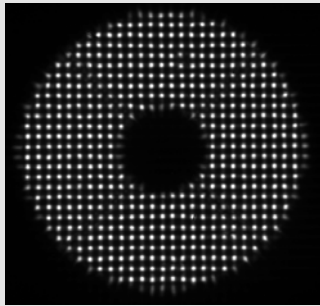


SPOT-OPTICS

SpotOptics
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Sensoft User's Manual

Wavefront sensor control and analysis
software

Version 9.2 – March 2011

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Chapter 1: Sensoft software installation

1.1 System requirements

1.1.1 System requirements for PC


- Windows XP/Windows 7
- 2GB RAM (or more)
- A video card with 32-bit True color graphics capability and 256MB (or more) of video memory
- About 120Mb of hard disk space to store the dark calibration images for the uncooled camera
- Your system can be shipped with one of the following cameras
 - The standard uncooled camera has USB 2.0 control and requires a 2mt (or longer) USB cable (supplied). No special hardware is required
 - The standard cooled camera has USB 2.0 control and requires a 2mt (or longer) USB cable (supplied). No special hardware is required
 - An uncooled camera with Firewire control can be mounted. It requires a 6-pin-to-6-pin 2mt (or longer) 1394 cable and a 1394 Open Host Controller Interface (OHCI) (or Firewire) card to be inserted in the PCI bus of the PC (supplied)
 - An uncooled camera with Gigabit Ethernet (1000Base-T) control can also be mounted. It requires a CAT6 Ethernet cable to be connected to the Ethernet port of the PC. In order to use the full image acquisition speed the PC should mount a 10/100/1000 Ethernet card
 - *Different cameras can be mounted on request*
- If your system has motorized parts we will provide you with
 - An external 12V/1000mA DC power supply for any of the motorized units for Optino, ECM25, BE25 or BE60 (supplied)
 - An external 24V/48W power supply for Sfera/Stella/Opal/MIPS (supplied)
- **Microsoft Office** to open the Excel file created during the Shack-Hartmann analysis

1.1.2 Additional requirements for laptops for uncooled Firewire camera

- With the uncooled Fire wire camera, a 1394 OHCI CardBus card installed in a PCMCIA slot or a built-in 1394 port
- An external 12V/500mA DC power supply

1.2 Installation

1.2.1 Installing Sensoft

-  *Sensoft should be installed before connecting the camera*
- The Sensoft CD-ROM must be inserted in the CD-ROM drive
- **To install the Sensoft and the drivers on a Windows 2000, Windows XP or Windows 7 system you must be logged in with Administrator privileges**
- Click on the Setup icon contained in the CD-ROM
- If your PC is running Windows 7 right click onto the file setup.exe and choose "Run/Execute as administrator" from the context menu to install the software as administrator.
- Following the standard procedure, install the Sensoft software package in the desired directory
- If the system was shipped with an uncooled camera, at the end of the installation copy the contents of the Dark directory from the CDROM into the directory where you installed Sensoft

1.2.2 Installing the hardware key

Sensoft can be used only with a dongle (hardware key) that must be connected to a USB port of your PC after the installation of the software. To install the USB device driver for the dongle correctly, follow the steps below:

- Install the Sensoft software from the installation CDROM
- Plug the dongle into a USB port
- ***To install the drivers on a Windows 2000/XP/7 system you must be logged in with administrator privileges.***
- Run the SmartkeyDriverInstaller contained in the Sensoft CDROM to complete the installation of the files required for the dongle key.
- If your PC is running Windows 7 right click onto the file SmartkeyDriverInstaller.exe and choose "Run/Execute as administrator" from the context menu to install the software as administrator.
- Restart the system

1.2.3 Installing the camera for getting Shack-Hartmann images

Different cameras (Peltier cooled, uncooled) can be mounted on the instrument. The procedure for connecting them is given below.

1.2.4 Installing the SBIG cooled CCD camera under Windows XP/Windows 7

The standard cooled CCD cameras that we supply with the instrument are manufactured by SBIG.

The standard cooled camera is connected to the PC or laptop using a USB connection provided with the instrument.



The cooled camera is very sensitive to light. Thus, the instrument should be used in an environment that does not have stray light falling directly on the test element or the instrument itself. You may wish to use a filter to cut out the stray light.

The following steps are required for the installation of the camera:

- Connect the camera to any of the USB ports of your PC using the USB cable
- Connect the camera power supply to the camera and switch it on. Wait until the red LED on the back of the camera box is on and not blinking
- Refer to the Operating manual provided by the manufacturer for the installation procedure of the CCD camera delivered with your system (Section 1.2 :Installing the USB Drivers for the First Time)

A total cable length of about 50m can be used with repeaters.

1.2.5 Installing the uncooled camera for the first time

Instruments manufactured before October 2005 have an IEEE-1394 (Firewire) based Imaging module camera with 1280x1024x7.5 μ pixels.

A total cable length of 72m can be used with repeaters and 4.5m cables for the Firewire camera.

An optional PCMCIA card can be used instead of the PCI card to control the Firewire camera from a laptop.

For instruments shipped after October 2005 two camera models are supported by Sensoft: PixelINK Firewire (IEEE-1394) camera model PL-A741 and the other with a Lumenera USB 2.0 camera model LU125M. Both have 1280x1024 pixels, each of 6.7 μ .

The USB/Firewire cable for the connection is provided with the instrument.

If you already installed an old version of Sensoft, you should go to the Upgrading the camera driver section.

1.2.5.1 Firewire camera

The camera kit includes a 6-pin 2m 1394 cable and a 1394 Open Host Controller Interface (OHCI) (also called FireWire) card to be inserted in the PCI bus of the PC. An optional PCMCIA card can be used to run the camera from a laptop.

Power down your PC.

Install the PCI card.

Switch on the computer.

Windows will automatically detect the OHCI card and run the "Add New Hardware Wizard". This wizard will search for a "Texas Instruments OHCI Compliant IEEE 1394 Host Controller". Click Next.

Select "Search for the best driver for your device." Click Next.

The wizard will then ask for locations to search for the drivers. Clear all of the check boxes and click Next.

When asked: "What do you want to install?" select "The updated driver." Click Next.

When the wizard finds the driver, the driver location should be <WINDOWS path>\inf\1394.inf. If the wizard does not find the driver, it will need to install it from the Windows program CDROM.

Click Finish to complete the installation.

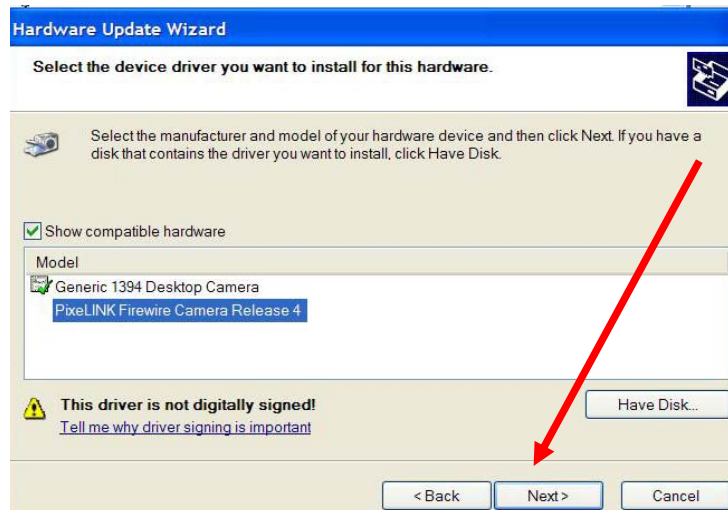
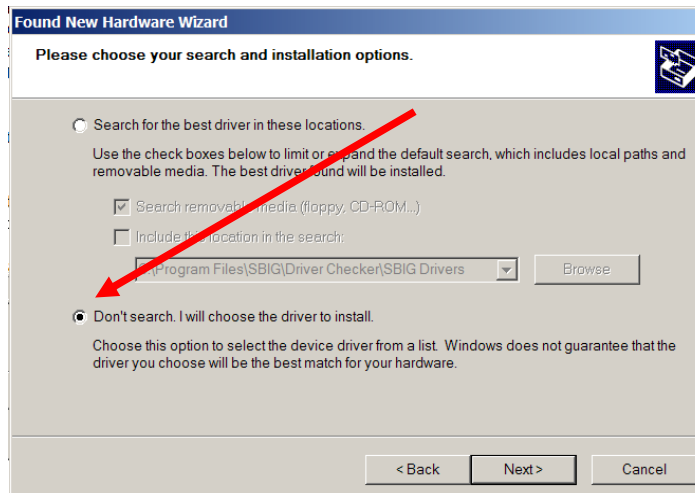
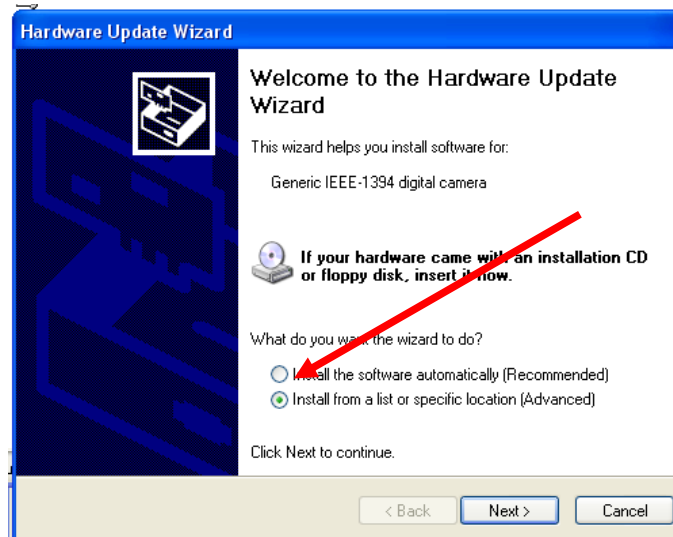
Connect the camera module to the OHCI card using the supplied 1394 cable. To complete the installation of the camera, restart the PC and log in with administrator privileges. Note: ***Windows will not recognize the camera unless it has been previously connected under administrator privileges.***

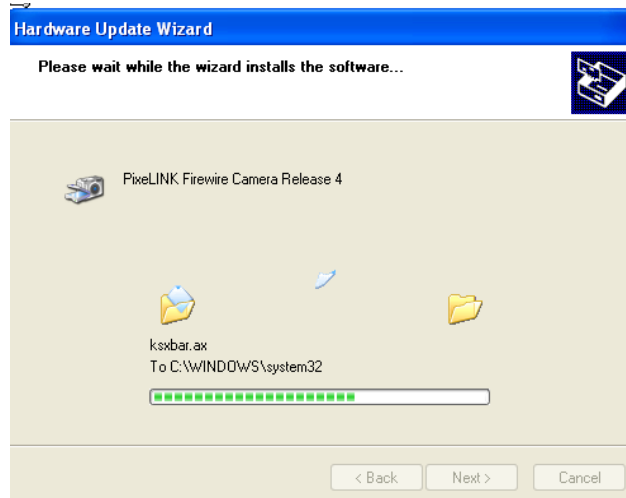
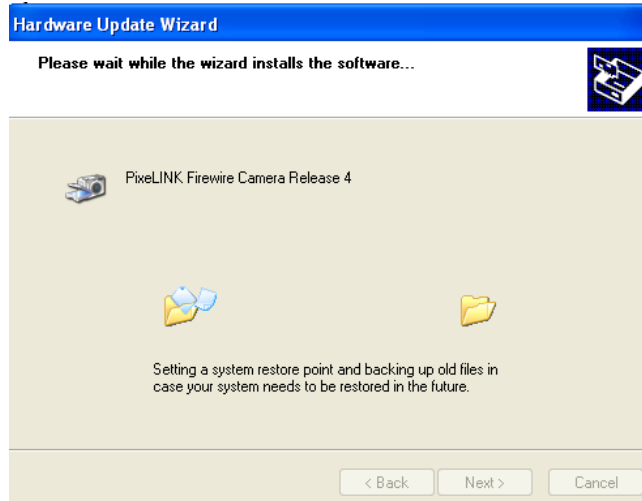
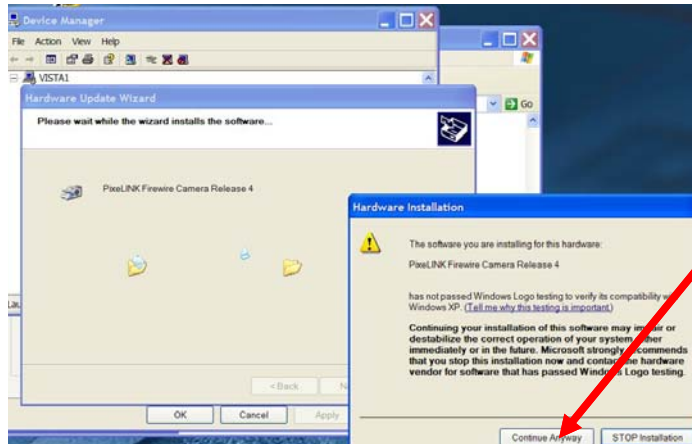
If you receive a message during the installation that the digital signature was not found, click Yes for proceeding.

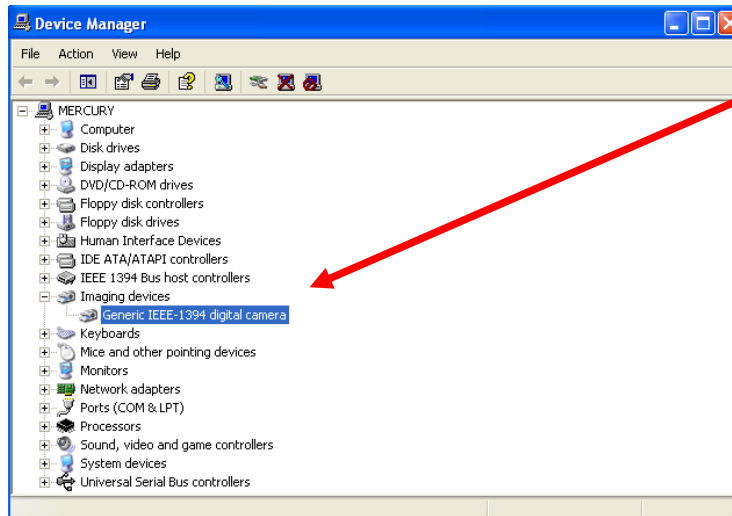
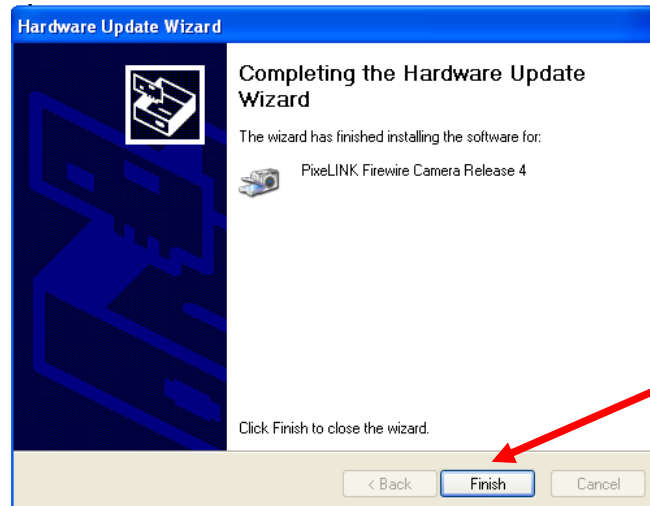
1.2.5.2 Firewire PixeLINK PL-A741 camera

During installation of Sensoft, the drivers for the Pixelink PL-A741 camera are copied to the system directories. At the end of the installation

- Connect the digital FireWire camera to the FireWire PCI adapter or a built-in FireWire port card (in the case of a PC) or to the PCMCIA FireWire adapter card dongle (in case of the laptop) using the 2m Firewire cable. If the connection is correct, the PC will immediately recognize the new Firewire device as a PixeLINK device. A green LED on the camera body indicates that the camera is working normally.
- The "Found New Hardware Wizard" will ask you for the location of the drivers: follow the procedure given in the following pages. Click "Next" to proceed to the next dialog.



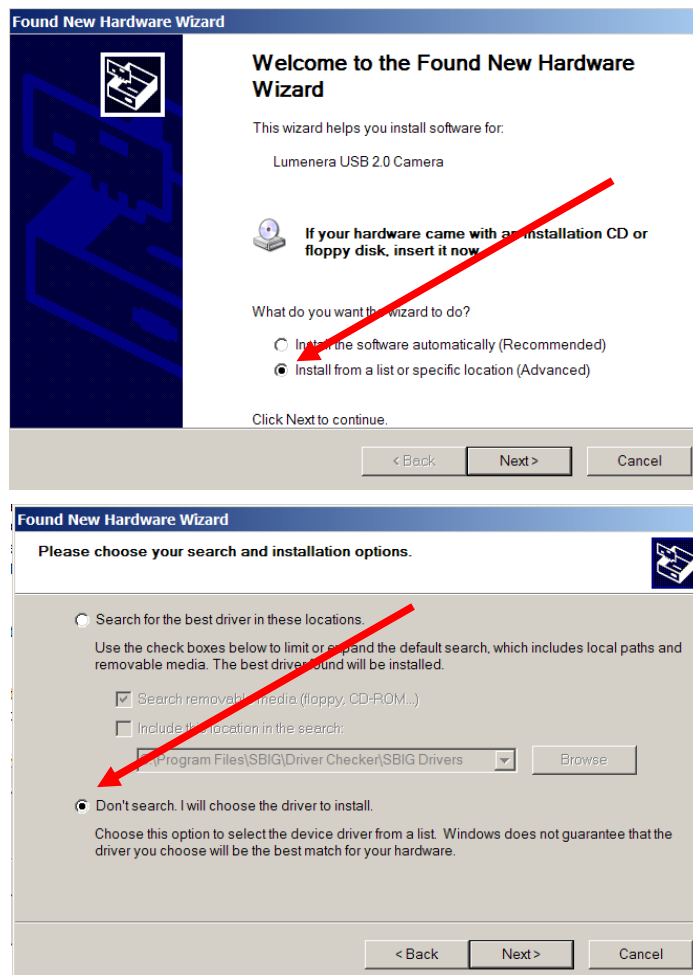


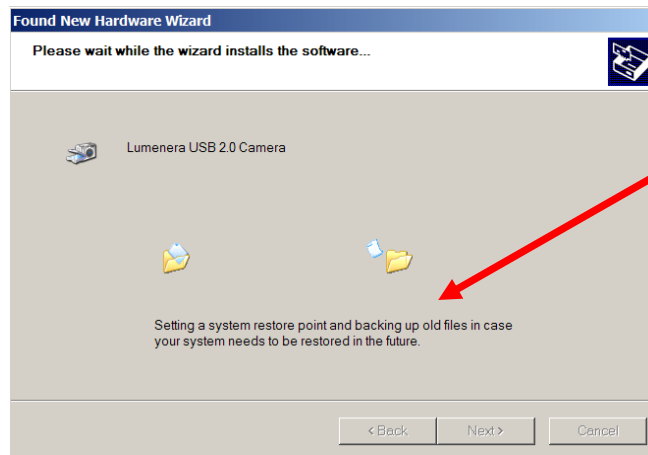
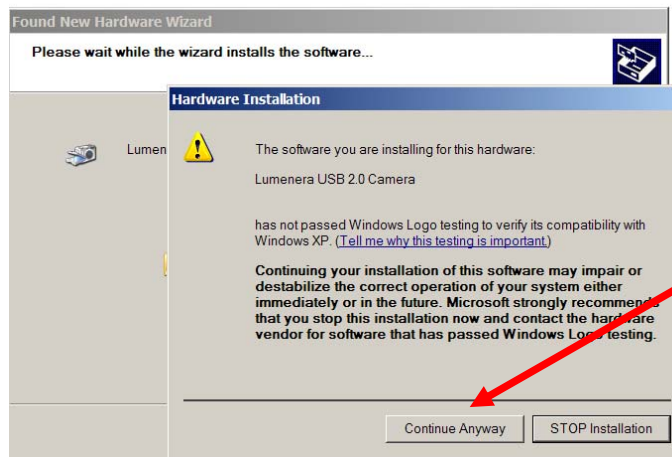
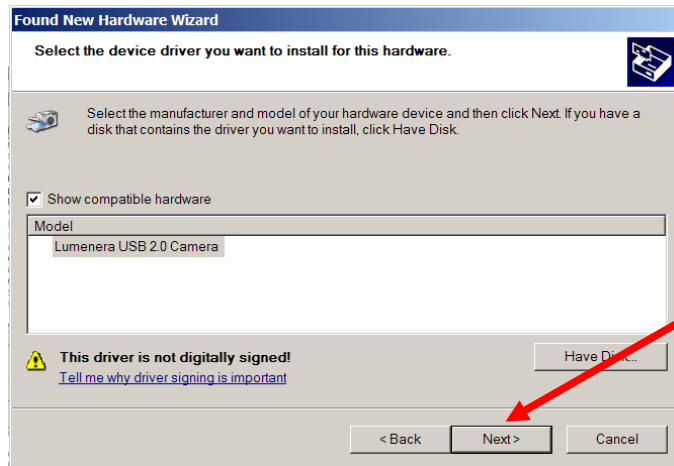


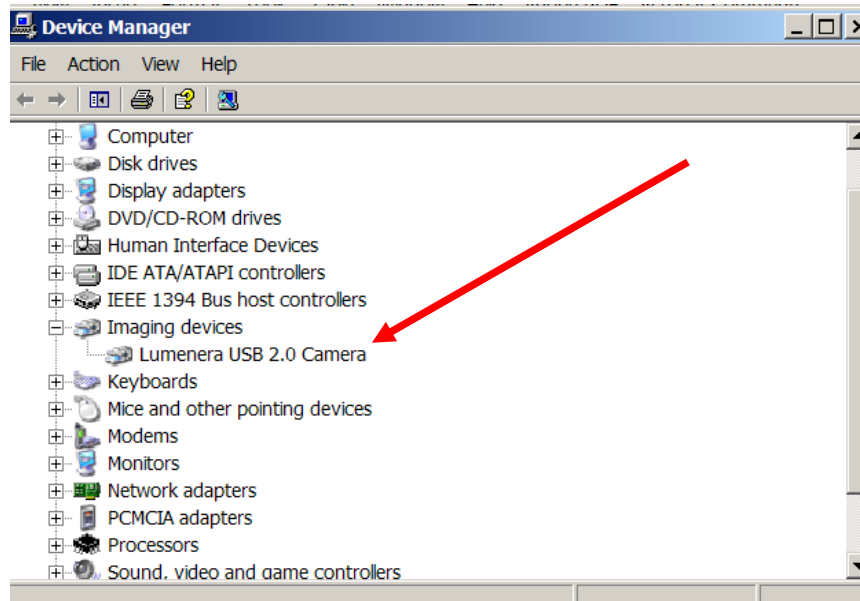
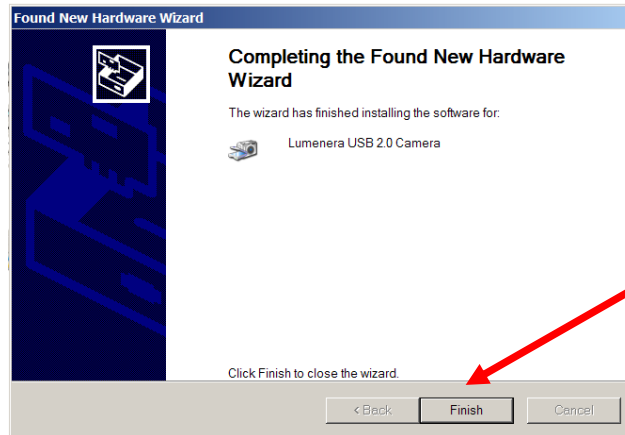
- At the end of the installation will be asked to reboot your PC. If the camera is successfully installed you should see the PixeLINK in your Control Panel under the Imaging Devices group.

1.2.5.3 Lumenera USB 2.0 camera

- During installation of Sensoft, the drivers for the Lumenera camera are copied to the system directories. At the end of the installation, connect the camera to the PC using the 2m USB cable provided with the instrument. If the connection is correct, the PC will immediately recognize the new USB device as a Lumenera device. A green LED on the camera body indicates that the camera is working normally.
- *The USB camera is only compatible with USB 2.0 or higher version of USB. Do not connect to a USB 1.1 port.*
- The “Found New Hardware Wizard” will ask you for the location of the drivers: follow the procedure given in the following pages. Click “Next” to proceed to the next dialog.










- At the end of the installation will be asked to reboot your PC. If the camera is successfully installed you should see the Lumenera in your Control Panel under the Imaging Devices group.

1.2.5.4 Troubleshooting the uncooled camera

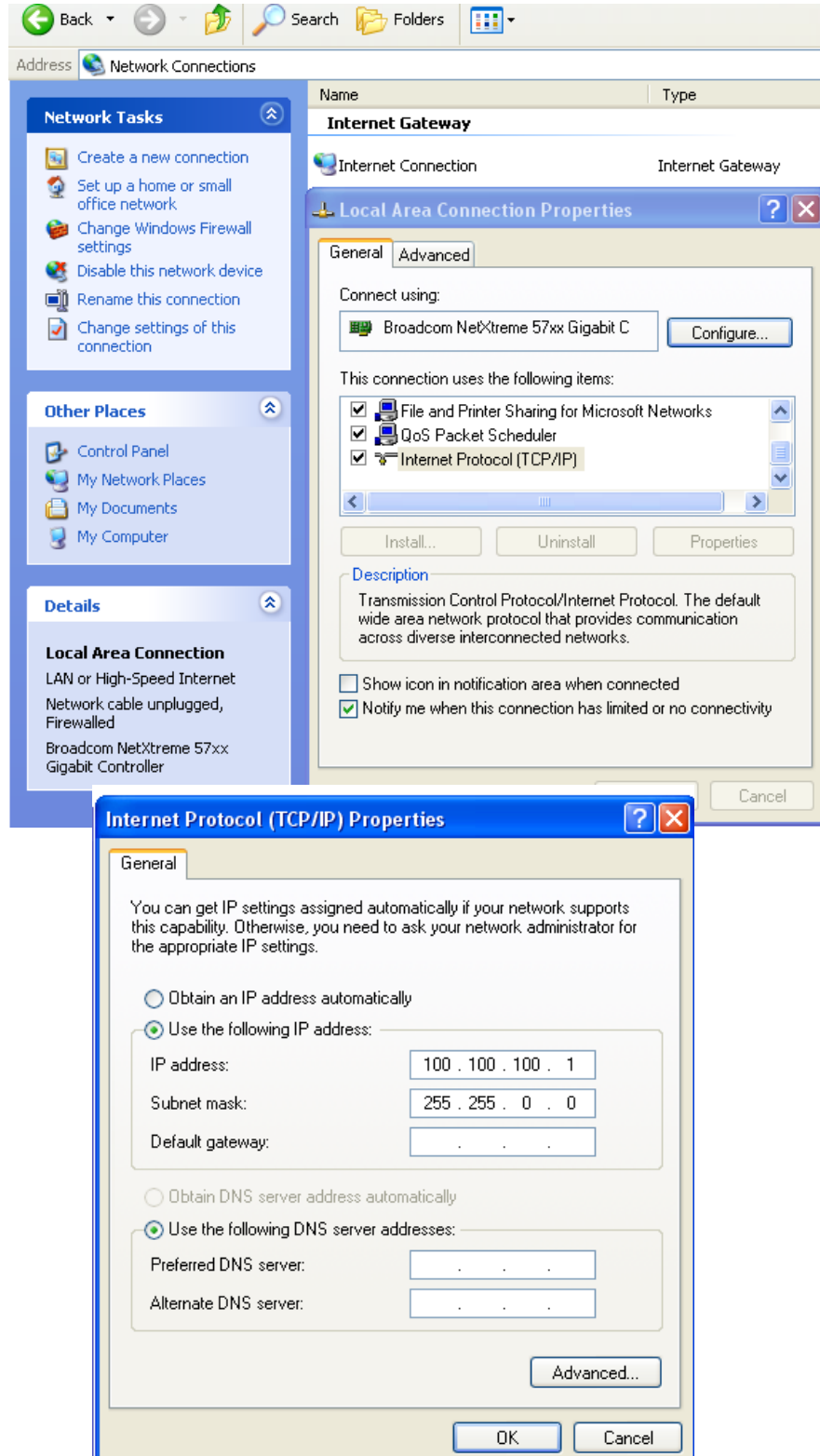
- A green LED on the camera body indicates that the camera is working normally.
- Launch Sensoft

-  Choose the gain of the camera in the [WFS/SH camera] page. The recommended setting is Medium or Low for minimum noise. However, in certain situations (e.g. when testing uncoated surfaces) a higher gain setting may be required for getting more sensitivity
-  It is recommended that wherever possible, an integration time as low as possible (about 10ms) be used to get low noise and minimum interference from the ambient light
-  Take an exposure by clicking on the [Live] button. In case it does not work correctly, try to unplug the connecting cable from the camera to the PC and reattach it. Otherwise reboot your PC by switching it off (hardware reboot)

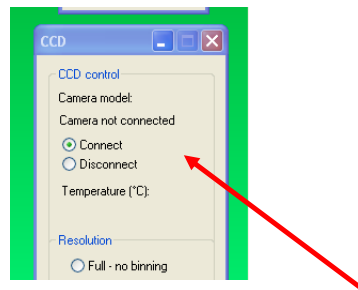
1.2.5.5 Phantom 4.2 GigaBit Ethernet camera

The IP address of the camera should be specified before the camera is connected for the first time.

