STAR WAVES

Pro II

Innovations Foresight

Software Reference Manual

POWERED BY ALCOR SYSTEM

June, 2015 revision – 3.1

For any improvement and suggestions, please contact customerservice@innovationsforesight.com
Some screen copies may not reflect the latest release of the product (hardware/software)

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1. Software startup and training

1.1. Computer requirements

The minimum computer requirements to run the software are the following:

- Window XP to Windows 8.1 operating systems
- HD screen resolution (1980 x 1020 pixels otherwise some features may not be visible)
- 65535 colors display adapter
- 500 Mo of disk space
- Processor: Intel Pentium III

1.2. Documentation contents

The documentation is made of two parts, one part describes the **simulation mode** of the software that helps you to familiarize with, and the second part is a real case.

1.3. Knowledge prerequisites

A basic knowledge of wave-front aberration theory is required to use this software (modal Zernike aberration).. Also knowledge operation of a Shack-Hartmann analyzer is required. This is not the purpose of this documentation to deal with or bring this knowledge to the user. Nevertheless, some information can be found here on the web by clicking these links:

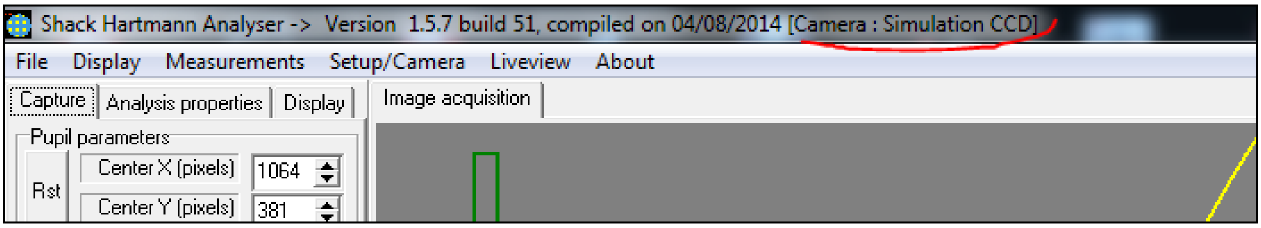
- http://en.wikipedia.org/wiki/Shack%E2%80%93Hartmann_wavefront_sensor
- http://www.imagine-optic.com/fileadmin/files/PDF/ARTICLES/imagine-optic_principles-and-history-of-shack-hartmann-wavefront-sensing.pdf
- http://en.wikipedia.org/wiki/Zernike_polynomials

In this documentation, all bold and italic items refers to string of chars written in this software such as labels, captions, titles and so on.

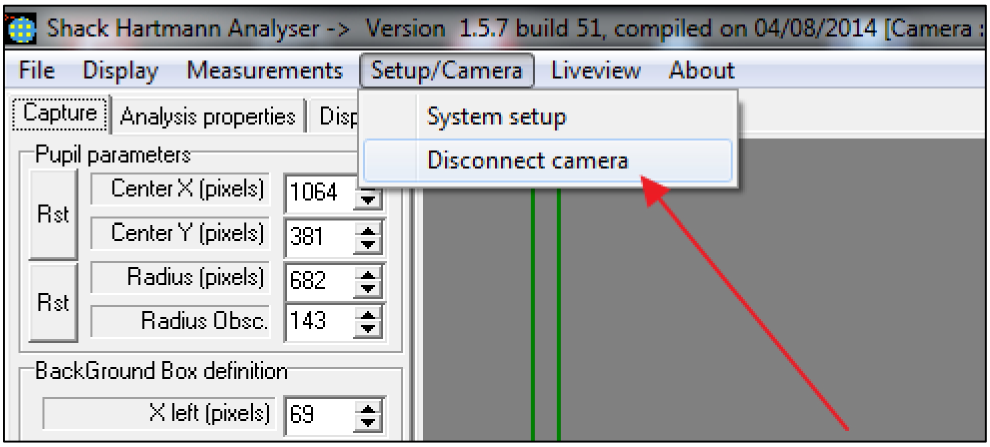
1.4. Software training : Camera setup

The best way to start and get used to the software and its capabilities without any hardware connected is to use it with the simulation mode. In that way, the user can get the capabilities of the software and get its features in a smoothest way.

On first startup, the software camera used to acquire data shall be set as "***Simulation CCD***":

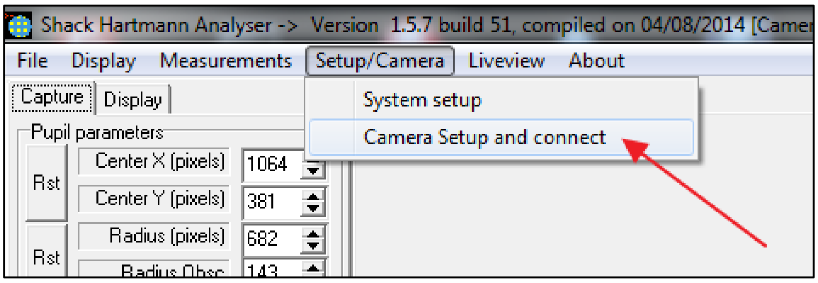


If it is not set that way, then go to this menu:

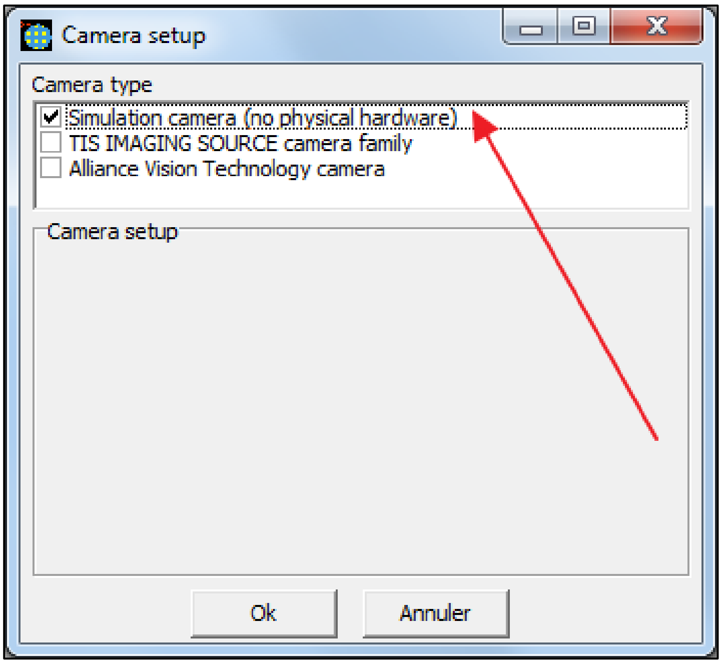


and click "***Disconnect camera***"

Again, click "***Camera Setup and connect***"

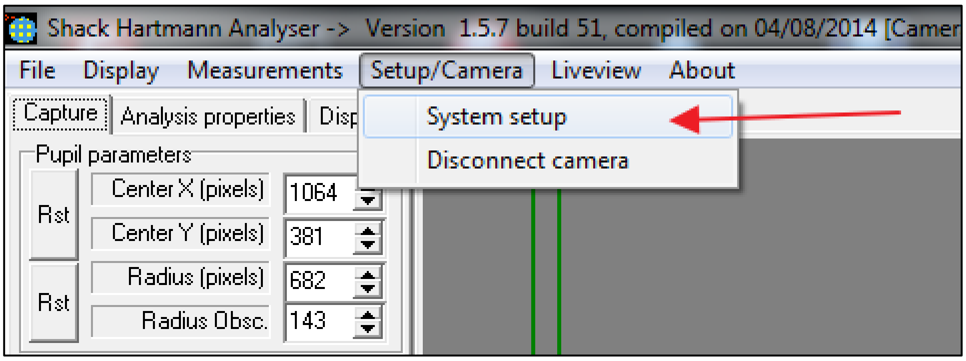


Then select "***Simulation camera (no physical hardware)***" and click "***OK***" at the bottom of the form.

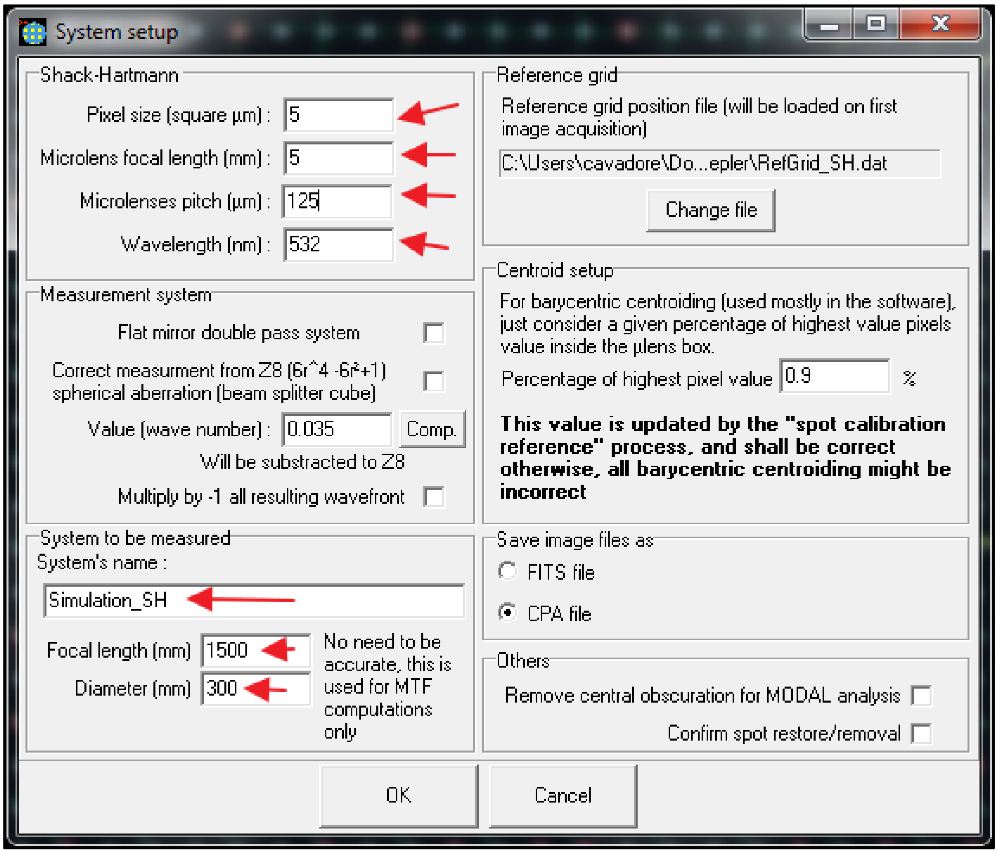


1.5. Software training : System setup

Please now proceed to another important step and click "***System setup***"



Then fill the items with the red arrow with figures as following, and disregard the other checkboxes or input. We will come back to them later on.

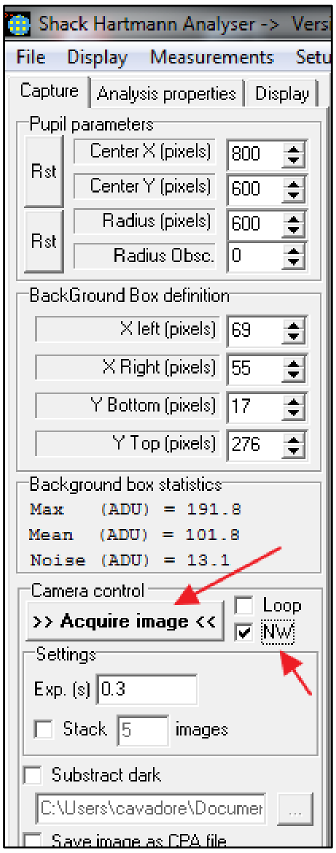


Then click "***OK***"
Software system setup is very important, if misconfigured, it can lead to large errors. So pay attention and take time doing it. It is saved into the database registry. Note : you can save and load system setups that are stored into text readable ***.ini** files.

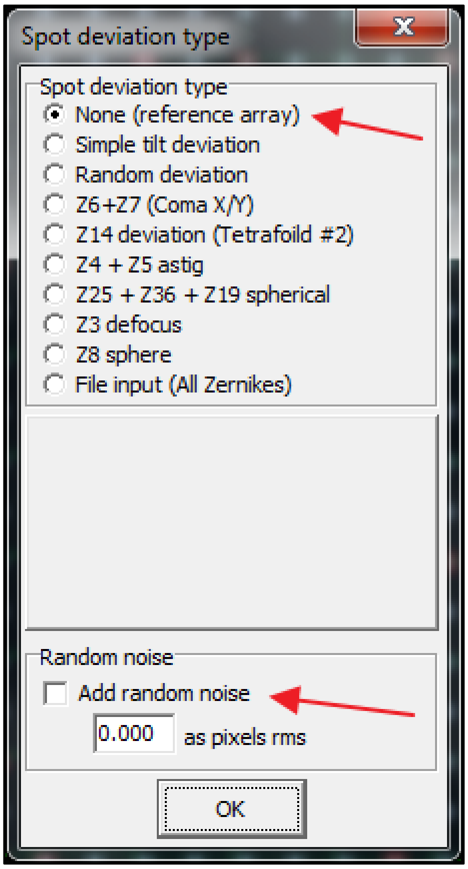
Once this is achieved, on the "***Capture***" left tab into the software main form, check the "***NW***" box and then click "***>>> Acquire image <<<***" . The "***NW***" checkbox will disable all wave-front computations and is intended to look at the image quality without waiting for wavefront computation to complete.

