelay=1 + readout & Calculation -> framedelay=2
startskip	long	iteration	10	no	Number of iteration to skip before collecting statistics
skipevery	long	iteration	0	no	In phase screen, skip by "skipby" steps every "skipevery" iterations (0=none). See doc
skipby	long	iteration	10000	no	See above. This is to get better statistical coverage
stats_every	long	iteration	4	no	Compute stats every so many iteration
jumps2swapscreen	long	Unitless	0	no	Number of jumps (i.e. niter/skipevery) after which screens will be swapped (rotation, 2->1, 3->2... 1->last). Default is no jump.
modalgainfile	string	N/A	""	no	Name of file with mode gains

opt structure

VARIABLE NAME	TYPE	UNITS	DEFAULT	REQ?	COMMENT
phasemaps	string	N/A	none	no	Filename of phasemap. Z scale should be in microns
alt	float	meter	0	no	Equivalent altitude in m.
misreg(2)	float	pixels	[0,0]	no	Misregistration [x,y] (similar to DM, see above)

5. Scripting and Hacking Yao

5.1 Scripting

Thanks to yorick and the structure of yao, scripting is relatively easy. The principle is as follow:

- read the parfile
- init yao (aoinit)
- Loop on parameters you want to loop on:
  - set parameters
  - if needed, redo the aoinit (some parameters will need that)
  - go through the loop N iterations
  - store the results
- Plot/save results

Here is a simple example you can find in the examples directory (`yao_loop_example.i`):

```
require,"yao.i";

// check if generic phase screens exist, if not, create them:
write,"CREATING PHASE SCREENS";
if (!open(Y_USER+"data/screen1.fits","r",1)) {
  create_phase_screens,1024,256,prefix=YUSER+"data/screen";
 }
```

```
// the "wait" is needed here:
window,33,wait=1;

// read out parfile
aoread,"test.par";
atm.dr0at05mic = 35; // be more gentle

// Define vector on which we want to loop and final strehl array.
// We want to estimate performance for 3 values of the guide star
// magnitude and 4 values of the loop gain (for instance)
gsmagv = [6,9,12];           // guide star mag vector
gainv  = [0.01,0.1,0.5,1.0]; // gain vector
// strehl array to store results:
strehlarray = array(0.,[2,numberof(gsmagv),numberof(gainv)]);

// loop on gsmag and gain
for (ii=1;ii<=numberof(gsmagv);ii++) {
  for (jj=1;jj<=numberof(gainv);jj++) {
    wfs(1).gsmag=gsmagv(ii);
    loop.gain=gainv(jj);
    // it's safer, but not always necessary, to call again
    // aoinit (here for gsmag). some parameters do not need it.
    aoinit,disp=1;
    // Setup loop:
    aoloop,disp=1;
    // go: do all loop.niter
    go, all=1;
    // after_loop() is now called automatically at last iter of go()
    strehlarray(ii,jj) = strehllp(0); // fill in result array
    // and display results as we go:
    window,33;
    fma;
    for (ll=1;ll<=ii;ll++) {
      plg,strehlarray(ll,),gainv,color=-ll-4;
      plp,strehlarray(ll,),gainv,color=-ll-4,symbol=4,size=0.6;
      ylims=limits()(3:4); ymax=ylims(2); yspace=(ylims(2)-ylims(1))/15.;
      plt,swrite(format="gsmag=%d",gsmagv(ll)),0.011,ymax-yspace*(ll-1), \
        justify="LT",tosys=1,color=-ll-4;
    }
    logxy,1,0;
    xytitles,"Loop Gain",swrite(format="Strehl @ %.2fmicrons",(*target.lambda)(0));
    window,0;
  }
}
```

You can do all kind of scripting like this to find for instance the optimal working point for a system in given conditions (above, what is the best gain for a given GS magnitude). We could also have added a loop on `wfs.ittime` in the example above. One has however to be careful: Probing multi-dimensional spaces can quickly be overwhelming in execution time. Generally, I consider that 10000 iterations are needed to give a statistically significant answer. So for instance, in the example above. that would mean 4x3x10000=120000 iterations total. At 90 iterations/seconds, this means 1300 seconds (about 20mn). Adding 4 points for `wfs.ittime` would lead to 480000 iterations, or 1 hour and 20mn. This can quickly become prohibitive.

5.2 Hacking Yao

At one point or another, if you are serious about simulating your system, it is likely that you will need this or that feature, or modification to the existing yao code.

Go ahead and dive. Feel free to modify yao. It's open source after all. The goal of this too-short section is to give you some head start for doing just that: hacking yao.

So, various points, in no particular order:

- The functions are kind of gathered by themes. The main file is `yao.i`, and includes the base functions `aoread(), aoinit(), aoloop(), go(), after_loop()` and more. Other important include files are:
  - `yao_wfs.i`: All functions related to WFS and their initialization.
  - `yao_dm.i`: All functions related to DM and their initialization.
  - `turbulence.i`: Functions to generate turbulent phase screens. Some more turbulence functions are in yao.i
  - `yao_structures.i`: Definitions of yao structures.

- `aoutil.i and yao_util.i`: check_parameters, and in general utility functions that didn't fit anywhere else.
- `yao_fast.i and yao_utils.i`: Interface functions to the C routines. Mostly declaration of prototypes as per yorick plug_in APIs.
- `yaokl.i`: KL creation functions.
- `yao_fast.c`: C code for the SHWFS and CWFS, plus some Poisson and Gaussian noise fast functions.

- Many variables are defined in extern. This means they are available at any level. Here is a subset of them:
  - All the yao structures: wfs, dm, atm, sim, mat, tel, target, gs, loop. There are sufficient examples in the code of how to address them. These will contain most of the information you may want.
  - Variables that may be useful to catch and store/analyze when the loop is finished are (loop in `go()` and `after_loop()` for more details):
    - `imav(sim._size,sim._size,#_target,#_lambda)`: the averaged images for each target and at each requested wavelength.
    - `strehl(#_target,#_lambda)` contains the long exposure image Strehl ratio for each target and each requested wavelength.
    - `fwhm(#_target,#_lambda)` contains the long exposure image FWHM for each target and each requested wavelength [mas].
    - `e50(#_target,#_lambda)` contains the long exposure image 50% encircled energy diameter for each target and each requested wavelength [mas].
    - `cbmes, cbcom, cberr` are the "circular buffers" that contain all WFS measurements, DM commands and DM errors (updates to DMs at each iterations). Only saved if keyword `savecb` is set in call to `aoloop()`.
  - `iMat, cMat`: Interaction and control matrices. One axis is the WFS axis. The WFS measurements are put in sequence: all X, then all Y for WFS#1, then all X, then all Y for WFS#2, etc... The other axis is the DM axis. Here also, all valid actuators for DM#1, then DM#2, etc...
  - `modToAct, mesToMod, eigenvalues`: The U, transpose of V and eigenvalues of the SVD inversion. Over the unmasked eigenvalues, cMat is computed as follow:

```
cmat = ( modToAct(,+) * mev(+,) )(,+) * mesToMod(+,);
```

6. Conclusion

There is a lot of things missing in this documentation. I will try to complement it as time allows. I hope however that this will help you getting the best out of yao and avoiding frustration. Yao is a fairly complete AO simulation tool. It is flexible and fast. Flexibility means I can not exert too much control over the user input parameters. If I were to do that, I would necessarily impose a carcan over your creativity, and we want to avoid this at all cost. So, yes, there is a steep learning curve, but at the end, you should be able to wrestle yao into submission! I have only one more advice to give: check your results. And recheck them. And make sure it makes physical sense.