- Access the Control Panel/Network Connections/Local Area Connection Properties Page
- Access the Properties for the Internet Protocol(TCP/IP)



- Click on the “Use the following IP address” and enter the IP address 100.100.100.1 and the subnet mask 255.255.0.0. The default gateway should be left undefined
- Connect the power supply and the GigEthernet cable to the camera
- On the other side, the GigEthernet cable should be connected to the LAN port of the PC
- Launch Sensoft and click on the Connect button in the CCD dialog.

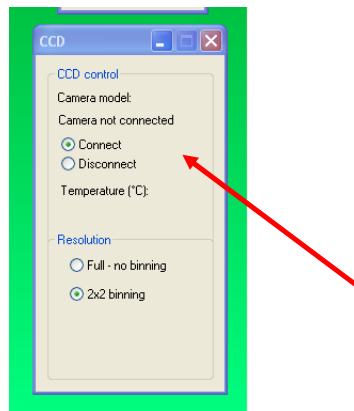


1.2.5.6 VDS Gigabit Ethernet camera

The drivers for the VDS camera are provided by the manufacturer of the camera. Please refer to the camera manual given by the manufacturer for the correct installation of it.

This procedure should be followed when the camera is connected for the first time and whenever the power supply has been disconnected

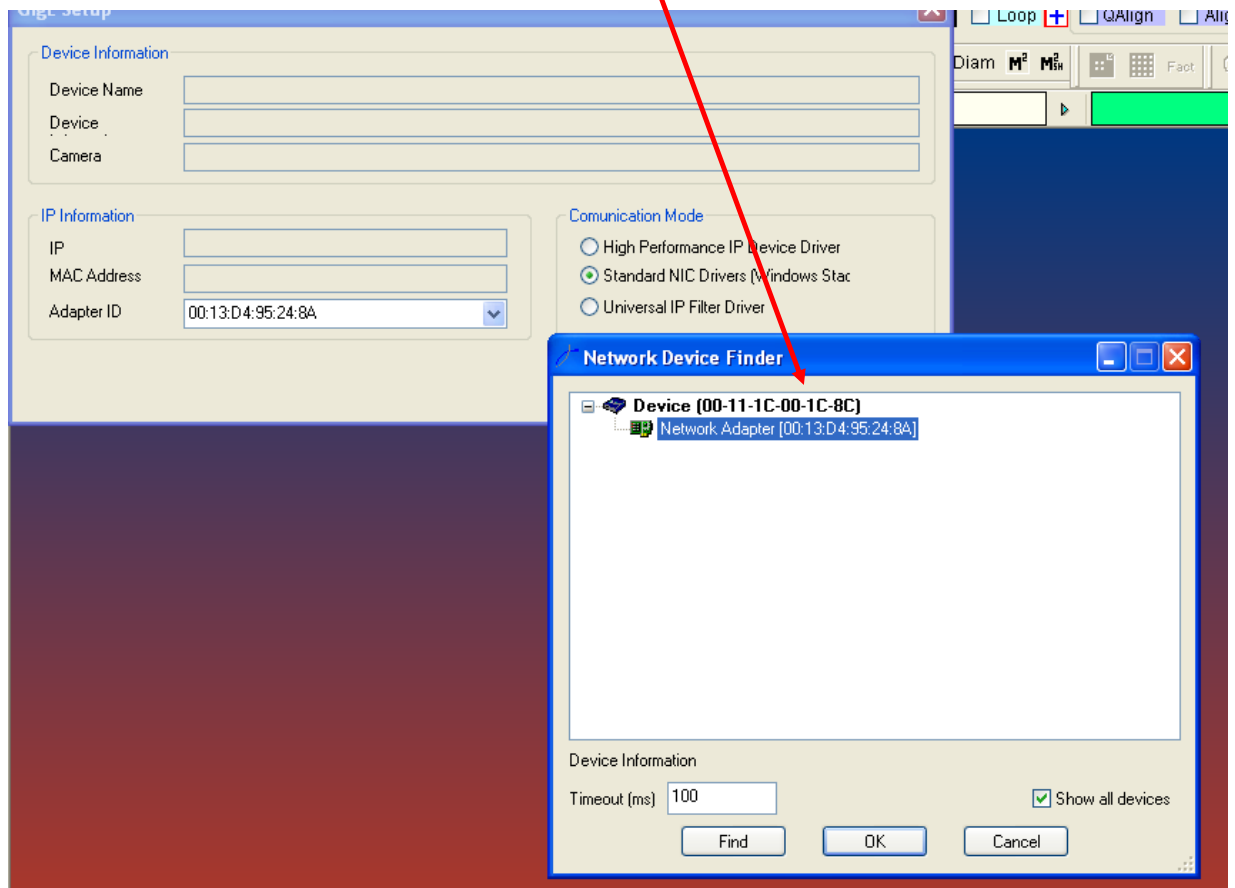
- Connect the power supply and the Gigabit Ethernet cable to the camera
- On the other side, the Gigabit Ethernet cable should be connected to the LAN port of the PC
- Launch Sensoft and click on the Connect button in the CCD dialog.

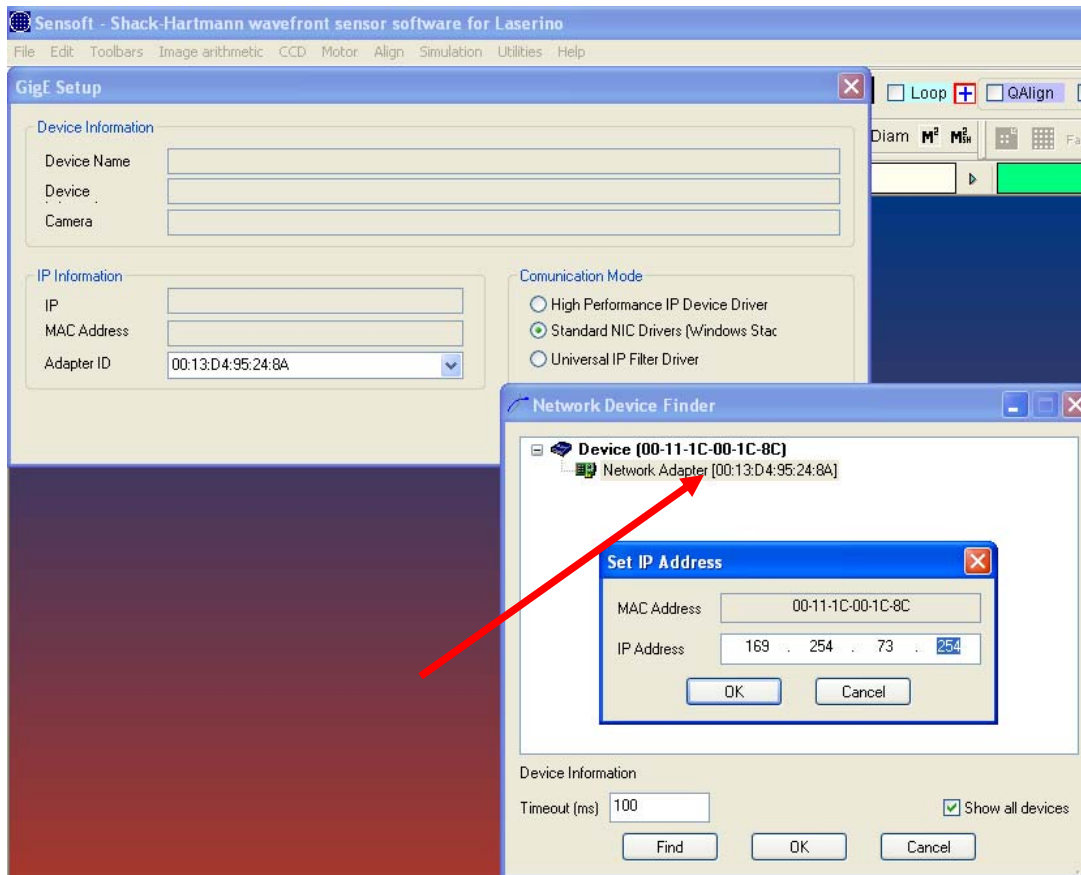


- You will get the message “Device not configured”
- Press OK

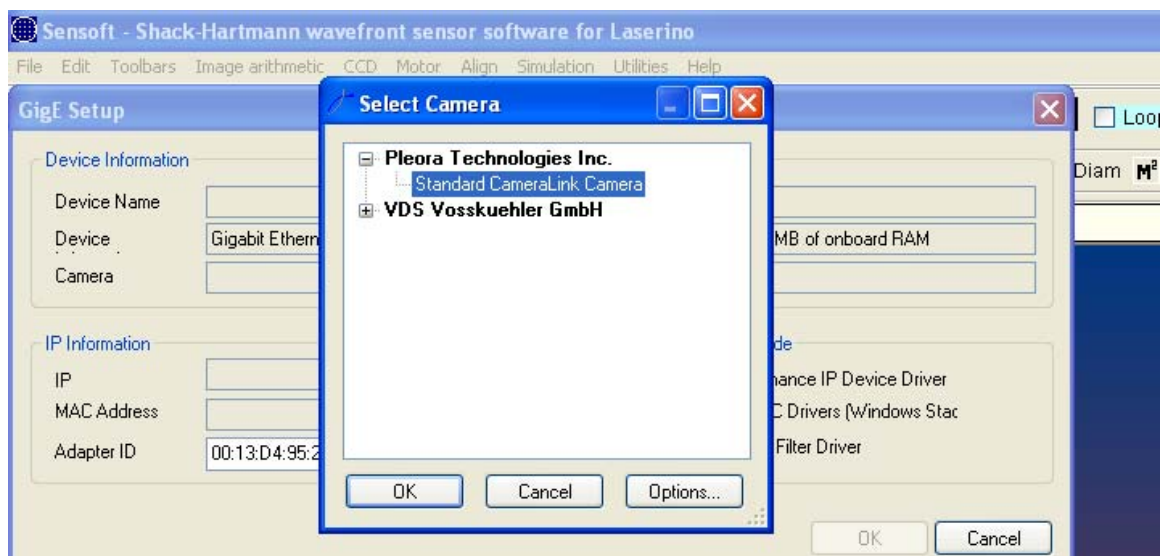


- Click on the displayed Network Adapter

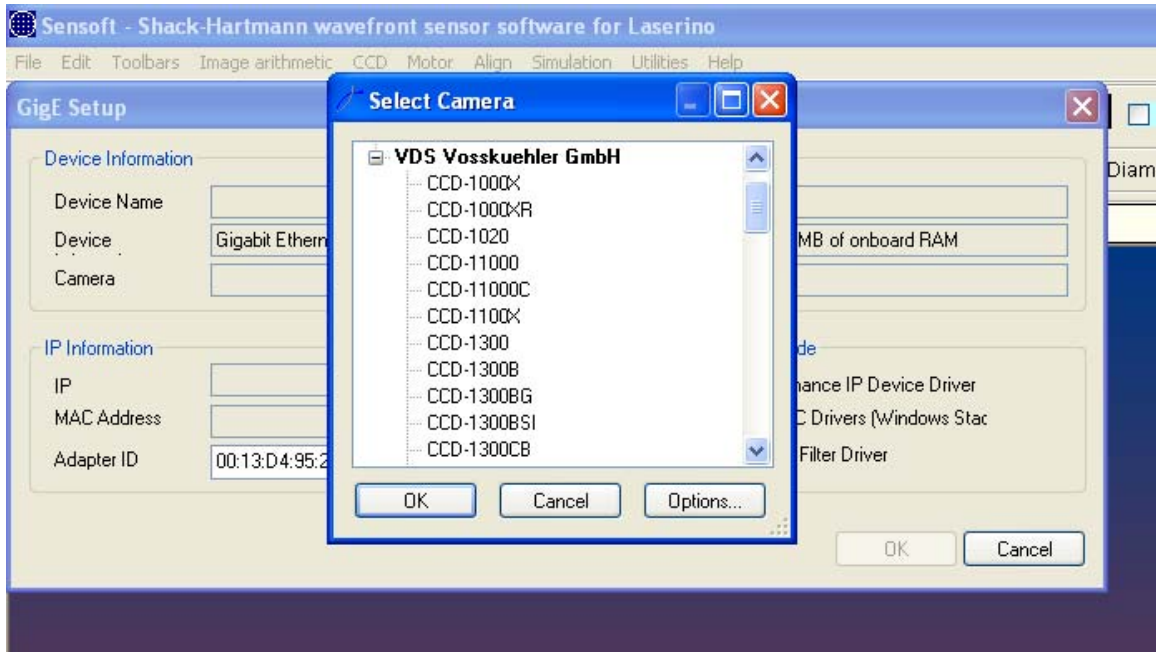




- Click again on the Network Adapter and you will get the list of the VDS Vosskueler GmbH cameras



- Select the appropriate camera model from the list and press OK.
- If everything was done correctly you will get the camera connected and the camera model displayed in the camera dialog on the bottom-right corner of the display.



1.2.6 Optino/Beam expander/Motorized external calibration unit (ECM)

- If your system has a motorized component you will need to complete the installation installing the drivers for the motor
- Connect a 12V/1000mA-power supply (tip (inner) polarity: positive) to the motor.

1.2.6.1 USB motor control

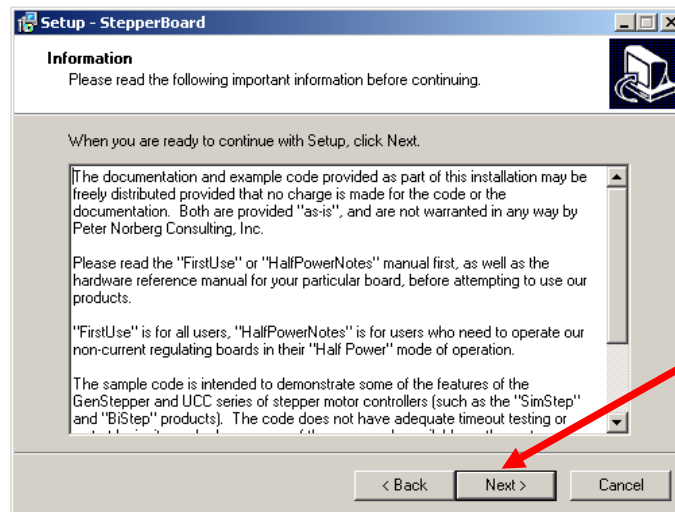
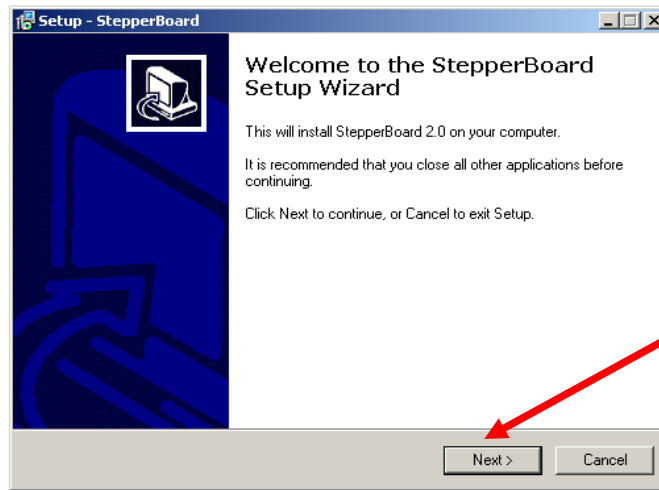
Connect the USB cable from the motor to the PC.

- Wavefront sensors shipped starting from 2010 mount stepper motor control card model Stepper Board.
- Wavefront sensors shipped before 2010 have a stepper motor controller card model MT2. Please refer to the MT2 motor control section for the installation.

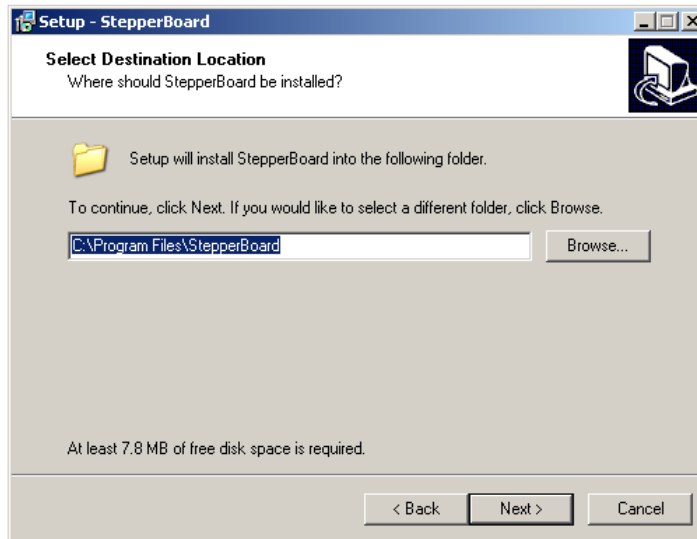
1.2.6.2 Motor control with Stepper Board card

- To install the driver for the stepper motor insert the CDROM labeled “*Stepper Motor Control Solutions*” and follow the procedure given in the following pages. Click “Next” to proceed to the next dialog. Remember that under Windows 7 you will have to right click on to the executable and
- The “Found New Hardware Wizard” will ask for the location of the driver.

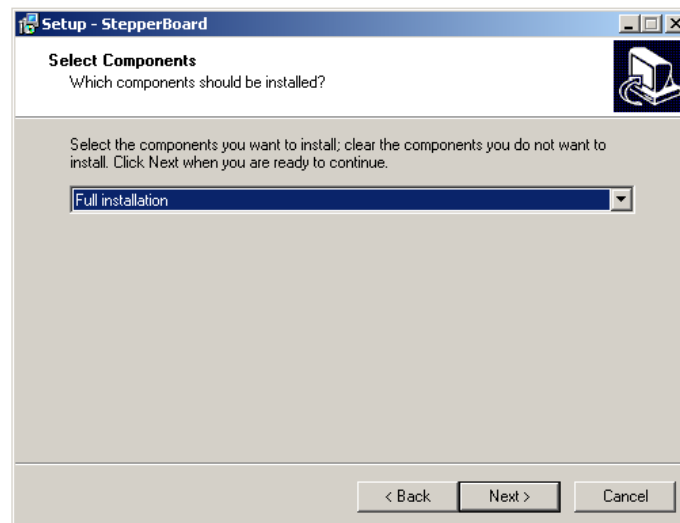
Follow the selections given in the next dialogs: click the Next button to proceed with the next request.

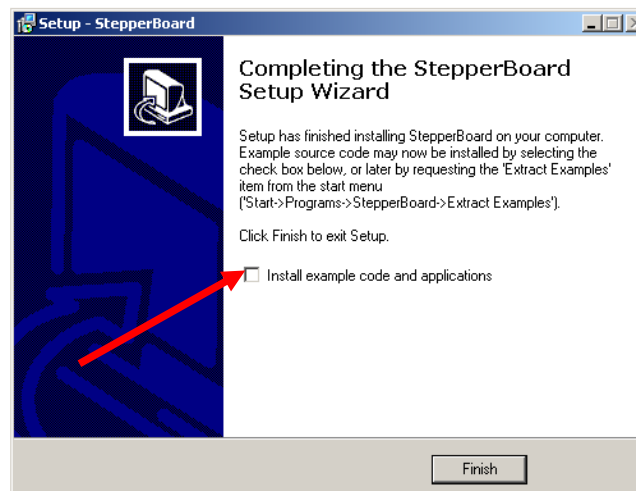
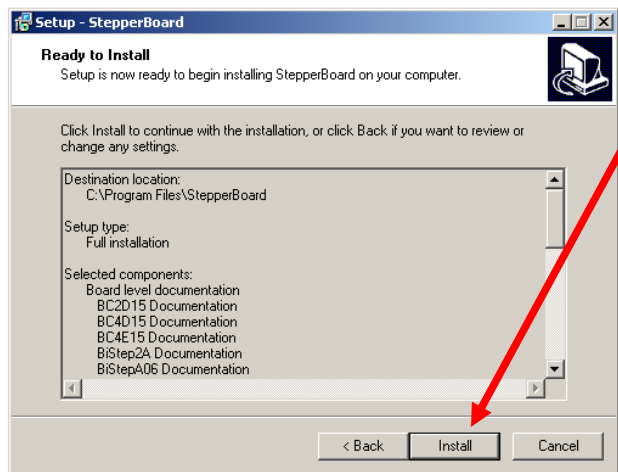
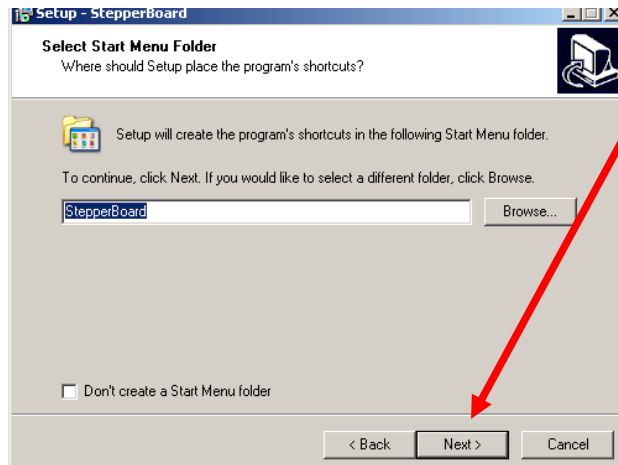


- Specify the installation folder and click “Next” to proceed to the next dialog.



- Select the components to install. The default option will install all components (suggested)



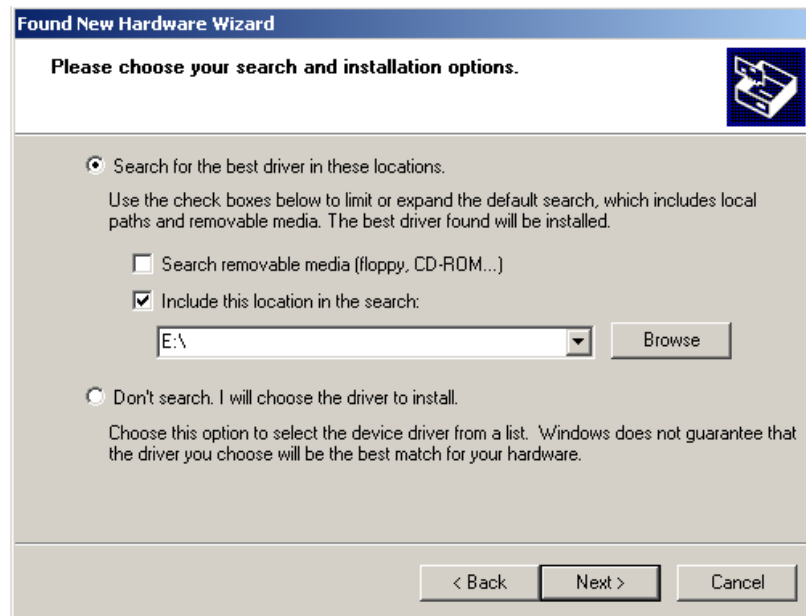


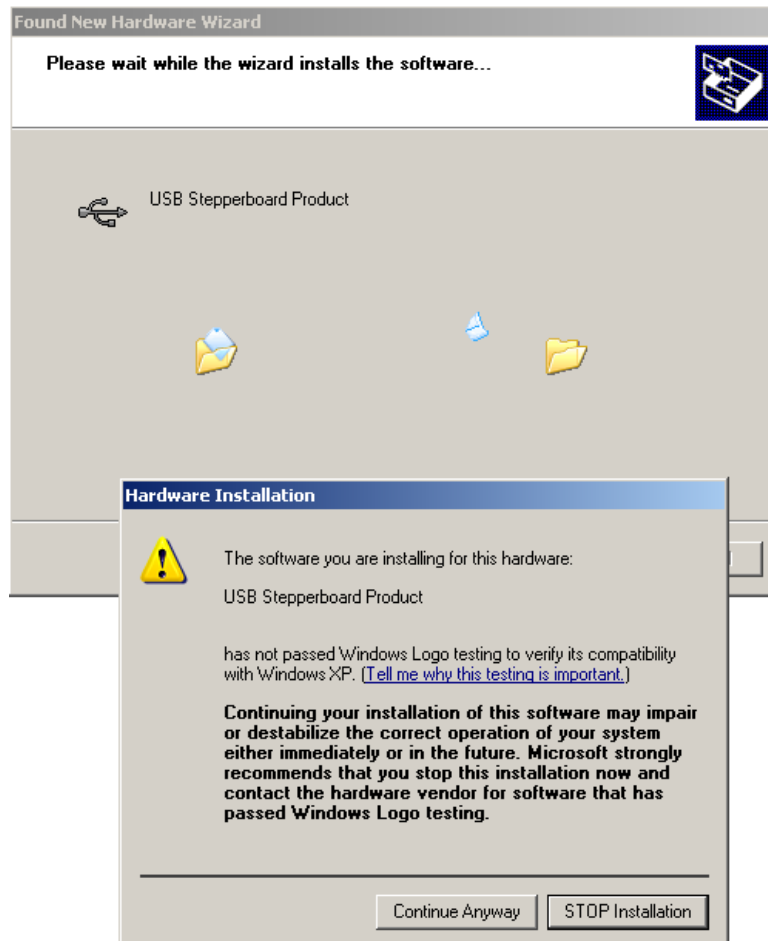
Connect the USB cable from the motor to the PC without ejecting the CDROM previously inserted in the device. If the connection is correct, the system will immediately identify FOR THE FIRST TIME the new hardware as USB to serial converter.



The “Found New Hardware Wizard” will ask for the location of the driver. Follow the selections given in the next dialogs: click the Next button to proceed with the next request.

- Specify the identifier of the CDROM device in the searching path (here E:\)



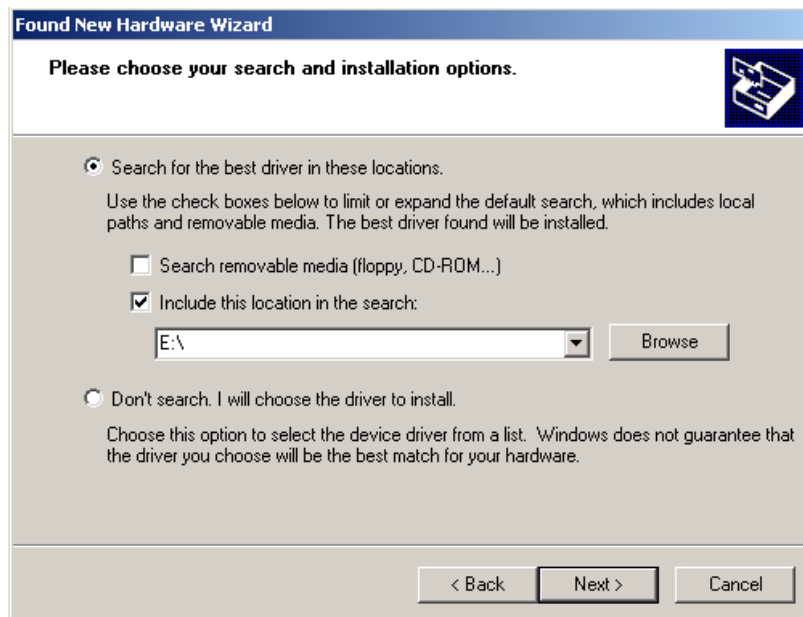


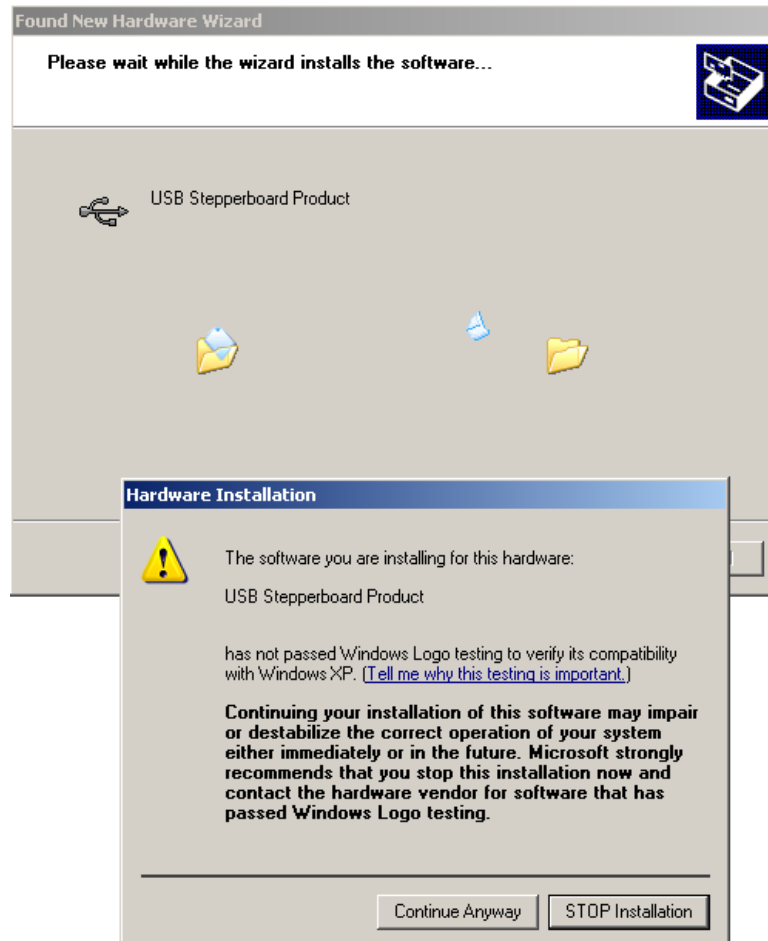
- After this installation the system will immediately identify FOR THE SECOND TIME the new hardware as USB Stepper board Product.