1.6. Software training : Building a reference grid

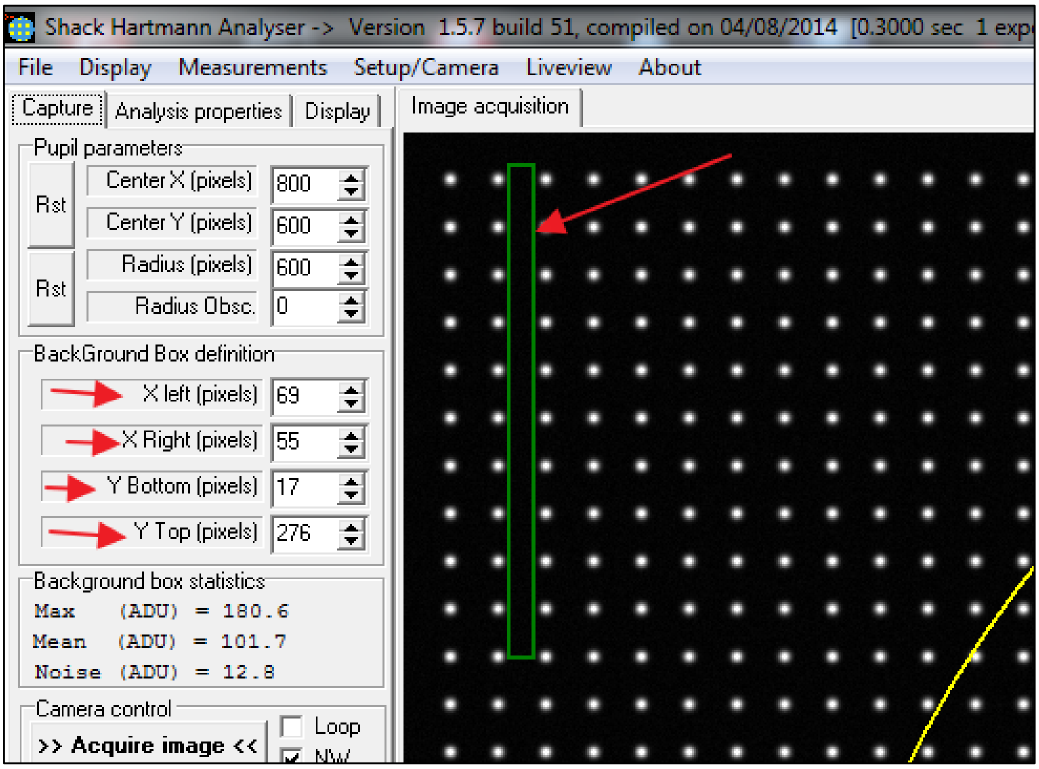
All wavefront computations are carried out using a reference grid that represents a reference wavefront. This reference wavefront can be, for instance, a close to perfect wavefront.



Check that "***Loop***" and "***Stack***" checkboxes are left unchecked.
Then, this simulation window appears (***spot deviation type***). This will let the user to choose the spot array to be simulated. For doing a reference spot array, check "***None (reference array)***" and be sure to leave "***Add random noise***" unchecked.

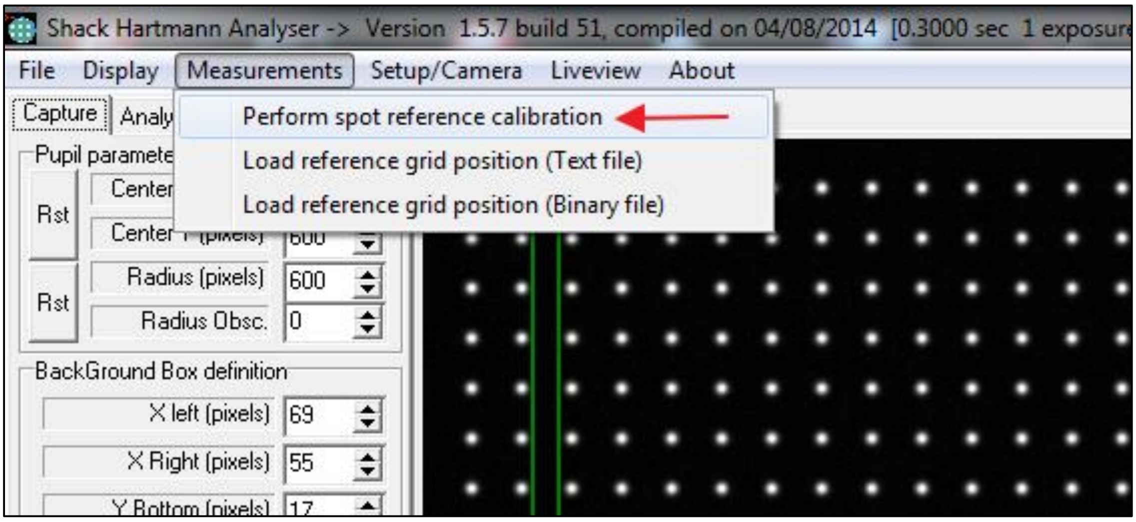


After a few milliseconds, appears an array of regular spots underneath the "***Image acquisition***" that represents the wave-front to be used as a reference. This wave-front, in actual life, will be generated by a pinhole, for instance, or whatever that can be a reference for your measurements.

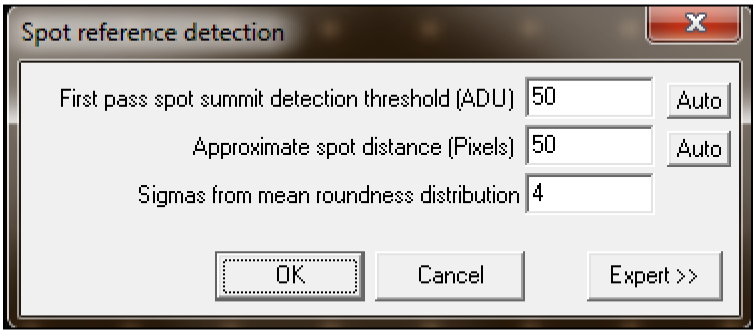


The "***Background Box definition***" is a green rectangle box where noise and background computations are carried out. It shall not contain inside any spots or any bright features. This is the background offset and noise level that is computed within this box. If a bright feature is present inside the rectangle, the box coordinates shall be changed so that no spot and/or bright features are interfering inside this box.
In simulated mode, the offset inside this box is around 102 ADU and the noise is 12.8 ADU

Once this step passed, the reference grid position shall be extracted to perform further measurements. This is a mandatory step, otherwise no measurement can be achieved ! Then click on this menu:

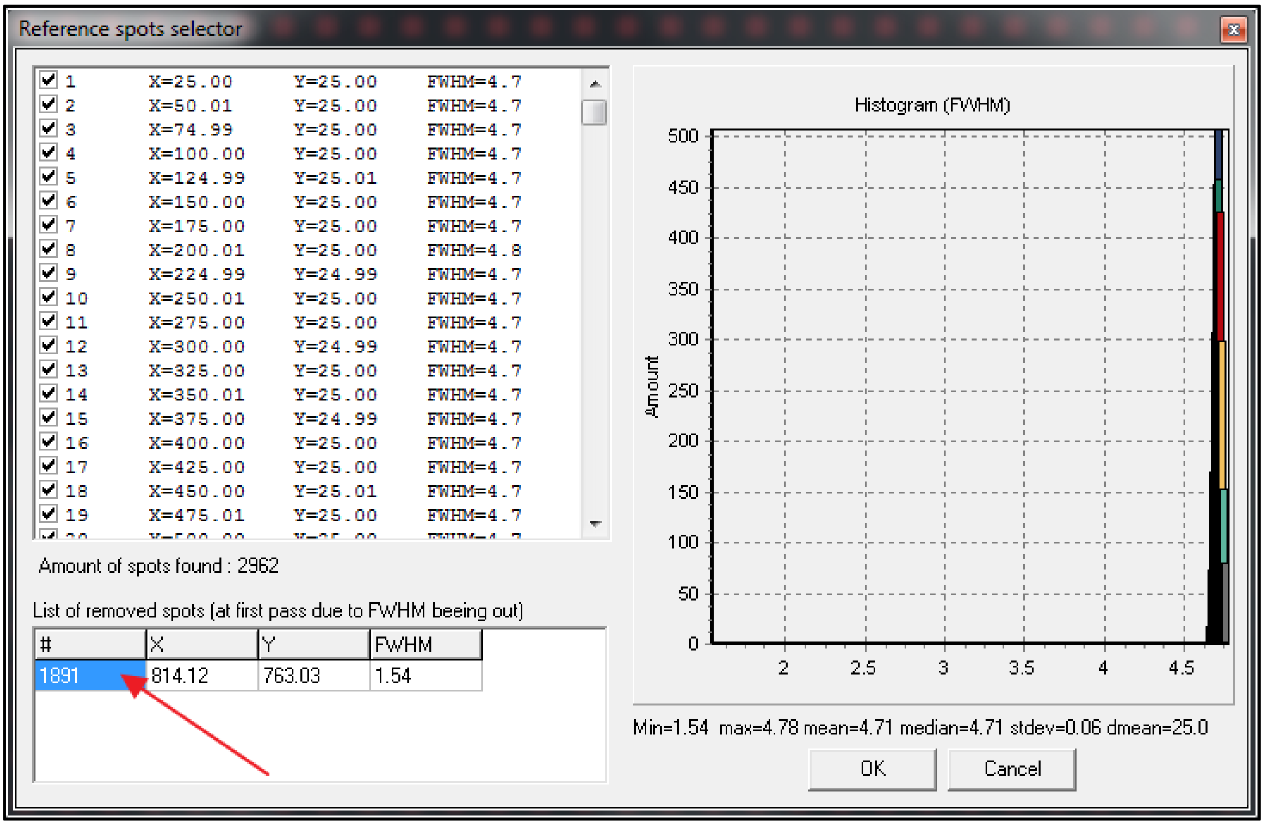


This form appears:

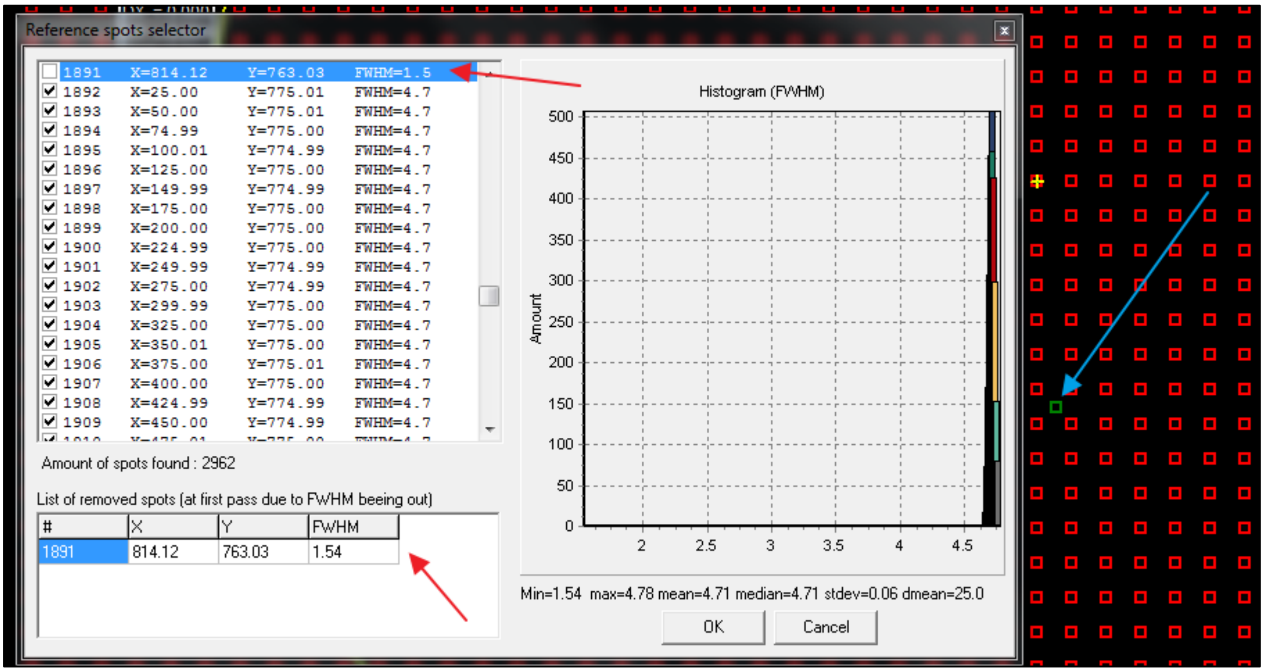


"***First pass spot summit detection threshold***": click "***Auto***" button to get an automated computed figure by the software, this is the pixel level threshold where the software shall perform a spot detection. The higher, the fastest, but some spots can be missed, the lower the slower is the detection algorithm.
"***Approximate spot distance (Pixels)***": is the approximate distance between spots, the "***Auto***" button provides a good figure if the "***system setup***" form has been filled properly.
"***Sigmas from mean roundness distribution***": Indicates the amount of "sigmas" from the mean distribution of spot roundness. If set to 4, for instance, the software will keep all spots that have a roundness of the mean roundness of all the detected spots plus/minus 4 times the standard deviation of all the detected spots.

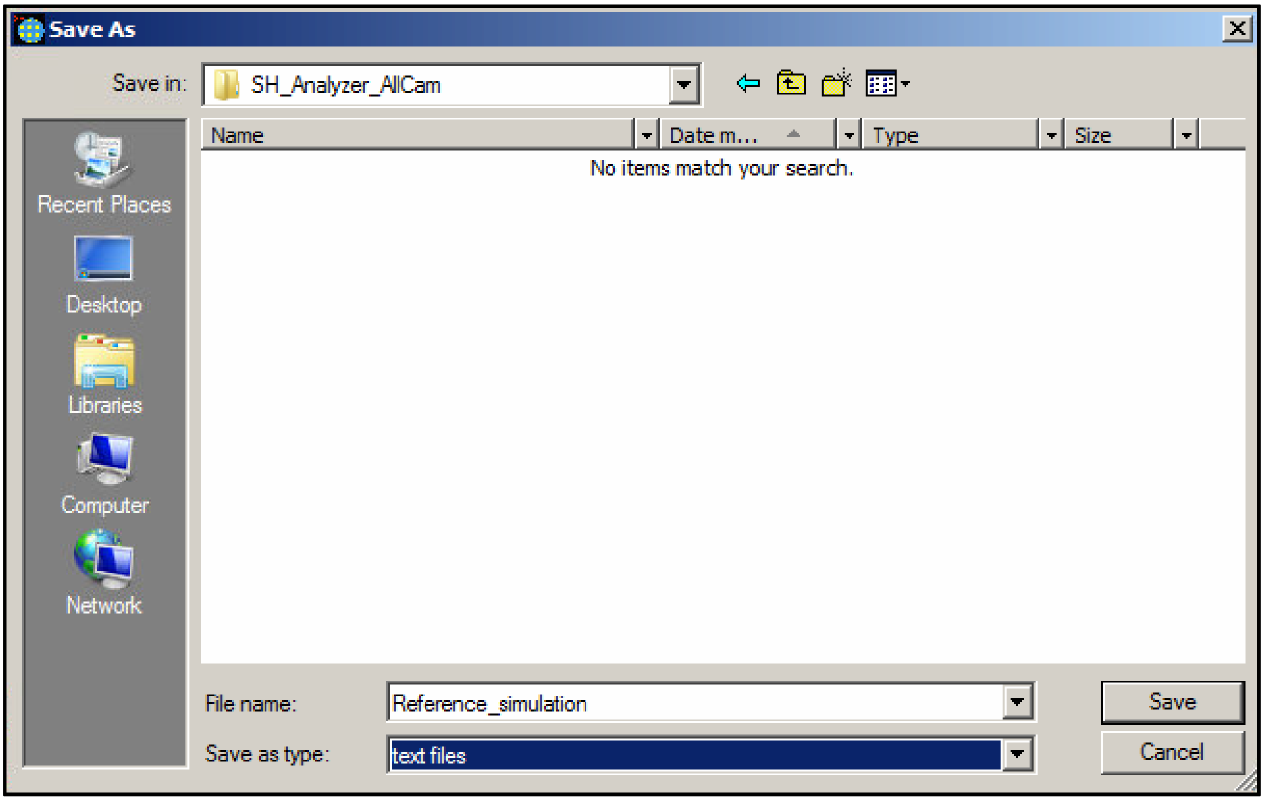
Once the software has finished extracting the spots, this form appears:



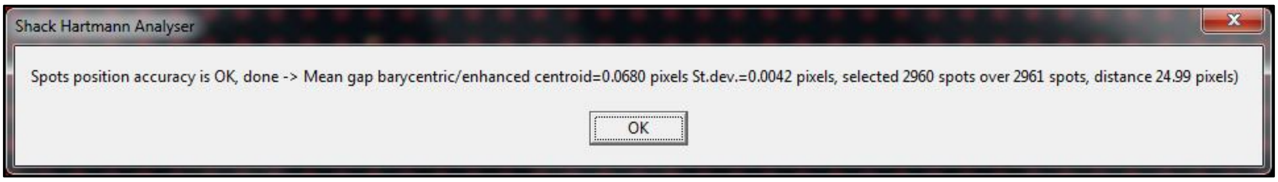
This is providing a list of 2962 detected spots, and only one has been automatically been removed from the list because its size is outside the main distribution size of spots.
The spot #1891 can be selected with a mouse left click and the software jumps to this spot on the main list and is being shown into the display as a green squared spot.
Spot can be manually eliminated or re-inserted if necessary.



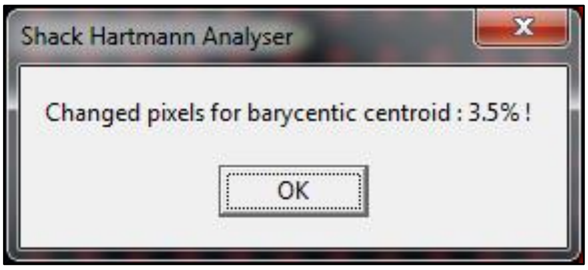
If "***OK***" is clicked, then a save box dialog appears, prompting the user to save the list of reference spots position to be used into a file.



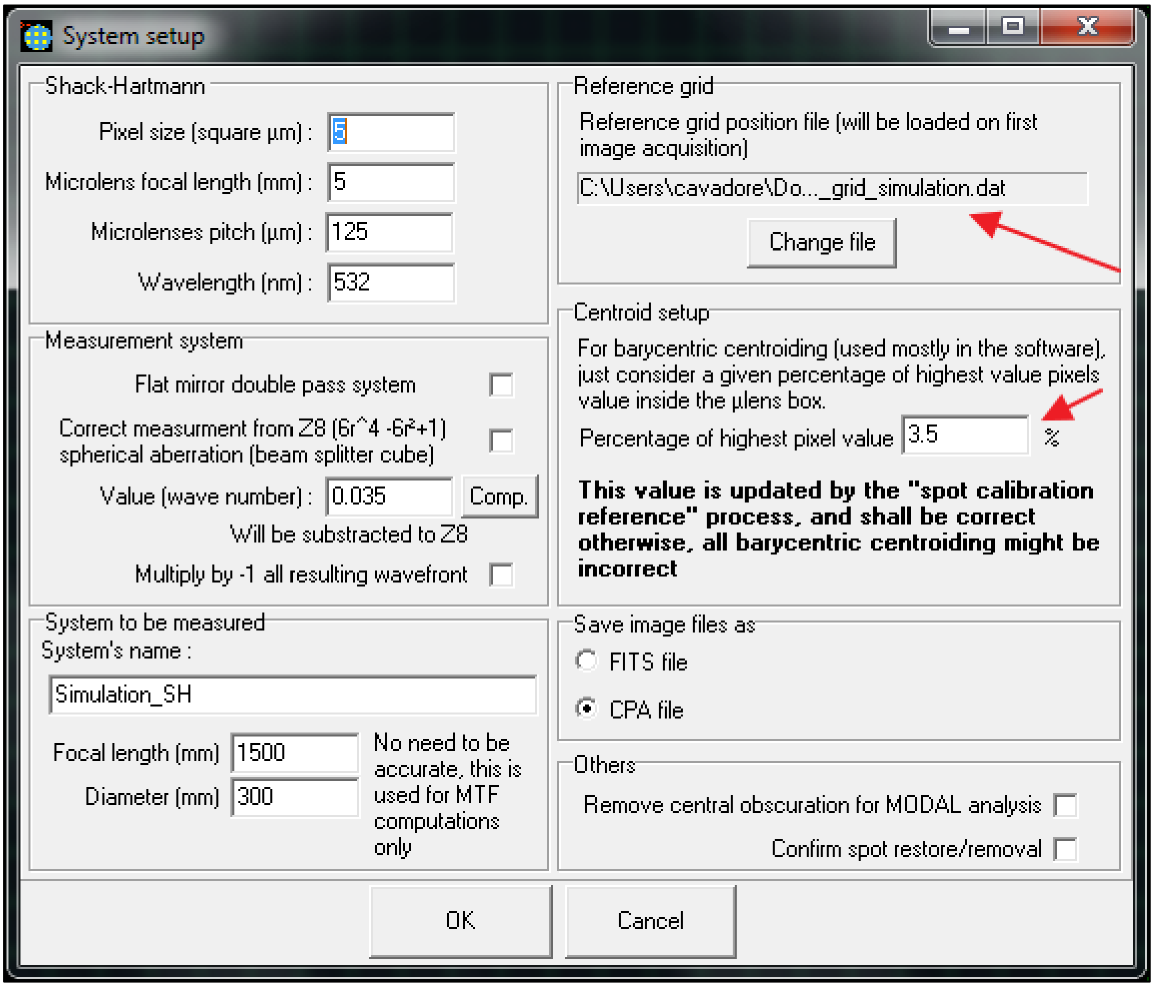
Enter the filename it will have, the software saves reference grid information both in ASCII and Binary fashions, here namely: ***Reference_grid_simulation.dat*** and ***Reference_grid_simulation.txt***
The text file (with .txt extension) can be opened for inspection and manually edited if required.
Once the file generated, the software displays this information, providing that all operations went fine.



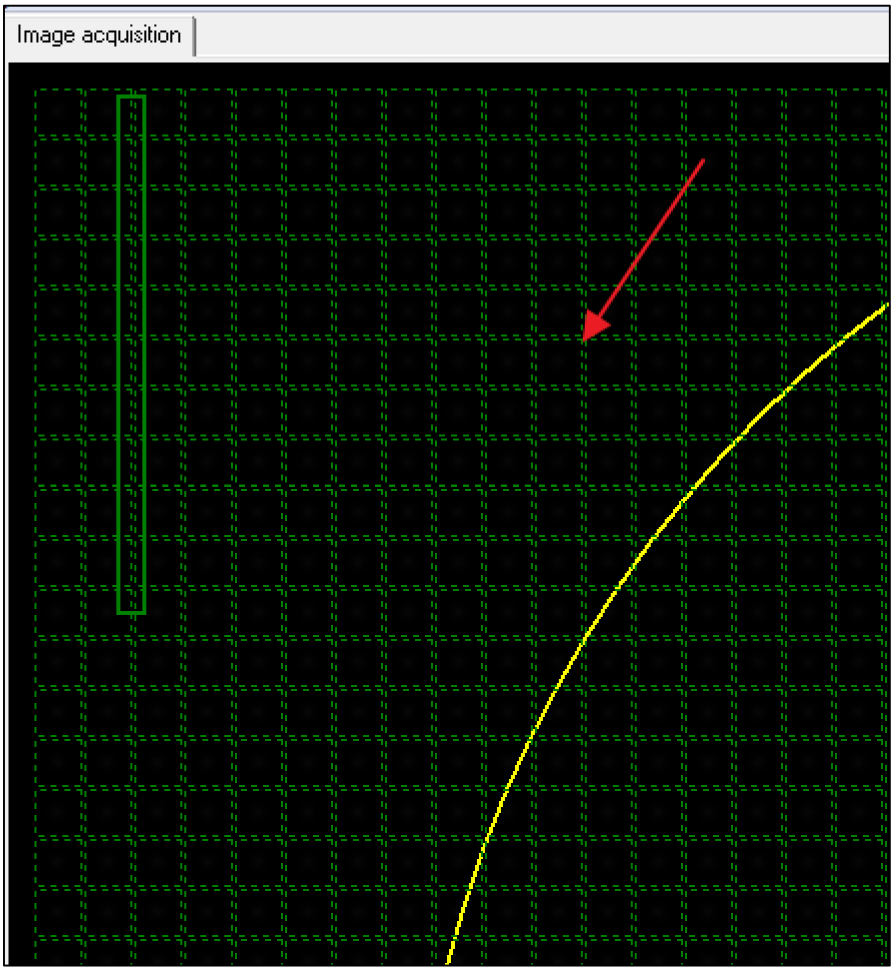
Then the software computes the best ratio of pixels to be used inside the area of computation to be used for barycentric centroiding.



The spot reference file position grid and the amount of pixels to be used is part of the system setup and can be found for checking in the “***System setup***” form that has been previously filled. This can also be changed manually if required by the user.

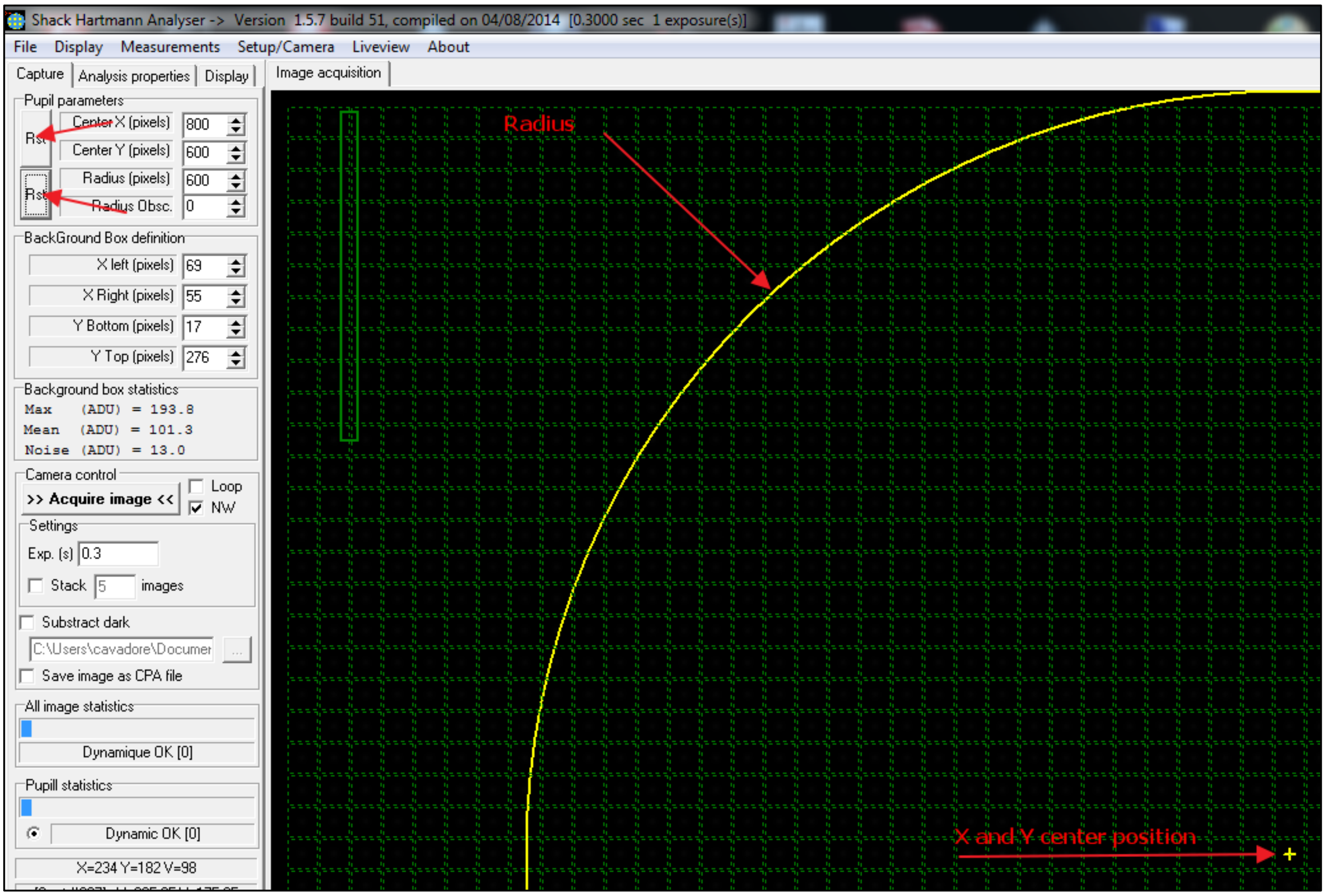


The reference grid is now displayed as squares with green dotted lines, the center of the square is the reference position of the spot, and distance to this reference will be used to compute wavefront.
This reference grid is used to compute the wavefront with respect to this reference wavefront
It should be a regular pattern, with no overlapping squares



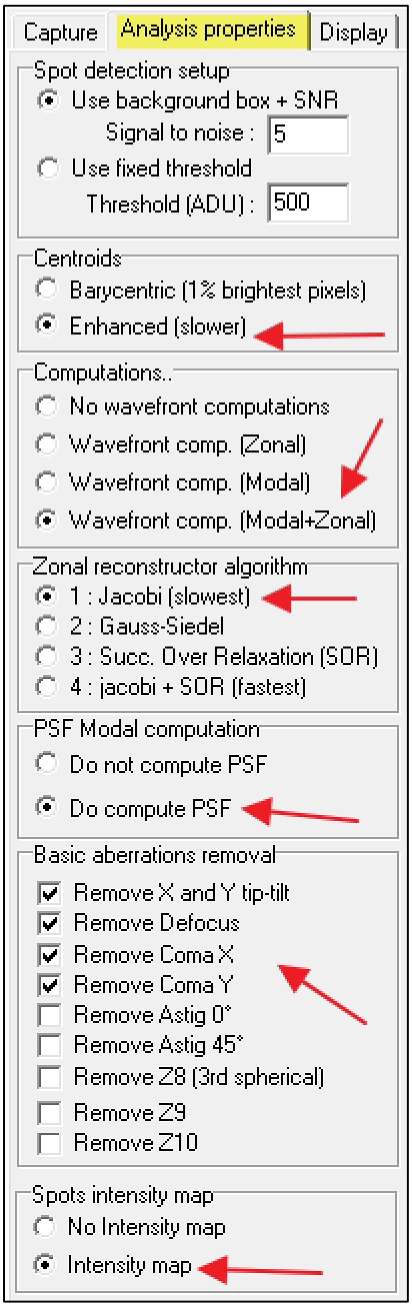
1.7. Software training : Measuring a wavefront compared to the reference wavefront grid

The next step is to define the pupil to be analyzed; This is a circle shape that can have central obscuration.