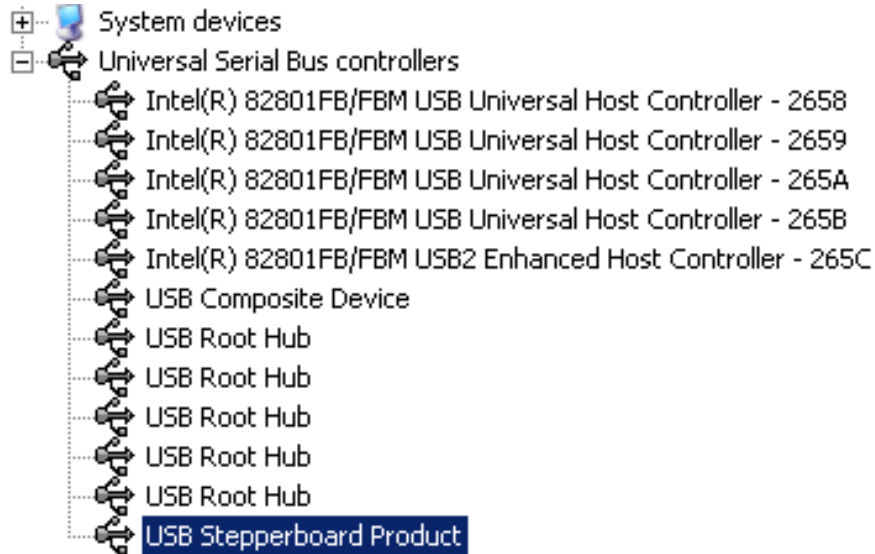
The “Found New Hardware Wizard” will ask for the location of the driver. Follow the selections given in the next dialogs: click the Next button to proceed with the next request.


Specify the identifier of the CDROM device in the searching path (here E:\)





If the drivers have been correctly installed, the USB Stepper board Control Unit will appear in the Control Panel under the USB Serial Bus Controllers, as well as among the COM port devices. Sensoft will detect automatically if multiple motors are connected and will identify if they correspond to the collimator, the motorized beam expander or the motorized external calibration unit



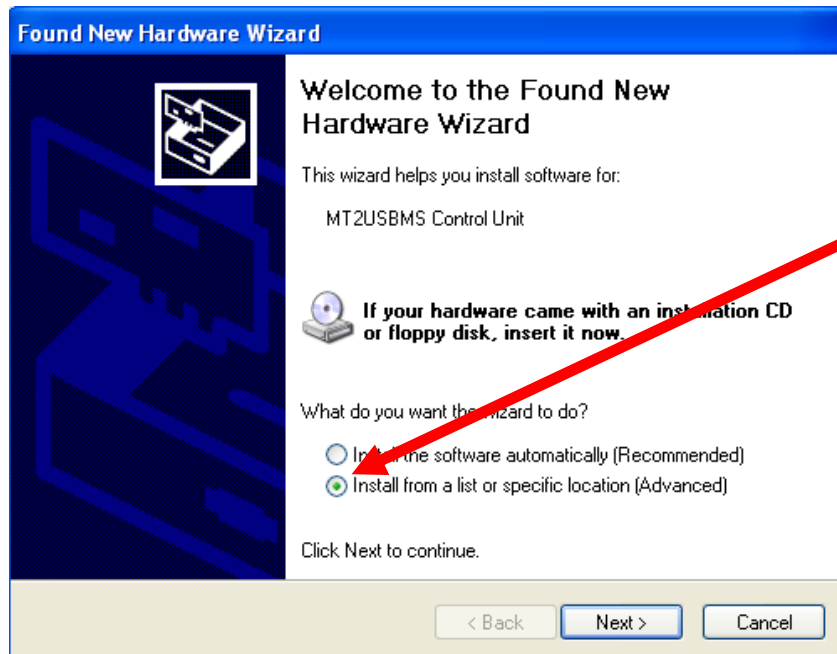
 **NOTE:** when the motor controller will be connected to the different USB port respect to the first installation, the system will again prompt for the driver installation. You will have to repeat the driver installation procedure

1.2.6.3 Motor control with MT2 card

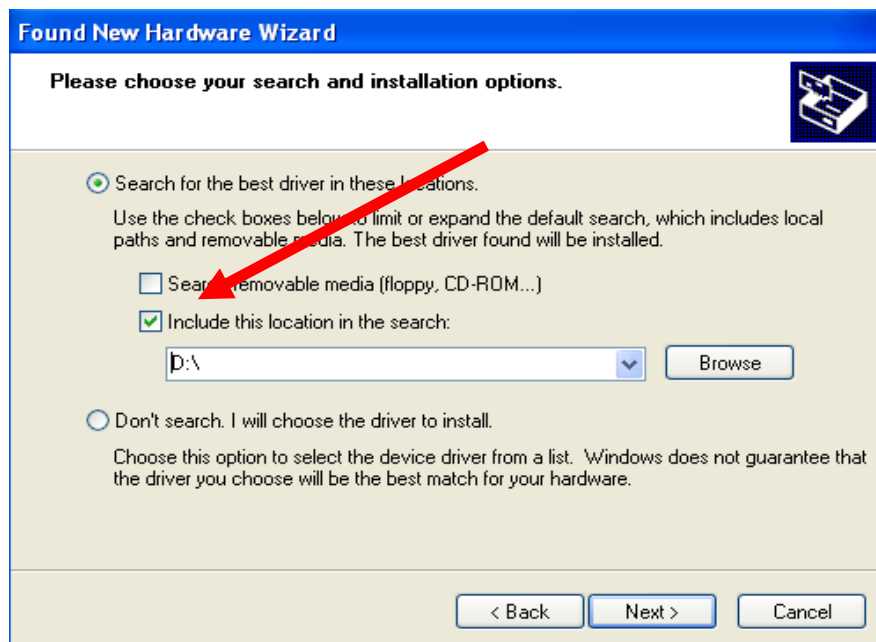
- If the connection is correct, the system will immediately identify the new hardware as MT2USB card (or MT2SBMS if the card supports micro stepping).

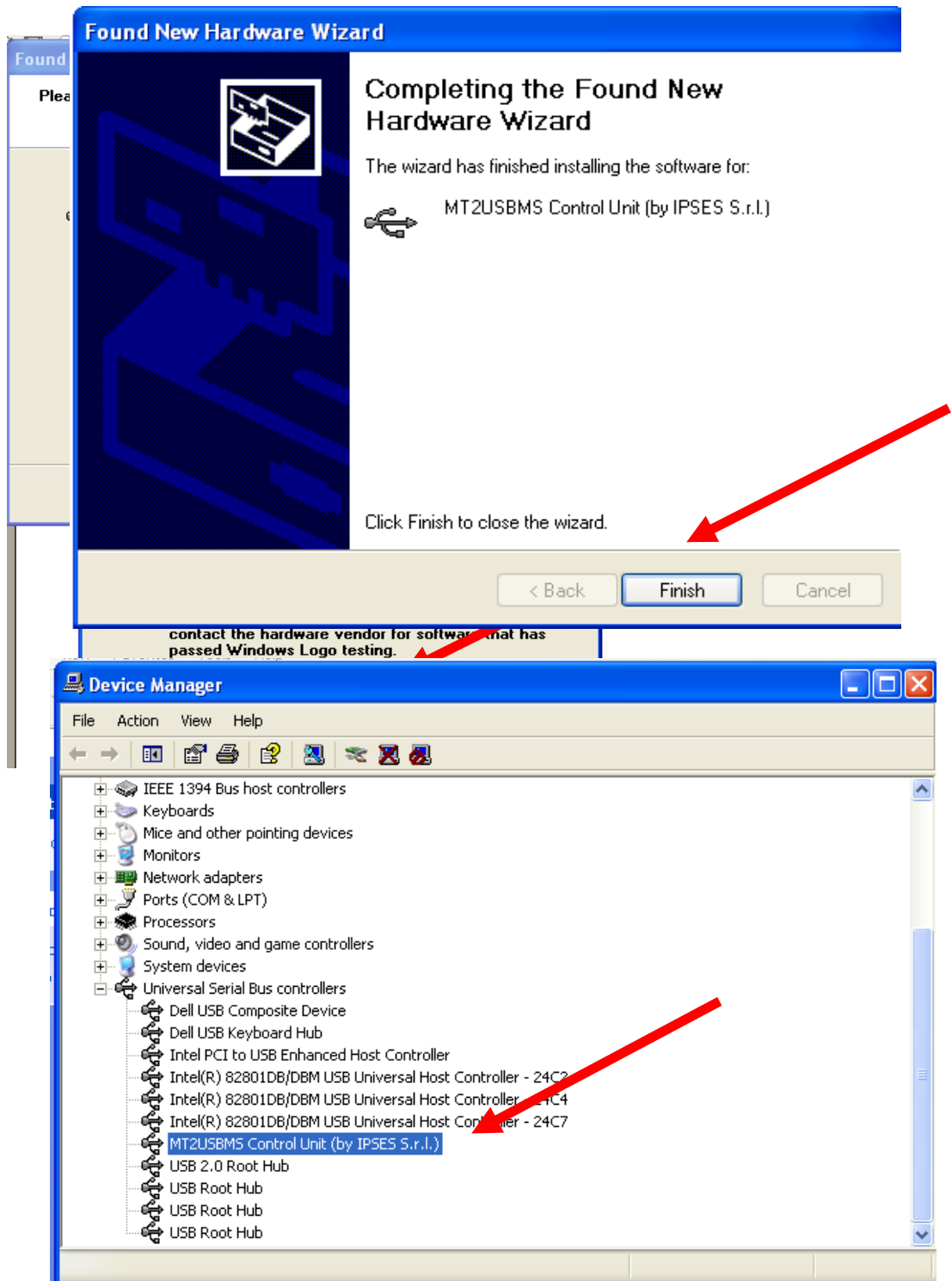


The “Found New Hardware Wizard” will ask for the location of the driver. Follow the selections given in the next dialogs: click the Next button to proceed with the next request.



Specify the identifier of the CDROM device in the searching path (here D:\)





If the drivers have been installed correctly, the MTS2USB Control Unit will appear in the Control Panel under the USB Serial Bus Controllers. Sensoft will detect automatically if multiple motors are connected and will identify if they correspond to the collimator, the motorized beam expander or the motorized external calibration unit.

1.2.6.2 Motor control through serial port

- Connect Optino collimator motor using a serial cable.
- If the connection has been done correctly, Sensoft will automatically detect the serial port for collimator, beam expander and external calibration unit. Click the Home button. If everything is OK, you will get an OK message in the status field. If the message is “Not OK”, check the power supply and the cables.

1.2.7 Connecting and operating the motors for Stella/Sfera MIPS and OPAL

- Connect a the external 24V/48W power supply for supplied with the instrument
- Connect the serial cable to the serial connector put on the back of the instrument
- On the other side connect the serial cable to a USB port of the PC using a serial to USB converter
- All of the motors inside the instrument are connected in a daisy chain where the first motor acts as a master of the chain.
- If the connection has been done correctly, Sensoft will automatically detect the serial port for the motors and will display a dialog showing how many motors have been found on the same chain

1.3 Miscellaneous

1.3.1 Upgrading the camera driver

- To upgrade the drivers on a Windows 2000 or Windows XP system you must be logged in with administrator privileges.
- Connect the camera at installation time. Windows 2000/XP will not recognize the camera unless it has been previously connected under administrator privileges.

In the System Panel (Control Panel), go to the Imaging Device group in the Device Manager; if you find the ‘PL_A630’ module you need to upgrade the driver.

- Select the Imaging Device group in the Device Manager of the System Panel (Control Panel)
- Select the Properties of the PL-A630 entry

- In the Driver page, press the button Update Driver. Select the CDROM unit containing the Sensoft Optino installation CDROM to detect the new driver
- At the end of the upgrade, you should find the 'PixelINK™ 1394 Camera' module installed

1.3.2 Using the camera with hubs for long cable lengths

The standard cable supplied with the IEEE-1394 based Imaging module is of a length of 2m. Using repeaters that connect cables of length 4.5m, a cable length of up to 72m can be obtained (14 repeaters).

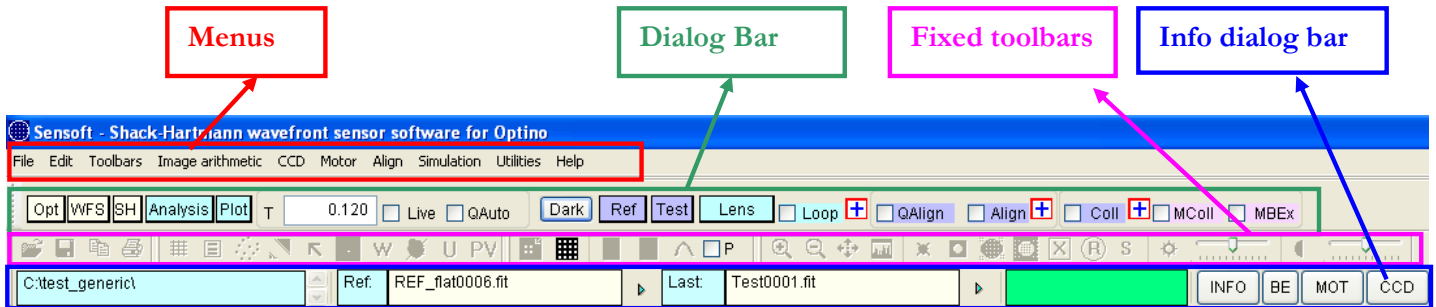
The hub gets its power supply from the PCI card. In the case of a laptop, a power supply of at least 1amp should be used. Each hub consumes 3W. In case the connections are not made properly, the green light on the hub will not be lit.

For the SBIG cameras, repeaters can be used to increase the cable length up to 50m

Chapter 2: Sensoft User Interface

2.1 The opening screen

When you run Sensoft for the first time, the following screen appears:



2.1.1 The dialog bar

The controls placed on the dialog bar allow the selection of parameters required for the analysis as explained below:

Opt:

- Select the optical test setup
- Enter the optical parameters for the optical system under test
- Enter the description for the test
- ❗ **Note:** the optical setup parameters can be saved to a default file using the Save optical configuration function in the File menu. The parameters can be re-loaded from the file using the Load optical configuration function in the File menu

WFS:

- Specify the camera setup (for uncooled camera: binning and flip parameters, gain regulation; for cooled camera: binning and temperature regulation parameters) and the number of images to average both for reference and optical system SH image. The average of images will reduce noise (i.e. due to air effects).
- Define the orientation of the image with respect to the plate as explained in section 4.8.1

Note: the optical setup parameters can be saved to a default file using the Save optical configuration function in the File menu. The parameters can be re-loaded from the file using the Load optical configuration function in the File menu

SH:

- Select the directory for storage of results from on-line and off-line analysis

- Select the SH images to be used for analysis (in off-line mode)
- Select the Zernike terms to be fit to the data
- Specify the threshold and ellipticity parameters for centroiding
- Select the output graphs that you wish to see after the analysis is over
- Use the utilities option

Plot:

- Plots the output graphs for SH analysis using the files created during the latest analysis (without re-running the analysis)
- The output table of any previous run (e.g. using the Open SH results File (.cof) item in the File Menu) must already be open

Analysis:

- Used for running the SH analysis program in off-line mode

Live:

- For starting/stopping the camera exposure

QAuto:

- For quick automatic optimization of exposure time. Use this feature when you can see a non empty/dark image on the screen

Dark:

- Sensoft is shipped with the dark images already stored on the CD. These images are copied to the appropriate directory (where Sensoft is installed)
- Click this button if for any reason you need to redo the dark calibration. If your system was shipped with a CMOS camera a series of dark calibration images for the Shack-Hartmann camera will be taken automatically. Images will be taken up to 100msec of exposure and with different gain factors. About 120Mb of disk space is required to store the images. If your system was shipped with a CCD camera a series of dark calibration with different binning factors will be taken.

Ref:

- Used for taking the reference SH image to be used in all the subsequent SH analysis. The number of images to average is selected in [WFS] folder. The prefix to be used for reference image can be selected in the [SH] folder. The default prefix is "REF_flat", "REF_parallel", "REF_spherical", "REF_pinhole", according to the suggested reference setup that is specified on the bottom bar whenever a test configuration is selected in [Opt] folder

Test:


- Used to check the parameters for a correct analysis of the SH images
- The number of SH images to average is selected in [WFS] folder. Requires a previous acquisition and analysis of the reference image
- The software checks for the optimum intensity in both the reference and optical system image: then the optical parameters specified in [Opt] folder are checked by computing the normalized radius of the pupil

- Finally, fitting the first seven default Zernike terms to the data a standard analysis is performed


Lens:

- Perform the analysis of the optical system SH image
- The number of SH images to average is selected in the [WFS] folder. Requires a previous acquisition and analysis of the reference image
- After the SH image is obtained, the selected Zernike terms are fit to the data and the graphs selected in the [SH] folder are plotted together with the table of the aberration coefficients
- The prefix for the lens image can be selected in the [SH] folder. The default prefix is "Lens"

Loop (Professional and Engineering versions only):


- Perform the on-line analysis of the optical system SH image in a continuous loop
- Requires a previous acquisition and analysis of the reference image
- Requires a previous run with Test analysis to establish the correct normalized radius
- Open the [Loop param] dialog by pressing on the  button close to the Loop box in the dialog bar and select the range of values for alert for the 10 default Zernike coefficients and the graph that you would like to display
- Close the [Loop param] dialog and start the Loop by checking the Loop box
- After the SH image is obtained, the Zernike terms selected in [SH] folder are fit to the data and the graph selected in the [Loop param] dialog is plotted
- A coefficients toolbar displays the value of the first 10 default Zernike coefficients
- A red or green background for the Zernike fields indicates that the value of the coefficients obtained from the analysis is outside the tolerance given in the dialog that is opened
- During the loop, the values of the first 7 coefficients can be saved in a log file on request and the coefficients can be sent to an external machine through serial communication
- During the loop the SH image acquired in continuous mode can be displayed if this is specified in the [Loop param] dialog. When the SH image is displayed the indications for alignment of lens vs. reference image (see next section) are also given

CAlign, QAlign and Align:

- Used for on-line alignment of the optical system SH image (herein lens) with respect to the center of the camera chip (CAlign) or to the reference image (QAlign and Align). QAlign and Align require that the reference image has been taken in advance. The software gives the indication of the movement to be done (in terms of up down, left right) to align the lens image. When the alignment is inside the tolerances specified in the [Tolerances for alignment] dialog that is opened by pressing on the 

button close to the Align box, when the alignment has been obtained the green circle is filled with a white one

Coll:

- Used for on-line collimation of the optical system under test. Does not require any reference image. The software gives the indication of the movement (inside or outside) to collimate the beam from the optical system under test. When the collimation is inside the tolerances specified in the dialog that is opened by pressing on the  button close to the Coll box, the light is parallel and the green or red circle (indicating the divergence or convergence of the light) is filled with a white one. At this point the loop is automatically stopped

MColl (Optino Pro and EE Vis versions only):

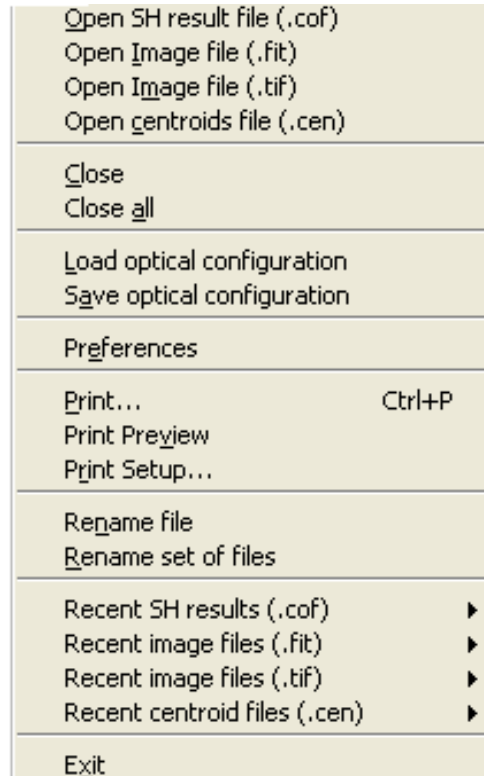
- Used for obtaining collimated parallel light with the motorized collimator pinhole light from the internal light source of Optino
- Does not require any reference image
- The software analyzes the beam coming from the optical system under test optimizing the exposure time and move the motor (inside or outside) inside Optino to obtain collimated light
- When the collimation is inside the tolerances, a beep is signaling that the correct collimation has been reached. At this point the on-line loop is automatically stopped

MBexp (Optino Pro and EE Vis versions only, when system is shipped with motorized beam expander):

- Used for obtaining collimated parallel light with the motorized lens inside the beam expander
- Does not require any reference image
- Same as for the MColl command applied to the beam expander

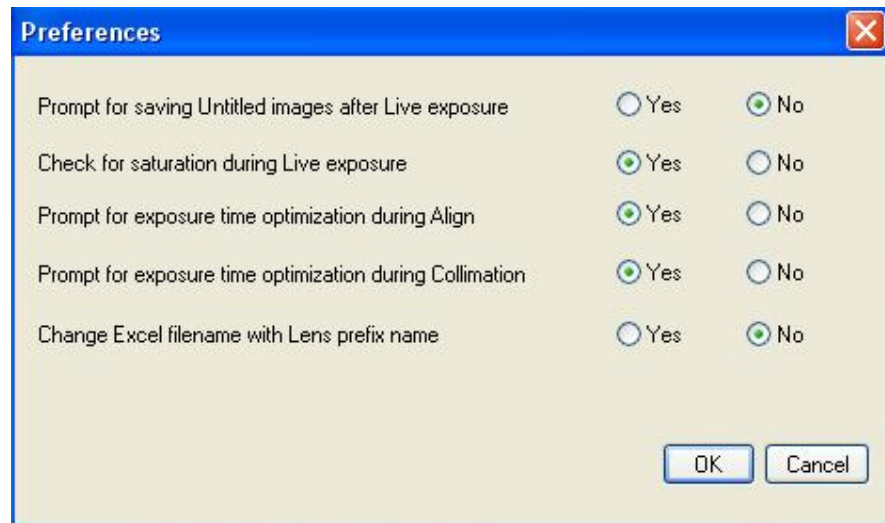
2.1.2 Menus

2.1.2.1 File menu



- **Open** all the files supported by Sensoft:
 - SH results file:** output results file (with **.cof** extension)
 - Image file** (with **.fit** extension)
 - Image file** (with **.tif** extension) can be also opened if they contain 8-bits images; they can be displayed by Sensoft but not analyzed. To analyze these images you should convert them into **.fit** format using the Save As function in File Menu
 - Centroids file** (with **.cen** extension)
- **Close** active view/file on the display
- **Close all** views/files on the display
- **Load/Save** configuration files with all the parameters specified in Sensoft dialogs [Opt] and [WFS] that can be useful for the analysis of the optical system under test
- **Save** images and export graphs
- **Preferences** allow users a number of options that can be set and saved so that these options are selected automatically when Sensoft is run.
- **Print** the current image/graphic on the display on the default printer
- Open the most **recent** files created by Sensoft

2.1.2.2 Preferences in File menu



A number of options can be selected automatically when Sensoft is launched to speed up switching among Sensoft tasks:

- Prompt for saving Untitled images after Live exposure
 - “No”: if you never want to save the Untitled image taken during a Live exposure.
 - “Yes”: if you would like to save the Untitled image taken during a Live exposure.
- *- This option is enabled only if your system was shipped with a fast CMOS camera.*
- Check for saturation during Live exposure
 - “Yes” : the software checks for saturation when an image is acquired; the background of the exposure time box in the Dialog Bar change color according to the saturation level
 - “No”: the software does not check for saturation when an image is acquired. The exposure time box in the Dialog Bar has a white background
- Prompt for exposure time optimization during Align
 - “No”: you never want exposure time optimization at the beginning of the Align or QAlign procedure
 - “Yes”: the Align or QAlign procedure starts with the exposure time optimization
- Prompt for exposure time optimization during Collimation
Same as above applied to Collimation task
- Change Excel filename with Lens prefix name

- “Yes”: a new Excel file for storing output results from Shack-Hartmann analysis is created whenever you change the Lens prefix in [SH/Directories]
- “No”: output results are appended to the same Excel file for all the images created and analyzed in the same directory even when different Lens prefixes are used

2.1.2.3 Edit menu

When an image or graphic views are displayed on the screen it is possible to copy the active view and paste the content to a World or Excel document.

When the Shack-Hartmann analysis output result form is displayed users can select and copy:

- the Zernike coefficients
- the image table
- the Quality table
- the full output report

The screenshot shows the Sensoft software interface with the 'SH analysis of: Test single image' window open. The window contains three tables:

Image	Date	Time	Exp.time	Thresh.	Ellipt.
Test: TEST0001	2007-02-24	11:57:45	.014 sec	.073	.70
Ref: REF_FLAT0006	2007-02-24	11:57:28	.014 sec	.064	.70

This table is identified as the 'Image table'.

Aber	m n	Cx(nm)	Cy(nm)	C(nm)	Angle
Def	0 2			-1.4	
Tilt	1 1	-27.6	139.2	141.9	101.2
Coma	1 3	-1.5	-0.3	1.5	-168.6
SA3	0 4			0.7	
Ast3	2 2	1.7	-0.1	1.7	-2.1
TCom	3 3	0.8	-0.1	0.8	-5.2
QAst	4 4	0.9	0.0	0.9	-0.9

This table is identified as 'Zernikes'.

Quality	Max	Min	Average	P-V	Rms	Strehl
Residual	4.5	-6.5	-4.3	10.9	1.9	0.999
Actual *	5.9	-6.5	-5.3	12.3	2.3	0.998
Potential	4.5	-6.5	-4.3	10.9	1.9	0.999

This table is identified as the 'Quality table'.

Additional information at the bottom of the window:

- * Actual Quality: tilt subtracted
- Normalized pupil: 1.000
- No of spots used: 378
- Probability of goodness of fit: 1.00

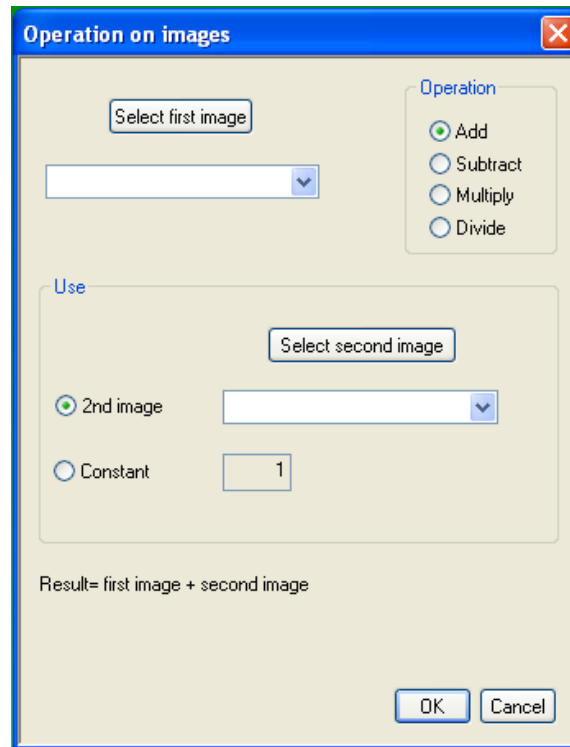
2.1.2.4 Toolbars menu

From this menu users can Show-Hide the toolbars defined in the Sensoft User Interface

2.1.2.5 Image arithmetic menu

Sensoft allows users to perform image arithmetic on images.

The dialog showed below is displayed when the image arithmetic item is selected on the menu



- Select two images (having the same rows x columns dimension)
 - Add pixel values for corresponding row and column
 - subtract the pixel values of the second image from the correspondent pixel value of the first image
- Select one image
 - Add, subtract, multiply or divide the pixel values by a constant value

When the OK button is pressed the image resulting after the selected operation will be displayed on the screen.

2.1.2.6 CCD menu

This menu is enabled only if your system was shipped with a cooled CCD or a Hamamatsu CCD.

User can connect or disconnect the camera driver using items in this menu

2.1.2.7 Motor menu

This menu is enabled only if your system was shipped with a motorized unit. User can Show-Hide the motor toolbar and select if the motor bar should be displayed when Sensoft is launched

2.1.2.8 Align menu

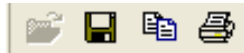
User can Show-Hide the align toolbar that appears when the Align option is selected during the Loop task

2.1.2.9 Simulation menu

This menu is enabled only if your system was shipped with any of the packages included in the Simulation (Shack-Hartmann simulation, Telescope simulation and Diffraction analysis simulation).
User can Show-Hide the motor toolbar and select if the simulation bar should displayed when Sensoft is launched

2.1.3 Fixed toolbars

2.1.3.1 Main toolbar



Save, Copy and Print the current view content

2.1.3.2 Graphics toolbar



Individual plots can be modified by using the buttons of the toolbar. Each button corresponds to a different operation that can be performed on the plot.