By clicking the "***Rst***" buttons, the center of the pupil is the center of the image and the radius of the pupil is the half height of the image. In actual life this will not likely be the case, and pupil center can be defined by left click into the image while holding the Shift key, and radiuses be set by setting figures. For simulation mode, using "***Rst***" buttons is a fast way to define them.

Now coming to "***Analysis properties***" allows setting the centroiding algorithm. Barycentric uses a fast and efficient centroiding algorithm that can cope with any spot shape, but it is less accurate than "***Enhanced***". Nevertheless this latter does not converge well with irregular spot shape. For simulation, since spot shape are perfect, use "***Enhanced***"

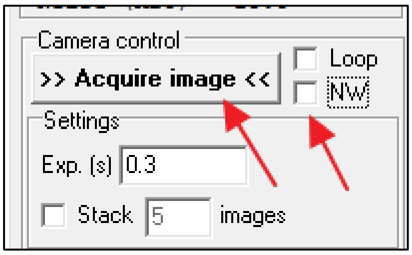


The "**Computation**" group box defines the kind of data to be computed. Modal reconstruction is performing a Zernike decomposition mode wavefront fitting. Zonal wavefront is achieving a zonal (or 3D modeling) from spot deviation with respect to reference. Please select "**Wavefront comp. (Modal+Zonal)**"

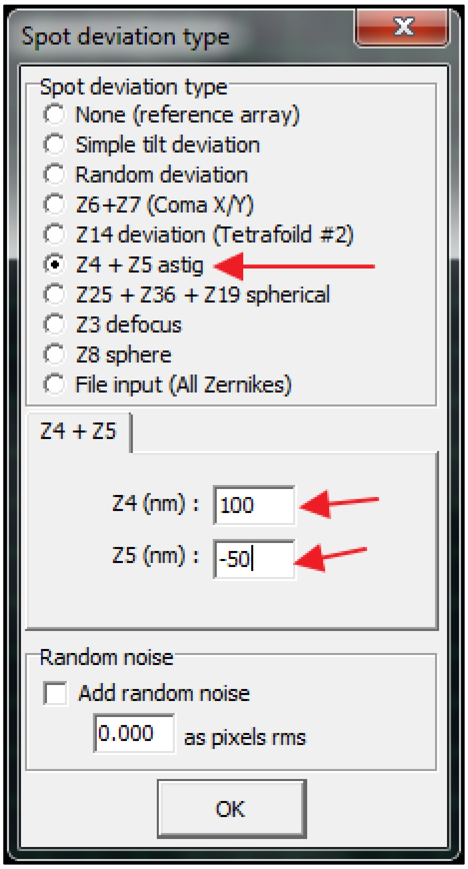
Several zonal reconstructions are available, some are speed optimized, and others are accuracy optimized.

The **basic aberration removal** group box allows discarding into the resulting wavefront all unwanted low order aberration types. This is a very convenient way of displaying the results that would be otherwise hidden into a simple tilt or a defocus of the wavefront.

Now, let's try a distorted wavefront compared to the reference, uncheck the "***NW***" option and click "***Acquire image***"



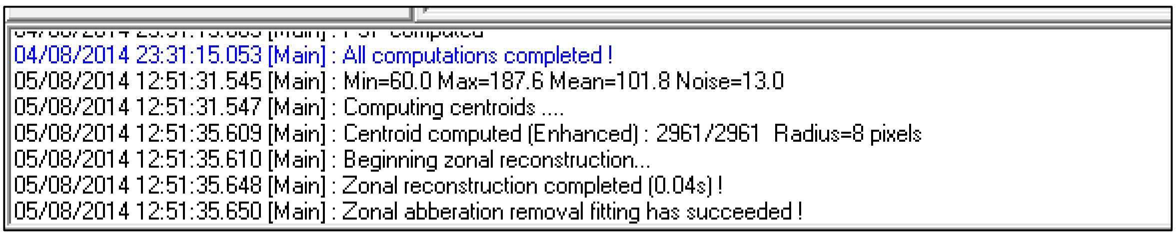
This form appears and a wavefront that exhibits first degree of astigmatism can be simulated this way:



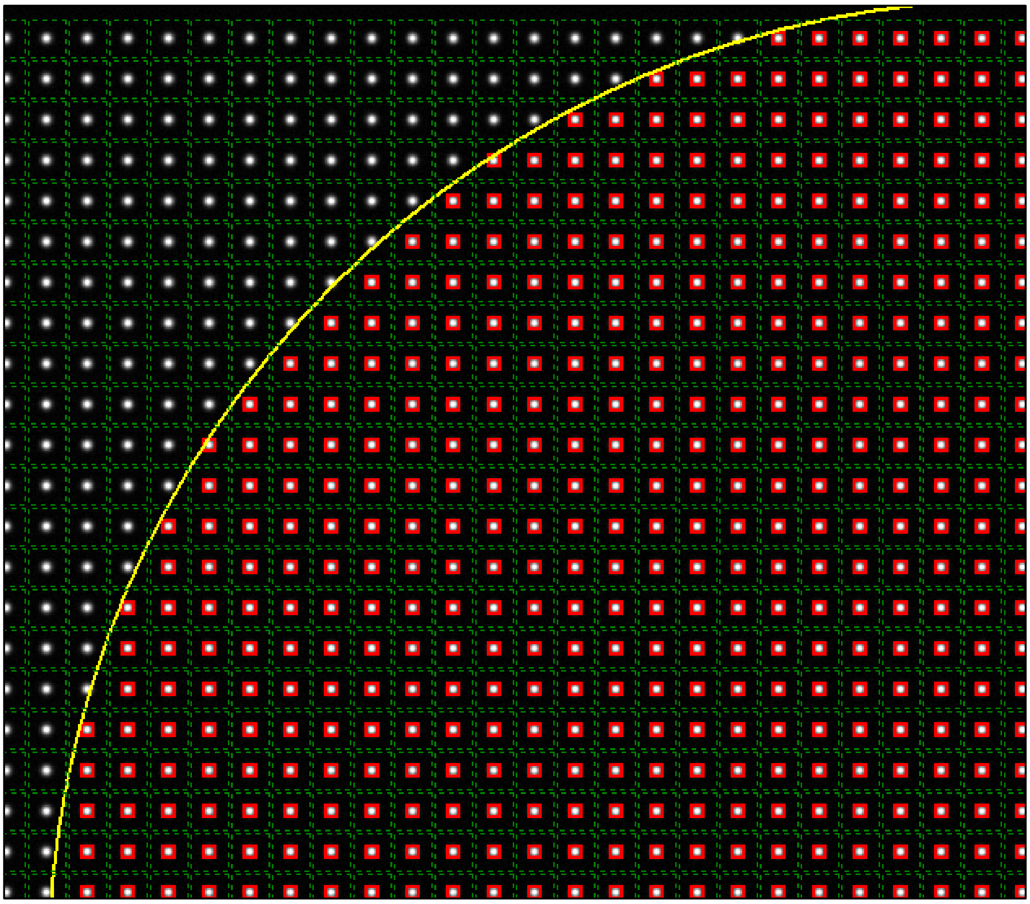
Set 100 nm to Z4 astigmatism and -50 nm to Z5, then click “***OK***”

All other aberrations terms will be nulled in this simulation. The software computes spot positions according to the user input and then centroids the spot and gets the X and Y deviation from the reference. Wavefronts are then computed from these spots deviation.

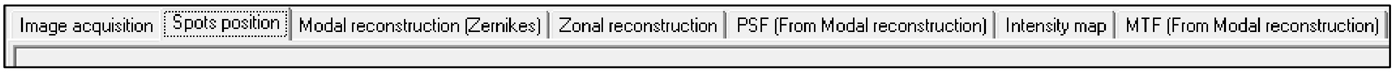
The bottom of the software shows a scrolling log event window, so that the user is made aware of pending operations



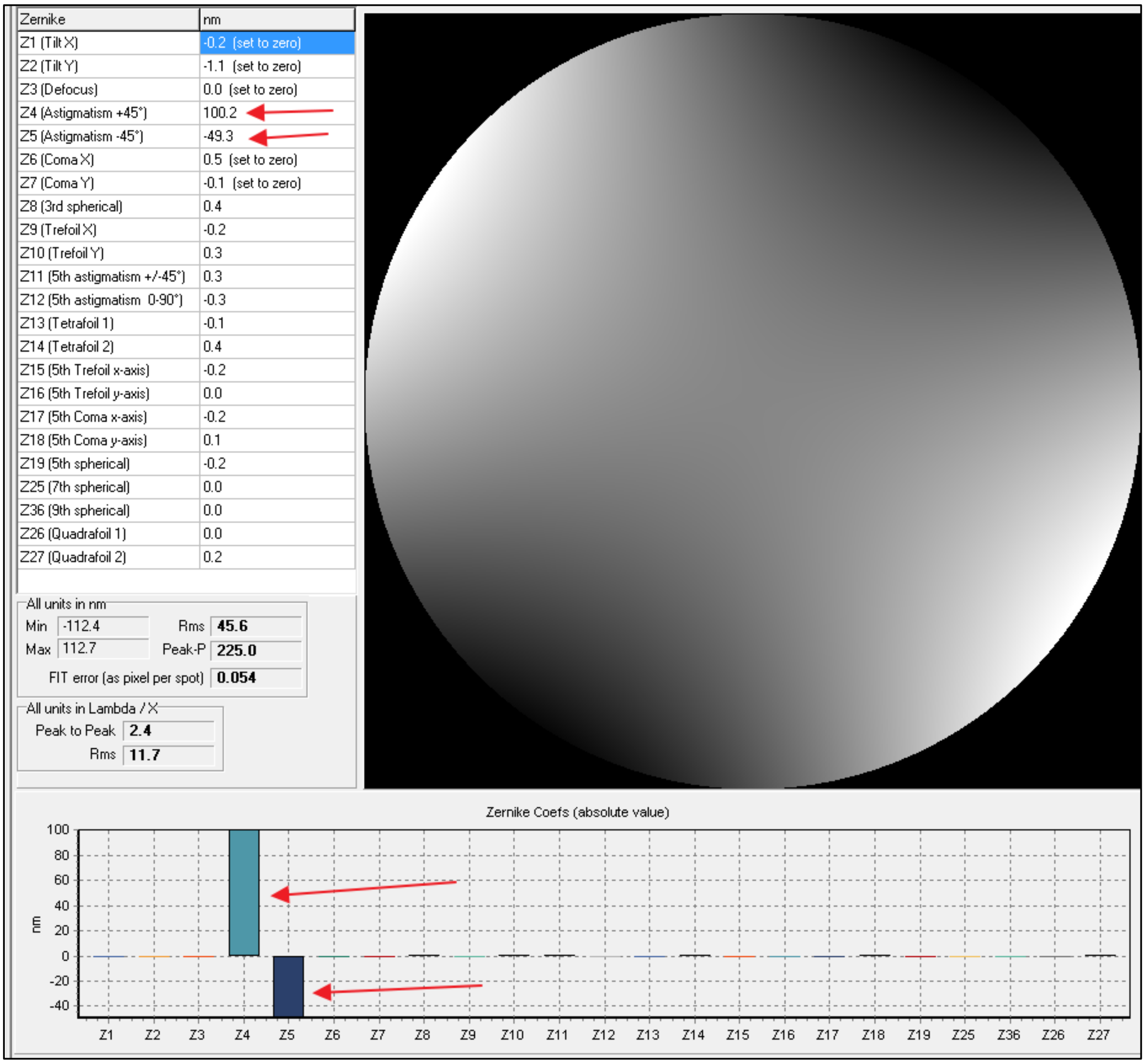
The valid centroids are only inside the pupil area and are displayed as red squares.



On end computing (the speed depends of the number of spots and the computer processor), many new tabs appears. These tabs presents computation results.



The “***Modal reconstruction (Zernikes)***” shows the wavefront as it is decomposed into Zernike modes. It displays the user canceled aberrations (Z1, Z2, Z3, Z6 and Z7) and all the computed ones. All aberration factors are close to zero (but not exactly zero due to centroiding noise), and only Z4 and Z5 are non-zero factor, and are very close to factors entered just after acquisition button was pressed.
This means that obviously the simulation is working well.