Graphics toolbar	
Button	Task
	Show/Hide a grid on the view to help identifying x y values (default FALSE).
	Show/Hide the legend on the view (default TRUE).
	Show/Hide points used for interpolation of curves in 2D graphics (default FALSE)
	Convert the view from to color to grayscale and back (default color).
	Change the size of the vectors of the residuals
	Change the number of contour levels on the wavefront
	Convert the wavefront scale into waves units (default lambda is 632nm).
	Display a 2D section of the wavefront at 0 deg and 90 deg and at 45 deg and 135 deg.
	Display X and Y coordinate labels in spots or mm units

PV	User can select the same scale (in waves or nm units) for all of the 3D and contour plots
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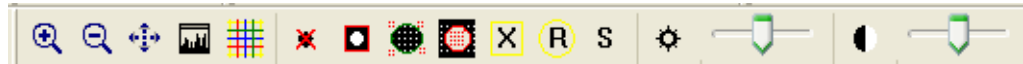
2.1.3.3 Spot profiling toolbar



This toolbar is active when the image view is active.





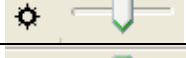
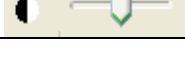
Spot profiling toolbar	
Button	Task
	Selection of a subframe on the current image
	Select full frame
	Select contour of spots during profile loop
	Select 3D view of spots during profile loop
	Select 2D X and Y profile of spots during profile loop
<input type="checkbox"/> P	If checked start profiling of spots found in the selected subframe

2.1.3.4 Image toolbar

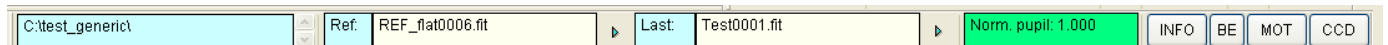


This toolbar is active when the image view is active.

Image toolbar	
Button	Task
	Zoom+
	Zoom-
	Zoom full
	Histogram
	Superpose grids of different shapes (squared, circular, linear) on the images
	Show/Hide a green cross on the image where the center of the last analyzed reference has been found
	Start removal of bad spots procedure
	Select and remove spots contained in a user defined rectangle
	Select and remove spots contained outside a user defined circle

	Select and remove spots contained inside a user defined circle
	Select and remove spots contained inside or outside a rectangle whose coordinates on the image are defined by user
	Select and remove spots contained inside or outside a circle whose coordinates on the image are defined by user
	Close removal of bad spots procedure saving the modified image
	Change brightness on image
	Change contrast on image

2.1.3.5 Info dialog bar



The info dialog bar displays

- The name of the directory where the output results are saved (selected in [SH/Directories])
- The name of the last calibration (reference) image
- The name of the last image analyzed for the optical system under test
- The normalized radius from the last analyzed image.
- The buttons to Show/Hide
 - The Info toolbar
 - The Beam expander info toolbar (only if the instrument includes the beam expander unit)
 - The Motor toolbar (only if the instrument has motorized units) for controlling the motorized units
 - The CCD bar (only if your system was shipped with a CCD camera (either cooled or uncooled)).

2.2 Floating toolbars

Floating toolbars can be Showed or Hided and their default position is on the right side of the screen

2.2.1 Info Toolbar

The Info toolbar gives the information about the optical setup and optical parameters entered in the [Opt] folder

Info			
Test	Lens S	Illum.	External
D (mm)	10.00	EFL (mm)	90.00
CFL (mm)	100.00	F#	9.00
Ref Th.	0.11	Ref El.	0.70
Lens Th.	0.19	Lens El.	0.70
Comb. F.	8.0	Annulus	Full

2.2.2 Beam expander info Toolbar

(Optino Pro and EE versions only, when system is shipped with beam expander):

The toolbar displays the optical properties of the beam expander/compressor configuration selected in the [Opt] folder

Bexp info			
Config.	BE6001		
D1 (mm)	25.00	FL1 (mm)	85.00
D2 (mm)	63.50	FL2 (mm)	354.87
Mag	4.20	Sep (mm)	425.73
D Out (mm)	28.98	Vig. fact.	0.35

2.3 Motor Toolbar

The motor toolbar can be used conveniently to operate the motor.

2.3.1 Optino/BE60/ECM

2.3.1.1 Motor control through serial port

When Sensoft is launched, the serial port connecting the motor is automatically searched.

The serial port should be set with the following parameters (check in the Control Panel/System/Device Manager/Ports /Communication ports/Properties/Port Settings):

- **Baud rate:** 9600 bits per seconds
- **Data bits :**8
- **Parity:** None
- **Stop bits :** 1
- **Flow control :** Xon/Xoff

Sensoft keeps the last position reached by the motor in memory. When Sensoft is launched and the motor has been found, the motor automatically moves to the last recorded position.

<p>Home (zero position)</p> <p>Move to last collimation position</p> <p>Select pre calibrated collimation position</p> <p>Move motor forwards</p>	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2" style="background-color: #0056b3; color: white;">Collimator ✕</th> </tr> </thead> <tbody> <tr> <td style="text-align: center;">Home</td> <td style="text-align: center;">Max</td> </tr> <tr> <td style="text-align: center;">Focus</td> <td style="text-align: center;">1350</td> </tr> <tr> <td style="text-align: center;">Pos</td> <td style="text-align: center;">1750</td> </tr> <tr> <td style="text-align: center;">+ >></td> <td style="text-align: center;">- <<</td> </tr> <tr> <td style="text-align: center;">Step +/-</td> <td style="text-align: center;">10</td> </tr> <tr> <td style="text-align: center;">Current</td> <td style="text-align: center;">1350</td> </tr> </tbody> </table>	Collimator ✕		Home	Max	Focus	1350	Pos	1750	+ >>	- <<	Step +/-	10	Current	1350	<p>Move to end</p> <p>Collimation position (Editable)</p> <p>Pre calibrated position (Editable)</p> <p>Move motor backwards</p> <p>No of steps for movement (Editable)</p> <p>Current position</p>
Collimator ✕																
Home	Max															
Focus	1350															
Pos	1750															
+ >>	- <<															
Step +/-	10															
Current	1350															

If your system has been shipped with more than one motorized unit, all the units will appear and can be activated from the motor dialog bar. Each motor is connected to a different serial port.

<i>Optino and Beam expander</i>																																					
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2" style="background-color: #0056b3; color: white;">Int. Collim. ✕</th> </tr> </thead> <tbody> <tr> <td style="background-color: #008000; color: white;">Collim.</td> <td style="text-align: center;">On</td> </tr> <tr> <td style="background-color: #ff0000; color: white;">Bexp</td> <td style="text-align: center;">Off</td> </tr> <tr> <td style="text-align: center;">Home</td> <td style="text-align: center;">Max</td> </tr> <tr> <td style="text-align: center;">Focus</td> <td style="text-align: center;">1187</td> </tr> <tr> <td style="text-align: center;">Pos</td> <td style="text-align: center;">1000</td> </tr> <tr> <td style="text-align: center;">+ >></td> <td style="text-align: center;">- <<</td> </tr> <tr> <td style="text-align: center;">Step +/-</td> <td style="text-align: center;">12</td> </tr> <tr> <td style="text-align: center;">Current</td> <td style="text-align: center;">1000</td> </tr> </tbody> </table>	Int. Collim. ✕		Collim.	On	Bexp	Off	Home	Max	Focus	1187	Pos	1000	+ >>	- <<	Step +/-	12	Current	1000	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2" style="background-color: #0056b3; color: white;">Bexpander ✕</th> </tr> </thead> <tbody> <tr> <td style="background-color: #ff0000; color: white;">Collim.</td> <td style="text-align: center;">Off</td> </tr> <tr> <td style="background-color: #008000; color: white;">Bexp</td> <td style="text-align: center;">On</td> </tr> <tr> <td style="text-align: center;">Home</td> <td style="text-align: center;">Max</td> </tr> <tr> <td style="text-align: center;">Focus</td> <td style="text-align: center;">1561</td> </tr> <tr> <td style="text-align: center;">Pos</td> <td style="text-align: center;">1000</td> </tr> <tr> <td style="text-align: center;">+ >></td> <td style="text-align: center;">- <<</td> </tr> <tr> <td style="text-align: center;">Step +/-</td> <td style="text-align: center;">1</td> </tr> <tr> <td style="text-align: center;">Current</td> <td style="text-align: center;">1561</td> </tr> </tbody> </table>	Bexpander ✕		Collim.	Off	Bexp	On	Home	Max	Focus	1561	Pos	1000	+ >>	- <<	Step +/-	1	Current	1561
Int. Collim. ✕																																					
Collim.	On																																				
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Step +/-	12																																				
Current	1000																																				
Bexpander ✕																																					
Collim.	Off																																				
Bexp	On																																				
Home	Max																																				
Focus	1561																																				
Pos	1000																																				
+ >>	- <<																																				
Step +/-	1																																				
Current	1561																																				
<p>Motor connection found and set as current for internal collimator – green and On, while BExp is red and off. The reverse is true when BExp motor is set as current</p>																																					

2.3.1.2 Motor control through USB port

When Sensoft is launched, the USB port connecting the motor is automatically searched for. An inquiry to the motor is giving back the motor ID that helps identifying the unit where the motor has been mounted. Once the connection has

been established, the motor control is identical with respect to what described for motors controlled through the serial port.

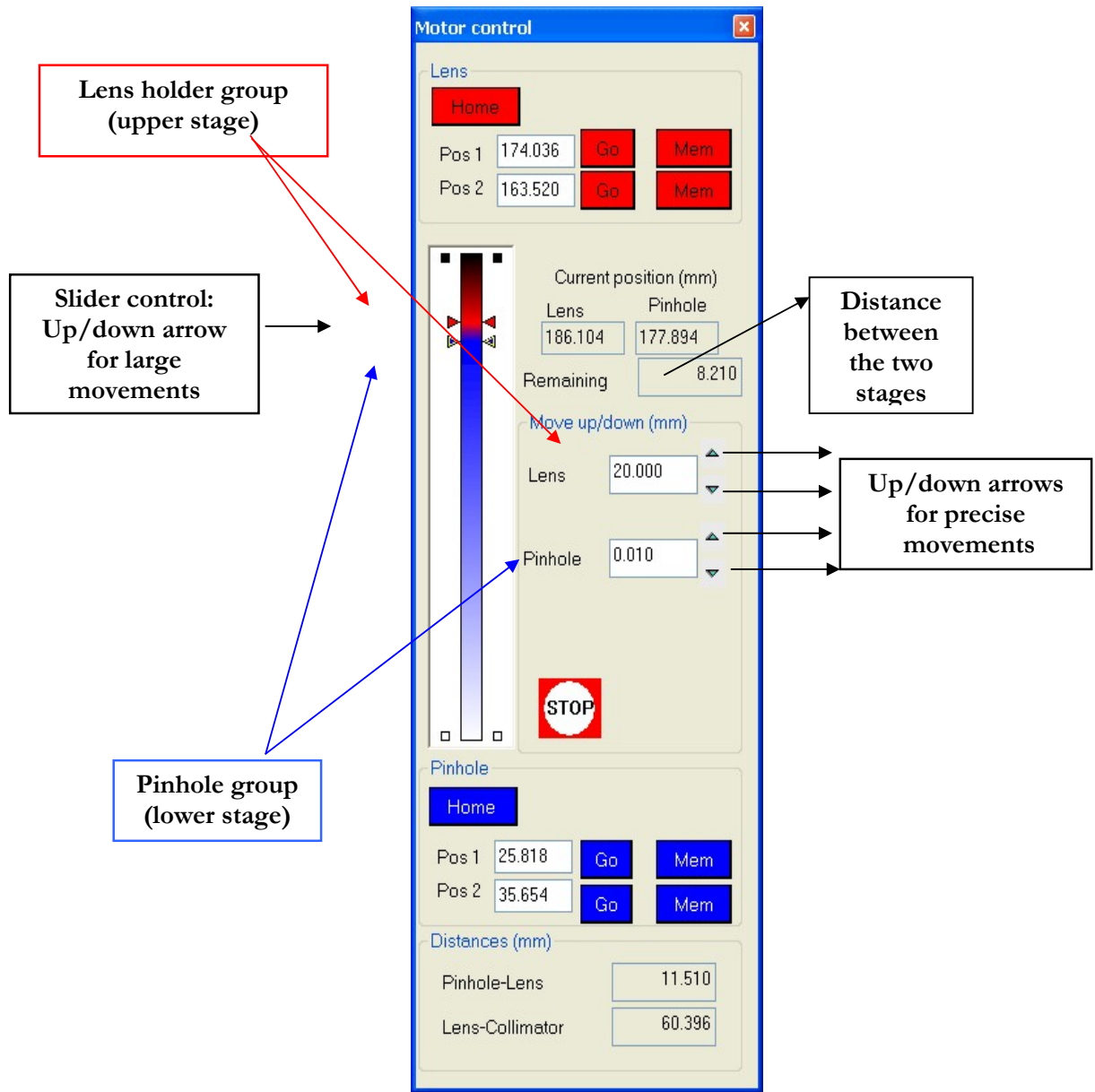
2.3.2 Lentino motor control

The 2 motors of Lentino are connected to one unique serial port. When Sensoft is launched, the serial port connecting the motors is automatically searched for scanning the serial ports from 1 to 10. If the motors are not connected properly to the serial connector or the power supply is not connected, a message will appear on the screen when you launch Sensoft, and you will have to exit the program, establish the connection and (re)launch Sensoft.

The serial port should be set with the following parameters (check in the Control Panel/System/Device Manager/Ports /Communication ports/Properties/Port Settings):

- **Baud rate:** 9600 bits per seconds
- **Data bits :**8
- **Parity:** None
- **Stop bits :** 1
- **Flow control :** Xon/Xoff

The motors can be fully controlled from the motor bar displayed on the right side of the PC screen. The motor bar is displayed in the figure in the next page.




Lentino: the stepper motor control

- Once the motor bar is displayed, the software sends an inquiry for getting the position of the motors. In normal conditions, the inquiry will return the last position reached by the motors, but if the serial cable or the power supply have been disconnected and reconnected, the inquiry will return an undefined position. In this case the dialog in the figure below will appear on the screen.




- By clicking Home the motors are reset to the Home (=0mm) position. Once the Home position is reached, the two red and blue arrows will be displayed at the top (red) and the bottom (blue) of the slide bar and you can proceed with the use of the instrument
- By clicking Manual, you can operate Lentino in manual mode (e.g. if you want to remove any optical-mechanical element that prevents you from going to Home position). You will be allowed only differential movements

 Once you have finished with the manual movement, use the Home command to reset the motors

2.3.2.1 Some points about the stepper motor control

- The position (in mm) of the plates is given with respect to the zero point of the motor
- Pinhole; the distance between the two plates is automatically updated during the movement and displayed in the field “Remaining” on the right of the slide control.

 **Sensoft automatically checks and prevents the collision between the two plates. However, caution should be used when a collimator is being used to ensure that the test element mounted on the upper plate does not collide with it.**

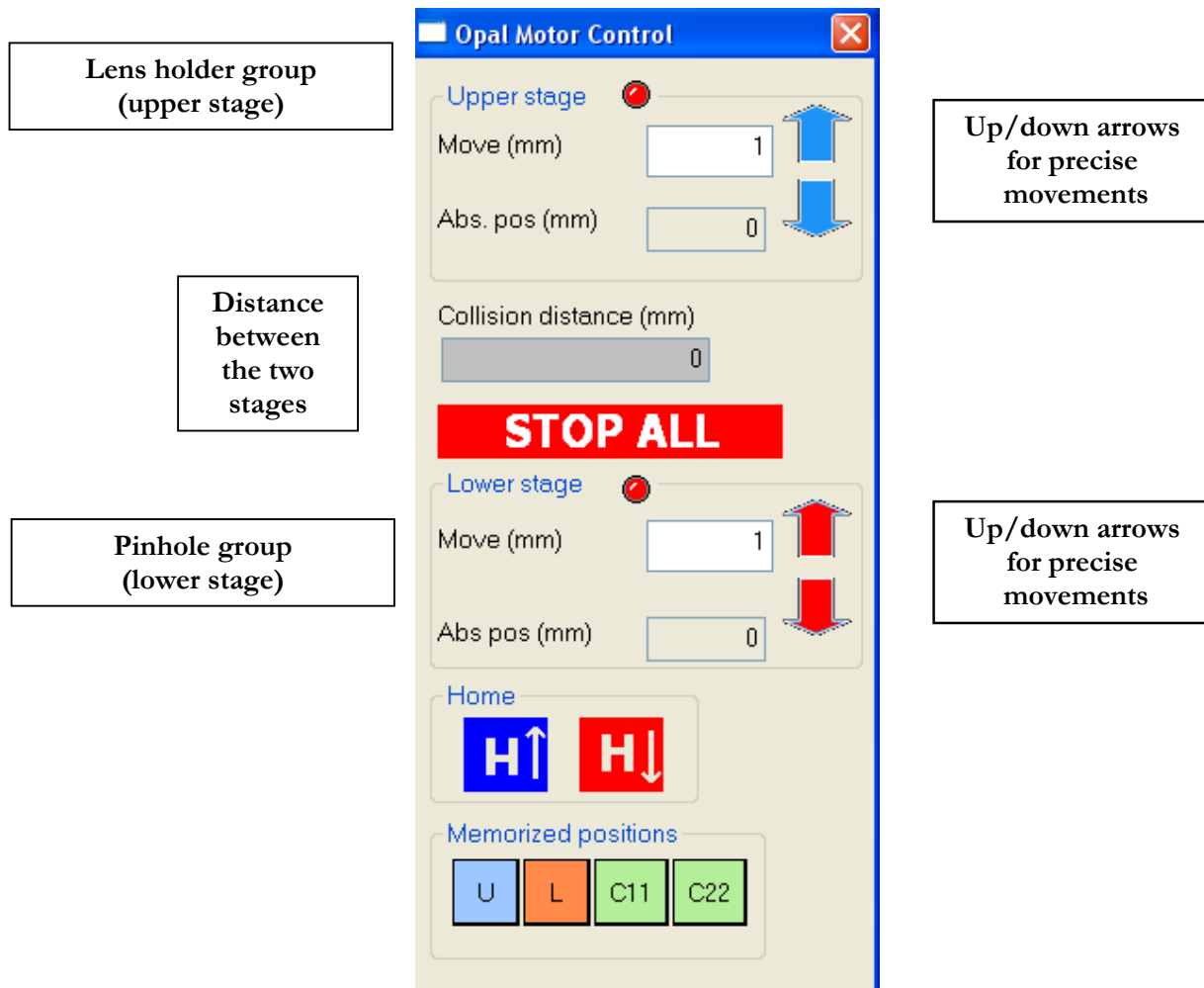
- If the motor needs to be moved by a large step (several mm), using the mouse, you can click and drag the arrows (red or blue) to the desired position. Once the mouse is released, the selected plate will start moving and the position field will be continuously updated until the desired position is reached.
- If the motor needs to be moved by a small amount and/or high precision is required, the step for the movement (in mm) of the selected plate must be entered in the Move up/down section. Then click on the up or down grey

2.3.3 Opal motor control

When Sensoft is launched, the serial port connecting the motor is automatically searched for scanning the serial ports from 1 to 10. The 2 motors of Opal are connected to one unique serial port. The serial port settings are defined inside Sensoft.

If the motors are not connected properly to the serial connector or the power supply is not connected, a message will appear on the screen when you launch Sensoft, and you will have to exit the program, establish the connection and (re)launch Sensoft. If the motors have been connected correctly the red LED button close to the stage description will turn to green.

The motors can be fully controlled from the motor bar displayed on the right side of the PC screen. The motor bar is displayed in the figure below.




Opal: the stepper motor control

- Once the motor bar is displayed, the software sends an inquiry for getting the position of the motors. In normal conditions, the inquiry will return the last position reached by the motors, but if the serial cable or the power supply have been disconnected and reconnected, the inquiry will return an undefined position and a message is displayed on the screen
- By clicking “Reset” the motors are reset to the Home (=0mm) position. Once the Home position is reached, the absolute position will be 0mm and you can proceed with the use of the instrument
- By clicking “Continue” the current position of the motors is maintained: this can be useful if some extra optical elements (i.e. microscope objectives) are mounted on Opal and need to be removed before going to Home

2.3.3.1 Some points about the stepper motor control

- The position (in mm) of the stages is given with respect to the zero point of the motor
- Pinhole; the distance between the two plates is automatically updated during the movement and displayed in the field “Collision distance” on the motor bar.

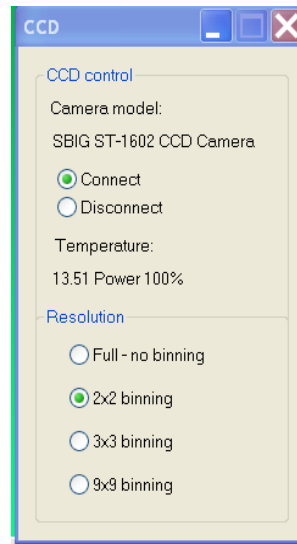
 **Sensoft automatically checks and prevents the collision between the two plates. However, caution should be used when a collimator is being used to ensure that the test element mounted on the upper plate does not collide with it.**

If the motor needs to be moved, the step for the movement (in mm) of the selected stage must be entered in the Move section. Then click on the up or down arrow

2.4 CCD Toolbar - Cooled CCD camera

The standard cooled camera can be controlled from the dialog that appears on the screen when you launch Sensoft. From the dialog users can

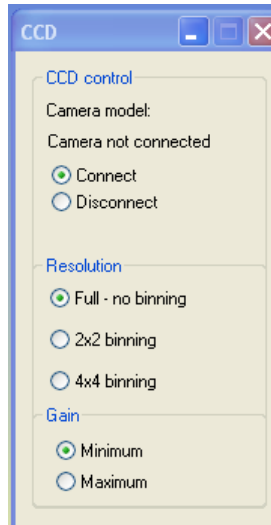
- Connect-disconnect the camera: the camera model is read from the camera hardware and displayed
- When the camera is connected, the temperature will be automatically regulated and its value continuously updated in the CCD dialog.
- Binning selection can be done as follows:
 - 1x1 (full image)
 - 2x2 (4 pixels)
 - 3x3 (9 pixels)
 - 9x9 (81 pixels)



2.4.1 CCD Toolbar – Hamamatsu uncooled CCD camera

When the Hamamatsu CCD camera is shipped with your system the CCD toolbar is slight different and is displayed in the figure below. This uncooled camera can be controlled from the dialog that appears on the screen when you launch Sensoft. From the dialog users can

- Connect-disconnect the camera: the camera model is read from the camera hardware and displayed
- Binning selection can be done as follows:
 - 1x1 (full image)
 - 2x2 (4 pixels)
 - 4x4 (16 pixels)
- Gain can be selected as minimum or maximum



2.4.2 Test coefficients toolbar

The toolbar is displayed during the [Loop] procedure. The value of the coefficients for the Zernike polynomials selected in [SH/Zernikes] is displayed and continuously refreshed during the loop; the coefficients specified in the loop param dialog are shown with a green background if the value is inside the tolerances, in red if it is not. The P-V and Rms of the computed (Residual) wavefront is also displayed.

Aber	C(nm)	Angle
Defoc	5	
Tilt	132	161
Coma3	27	-34
SA3	3	
Ast3	41	-15
TComa	13	-28
QAst	1	40
Coma5	7	144
SA5	-3	
P-V	97.80	
Rms	14.07	

2.4.3 Align toolbar

The toolbar is displayed during the [Loop] procedure when the [Align (Coma/Ast)] plot option is selected in the Loop param dialog. The graphics displaying the value of the coefficients for the Zernike polynomials Coma and Astigmatism (X, Y, and total component) is continuously updated during the loop.


You can choose to focus on the total coma and astigmatism and/or the components by clicking on the Align toolbar that appears once the loop is started.



2.5 Test setup dialog bar

The test setup dialog bar is displayed on the bottom of the screen when you launch Sensoft. The picture of the bar and the explanation of its content fields are given below.



- The description of the test configuration selected in [Opt] folder
- Suggestion on the setup required for the acquisition of the calibration image
- Flux box: highlighted at the end of the SH analysis computation. Check if the exposure time and then the flux was optimized in the SH image under analysis. The background color of this field assumes the same colors as the exposure time box: blue if flux is not enough, red if the image is saturated, yellow or green if the exposure time was OK
- Collimation box: highlighted at the end of the SH analysis computation. Check if the SH image under analysis was taken using parallel light. The background of this field is green if the image was collimated, red if the image was taken in diverging or converging beam
- Alignment box: highlighted at the end of the SH analysis computation. Check if the SH image under analysis was aligned with respect to the calibration reference image assumed for the analysis. Red background means that the alignment is outside the tolerances defined in the Align dialog that is displayed by clicking on the  button close to the Align box in the dialog bar on the top of the screen, green means that the alignment is inside the tolerances

Chapter 3: Input parameters

3.1 Definitions of optical parameters: test with Optino/OMI/Opal

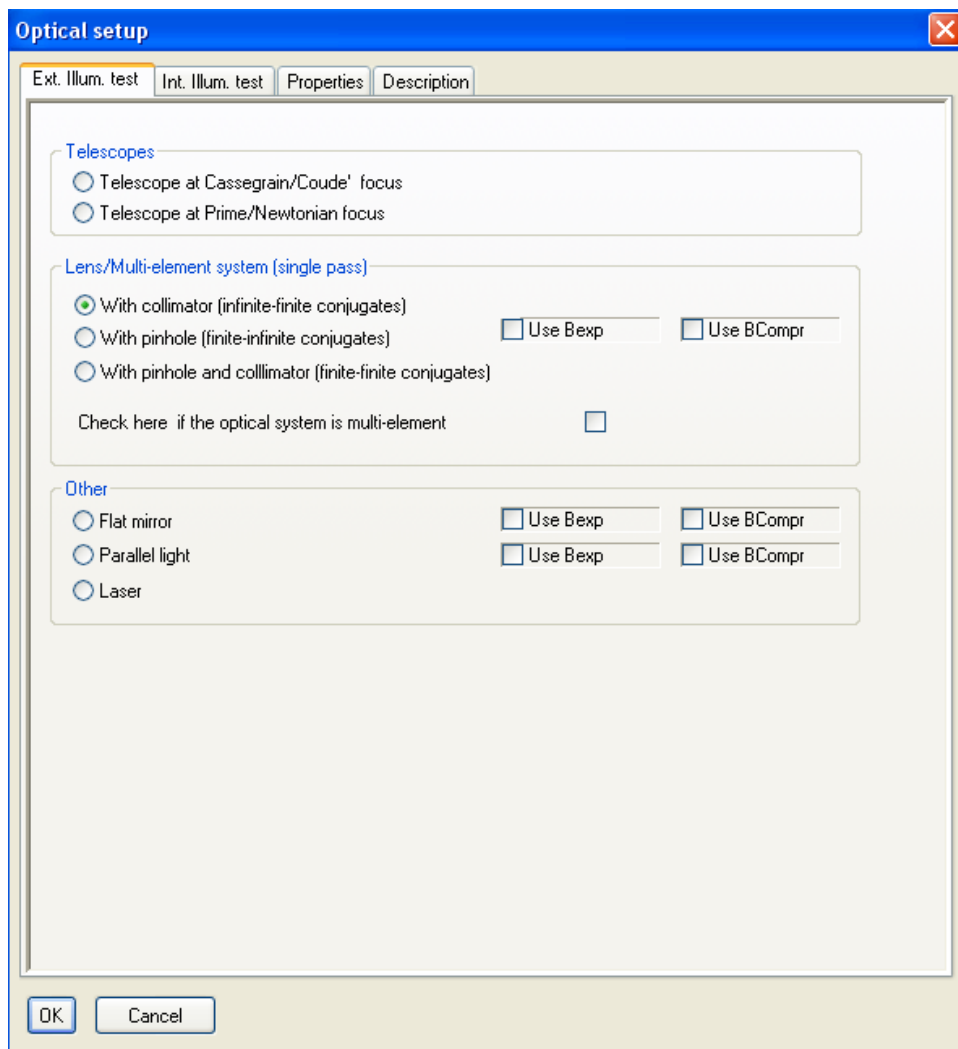
Test with Optino/OMI/Opal can be done in transmission and reflection.

3.1.1 Test in external illumination mode

The element to be tested is mounted externally. This is also called test in single pass, as the light passes through the test element only once.

The selection of the test type is done clicking on the [OPT] button in the dialog bar:

If the system has been shipped with a Beam Expander/Compressor unit, the choice of Bexp or BComp is allowed for some of the test setup. Please refer to the Test Reference Manual for the selection of the correct setup for your optical test.

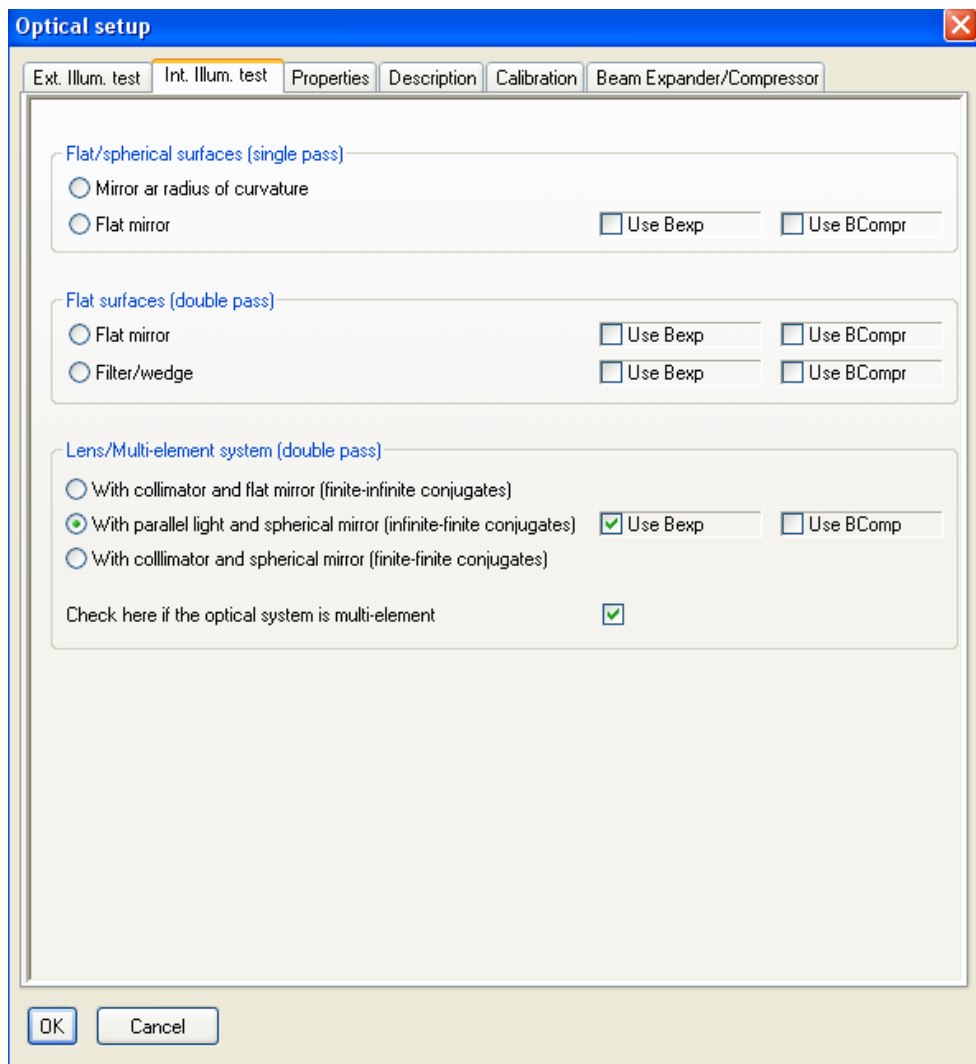


3.1.2 Test in internal illumination mode

The test element is illuminated from a light source from inside Optino/Opal. This is not available with OMI. Test can be in single or double pass.

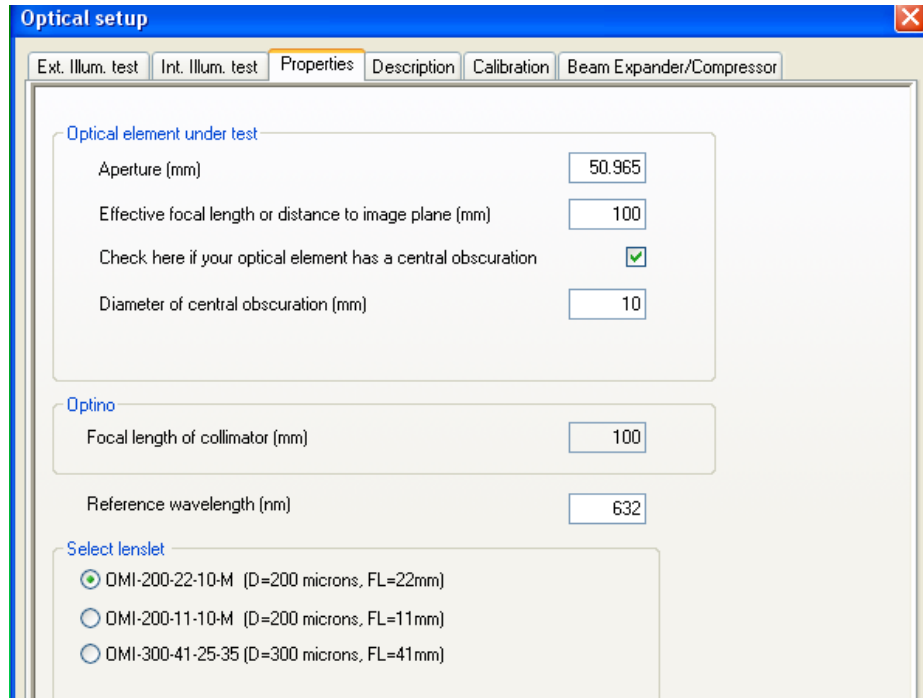
The selection of the test type is done clicking on the [OPT] button in the dialog bar.

If the system has been shipped with a Beam Expander/Compressor unit, the choice of Bexp or BComp is allowed for some of the test setup. Please refer to the Test Reference Manual for the selection of the correct setup for your optical test.



3.1.3 Optical parameters

The optical parameters required for the various tests are given below:



For all tests:

- Aperture of the test element (mm). If it is rectangular, enter the maximum dimension
- For complex optical systems it is preferable to use the size of the exit pupil instead of the aperture
- If the test element has a central obscuration (annulus): enter its diameter (mm)

For converging elements:

- If the test is done in parallel light: focal length (mm)
- If the test is done with light source at finite distance: distance from principal plane to the image (or, if the exit pupil is used instead of the aperture, distance from exit pupil to image) (mm)

For tests done with collimator:

- Focal length of collimator (mm)

Reference wavelength (nm):

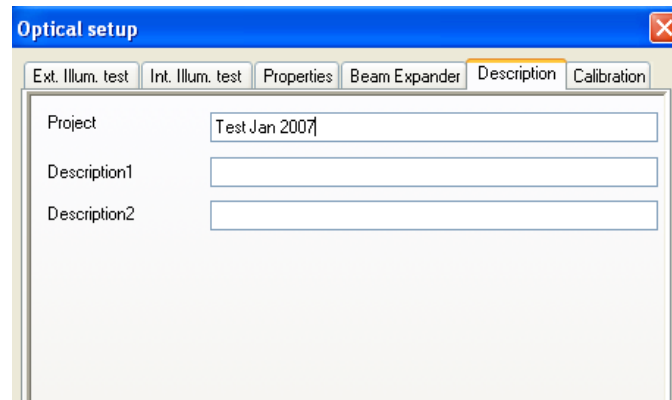
- This is used in the computation of the Strehl ratio
- It is also used for expressing the wavefront in waves

Select lenslet (only if the system supports multiple lenslet arrays):

The standard lenslet arrays that can be provided with SpotOptics wavefront sensors have the following characteristics:

- D=200 μ , FL=22mm
- D=200 μ , FL=11mm
- D=300 μ , FL=41mm
- Other lenslet arrays can be supported on request

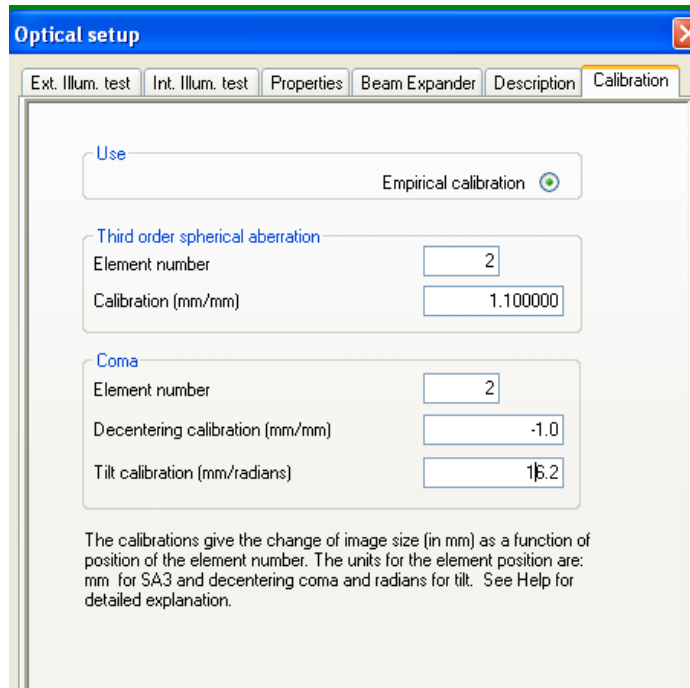
3.1.4 Description of the test



Enter the Project title and the description of the test in [OPT/Description. The Project title will appear as title in the output files created by Sensoft.

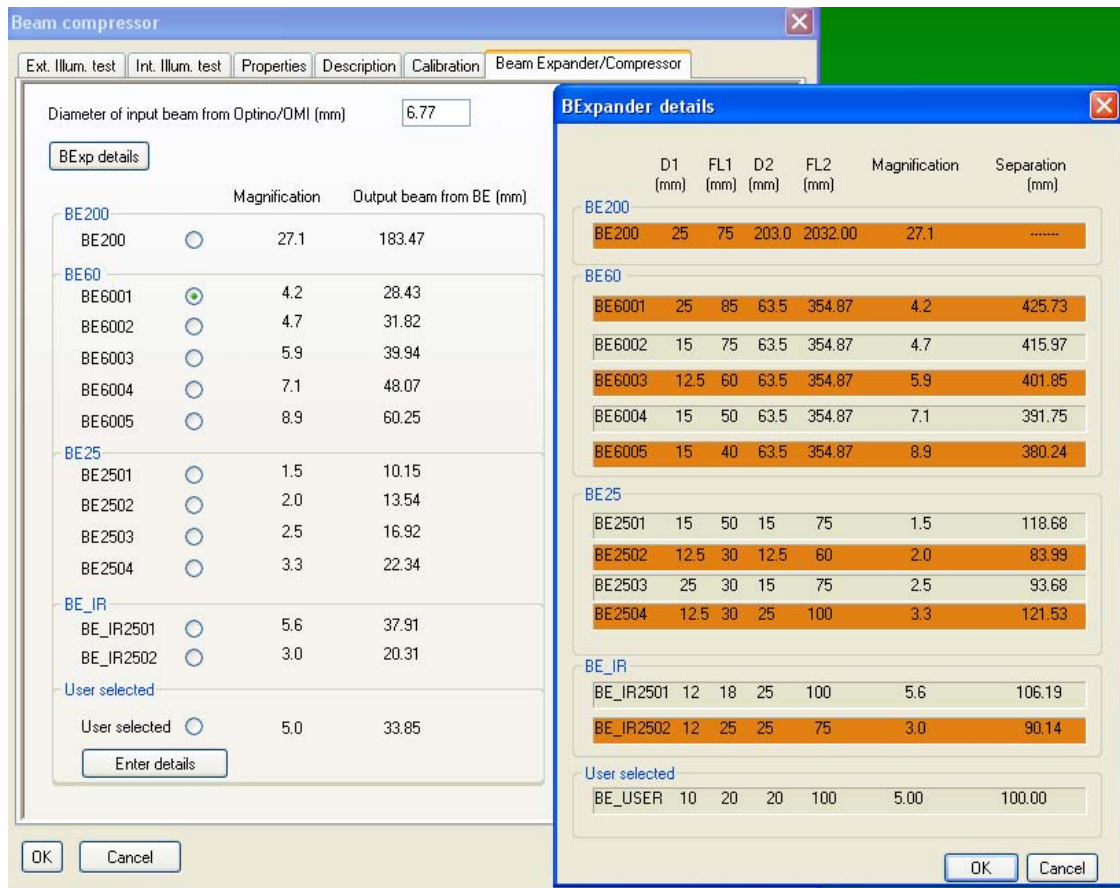
3.1.5 Calibration for coma and SA3 (for complex optical systems)

- For complex optical systems, the calibration for the correction of coma and SA3 are entered on a separate page [OPT/Calibration]. See main manual

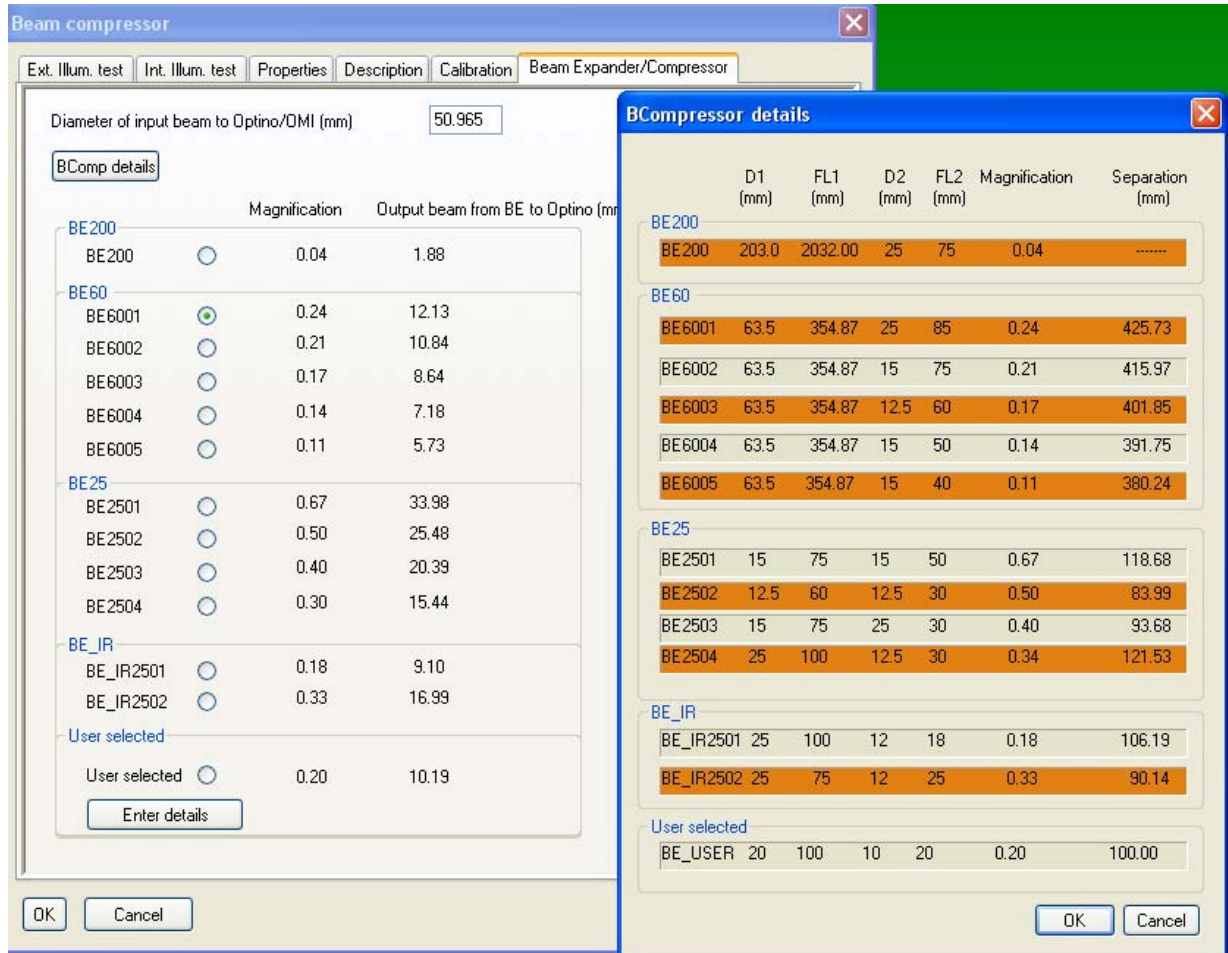


3.1.6 Tests done with beam expander/compressor

- If a beam expander is used, then depending on the magnification factor required, the correct BE configuration is chosen



- If a beam compressor is used, then depending on the magnification factor required, the correct BComp configuration is chosen



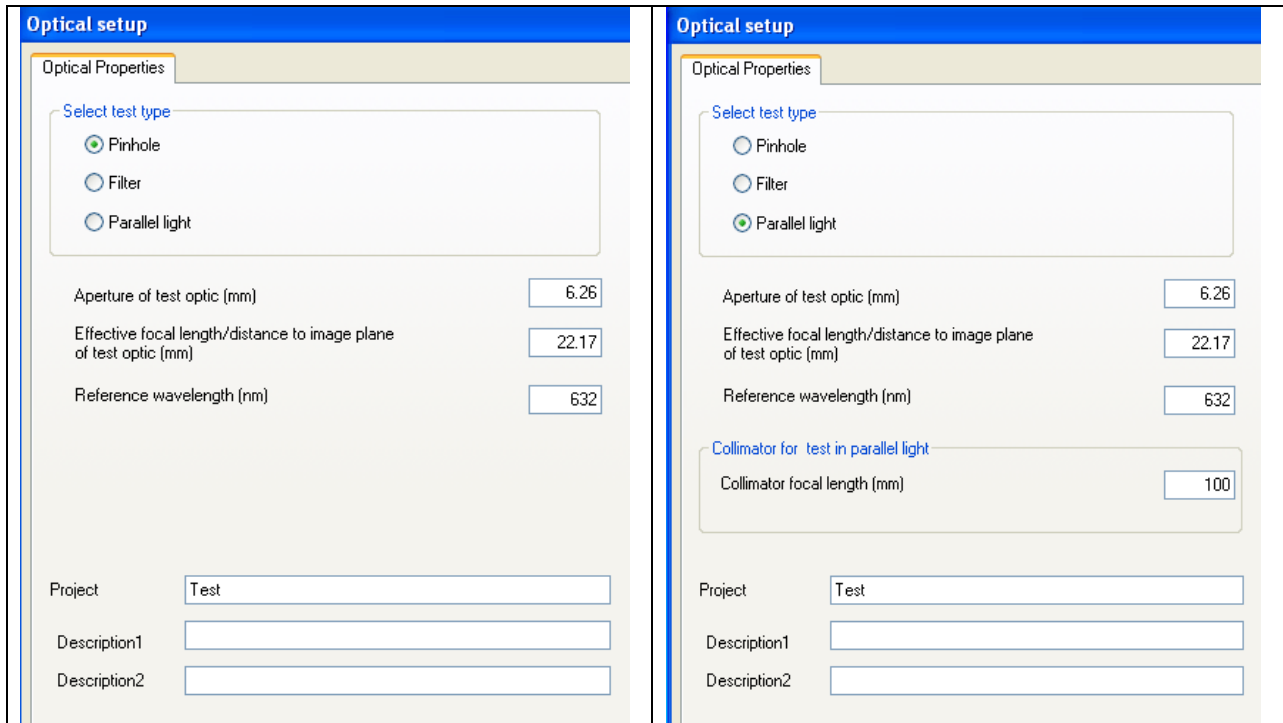
3.2 Notes on the input parameters

3.2.1 Why focal lengths are used for flat elements

Clearly, for flat elements (e.g. mirrors and filters), the focal lengths f_{test} and f_{col} are not required. However, Sensoft allows you to see the spot diagram corresponding to the wavefront from a flat element as if it were focused by a perfect lens of a given focal length. By default Sensoft sets $f_{test} = f_{col} = 100\text{mm}$.

3.3 Definitions of optical parameters: test with Lentino

Test with Lentino can be done in transmission with external illumination.



The optical parameters required for the various tests are given below:

For all tests:

- Aperture of the test element (mm). If it is rectangular, enter the maximum dimension
- For complex optical systems it is preferable to use the size of the exit pupil instead of the aperture
- If the test element has a central obscuration (annulus): enter its diameter (mm)

For converging elements:

- If the test is done in parallel light: focal length (mm)
- If the test is done with light source at finite distance: distance from principal plane to the image (or, if the exit pupil is used instead of the aperture, distance from exit pupil to image) (mm)

For tests done with collimator:

- Focal length of collimator (mm)

Reference wavelength (nm):

- This is used in the computation of the Strehl ratio
- It is also used for expressing the wavefront in waves

Description of test:

- Enter the Project title and the description of the test in. The Project title will appear as title in the output files created by Sensoft.

3.4 Definitions of optical parameters: test with Sfera

Test with Sfera can be done in transmission with external illumination.

The optical parameters required for the various tests are given below:

For all tests:

- Aperture of the test element (mm). If it is rectangular, enter the maximum dimension
- For complex optical systems it is preferable to use the size of the exit pupil instead of the aperture
- If the test element has a central obscuration (annulus): enter its diameter (mm)

For converging elements:

- If the test is done in parallel light: focal length (mm)
- If the test is done with light source at finite distance: distance from principal plane to the image (or, if the exit pupil is used instead of the aperture, distance from exit pupil to image) (mm)

For tests done with microscope objective

- Focal length of collimator (mm)

Reference wavelength (nm):

- This is used in the computation of the Strehl ratio
- It is also used for expressing the wavefront in waves

Select lenslet (only if the system supports multiple lenslet arrays):

The standard lenslet arrays that can be provided with SpotOptics wavefront sensors have the following characteristics:

- D=200 μ , FL=22mm
- D=200 μ , FL=11mm
- D=300 μ , FL=41mm
- Other lenslet arrays can be supported on request

Description of test:

- Enter the Project title and the description of the test in. The Project title will appear as title in the output files created by Sensoft.

3.5 Saving and recalling the optical parameters

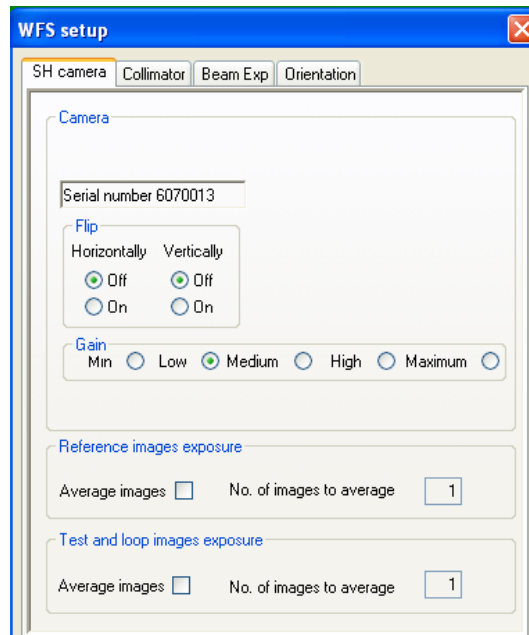
The user-defined parameters can be saved and reloaded later by using the Save/Load configuration option under the File menu

Open SH result file (.cof)	
Open Image file (.fit)	
Open Image file (.tif)	
Open centroids file (.cen)	
<hr/>	
Close	
Close all	
<hr/>	
Load optical configuration	
Save optical configuration	
<hr/>	
Preferences	
<hr/>	
Print...	Ctrl+P
Print Preview	
Print Setup...	
<hr/>	
Rename file	
Rename set of files	
<hr/>	
Recent SH results (.cof)	▶
Recent image files (.fit)	▶
Recent image files (.tif)	▶
Recent centroid files (.cen)	▶
<hr/>	
Exit	

3.6 Input parameters for WFS

3.6.1 Camera settings – uncooled CMOS camera

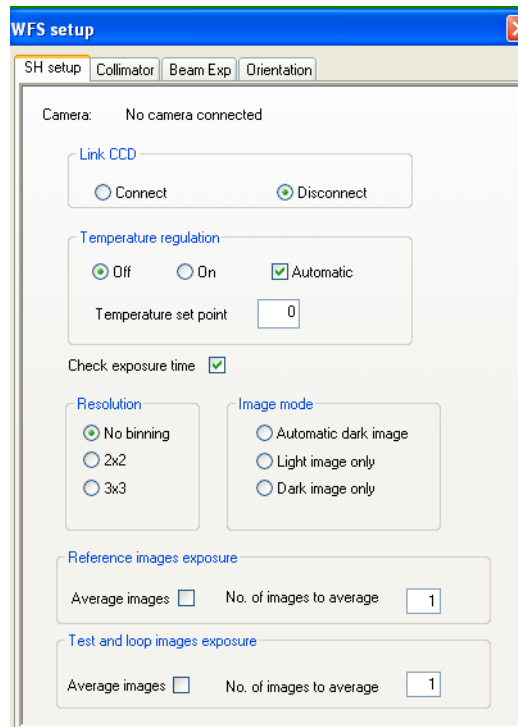
If your system has an uncooled CMOS and the camera is correctly installed and connected to the instrument when Sensoft is launched, the serial number of the camera is read from the camera firmware and displayed in the [WFS/SH camera].



- Camera gain should be used as low as possible (minimum or low values are suggested) but gain should be increased if the illumination from the light source is not sufficient to get a good contrast on the image
- Average of several reference or test image can be requested to improve the signal to noise ratio on the image. In this case images will be added in memory and then the average will be saved on disk

3.6.2 Camera settings – cooled CCD camera

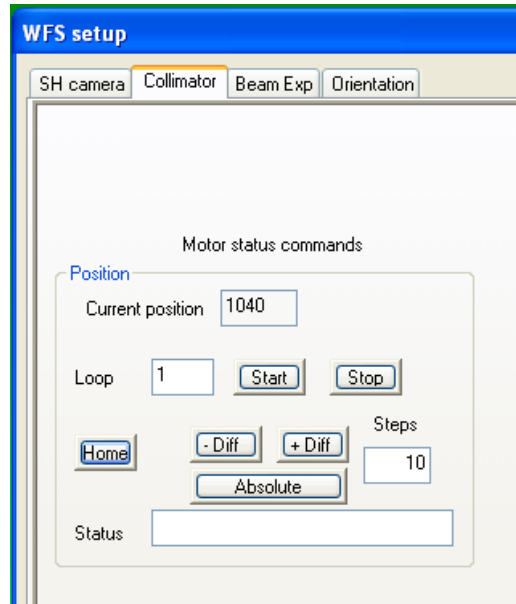
If your system has a cooled CCD camera correctly installed you can change some camera parameters in [WFS/SH camera].



- Camera can be connected or disconnected
- Temperature regulation can be put automatically on when CCD is connected or can be activated manually
- Full resolution or binning can be selected
- User can select to acquire dark or light images or an image whose dark is automatically subtracted during Live exposure (in normal operation Sensoft will light images will be preset)
- Average of several reference or test image can be requested to improve the signal to noise ratio on the image. In this case images will be added in memory and then the average will be saved on disk

3.6.3 Motor control and diagnostics in Optino

If your system has one or more motorized units controlled by a serial port you can control and debug each of the motors from [WFS/Motorized Unit] where Motorized Unit will be substituted by the your current units (Collimator, Beam expander, Motorized External Calibration unit etc.)



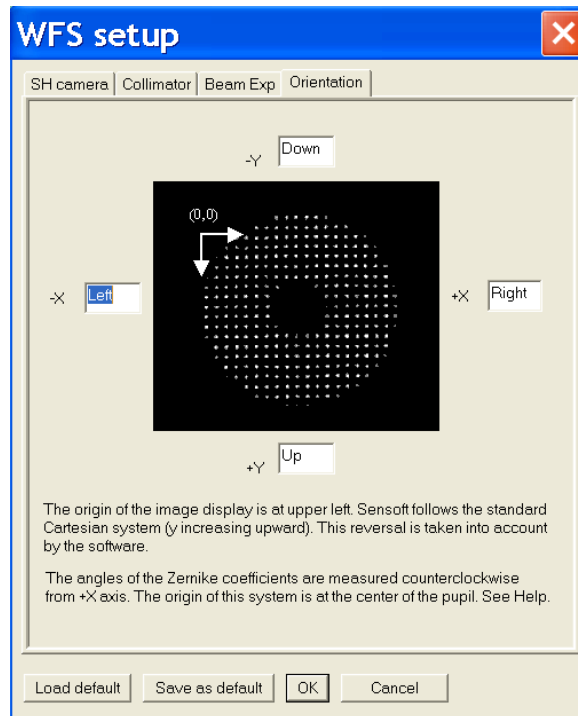
- Home, differential and absolute movements can be checked. At the end of the movement the status (OK or KO) will be displayed in the Status field
- The motor can be moved in a Loop from Home position to Absolute position entered in the Steps field for testing it.
- The Loop is started by pressing on the Start button and can be stopped in any moment using the Stop button
- During the Loop the status field will be refreshed continuously

3.6.4 Orientation

The orientation of the pupil coming from the test system can be calibrated with respect to the mounting of the optical system (like Left, Right, Top and Bottom).

The simplest way to do this is to cover the Top part of the beam and then note the obscuration on the SH image. Repeat it for the Right side. Enter this in the section WFS as shown below.

The orientation is used in the plots of the wavefront/surface, as well as for the indications given by Sensoft to correct for coma.