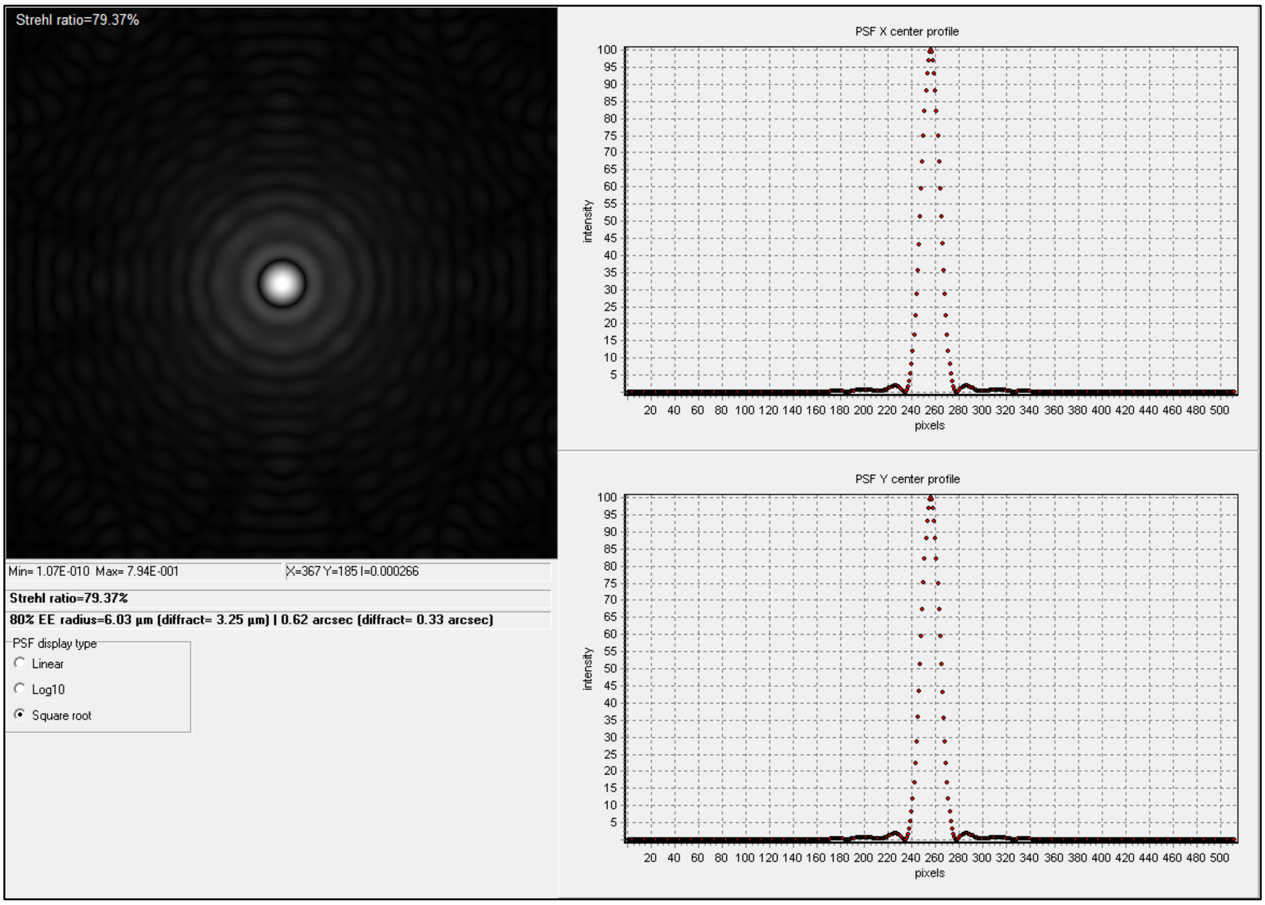


Wavefront map and graphic bars are displayed, only Z4 and Z5 are visible as expected.

The rms and p-p figures are computed from the wavefront map.

The PSF tab gives the resulting Point Spread Function from the modal wavefront map. This is what can see the user with a perfect eyepiece at the system output. Also X and Y cross sections are displayed.

The strehl ratio factor is computed in this tab, this shows how your optical system will perform, the higher is the better.
This tab also displays the encircled energy radius where 80% of the energy sits and resolution. All these figures are compared to the diffraction limited figures that would produce a perfect system.



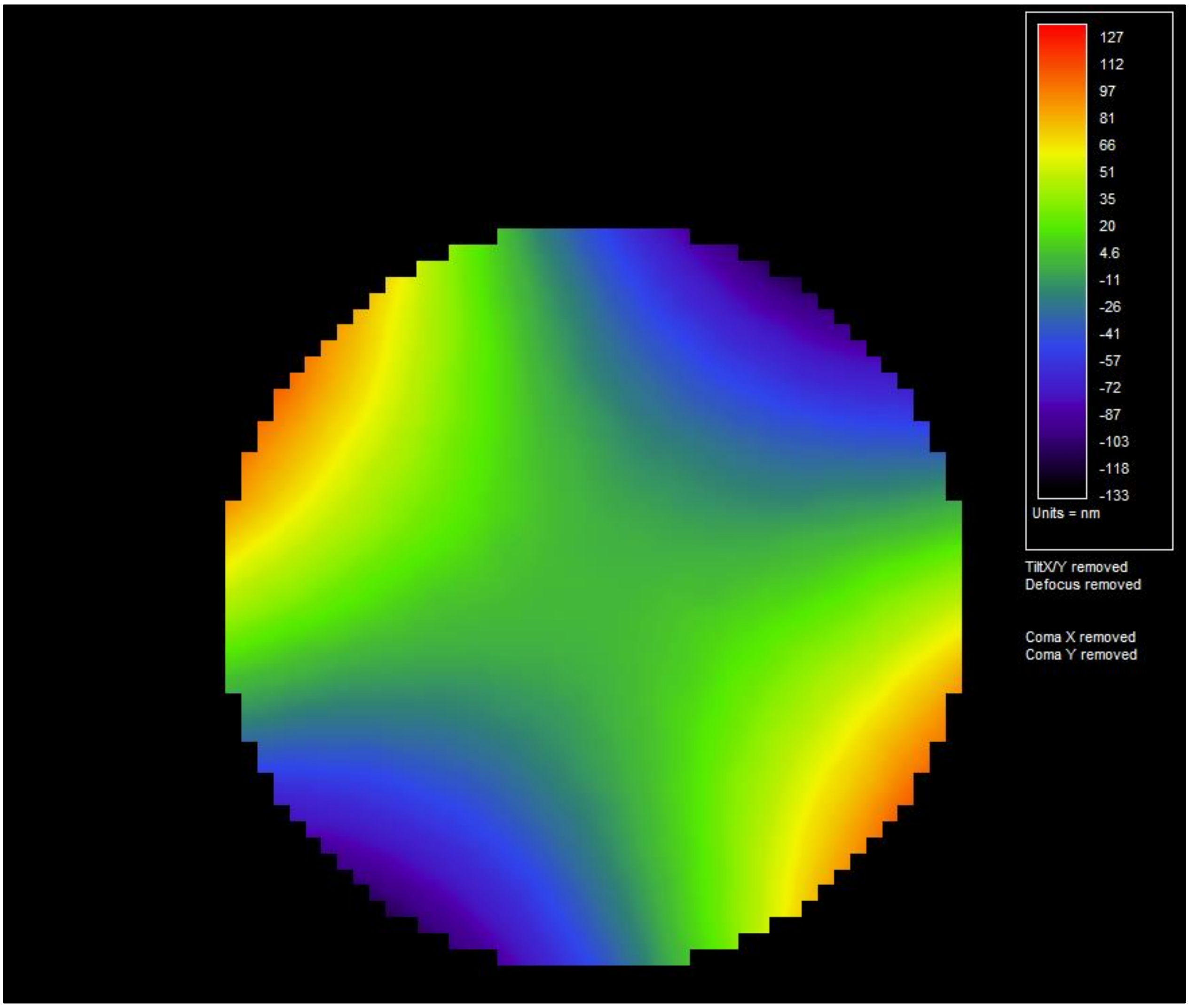
The Zonal reconstruction is also computed (if requested by the user) and shows a 3D reconstruction of the wavefront. It has more resolution that the modal reconstruction, but is more prone to local spot centroiding errors.

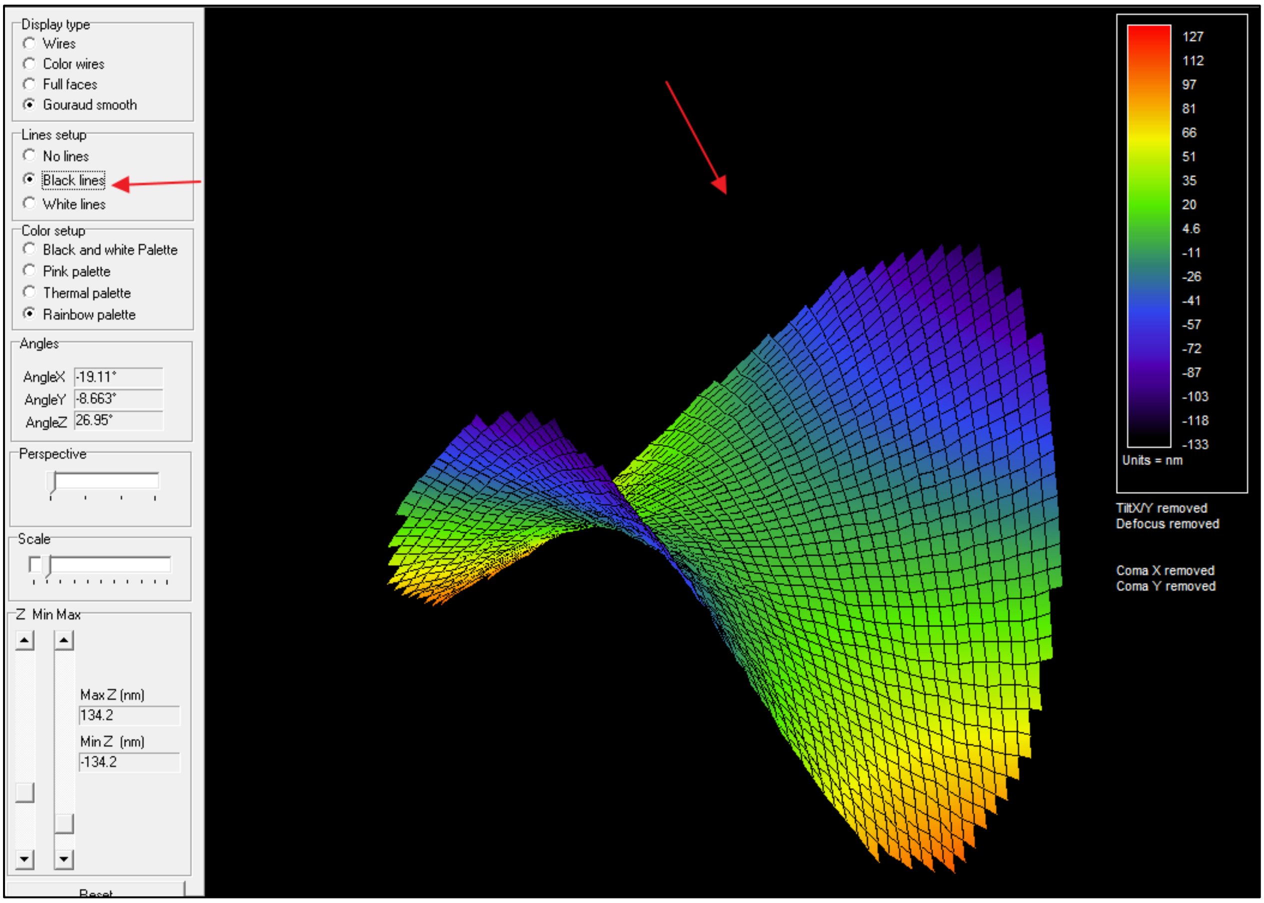
The 3D plot can be inspected from different point of view; by left clicking the zonal window display and hold down the mouse left button and moving around the plot.

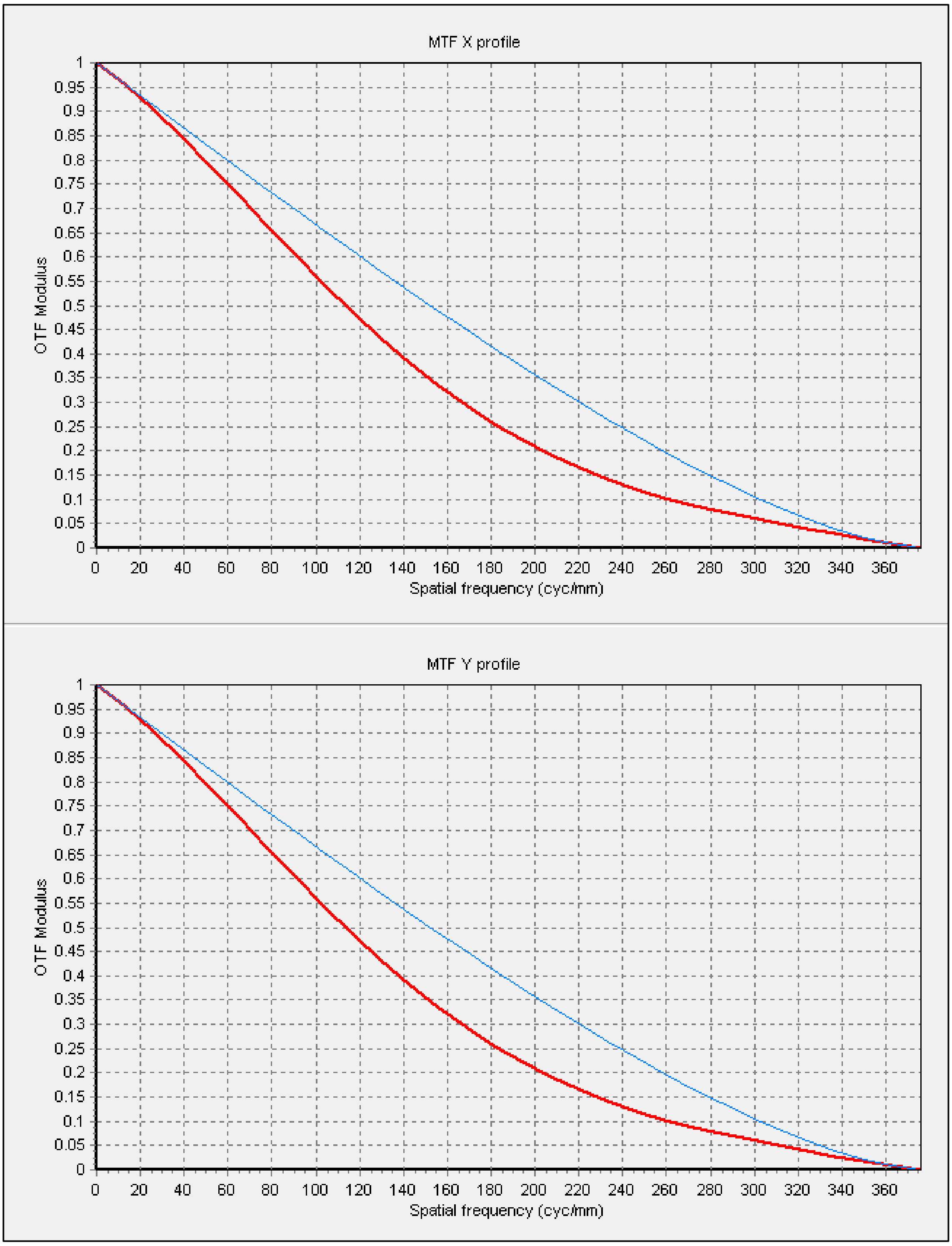
A lot of display setup options can be tuned to change color, scale… since this is quite obvious, the user can play with these options and see their effect.

The rms and p-p figures from this reconstruction are also computed, and should be close to figures retrieved from the modal reconstruction. There are not exactly the same because the zonal reconstruction is far more sensitive to a badly computed spot centroid.