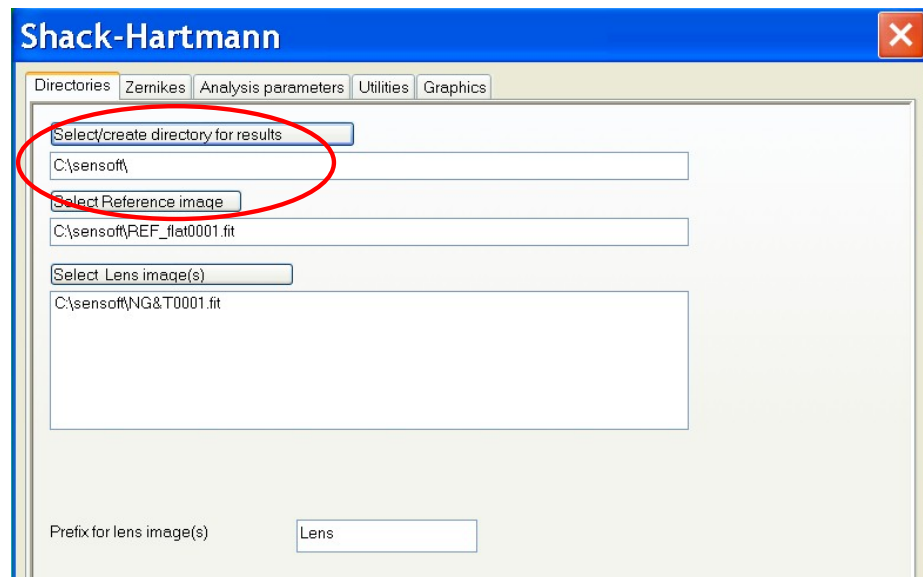


3.7 Input parameters for Shack Hartmann analysis

3.7.1 Definition of directory for output results

In the first page of the [SH/Directories] folder define the path for the directory where you would like Sensoft to store the output results (outdir_results). When you select a new directory the reference and lens image fields will be reinitialized with blanks.

Where: The directory for storing the images and output files is specified in [SH/Directories]



3.7.2 Definition of prefix for lens image

In the first page of the [SH/Directories] folder define the prefix that you would like to use for the image name created during analysis. This choice does affect only the task started by clicking on the [Lens] button in the Dialog bar

3.7.3 Definition of Zernike coefficients to be used for the analysis

Go to the [SH/Zernikes] and choose the Standard Zernike coefficients to fit to the data. We recommend that to start with the 7 terms grouped under the Default item. The selection is done with a simple drag and drop of groups or individual terms from the central window to the window at left.

Sensoft allows you to select one of the following Zernike polynomials to fit to the data:

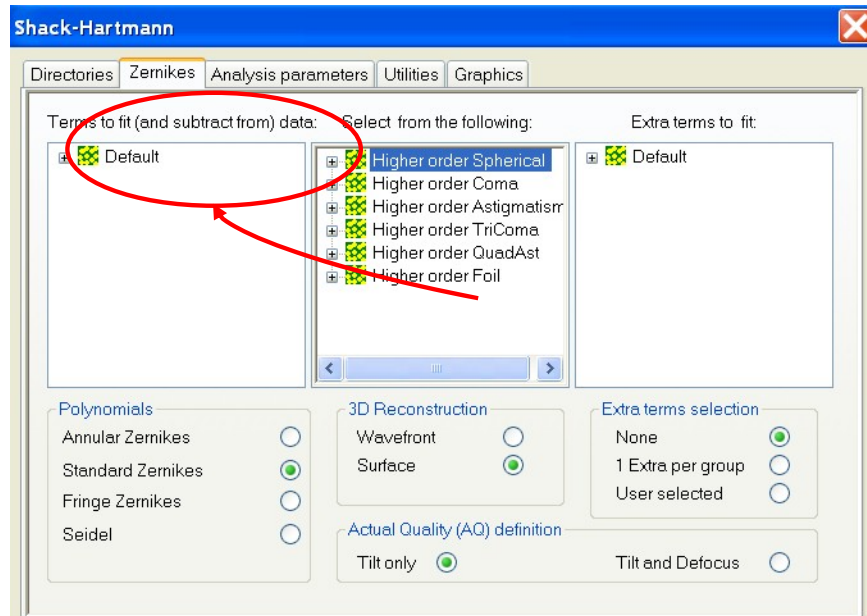
- Annular
- Fringe
- Standard

In addition, pure Seidel polynomials can also be fit to the data.

Please see separate chapter on **Zernike polynomials and Sensoft**.

Also, specify if you wish to see the wavefront or the surface. Select the Actual Quality definition as Tilt only or Tilt and Defocus.

Where: The selection is done in [SH/Zernikes]



3.7.4 Threshold

An important factor for finding the centroids is the threshold. This determines the level over which pixels are included as part of the spot. Sensoft uses a complex criterion for this, and does it automatically. The user can override the automatic threshold computation if required.

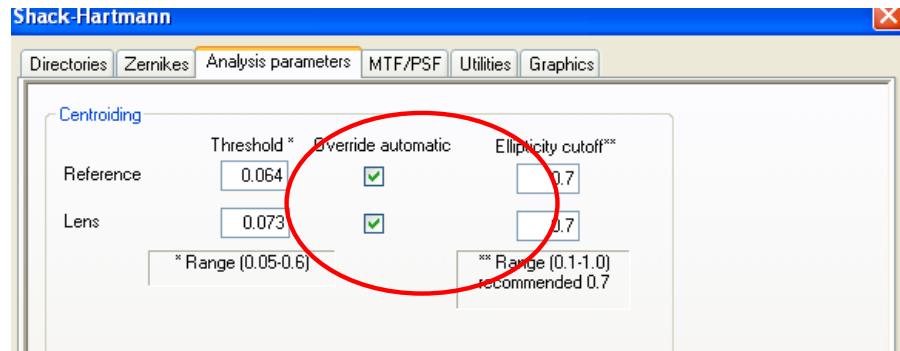
Typical value: For good quality images, a value of 0.05 to 0.10 is normally found by the software. Values up to 0.3 can be used in certain rare cases.

Where: The selection is done in [SH/Analysis Parameters]



Note:

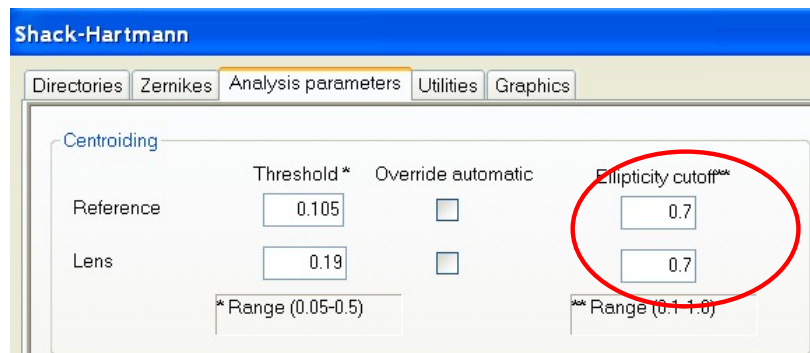
The value of the threshold can cause small differences (of the order of a few nm) in the values computed by Sensoft. A higher threshold (compared to the one computed by Sensoft automatically) can be used to remove elongated or bad spots



3.7.5 Ellipticity

Sensoft can reject elongated spots that might arise due to spurious effects. The recommended ellipticity cutoff is 0.7 (i.e. all spots with an ellipticity higher than this will be rejected).

The ellipticity of the spot is defined as $\epsilon=(1-b/a)$, where b and a are the major and minor axes of the spot. $\epsilon=0$ corresponds to a round spot.



Default value: For good quality systems, a value of 0.7 is generally sufficient. For bad surfaces, a value of even 0.3 might be required.

Where: The selection is done in [SH/Analysis Parameters]



Note:

The distribution of the ellipticity for the spots in any SH image (as well as the flux and S/N ratio) can be plotted by opening a .cen file, and selecting the plots in [SH/Utilities]. Then click the [Utilities] pull-down menu or the Plot button in the Dialog bar

3.7.6 Annulus

You can ask Sensoft to include spots only in an annulus, by specifying the inner and other normalized radius (from 0 to 1.0). This can be useful in certain situations where elongated spots due to the turned-down edge affect the analysis.

Default values: (0, 1.0)

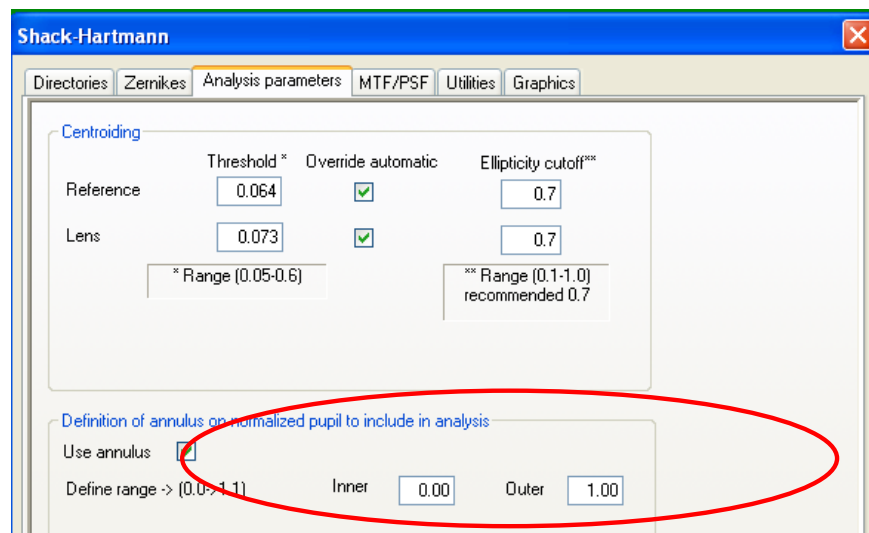
Range: 0 -> 1.0

Where: The selection is done in [SH/Analysis Parameters]



Note:

This can affect the values of the aberration coefficients, particularly the radial components like defocus and spherical aberration. It is preferable to use the ellipticity factor (section 4.7.5) to reject elongated spots at the edge



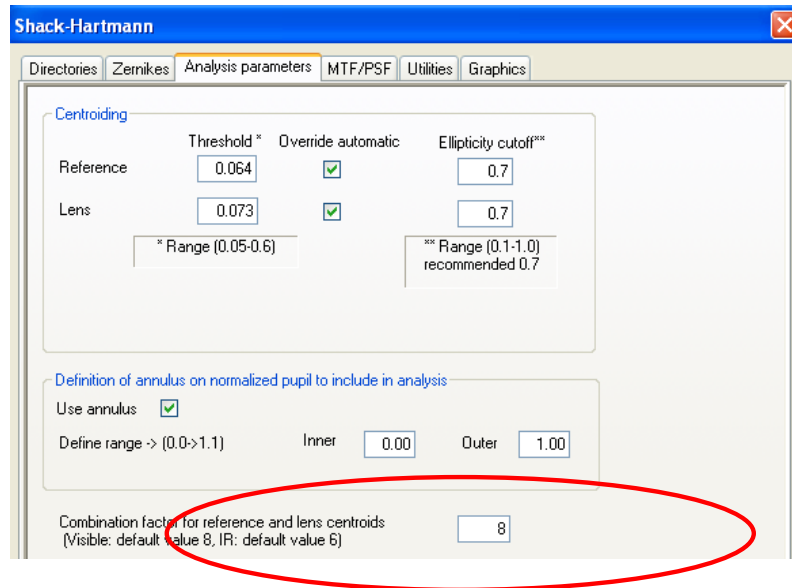
3.7.7 Combination factor

The combination factor is used for the combination of the reference and mirror spots. Normally the default value of 8 is sufficient. It might be needed to be changed only if there is difficulty in the automatic combination of spots, for example, if the test optical element has large aberrations.

Default value: 8 for Visible and 4 or 5 for NIR

Range: 6-8 (Visible)
4-5 (NIR)

Where: The selection is done in [SH/Analysis Parameters]



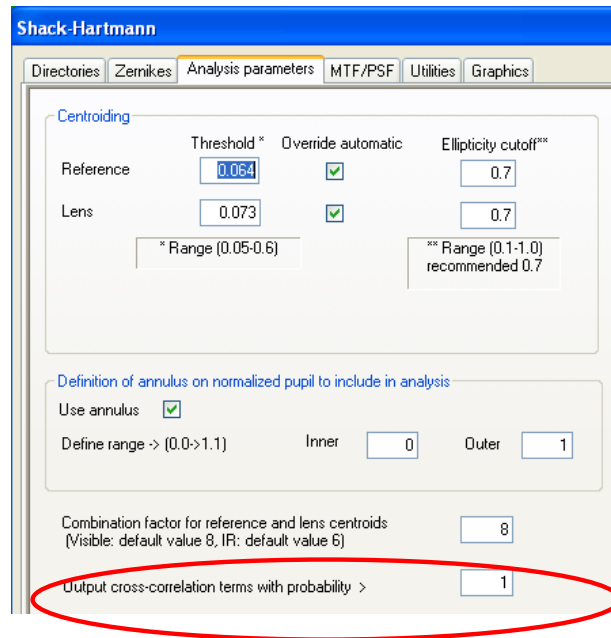
3.7.8 Correlation factor

This is for the advanced user who is interested in analyzing the cross-talk between the various Zernike coefficients computed by Sensoft. You can set the value of the probability (range 0 to 1.0): when the computed probability is greater than the value specified, Sensoft will print them out.

Default value: 1

Range: 0-1

Where: The selection is done in [SH/Analysis Parameters]



3.7.9 MTF from Shack-Hartmann analysis

The spot diagram obtained from the Shack-Hartmann analysis can be used to compute the Modulation Transfer Function (MTF) of an optical system. Sensoft allows the computation of the MTF after the subtraction of:

- AQ Zernike terms - Tilt or Tilt and Defocus as selected in [SH/Zernikes]
- PQ 7 Zernike terms -Tilt, Defocus, Coma3, SA3, Ast3, TriComa, Qast
- RQ Zernike terms - any Zernike term or terms selected in [SH/Zernikes]

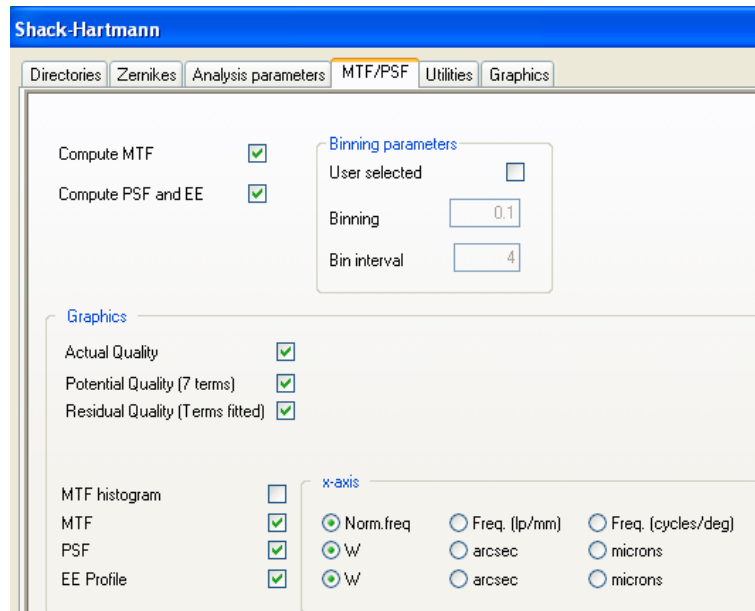
For details on how the MTF is computed from spot diagrams, see the reference by Smith. See also the section on diffraction in the chapter on Simulations.

Given the Shack-Hartmann analysis parameters and the parameters for the MTF histogram the program gives as output the following graphs:

- MTF histogram. The user can change the binning interval using this histogram
- MTF as function of: Spatial frequency (lines/mm or cycles/deg) or Normalized spatial frequency (in units of the cut-off frequency).

Important note:

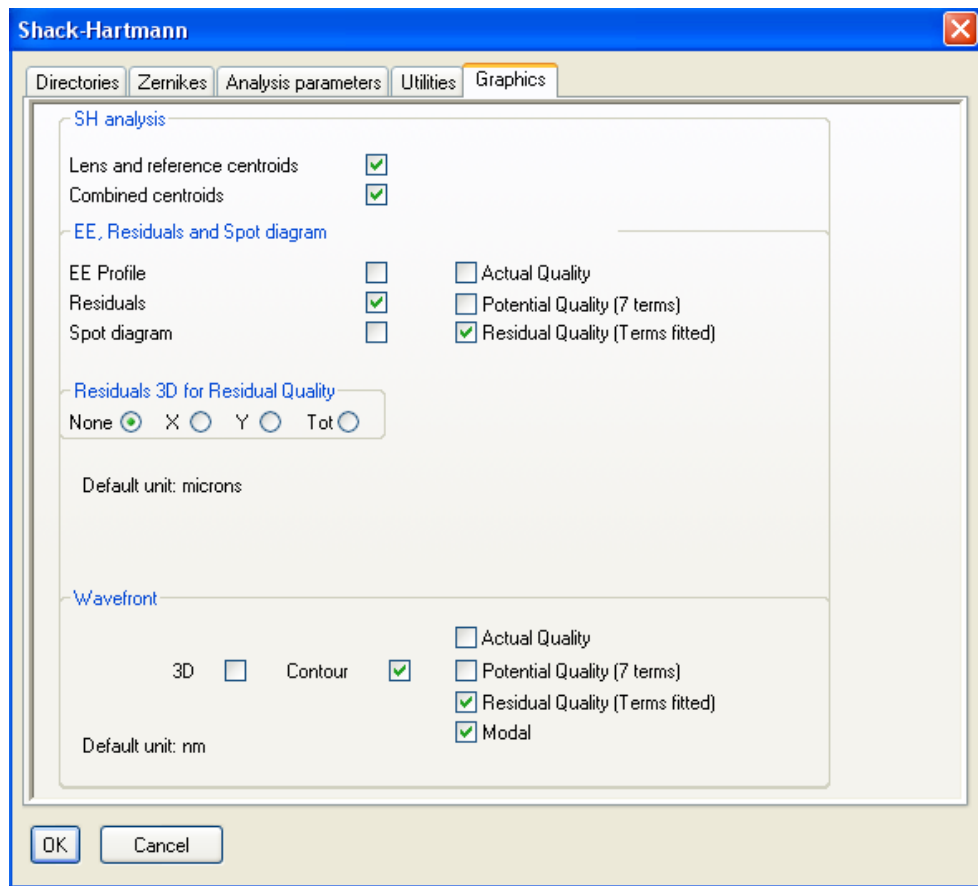
The program gives reliable results starting from a sampling of at least 200 spots on the pupil.



3.7.10 Selection of graphics

Users can select graphics to be seen at the end of the analysis procedure from [SH/Graphics]. Graphics can be divided into 3 groups:

- Centroids graphics display the position of the baricenter of the Shack-Hartmann spots found during the analysis both for the calibration (reference) image and for the Lens image
- Encircled Energy profile (EE), Residuals and Spot diagram graphics display in a different way the residuals after mathematical subtraction of:
 - AQ Zernike terms - Tilt or Tilt and Defocus as selected in [SH/Zernikes]
 - PQ Zernike terms- 7 Zernike terms – Tilt, Defocus, Coma3, SA3, Ast3, TriComa, Qast
 - RQ Zernike terms- any Zernike term or terms selected in [SH/Zernikes]
- Wavefront and contour graphics display the wavefront reconstructed after mathematical subtracting AQ, PQ and/or RQ Zernike terms. Zonal or Modal wavefront reconstruction can be selected



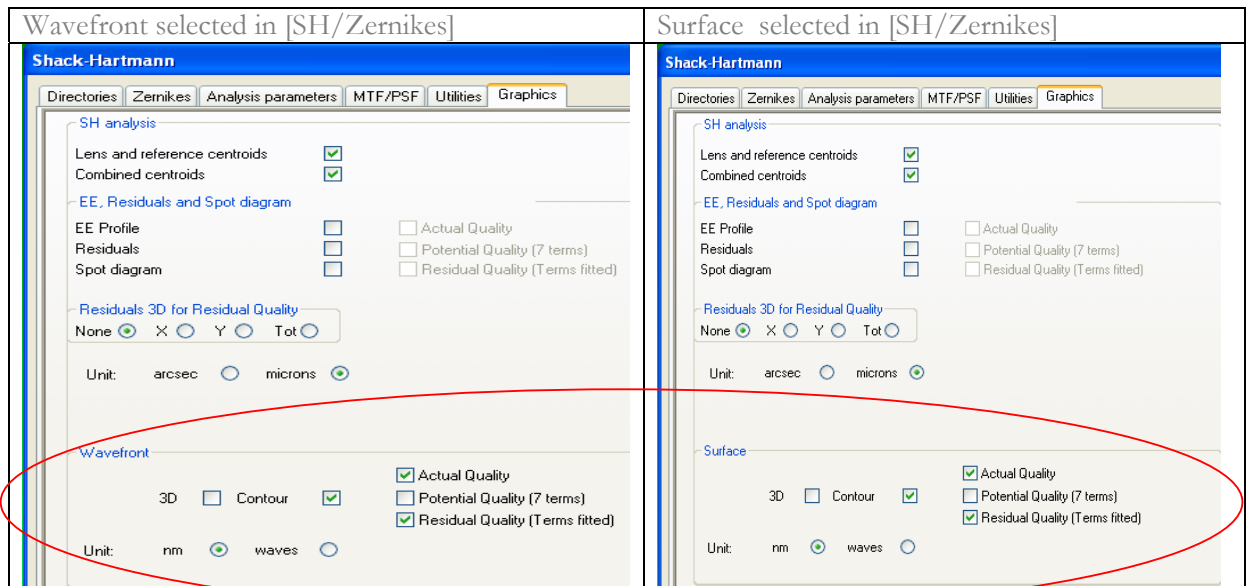
3.7.11 3D plots of wavefront or optical surface

Sensoft can compute the wavefront or the surface.

The difference between the plot of the wavefront and the surface lies in the following points:

- The sign convention is different. The wavefront is positive if it is retarded (with respect to the spherical wavefront). This is counter to the normal sign convention
- For the surface, the convention is the standard one: it is positive if it is advanced with respect to the spherical surface
- For reflection from a mirror, the wavefront is doubled. This is taken into account by Sensoft
- Whenever a test for a lens is done in double pass, the wavefront aberration is doubled. Sensoft takes this into account
- For a mirror, the test can be done in double pass (like the Ritchey-Common test). In this case, the wavefront is quadrupled. Again, Sensoft takes this into account

Where: The user can select to compute wavefront or surface in [SH/Zernikes] and the type of plot to see (wavefront or surface) in [SH/Graphics]



3.7.12 Output units

3.7.12.1 Spot diagram, distribution of residuals, Encircled Energy profile

The units can be either arcsec, or microns.

Default unit: microns

Where: In [SH/Graphics]

3.7.12.2 Wavefront

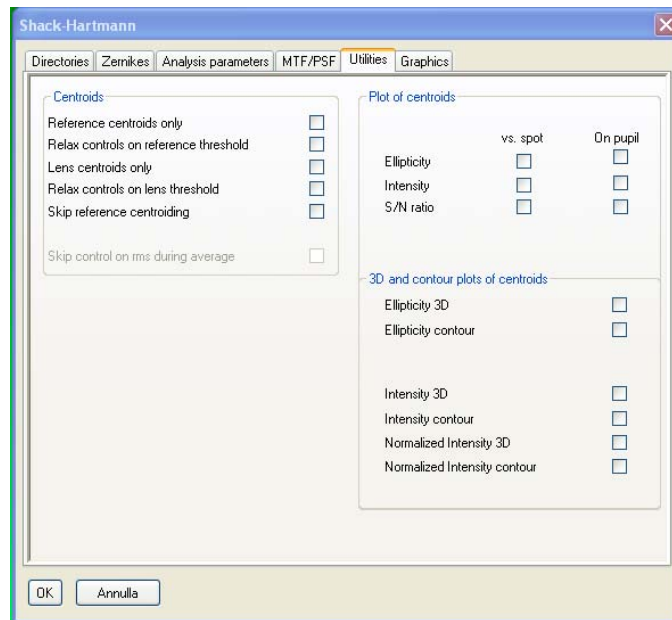
For the wavefront, the output can be either in nm or waves (in units of the wavelength specified in [Opt]).

Default unit: nm

Where: In [SH/Graphics]

3.7.13 Utilities

The **utilities** can be used for debugging, or for overriding some controls.



3.7.13.1 Centroids

- **Reference centroids only:** Sensoft will compute the reference centroids only and display the plot of the centroids it has found. The program will stop after the centroids have been found. This option is available only for analysis of a single frame.
- **Relax controls on reference centroids threshold:** Sensoft aggregates pixels together to define a spot, and uses certain criteria (such as the number of pixels in a spot) as a check. With this option, Sensoft can be forced to override the check and report all the spots found whose positions are then shown on a graph. The program will stop after the centroids have been found. It is recommended that a new image with a different exposure time is then taken, and the threshold changed if required. This option is available only for analysis of a single frame.
- **Lens centroids only:** As for the reference frame.
- **Relax controls on lens centroids threshold:** As for the reference frame.
- **Skip reference centroiding:** This can be used during analysis to avoid recomputing the reference centroids to save time (a legacy from the days when computers were slow!). This option is available for the analysis of single and multiple frames.

3.8 Off-line and on-line analysis

Analysis can be done in two ways:

3.8.1 Off-line analysis


- Enter the optical parameters in [Opt]
- Go to [SH] setup, select the reference and Test image names. Specify the Zernike polynomials chosen for the fit in [SH/Zernikes]. Choose the graphs that you wish to see after the analysis [SH/Graphics]
- Click the [Analysis] button
- Check the results and the graphs

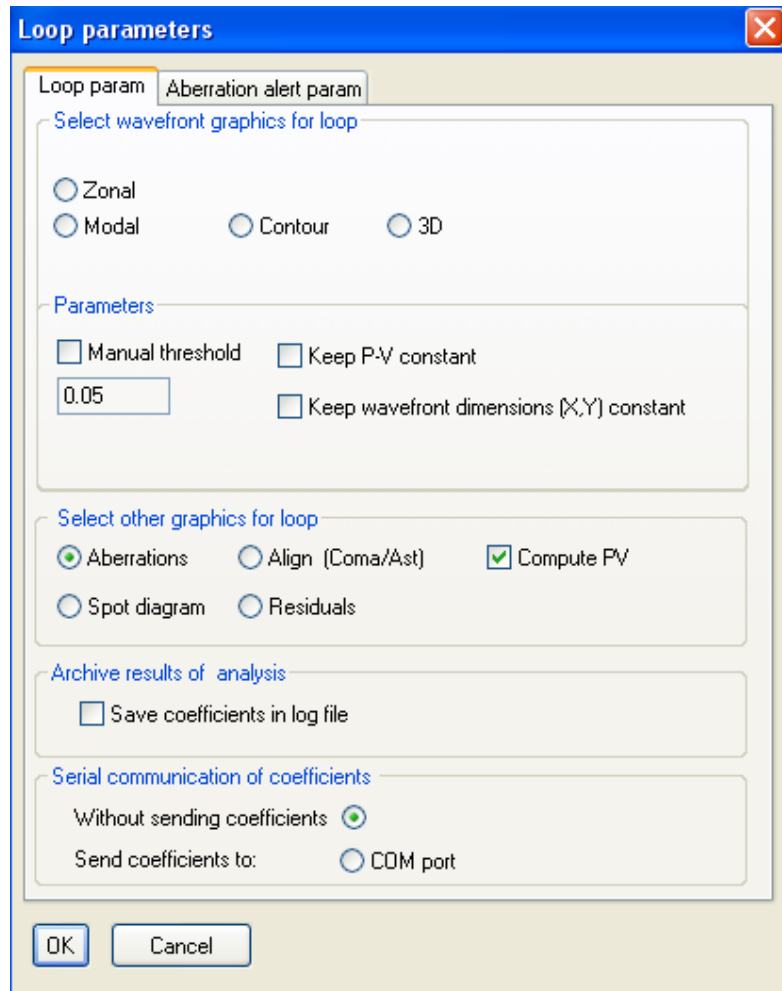
3.8.2 On-line (real-time) analysis

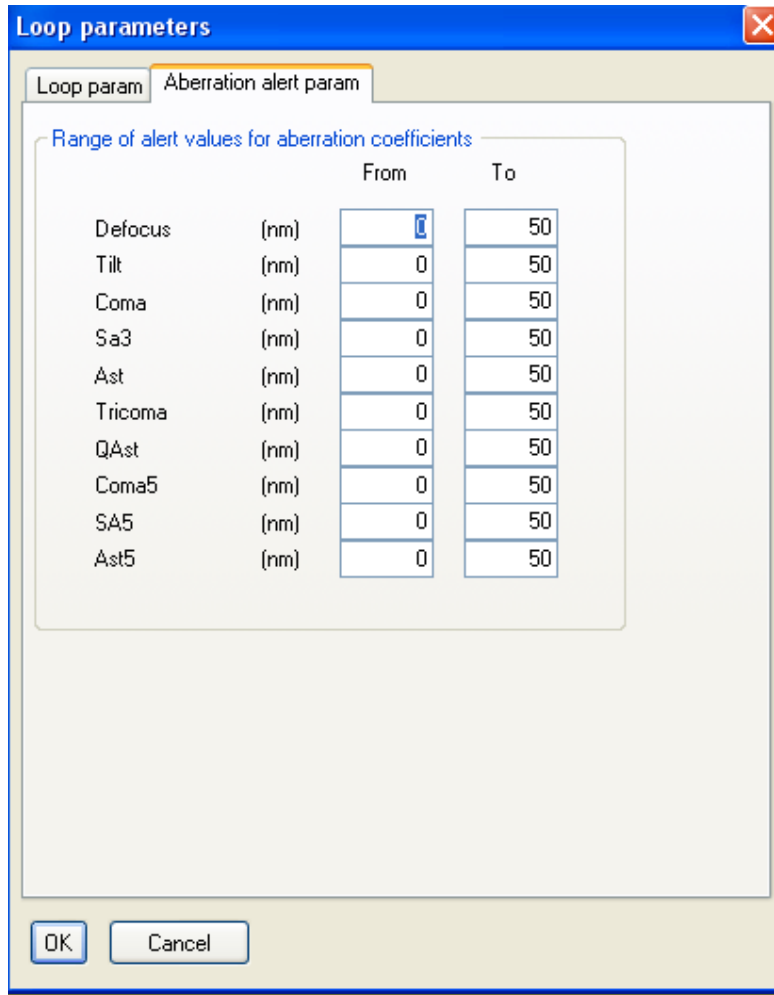
- Enter the optical parameters in [Opt]
- Do the optical setup for taking the reference image
- Optimize the exposure time using [Live] and [QAuto]; take the reference image with [Ref]
- Do the optical setup for taking the Test image
- Click [Live] and align the Test image with the reference image, using the [Align] command
- Click the [Test] button. This will take the image of the Test element, and do a full analysis with the first 7 Zernike terms
- Check the normalized pupil and the combination of the spots, as well as other parameters that result from the analysis
- You can choose to rename the Test results by using the Rename command under File menu
- Now click the [Lens] button. It will do a full analysis using the Zernike coefficients that you have chosen to fit. An automatic threshold will be used for detecting the spots; only if specifically requested in [SH/Analysis parameters] the current threshold will be used

3.8.3 Parameters for on-line (real-time) analysis in a loop

You can also use the [Loop] option to compute the wavefront etc. in a loop.

Click on the  button close to the [Loop] check box on the dialog bar. The Loop param dialog will be displayed on the PC screen.





- Define the tolerance range of values for default 10 Zernike coefficients. This range is used to check if the aberration coefficient is acceptable for your quality control. The computed Zernike coefficient will be displayed on a green background in the coefficient bar if it is inside the defined range and on a red background red if the value is outside the range.

Aber	C(nm)	Angle
Defoc	5	
Tilt	132	161
Coma3	27	-34
SA3	3	
Ast3	41	-15
TComa	13	-28
QAst	1	40
Coma5	7	144
SA5	-3	
P-V	97.80	
Rms	14.07	

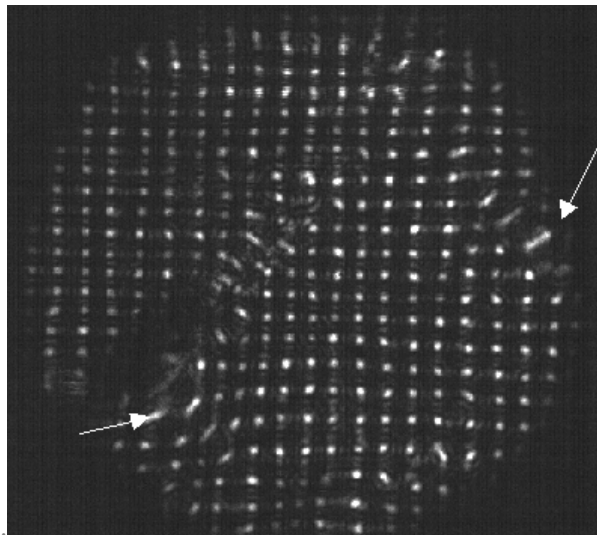
The coefficient bar displayed during the Loop

- Specify the type of graph that you wish to see
- For 3D and Contour of wavefront you can select zonal or modal wavefront reconstruction
- For Aberration, Align you have the choice of following the variation of P-V during the loop (check P-V will recomputed the wavefront for all of the iterations) or to have only the aberrations values if you need a faster computation.
- **(Only for Contour and 3D of wavefront):** during the analysis the P-V of the wavefront can vary and the graphic is scaled accordingly. Moreover, 1 or 2 weak spots on the edge of the Shack-Hartmann image can be added or not to the analysis, and this will change the final diameter of the contour graphics. In order to avoid these variations:
 - “Keep P-V constant”: check this box if you would like to keep the P-V levels value constant on the display during the loop: when positive levels are outside (higher than the values showed on the display) they are showed as the highest red level, when negative values are outside (lower than the values showed on the display) they are showed as the lowest blue level.
 - “Keep wavefront dimension (X,Y) constant”: check this box if you would like to keep constant the diameter of the graphics during the loop
- (Only for Professional and Engineering version) Check on “Save coefficient in log file” if you would like to save the coefficients in a .csv file during loop
- (Only for Engineering version) Define the COM port if you would like to send the analysis results to another computer using the serial communication

3.9 Rejection of bad spots in a SH image

This procedure is part of the advanced image analysis and is available only in the Sensoft Professional and Engineering versions.



Bad spots can be due to scattered light or to optical zones on the optical element under test. They are identified in the SH image because they can have a diameter slightly larger than the neighborhood spots, or because they are merged with another spot or they are completely out of the regular grid of spots normally resulting in the SH image. An example of a frame containing spots that can make difficult the SH analysis is in the figure below.



The frame bar on the top of the screen contains several buttons that can be used to identify and reject the bad spots.

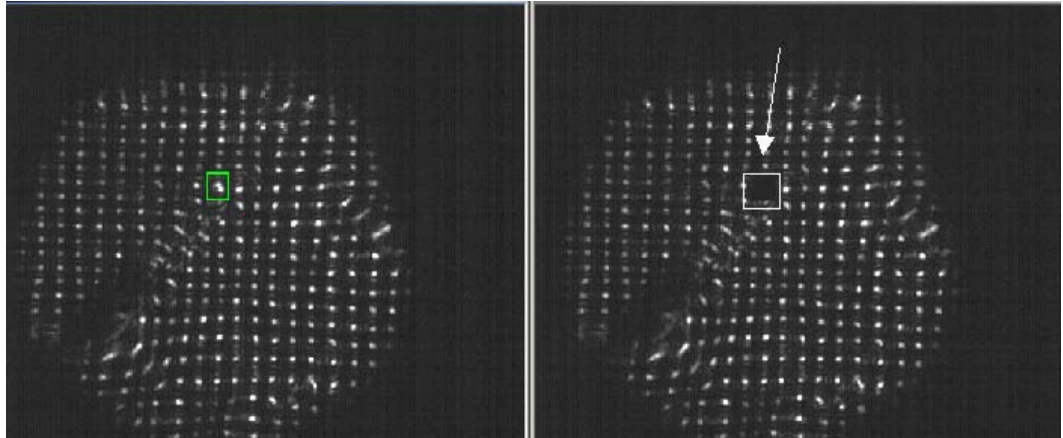


The procedure is as follows:

- Open a SH image with the Open command in the file menu.
- By clicking the  button, you will get a duplicate of the image.
- Click on the  button and draw a rectangle around the bad spots using the mouse.
- You are given the choice to discard the rectangle, and in this case you have to restart the procedure from the previous point or to accept the rectangle and in this case the corresponding spot will disappear from the duplicated image on the right.

- Repeat the procedure for all the bad spots in the image and then close the procedure by clicking the **S** button. You will be prompted for overwriting the original frame. You can also save the modified frame with a different name using the Save As command on the File menu.

An example of the display during the procedure is given in the figure below.



Chapter 4: Output from Sensoft

4.1 Output from Sensoft

4.1.1 How Sensoft works: basic introduction

- Compute centroids of the spots for both the Lens and Reference images
- Combine the centroids
- Compute the differences between the (x, y) positions of all the pairs of combined spots and compute what are termed as slopes or residuals
- Fit the derivatives of the selected Zernike polynomials to the data and compute the coefficients and their angles
- Reconstruct the wavefront
- Compute the Strehl Ratio
- Compute the spot diagram, and the Encircled Energy. This is in the focal plane of the converging lens. For flat surfaces, a perfect lens of focal length 100mm is assumed

4.1.2 Some definitions

After the computations of the Zernike coefficients, Sensoft will let you subtract out the contributions of the aberrations and look at the resulting (or residual) wavefront, D80 etc. Thus, in a single analysis, the user can see the current quality of the optical element, the potential quality of the optical element, as well as focus on any individual aberration of interest by not fitting it to the data.

4.1.2.1 AQ: Actual quality

For converging elements, this refers to the quality of the optical element after the subtraction of the contribution of **tilt and defocus** (as computed from the Zernike coefficients).

For flat elements, this refers to the quality of the optical element after the subtraction of the contribution of **tilt** (as computed from the Zernike coefficients)

4.1.2.2 RQ: Residual quality

For all the elements, this refers to the quality of the optical element after the subtraction of the contribution of the Zernike coefficients fit by the user.

4.1.2.3 PQ: Potential quality


For all the elements, this refers to the quality of the optical element after the subtraction of the contribution of the first 7 Zernike coefficients (tilt, defocus, 3rd order coma, 3rd order spherical aberration, 3rd order astigmatism, triangular coma and quadratic astigmatism).

4.1.3 Zernike coefficients

When users run the analysis, results are summarized in an output table. The output table is automatically opened at the end of the analysis or can be opened off-line clicking on the item 'Open SH results file (.cof)' from the File menu.

The table gives the values of the Zernike coefficients in nm:

- Cx: coefficient in x-direction
- Cy: coefficient in y-direction
- C: Total coefficient
- Angle: the orientation of the aberration (in degrees)

The angle is measured from the +x direction of the SH image. The values of the total coefficient are displayed on a red or green background the background color depends from the tolerances defined in the Loop Param dialog that is displayed by clicking on the  button close to the Loop box.

Details
RMS/EE
Diagnostics
PQ - 7 Zernike terms
Statistics

SH analysis of: Test single image.

Image	Date	Time	Exp.time	Thresh.	Ellipt.
Test: TEST0001	2007-02-24	11:57:45	.014 sec	.073	.70
Ref: REF_FLAT0006	2007-02-24	11:57:28	.014 sec	.064	.70

Standard Zernike coefficients

Aber	m n	Cx(nm)	Cy(nm)	C(nm)	Angle
Def	0 2			-1.4	
Tilt	1 1	-27.6	139.2	141.9	101.2
Coma	1 3	-1.5	-0.3	1.5	-168.6
SA3	0 4			0.7	
Ast3	2 2	1.7	-0.1	1.7	-2.1
TCom	3 3	0.8	-0.1	0.8	-5.2
QAst	4 4	0.9	0.0	0.9	-0.9

Surface (values in nm)

Quality	Max	Min	Average	P-V	Rms	Strehl
Residual	4.5	-6.5	-4.3	10.9	1.9	0.999
Actual *	5.9	-6.5	-5.3	12.3	2.3	0.998
Potential	4.5	-6.5	-4.3	10.9	1.9	0.999

* Actual Quality: tilt subtracted
 Normalized pupil: 1.000 No of spots used: 378 Probability of goodness of fit: 1.00

The values of the wavefront P-V, Rms and Strehl ratio are given in the Quality table.

Finally the indication of the goodness of fit is given together with the number of spots used for analysis and the normalized pupil found.

4.1.3.1 Printing the output table

The output table components can be printed out using the Edit menu items. A more detailed report can be printed out from the .sha file contained in the directory where the SH images have been saved. This is obtained when the Print item is selected in the File menu when the output table is active.


The .sha file contains also the error estimation for the various coefficients as result of the least-square fit.

4.1.4 Diameter of image in focal plane due to individual aberrations

The Zernike aberration coefficients refer to the wavefront. The effect of the aberrations is to spread out the image in the focal plane.

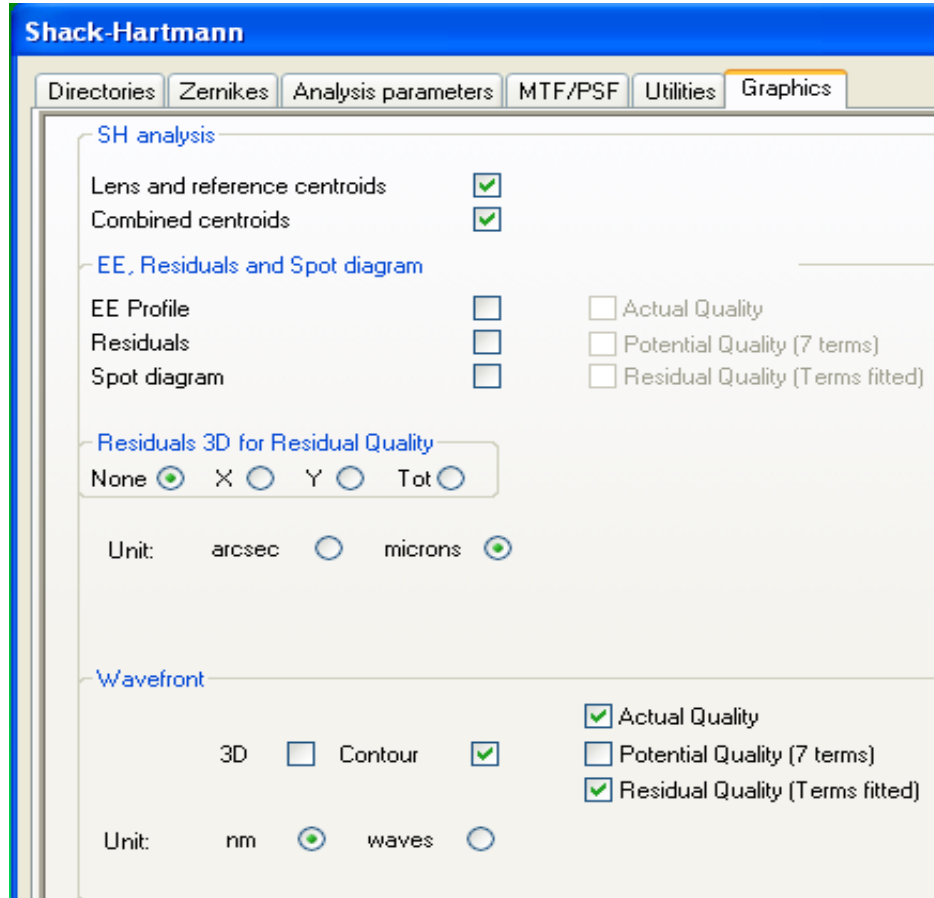
Sensoft gives the size of the image (containing 100% Encircled Energy) in the focal plane corresponding to each of the first 7 aberrations. This helps understand the importance of each individual aberration.

The units can be in arcsec (used in astronomy) or microns.

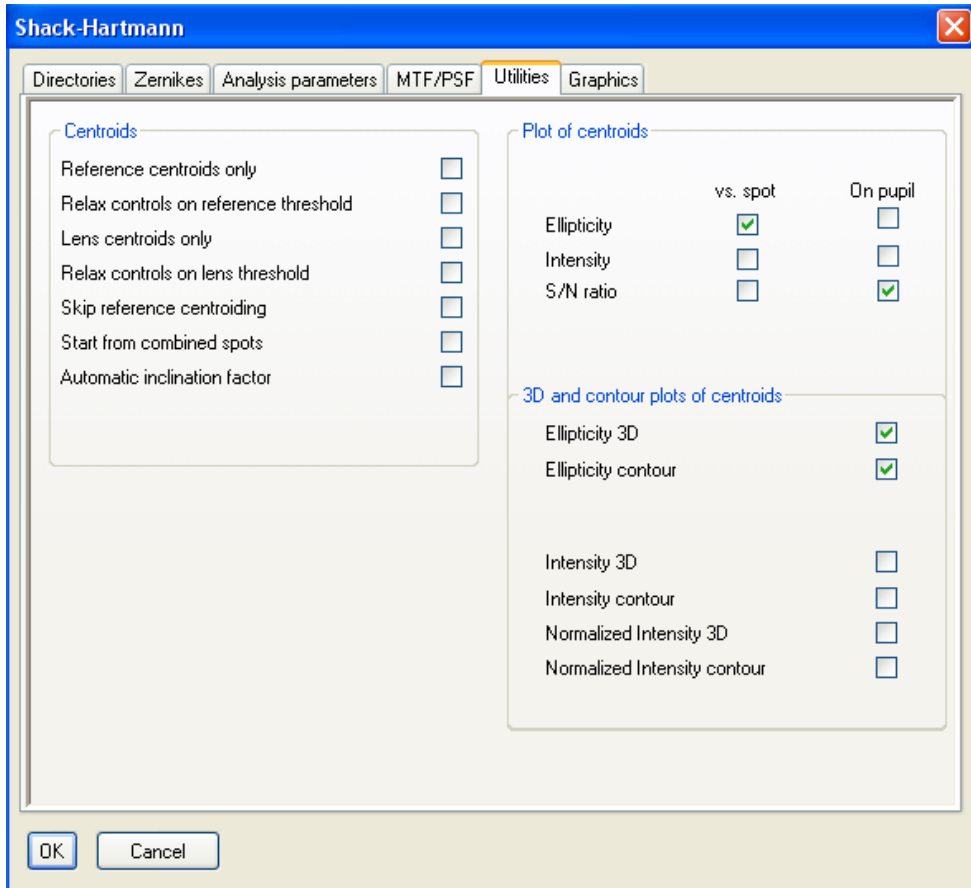
 Note: The spot diagram also gives the same information if the particular aberration is not fit to the data and the effect of the rest of the aberrations is subtracted out.

4.1.5 Graphics

Sensoft can be asked to plot a number of graphs, chosen in [SH/Graphics]. Once the analysis is over, all the graphs selected by the user are automatically plotted. For off-line plotting, open the analysis file (with '.cof' extension) and click on Plot.



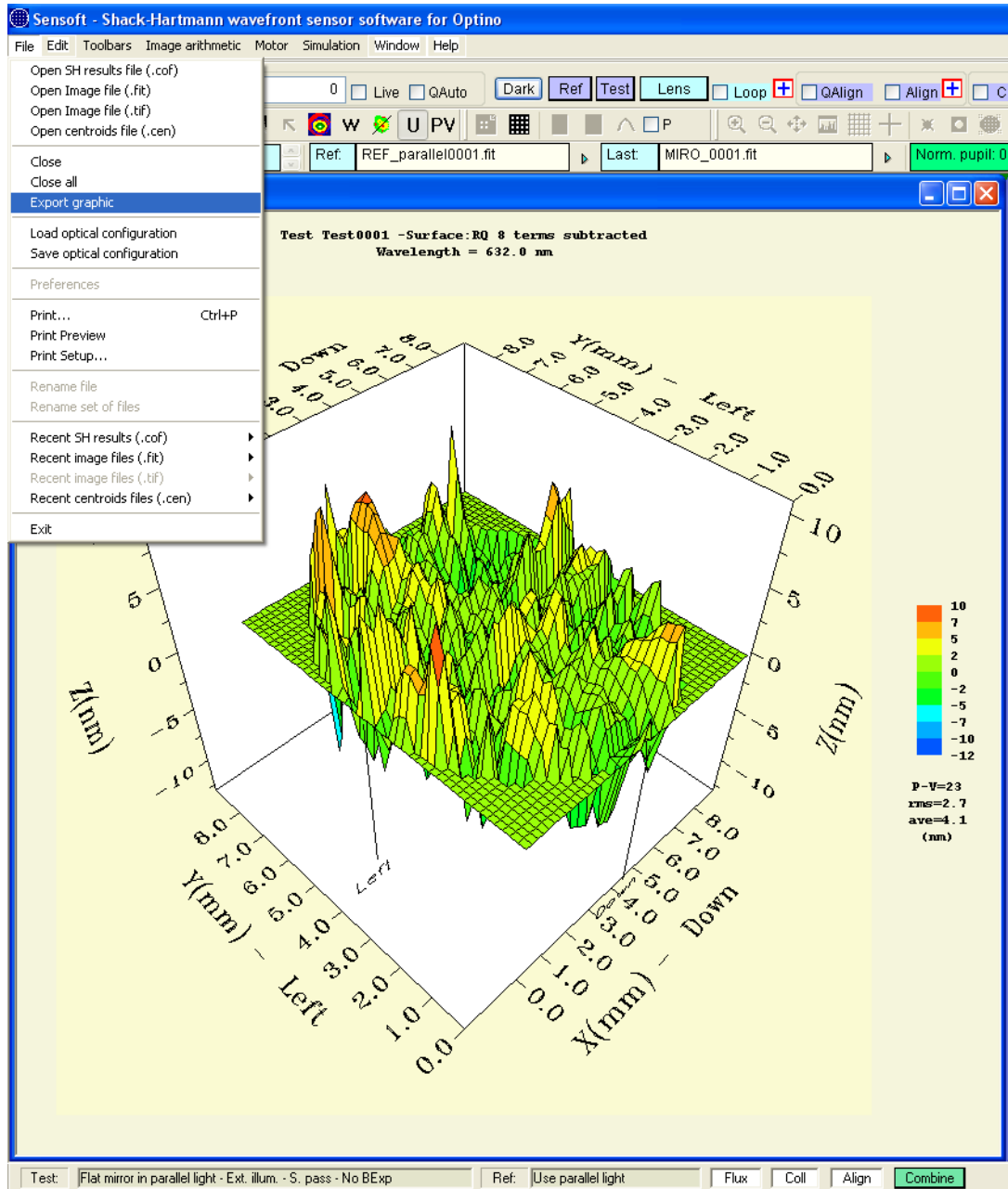
Additional graphics concerning the centroid analysis can be selected from the Utilities table.



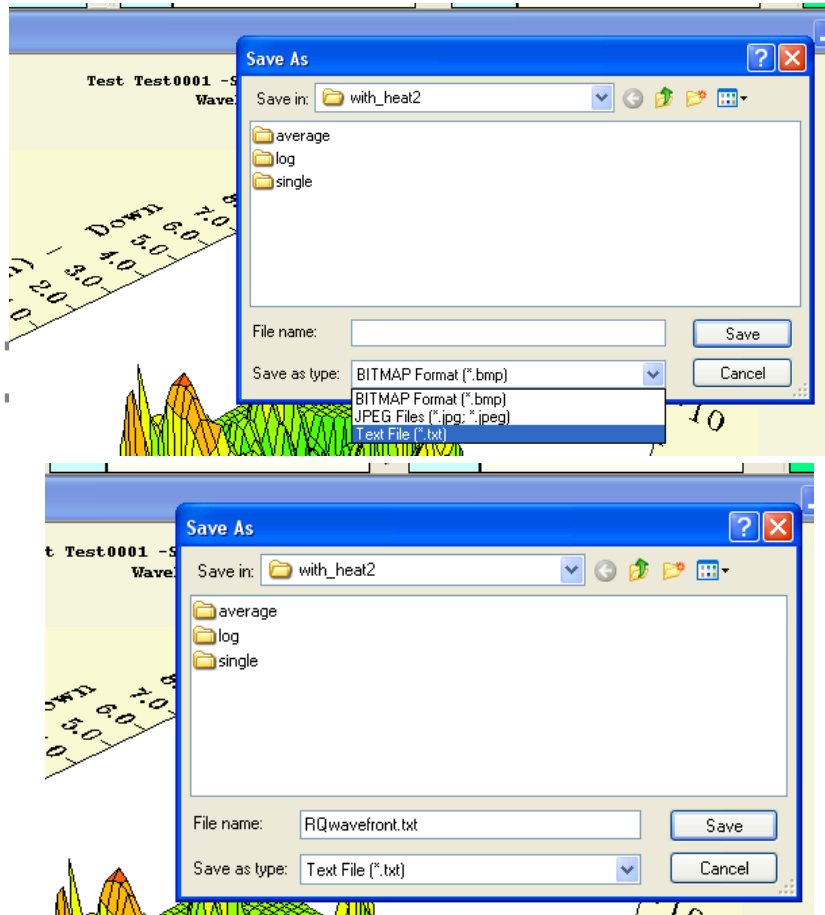
mouse buttons. 2D graphs (other than the wavefront) can be zoomed by marking the area of interest using the Shift key and the left-hand side mouse button. You can unzoom by using the R-key. The Graphic toolbar can be also used to manipulate the graphics.

4.1.5.1 Exporting graphics in JPEG, BITMAP or TEXT format

2D and 3D graphs can be saved in JPEG or BITMAP format using the Export graph function from the File menu and selecting among the available format. The 3D and contour of the wavefront can be also saved in ASCII format.

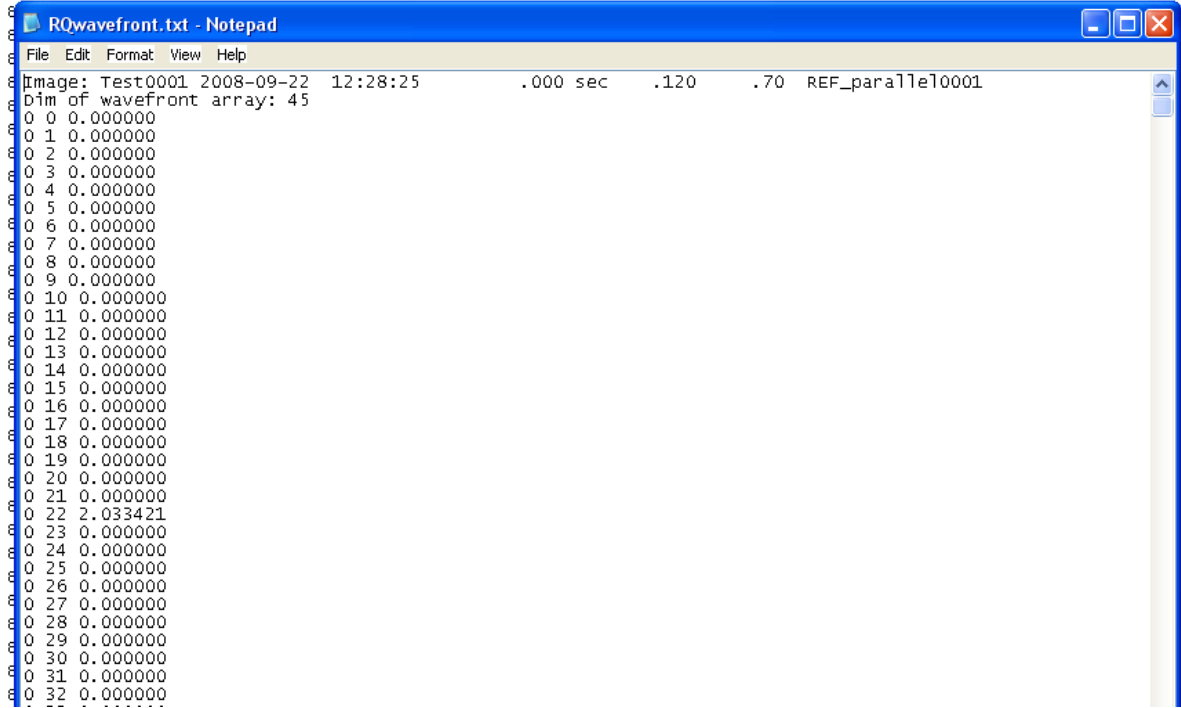


- Select the file format



If the text/ASCII export was selected (only 3D and contour of wavefront) the output file contains

- The description of the image
- The dimension of the wavefront array
- Row index, column index and wavefront value in nm (X,Y,Z)



```
RQwavefront.txt - Notepad
File Edit Format View Help
Image: Test0001 2008-09-22 12:28:25 .000 sec .120 .70 REF_parallel10001
Dim of wavefront array: 45
0 0 0.000000
0 1 0.000000
0 2 0.000000
0 3 0.000000
0 4 0.000000
0 5 0.000000
0 6 0.000000
0 7 0.000000
0 8 0.000000
0 9 0.000000
0 10 0.000000
0 11 0.000000
0 12 0.000000
0 13 0.000000
0 14 0.000000
0 15 0.000000
0 16 0.000000
0 17 0.000000
0 18 0.000000
0 19 0.000000
0 20 0.000000
0 21 0.000000
0 22 2.033421
0 23 0.000000
0 24 0.000000
0 25 0.000000
0 26 0.000000
0 27 0.000000
0 28 0.000000
0 29 0.000000
0 30 0.000000
0 31 0.000000
0 32 0.000000
```

4.1.5.2 Printing graphs and tables

Click on the graph that you wish to print, adjusting its size as desired. Use the Print option in the File menu. Similarly, the table obtained after the analysis can also be printed (without the possibility of adjusting its size).

In both cases, the Print Preview command can be used prior to print out.

4.2 Using Excel with Sensoft: comparison of the Zernike coefficients and other results

When you acquire and analyze a “Lens” image by clicking the [Lens] button in the dialog bar of Sensoft, at the end of the Shack-Hartmann analysis a Comma-separated value (.csv) file is created/updated, whose name is taken from the prefix selected for the “Lens” image. The .csv file can be opened with Excel.

The file is created in the “directory for results” (outdir_results) field selected in the [SH] folder. For example, if the prefix “PN” has been selected in the [SH] folder, the file “PN.csv” will be created during the analysis.

You can open the Excel file by launching Excel and selecting it from in the outdir_results directory.

Results from analysis of images with the same prefix, but different counters (like Mir001, Mir002 etc.) are presented in different columns.