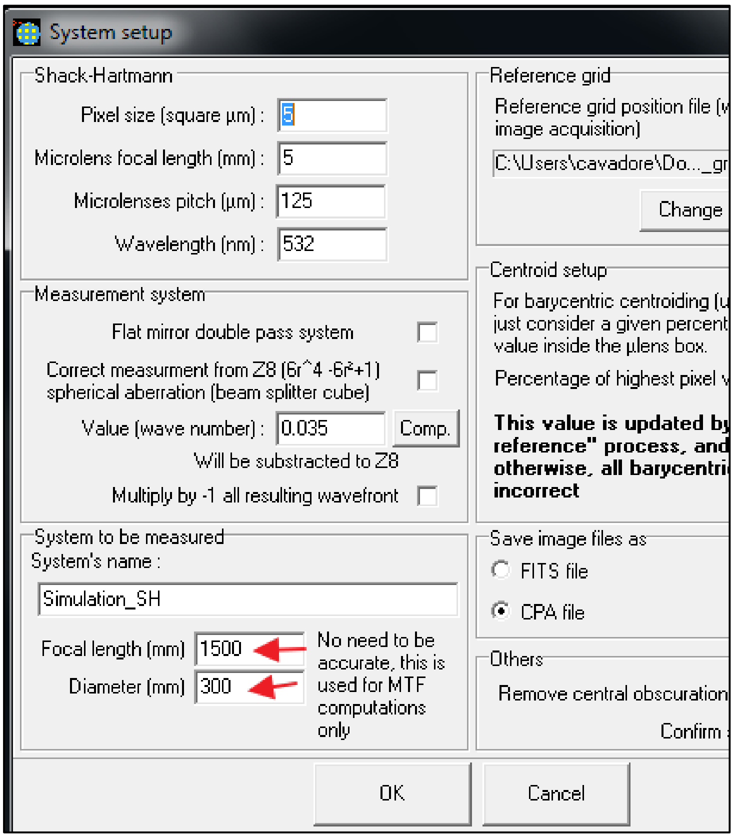
Warning : zonal reconstruction requires a good amount of spots (> 3000), failure to comply so may lead to some inaccuracies and different results when compared to the modal reconstruction. Modal reconstruction does not require so much point to provide reliable wavefront estimation.


127
112
97
81
66
51
35
20
4.6
-11
-26
-41
-57
-72
-87
-103
-118
-133
Units = nm
TiltX/Y removed
Defocus removed
Coma X removed
Coma Y removed


Display type
Wires
Color wires
Full faces
Gouraud smooth
Lines setup
No lines
Black lines
White lines
Color setup
Black and white Palette
Pink palette
Thermal palette
Rainbow palette
Angles
AngleX -19.11°
AngleY -8.663°
AngleZ 26.95°
Perspective
Scale
Z Min Max
Max Z (nm)
134.2
Min Z (nm)
-134.2
127
112
97
81
66
51
35
20
4.6
-11
-26
-41
-57
-72
-87
-103
-118
-133
Units = nm
TiltX/Y removed
Defocus removed
Coma X removed
Coma Y removed

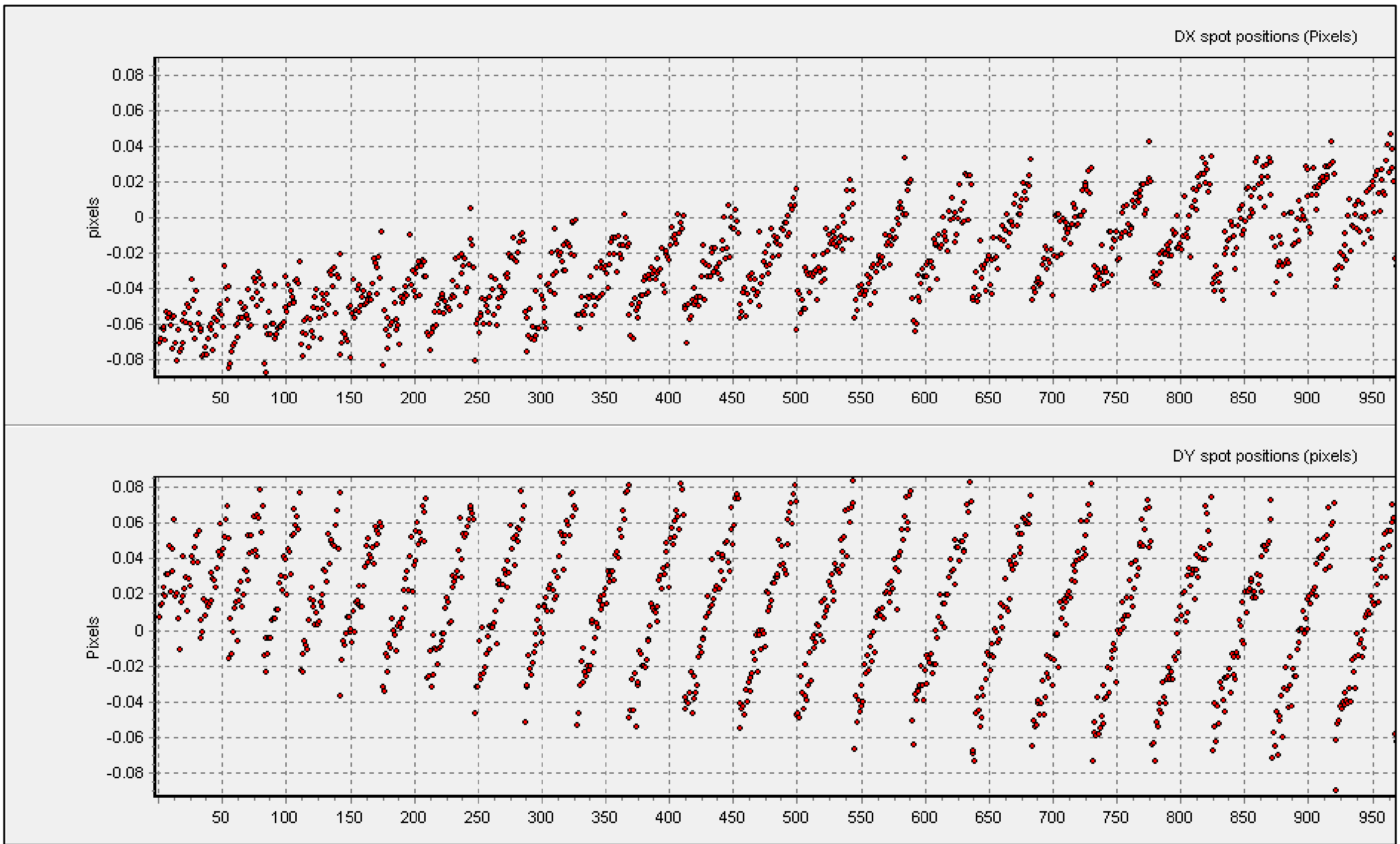


The MTF X and Y profile are computed and displayed as 2D plots. The red curve is the current system performance and the blue line is the performance of the same system with no wavefront errors.
This is achieved provided the following data has been input properly:



The spot position tab is also a very useful tab. It shows each spot deviation expressed in pixels from the reference center grid position. For instance, spot #26 is offset by -0.007 and + 0.007 pixels from the reference. Spot offset (or deviation) is shown into two 2D plots in X and Y directions, showing the distribution of offsets for all spots inside the pupil.

Note that the software is able to measure very small spot offsets especially if image signal to noise ratio is good (say is able to measure 0.002 pixel of offset)

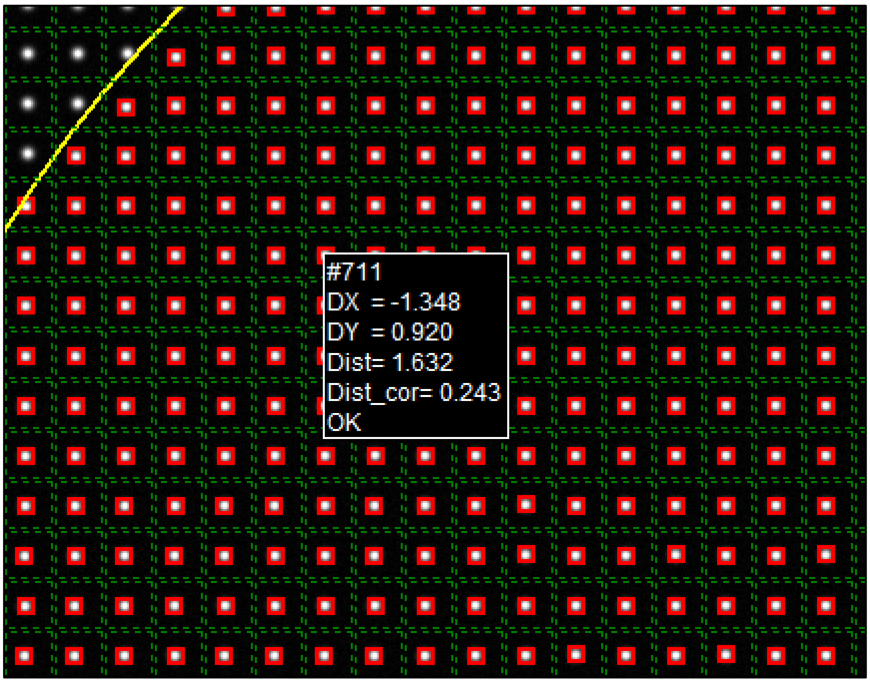


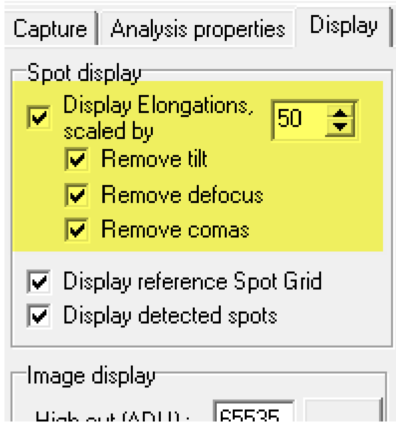
Spt #	X (ref)	Y (ref)	DX	DY
26	650.0029	25.0026	-0.0709	0.0074
27	674.9965	24.9978	-0.0687	0.0137
28	699.9995	25.0127	-0.0631	0.0145
29	724.9990	25.0000	-0.0636	0.0200
30	749.9969	25.0012	-0.0622	0.0234
31	775.0030	25.0016	-0.0694	0.0190
32	799.9953	24.9996	-0.0534	0.0313
33	824.9983	24.9999	-0.0574	0.0309
34	849.9941	24.9958	-0.0544	0.0466
35	874.9974	25.0114	-0.0614	0.0211
36	899.9924	24.9989	-0.0568	0.0454
37	925.0036	25.0004	-0.0746	0.0332
38	950.0065	24.9966	-0.0559	0.0621
86	574.9968	49.9938	-0.0708	0.0187

Statistics (pixels)

Mean |DX|	0.032	Rms	0.038
Mean |DY|	0.032	Rms	0.038
Mean DX	0.000		
Mean DY	0.000		
Distance	0.050	(mean)	

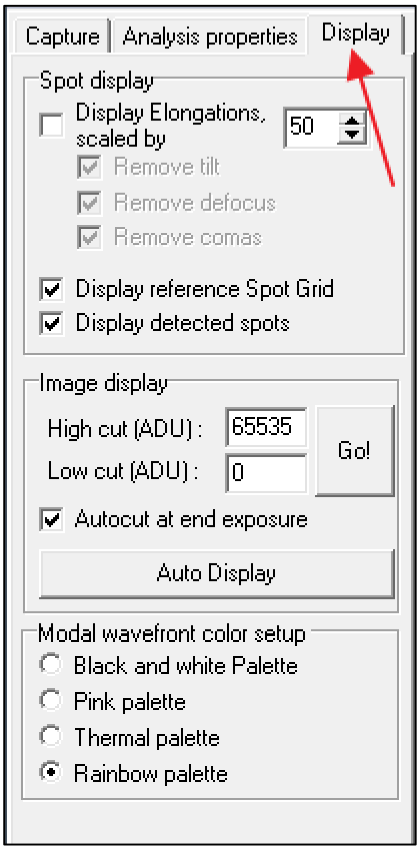
On image mouse move, into the red detected and used spots, a small black hint window will pop up to display the spot number, the DX and DY offset and the distance from the reference, all expressed in pixels. "***OK***" label mentions that this spot centroid has no error and being used to perform modal and zonal reconstruction. The **dist_cor** indicates the distance from the reference to the actual spot position when this is corrected from the aberrations that are checked (or not) from the spot display group box, in the display tab.



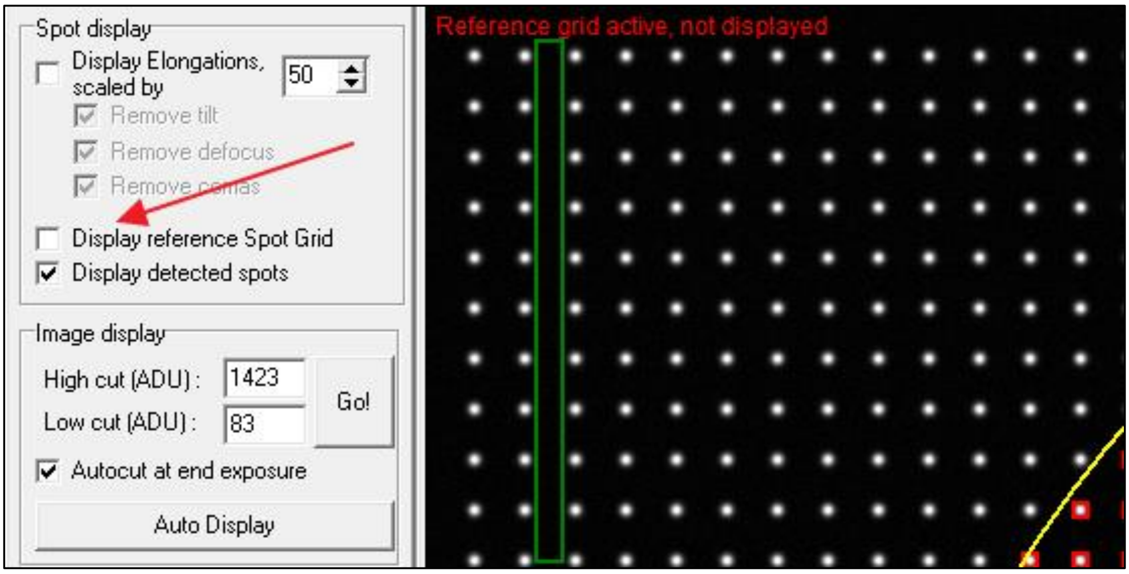


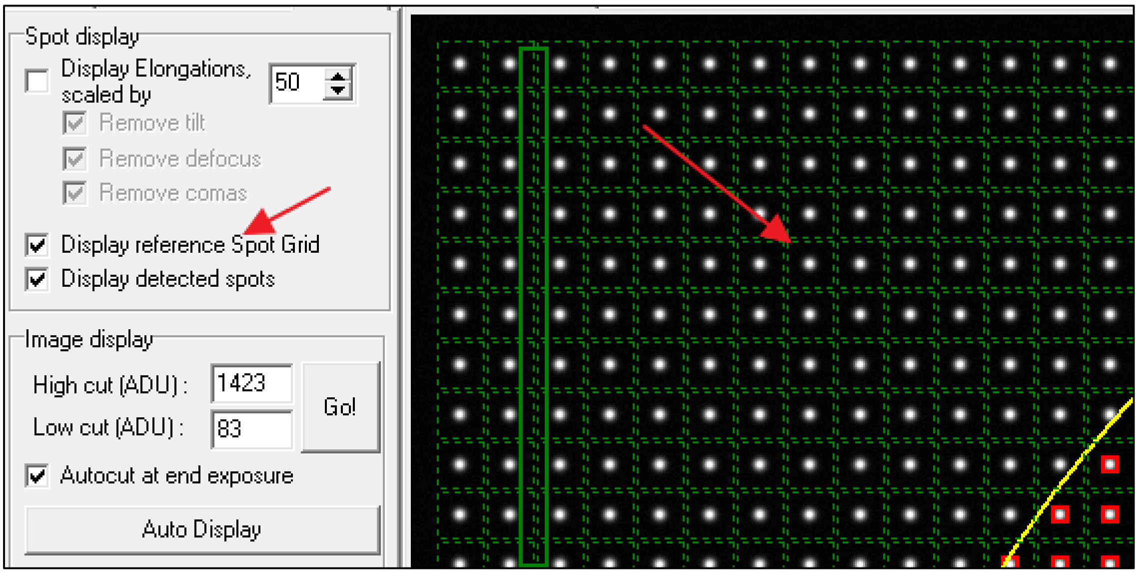
1.1.1.<u>Display features</u>

The software has many displays features that changes the way the image into the "***Image acquisition***" tab will be rendered.

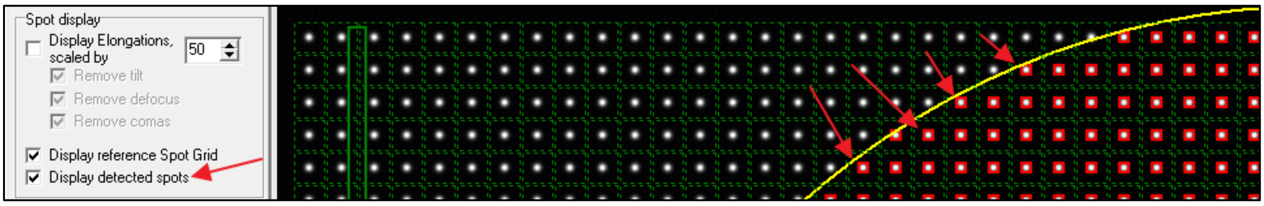


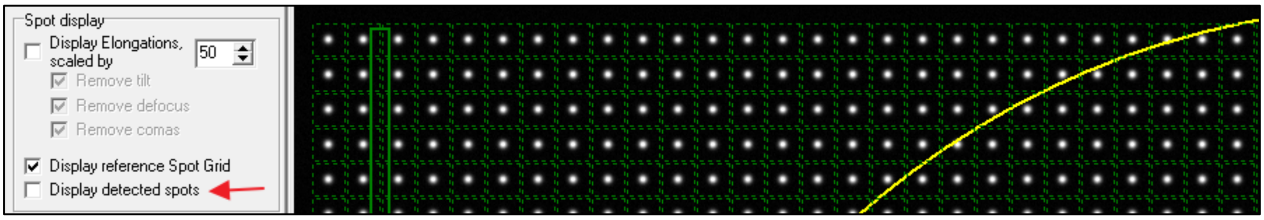
The reference spot grid, displayed as green rectangle dotted lines can be enabled or disabled for better / clearer displaying.



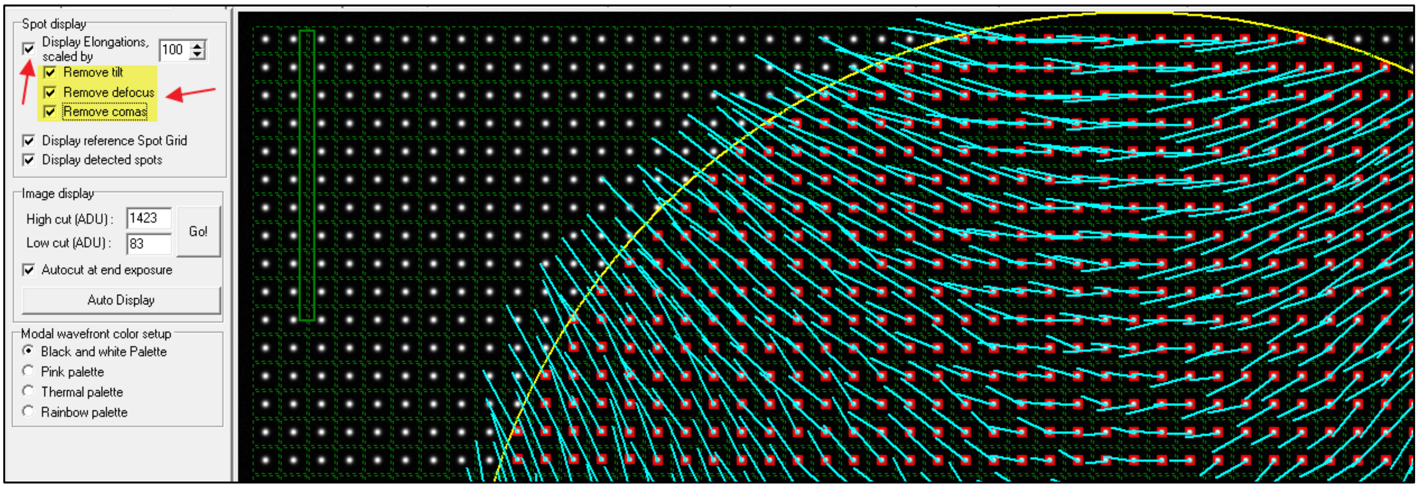


The user can also enable or disable detected spots used for wavefront reconstruction

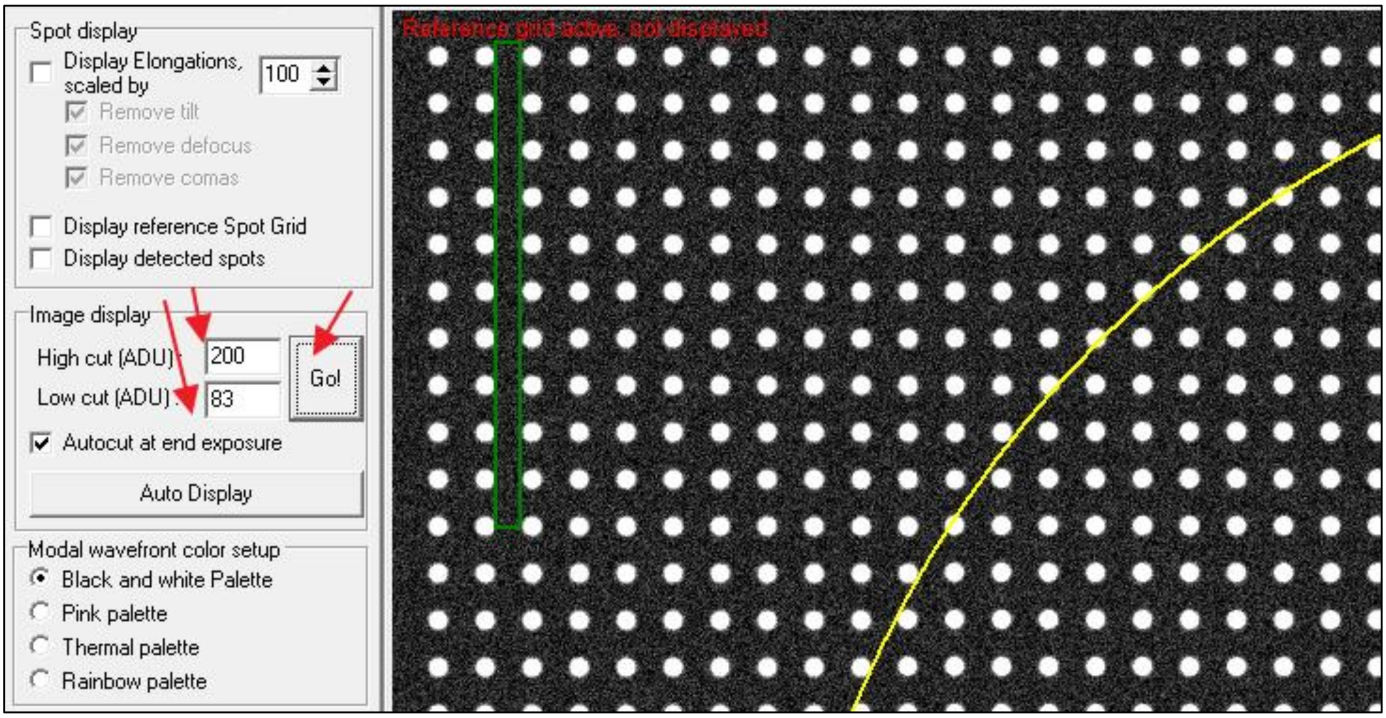




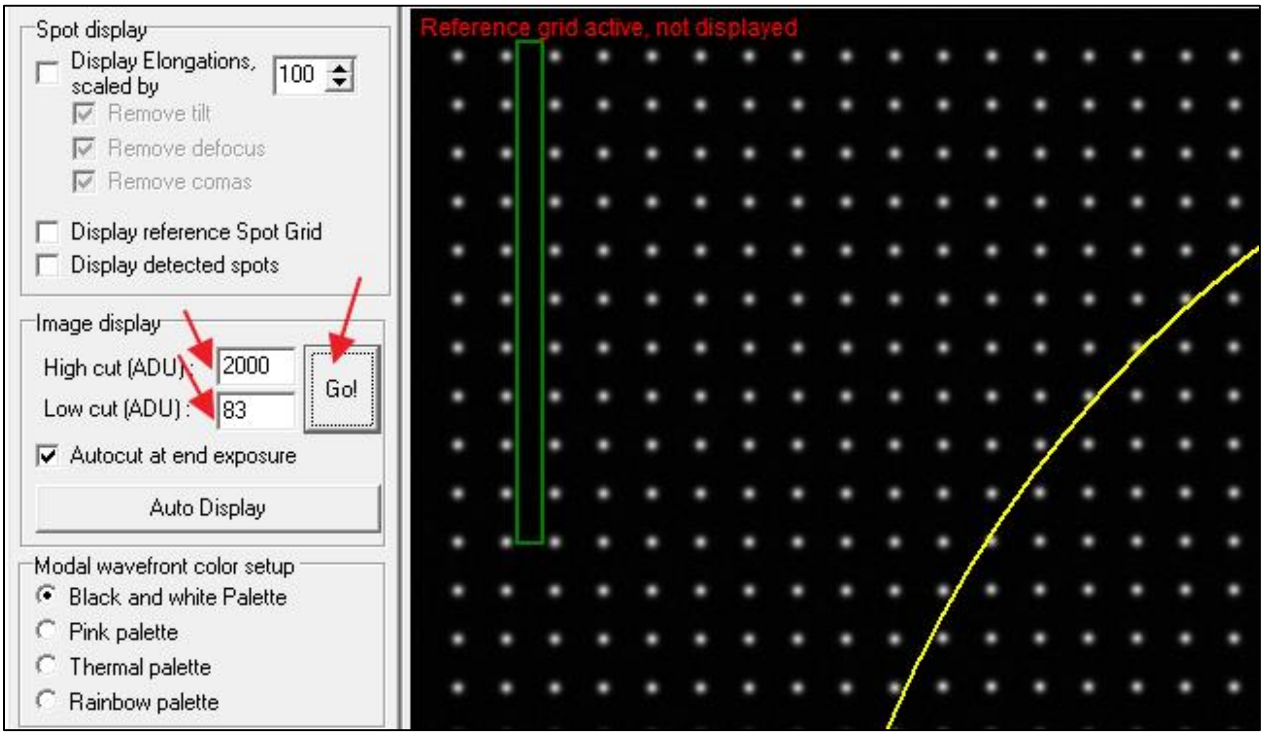
A very important feature is to show amplified spot deviation/offset. This can be achieved as follow, and basic aberration can be removed (tilts, defocus and comas) to provide a better view of the spot deviation from the reference. Amplification factor (here 100x) can be set to have a better view, because in most cases, this is a sub pixel deviation. This is a very powerful function that will be used in real conditions



Luminosity and contrast can be tuned into the image display box. Most of the time the software does this task automatically, but sometimes, the user may need to change this manually
Display cuts can be set, here 200 and 83 ADUs. It means that all pixels above 200 ADUs will be displayed as white, and all pixels below 83 ADUs will be displayed as black. Between 200 and 83, it will be display as a gray linear scale.

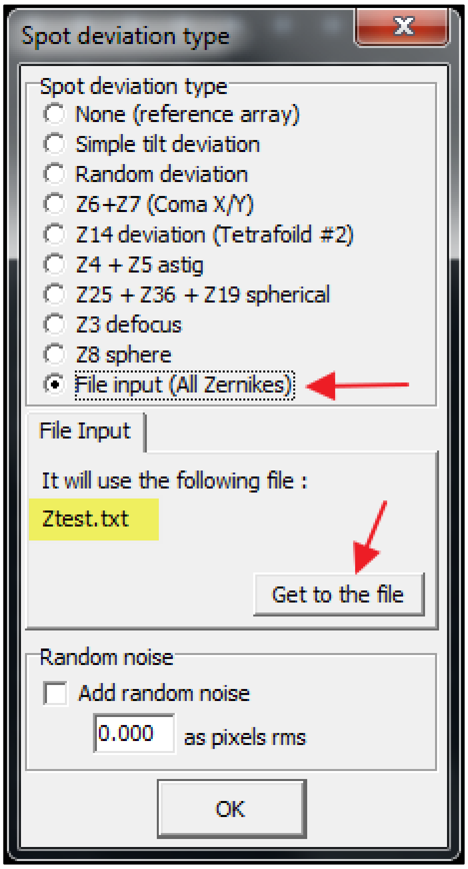


It is recommended to play with these figures to get used of this feature.



1.1.2.A more complicated wavefront to reconstruct

This software allows more complicated simulated spot deviations schemes (and thus more complicated wavefronts to be simulated)
Family group of other Zernike modes can be tested.
Moreover, a complete file with 23 zernike modes and random spot deviation can be used. After image acquire launch, check "***File input (All zernikes)***", the folder file to be used can be found by clicking "***Get to the file***", and the software will input the ***Ztest.txt*** file. This latter can be user edited.



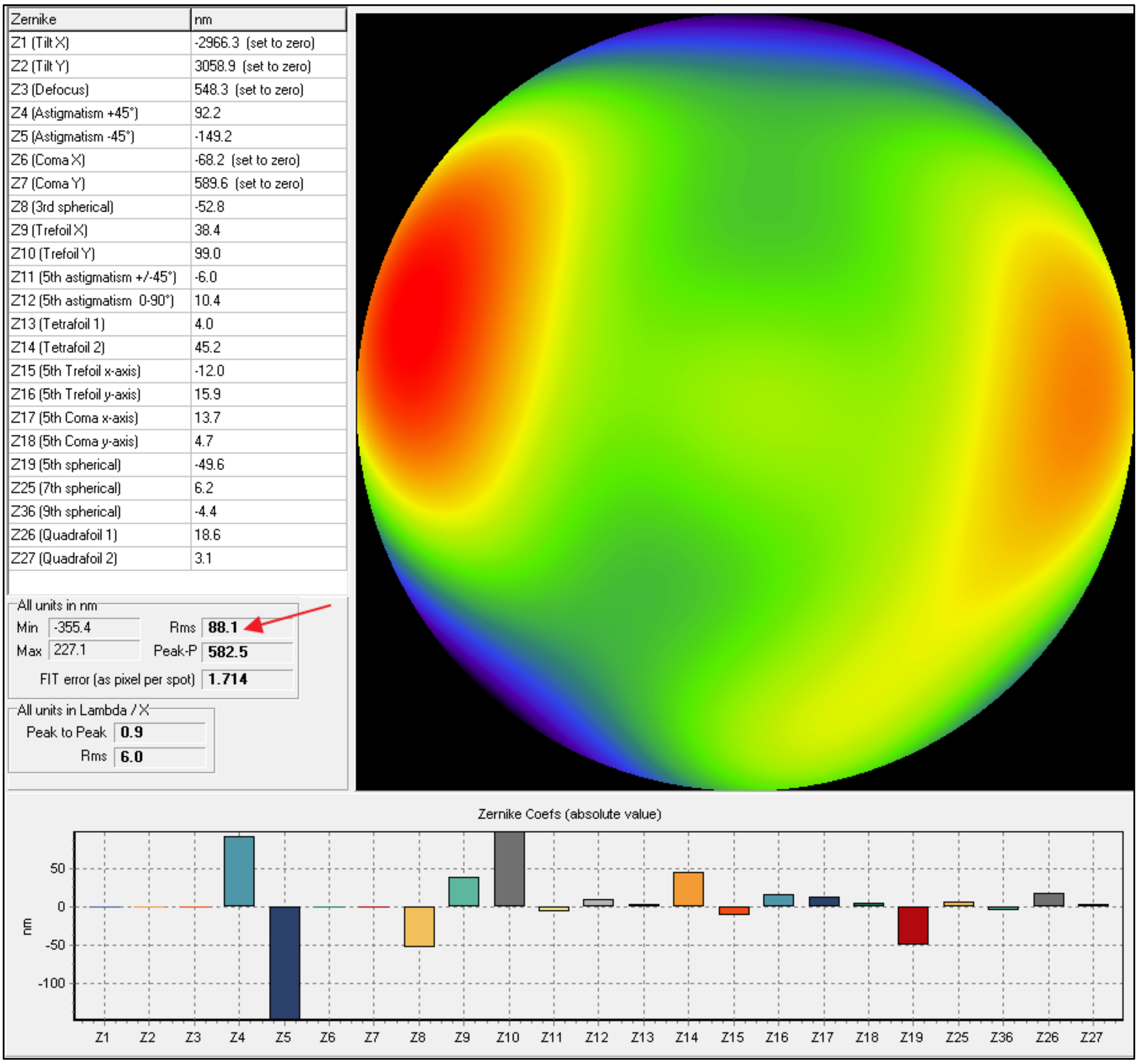
The text file must have the following syntax, with Zernikes factors as follows:

Ztest .txt

```
All units are nm
Z1=-2959
Z2=3057
Z3=550
Z4=89.6
Z5=-152.5
Z6=-71.1
Z7=591.7
Z8=-55
Z9=32.6
Z10=98.7
Z11=-4.5
Z12=11.8
Z13=5.9
Z14=44.4
Z15=-7.1
Z16=15.1
Z17=16.9
Z18=3.3
Z19=-48.9
Z25=6.1
Z36=-4.3
Z26=17.9
Z27=-0.4
RDX=0.07
RDY=0.07
```

RDX and RDY refer to rms random deviation of each spots in both directions.
Failure to comply with this file syntax will lead to display an error message.
Let's use this file with these factors and see what is happening.

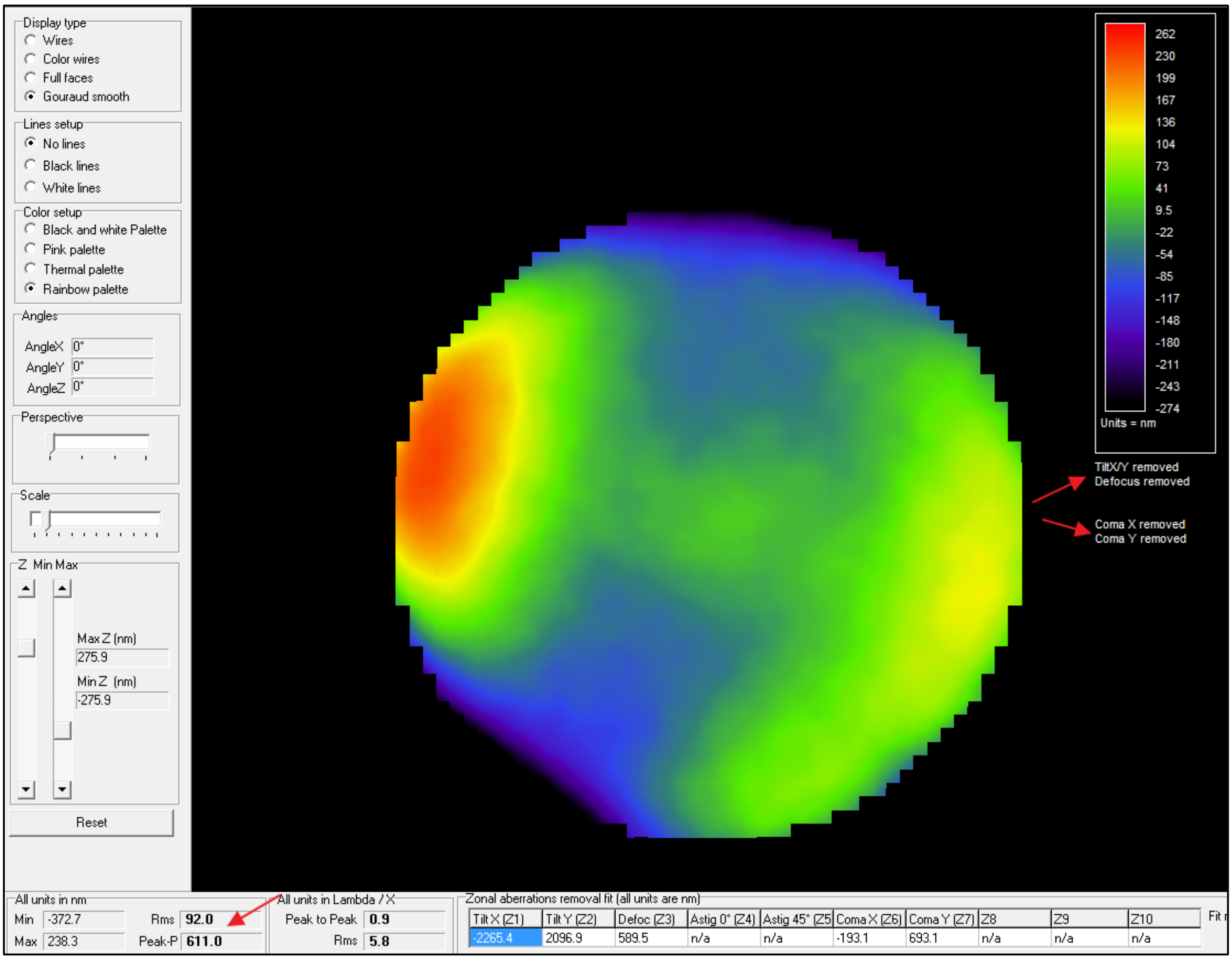
Once computation is achieved, the modal computed factors are very close to the input, but are not strictly the same because of the 0.07 pixel random noise added. Which mean that the higher the random noise of the spot position is, the lower the reconstruction accuracy will be.
Here a 88 nm rms error is displayed by the modal reconstruction.



Zernike	nm
Z1 (Tilt X)	-2966.3 (set to zero)
Z2 (Tilt Y)	3058.9 (set to zero)
Z3 (Defocus)	548.3 (set to zero)
Z4 (Astigmatism +45°)	92.2
Z5 (Astigmatism -45°)	-149.2
Z6 (Coma X)	-68.2 (set to zero)
Z7 (Coma Y)	589.6 (set to zero)
Z8 (3rd spherical)	-52.8
Z9 (Trefoil X)	38.4
Z10 (Trefoil Y)	99.0
Z11 (5th astigmatism +/-45°)	-6.0
Z12 (5th astigmatism 0-90°)	10.4
Z13 (Tetrafoil 1)	4.0
Z14 (Tetrafoil 2)	45.2
Z15 (5th Trefoil x-axis)	-12.0
Z16 (5th Trefoil y-axis)	15.9
Z17 (5th Coma x-axis)	13.7
Z18 (5th Coma y-axis)	4.7
Z19 (5th spherical)	-49.6
Z25 (7th spherical)	6.2
Z36 (9th spherical)	-4.4
Z26 (Quadrafoil 1)	18.6
Z27 (Quadrafoil 2)	3.1

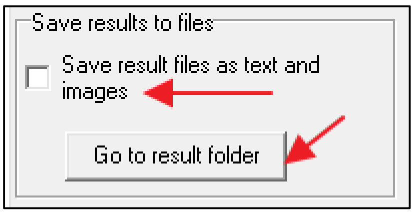
The zonal reconstruction shows a very close agreement with the modal reconstruction: the wavefront shape is the same and the rms figure is 92 nm (whereas is 88 nm using modal reconstruction).

Zonal display reconstruction also shows the removed aberrations.

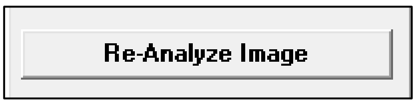


1.1.3. Saving data and image re-analysis

All computed data can be saved as bitmap and text files into a dedicated folder
This checkbox shall be enabled to allow data to be saved.



Computations settings can be changed and the wavefront reconstruction be achieved without acquiring a new image. Just change what is needed to be changed and then press this button:



2. Additional data

Table of Zernike polynomial used by this software, which can be different from other software (like Zemax), is presented hereafter.

Name	This software	Zemax (Zernike Fringe Polynomials)	Zernike table
Piston	Z0	Z 1 : 1	$Z_{0,0}$
Tilt X	Z1	Z 2 : (p) * COS (A)	$Z_{1,1}$
Tilt Y	Z2	Z 3 : (p) * SIN (A)	$Z_{1,0}$
Defoc	Z3	Z 4 : $(2p^2 - 1)$	$Z_{2,1}$
Astig + 45°	Z4	Z 6 : (p^2) * SIN (2A)	$Z_{2,0}$
Astig -45°	Z5	Z 5 : (p^2) * COS (2A)	$Z_{2,2}$
Coma X	Z6	Z 8 : $(3p^2 - 2)$ p * SIN (A)	$Z_{3,1}$
Coma Y	Z7	Z 7 : $(3p^2 - 2)$ p * COS (A)	$Z_{3,2}$
3rd order Spherical	Z8	Z 9 : $(6p^4 - 6p^2 + 1)$	$Z_{4,2}$
Trefoil X	Z9	Z 11 : (p^3) * SIN (3A)	$Z_{3,0}$
Trefoil Y	Z10	Z 10 : (p^3) * COS (3A)	$Z_{3,3}$
5th Astig +/-45°	Z11	Z 13 : $(4p^2-3)\ p^2$ * SIN (2A)	$Z_{4,1}$
5th Astig 90°	Z12	Z 12 : $(4p^2-3)\ p^2$ * COS (2A)	$Z_{4,3}$
Tetra foil 1	Z13	Z 18 : (p^4) * SIN (4A)	$Z_{4,0}$
Tetra foil 2	Z14	Z 17 : (p^4) * COS (4A)	$Z_{4,4}$
5th Trefoil axe x	Z15	Z 20 : $(5p^2 - 4)\ p^3$ * SIN (3A)	$Z_{5,1}$
5th Trefoil axe y	Z16	Z 19 : $(5p^2 - 4)\ p^3$ * COS (3A)	$Z_{5,4}$
5th Coma axe x	Z17	Z 15 : $(10p^4 - 12p^2 + 3)$ p * SIN (A)	$Z_{5,2}$
5th Coma axe y	Z18	Z 14 : $(10p^4 - 12p^2 + 3)$ p * COS (A)	$Z_{5,3}$
Quadrafoil 1	Z26	Z 26 : (p^5) * COS (5A)	$Z_{5,5}$
Quadrafoil 2	Z27	Z 27 : (p^5) * SIN (5A)	$Z_{5,0}$
5th order Spherical	Z19	Z 16 : $(20p^6 - 30p^4 + 12p^2 - 1)$	$Z_{6,3}$
7th order Spherical	Z25	Z 25 : $(70p^8 - 140p^6 + 90p^4 - 20p^2 + 1)$	$Z_{8,4}$
9th order Spherical	Z36	Z 36 : $(252p^{10} - 630p^8 + 560p^6 - 210p^4 + 30p^2 - 1)$	$Z_{10,5}$

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