The columns give the names and the values of:

- The details of the images analyzed
- If the analysis was done online (creating a new image) or off-line (using an old image)
- The test type giving the optical setup configuration used for the test
- The optical parameters used for the test

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Filepath= C:\test_jan2007\test_jan2007_Lens.csv												
2	Image	Date	Time	Date	Time	Analysis	Test type	Aperture	EFL	SH Diam	Sh FL	Collim FL	Wavele
3		Creation		Analysis		Online/Offline		(mm)	(mm)	(μ)	(mm)	(mm)	(nm)
4	LENS0006	2007-01-17	18:36:03	01/23/07	15:56:36	Offline	Lens - Parallel light	8.5	50	302	41	45	
5	LENS0006	2007-01-17	18:36:03	01/23/07	15:56:48	Offline	Lens - Pinhole	7.72	50	302	41	50	
6	LENS0007	2007-01-17	18:36:52	01/24/07	12:18:11	Offline	Lens - Pinhole	7.72	50	302	41	50	
7													
8													

- The coefficients of all the Zernike terms fit to the data (selected in [SH/Zernikes]. If a coefficient was not requested for analysis the corresponding position in the table will be marked with a dash.

	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
1														
2	No. of spots	Zernikes	Defocus	Tilt		Coma		SA3	Ast3		Tricoma		QuadAst	
3	(deg)		Coef (nm)	Coef (nm)	Angle (deg)	Coef (nm)	Angle (deg)	Coef (nm)	Coef (nm)	Angle (deg)	Coef (nm)	Angle (deg)	Coef (nm)	Angle (deg)
4	430	Standard	7.9	5153.2	-88.8	2.7	-46.4	-3	0.6	-37.4	1.3	-18	6.9	-9.5
5	430	Standard	7.8	5203.1	-88.8	2.6	-47.4	-3.2	0.6	-52.1	1.4	-18	7.2	-9.5
6	429	Standard	7.3	5203	-88.7	2.6	-53.9	-3.5	1	-48.7	1.9	-21.2	6.9	-11
7														
8														

- The diameter of the spot diagram containing the Encircled Energy
- The peak-to-valley (P-V) of the surface reconstructed from the residuals for Actual Quality (AQ), Potential Quality (PQ) and Residual Quality (RQ)

	CF	CG	CH	CI	CJ	CK	CL	CM	CN	CO	CP
1											
2	D50(A)	D80(A)		PV(A)		Strehl(A)	A_coeff	D50(P)	D80(P)		PV(P)
3	Value (mu)	Value (mu)	Rms (mu)	Value (nm)	Rms (nm)	Value		Value (mu)	Value (mu)	Rms (mu)	Value (nm)
4	3.01	4.68	3.32	62.9	11	0.988	2	2.9	4.77	3.27	73.6
5	3.33	5.2	3.69	64	10.8	0.989	2	3.22	5.3	3.64	77.4
6	3.3	5.19	3.68	64	10	0.99	2	3.2	5.24	3.63	67.3
7											

- The calibration (reference) image used for the analysis
- The collimation factor that will indicate if the test was done in parallel light
- The Align x and y factors that will give the alignment of the lens vs. reference

	CY	CZ	DA	DB	DC	DD	DE	DF
1								
2	Reference	Coll. factor	Align					
3			Dx(mu)	Dy(mu)				
4	C:\test_sfera_jan2007\REF_parallel0004.fit	-0.24	-42.4	-222.9				
5	C:\test_sfera_jan2007\REF_parallel0004.fit	-0.24	-42.4	-222.9				
6	C:\test_sfera_jan2007\REF_parallel0004.fit	-0.24	-34.1	-225				
7								

4.3 Interpretation of Zernike coefficients

<i>Zernike coefficients and their interpretation</i>	
Aberration	Comment
Defocus	Defocus is measured with respect to the reference image
Tilt	Measured with respect to the center of the reference image
Coma	Includes coma due to the shape of the optical elements, as well as due to their misalignment. The correction achieved using the diagnostics from Sensoft will correct the coma due to both effects
Spherical aberration	Can arise due to the use of the wrong focal plane or the wrong spacing between the elements. It can also be due to the wrong shapes of the optical elements (conic coefficients). The software suggests by how much the focal plane should be shifted to correct the observed SA. Temperature effects can also play a role
Astigmatism	Astigmatism can be inherent in the optics. It can also be due to support problems, as any imbalance in the forces applied by the supports will result in astigmatism. The wavefront plot of RQ can be used to identify which supports are not correctly adjusted. The orientation of the optical elements can be changed relative to each other to minimize this aberration
Triangular coma	If this has a high value, look for problems with the 3 fixed points used for supporting the optical element. Look also at the RQ wavefront map
Quadratic astigmatism	A high value indicates the presence of support problems with 4-fold symmetry (like the 4 lateral fixed points)

Chapter 5: Using Sensoft: basic guide

5.1 Basic concept of the Shack-Hartmann test

- Take a SH image (called *test* image). The positions of the spots as recorded by the camera depend on the aberrations of:

test element + SH system + auxiliary optical elements (like beam expander)

- Take a second SH image (called *reference* image). The positions of the spots as recorded by the camera depend on the aberrations of:

SH system + auxiliary optical elements

The difference between the two gives the aberrations of the test optical element.

5.2 Basic input parameters for Sensoft

Step 1: Create directory

Select/Create the directory for the results in [SH/Directories]

Step 2: Choose the appropriate Test setup

Identify the appropriate optical setup required (see chapter on test configurations) for your test.

- Select the [OPT/Ext. Illum. test] page if you illuminate the optical element with an external light source
- Select [OPT/Int. Illum. test] page if you illuminate the optical element with the internal illumination provided through the fiber entering Optino

Step 3: Enter the optical parameters

Enter the optical properties of the test element and collimator (if used) in the [OPT/Properties] page

Step 4: Enter description of the test



Enter the description of the test in [OPT/Description]

Step 5: Enter the calibration for coma and SA3 (for multi-element optical systems)

Enter the calibration on the [OPT/Calibration] page if required (for multi-element optical systems) for coma and SA correction

5.3 Get a good reference image and make sure that it is collimated

How you get the reference image depends on the test setup (see chapter on Optino/Puntino test configurations).

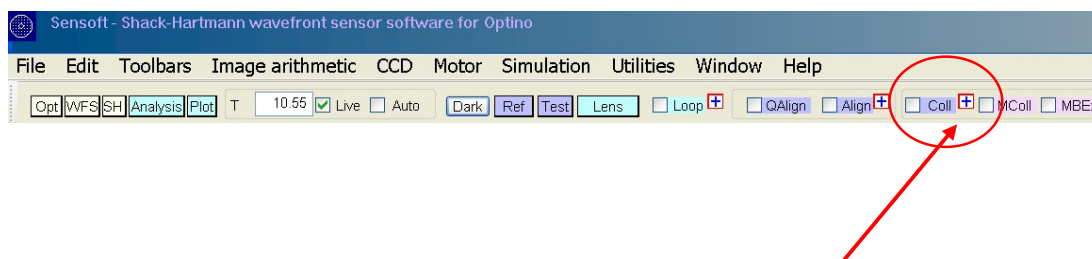
- **In external illumination mode**, use the pinhole light source PH50 (when using a collimator) or parallel light source Cal25 (when testing the lens at its focus). Cal25 gives an output beam of $\varphi=21\text{mm}$ for illuminating the test element. When using it for getting a reference image, it is recommended that a diaphragm of $\varphi=6.9\text{mm}$ be put in front of Cal25 so that a circular image is obtained on the camera
- **In internal illumination mode**, use a flat or spherical mirror, according to the test type
-  ***In all cases, the reference image should include the light passing through all the optical elements except the test element***
- Once you have the image on display and it is well centered on the camera, adjust the integration time and/or the light intensity to get a well-exposed image. Use the QAuto command next to Live to find the optimum integration time
- Use the Coll command to collimate the reference image. Move the appropriate elements for doing this (e.g. pinhole in external illumination mode, or the reference flat/spherical mirror in the internal illumination mode)
- Use the averaging option in [WFS/SH camera] page to get a high-quality image, by averaging at least 20 images
- Press the Ref button on the dialog on the top of your screen to acquire and analyze the reference image. The prefix for the reference image will be assumed from the suggested setup for the selected test configuration (REF_parallel, REF_flat, REF_spherical etc.)
-  ***The current test configuration and the correct setup for the reference are indicated by the software in the bar that is displayed on the bottom of your screen when you launch Sensoft***



5.4 Testing a single optical element

5.4.1 Get a good image of the optical element being tested and make sure that it is collimated

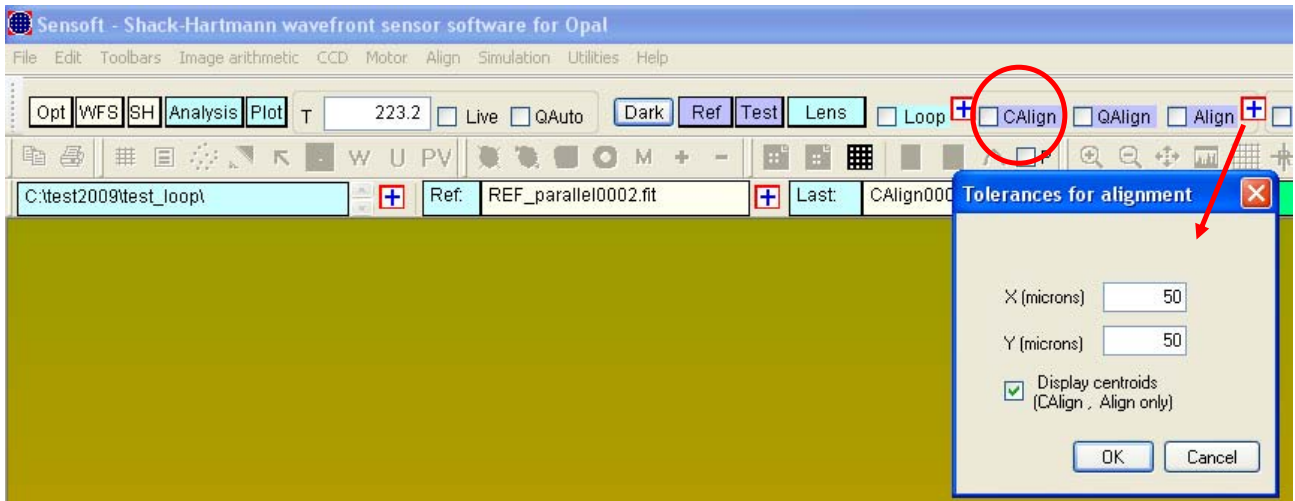
- According to the optical element being tested, choose the appropriate test method (see chapter on Optino/Puntino test configurations)
- Make sure that the correct optical parameters are used in [OPT]
- Adjust the test element to get a SH image. The spots should be well separated
- Define the orientation of the image (Top, Bottom, Left and Right) in the [WFS/Orientation] page by covering a part of the beam with say a pen and noting which part is obscured. These directions are then shown on the wavefront plots
- Once you have the image on display and it is well centered on the camera, adjust the integration time and/or the light intensity to get a well-exposed image. Use the QAuto command next to Live to find the optimum integration time
- Use the Coll command to collimate the light. Move the appropriate elements for doing this (e.g. pinhole, reference flat or spherical mirror)
- The tolerances for the Coll command can be changed by clicking the cross that appear close to the Coll box in the dialog on the top of your screen highlighted by the arrows in the figure below. The standard tolerance is 0.5, but you can also use a tolerance of 0.1-0.2.



5.4.2 The CALIGN procedure to align Reference or Mirror image with the center of the camera

The command **CAlign** has been implemented in Sensoft to allow the centering of the reference/test image with the center of the camera. The CAlign task can be selected by checking the correspondent button in the Dialog bar that is displayed on the top of the PC screen when Sensoft is launched.

During the CAlign procedure, the Shack-Hartmann image is displayed as usual with the superposed indication about the alignment: “Left/Right and Up/Down” or “Aligned” if the displacements δx and δy (in microns) measured with respect to the center of the camera are outside or inside the selected tolerances. However, some new features have been added to guide the user in the alignment procedure (see examples given below).



- a) **Display of the centroids.** The distribution of centroids found during the alignment can be displayed and used for checking the correct centering of the image. The flag for displaying the centroids can be selected in the Tolerances for alignment parameters (see figure above). The centroiding algorithm has been improved by adding the computation of three important couples of data. These data are explained in the next section and are displayed in the centroid plot as well as in the Align toolbar.
- b) **Computation of the collimation factor.** The collimation factor is computed during alignment and its value is continuously updated in the Align toolbar. This is slowing a little bit the Align procedure but gives the big advantage of reaching alignment and collimation within the same procedure

5.4.3 Definition of criteria for reaching a correct alignment

Four different set of parameters can now be used in order to check the correct alignment (see examples below).

1. The displacements δX and δY (in microns) with respect to the center of the image
2. The number of rows and columns of spots: in the Align toolbar these values are displayed in the Hor/Ver field. The values of rows should be equal to the value of columns in order to guarantee the symmetry in the image (green background in the Align toolbar); when the values are different the background in the Hor/ver field of the Align toolbar becomes red
3. The number of spots found in the first and last (left/right) columns: the difference between the two values should be ≤ 3 spots (green background)
4. The number of spots in the first and last (top/bottom) rows: the difference between the two values should be ≤ 3 spots (green background)

When one of the conditions above is not satisfied, the misalignment can be corrected by centering the image in X/Y or tilt in α/β

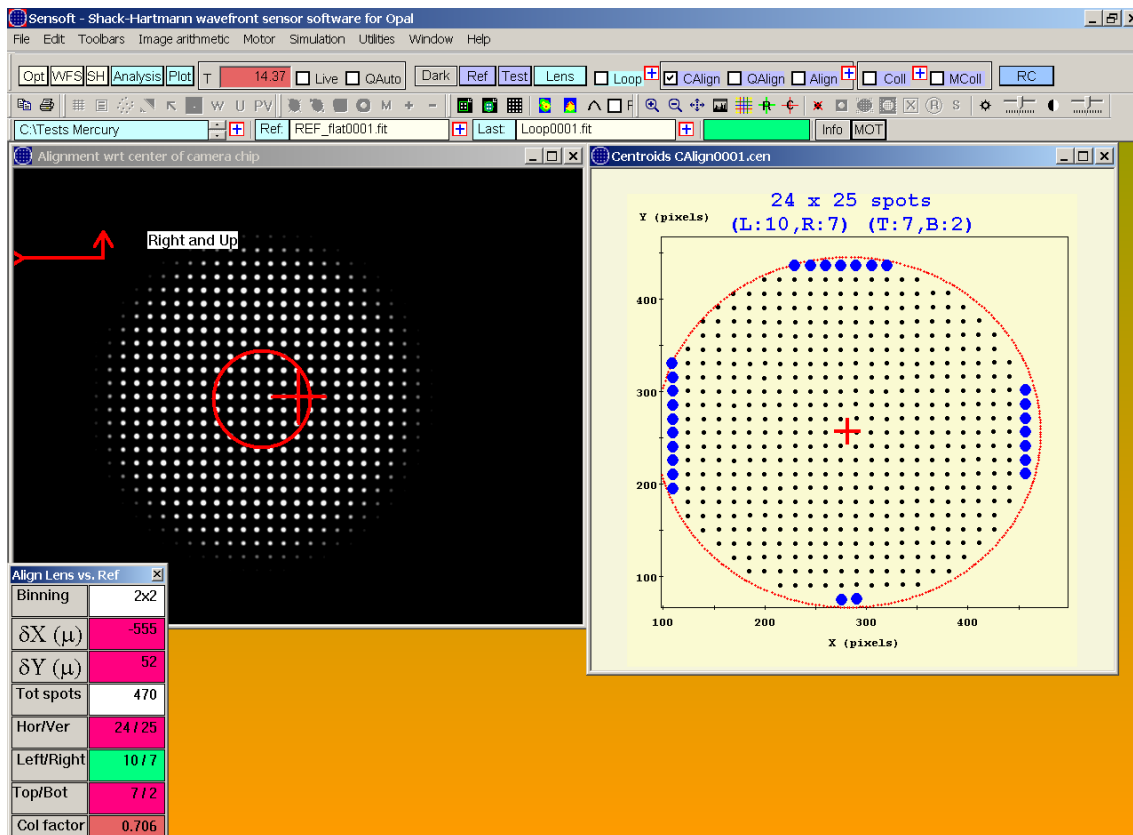
Once the alignment has been reached, the collimation factor can also be optimized keeping the alignment continuously under control.

The same criteria/parameters used for aligning the Shack-Hartmann image with respect to the center of the camera can be used for the Align procedure to find the alignment of the Mirror image with respect to the Reference image. Here again, alignment and collimation can be checked within the same procedure.

5.4.4 Examples of CAlign procedure

5.4.4.1 Bad misalignment of reference image wrt. center of the camera chip

1. The center of the camera is represented by the red cross
2. The center of the image is the center of the red circle



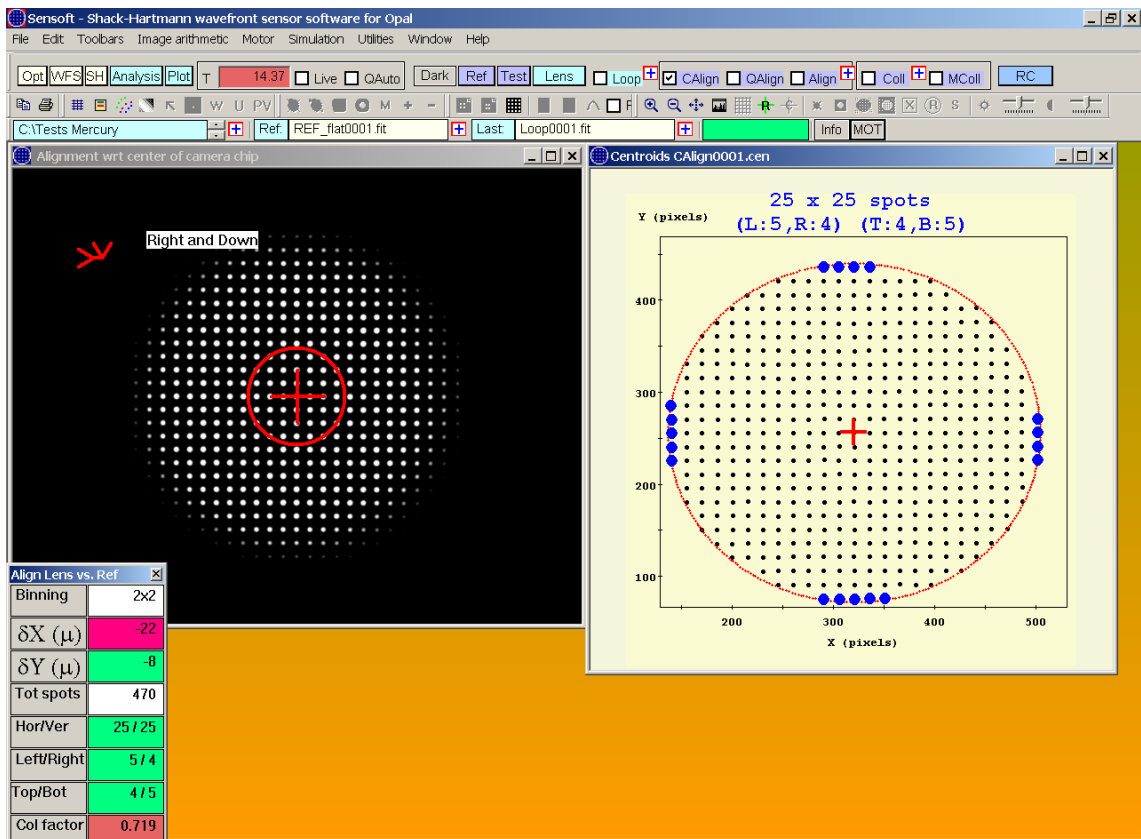
Condition 1: Not OK. δX and δY outside the tolerances defined for alignment

Condition 2: Not OK. Number of rows \neq columns

Condition 3: OK. Difference in number of spots between first and last column (Left/Right) is 3

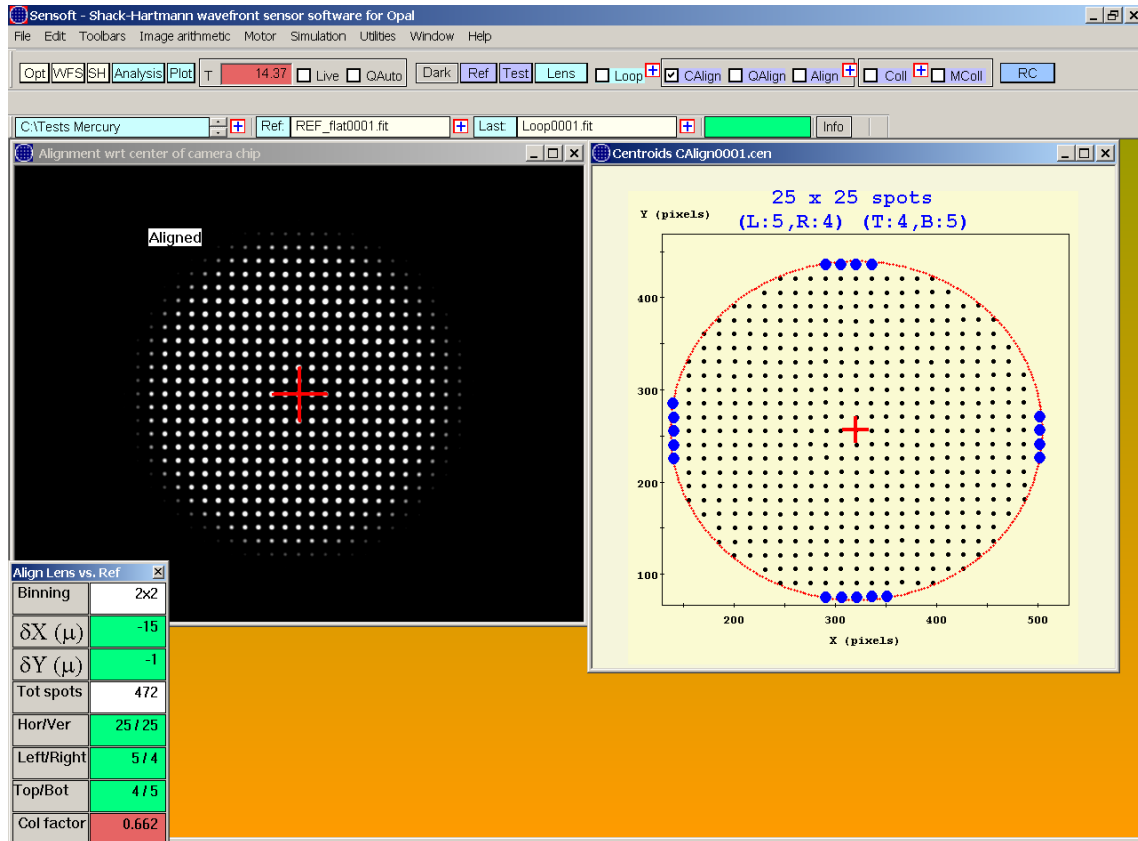
Condition 4: Not OK. Difference in number of spots between first and last row (Top/Bottom) is 5

5.4.4.2 Towards alignment of reference image wrt center of the camera chip



- Condition 1: Not OK.** δX outside the tolerances defined for alignment, δY OK
- Condition 2: OK.** Number of rows = columns
- Condition 3: OK.** Difference in number of spots between first and last column (Left/Right) is 1
- Condition 4: OK.** Difference in number of spots between first and last row (Top/Bottom) is 1

5.4.4.3 Reference image aligned wrt center of the camera chip



Condition 1: OK. δX and δY inside the tolerances defined for alignment

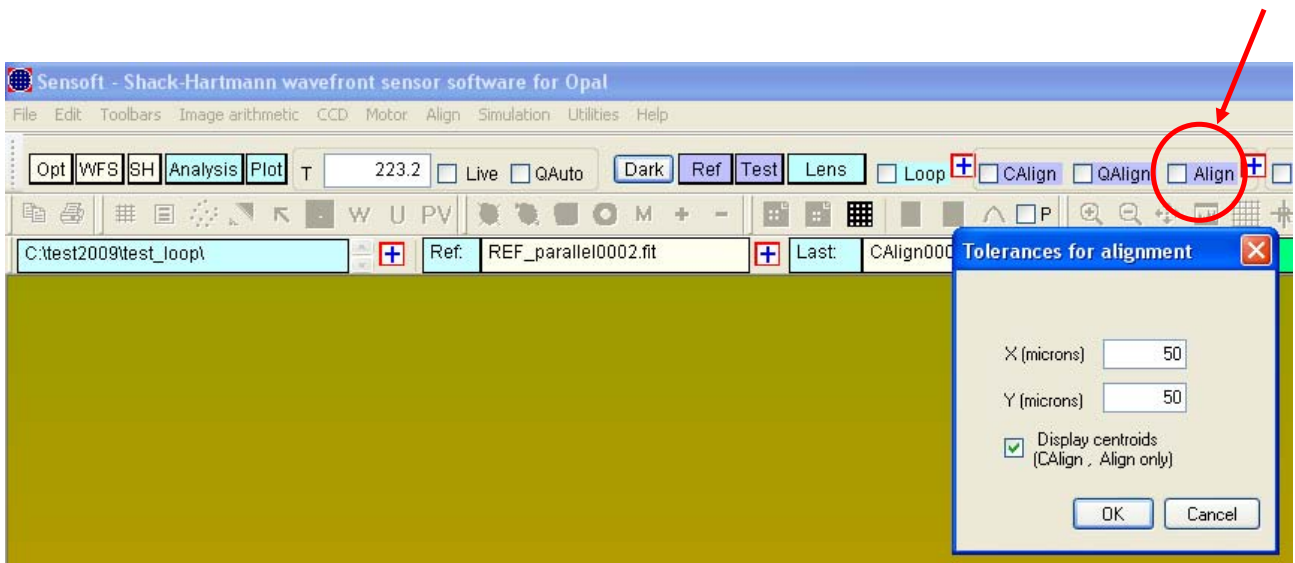
Condition 2: OK. Number of rows = columns

Condition 3: OK. Difference in number of spots between first and last column (Left/Right) is 1

Condition 4: OK. Difference in number of spots between first and last row (Top/Bottom) is 1

5.4.5 Align the Test and Reference images

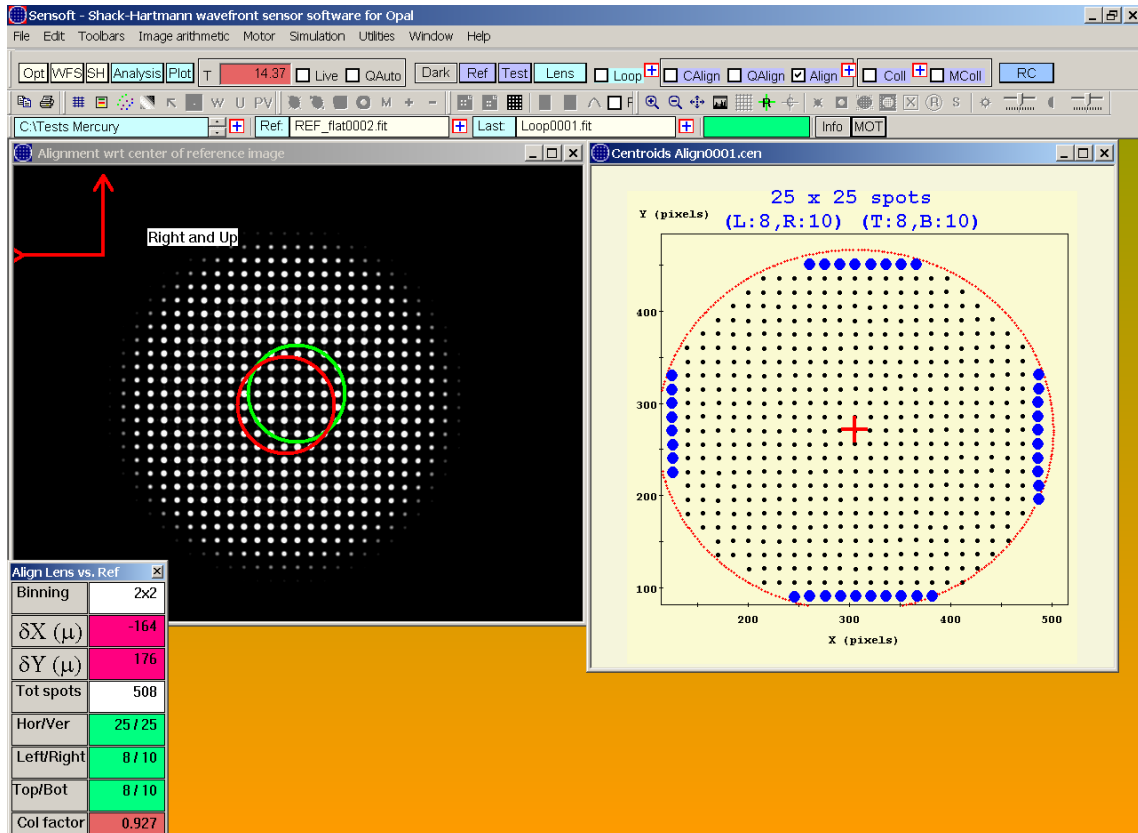
- Now use the Align command to align the image of the test element with that of the reference image. The final accuracy of coma (and to a smaller extent astigmatism) that is measured by Optino depends critically on this adjustment
- The tolerances for the Align command can be changed by pressing the cross that appear close to the Align boxes in the dialog on the top of your screen highlighted by the blue arrows in the figure below.
- The default value for alignment is 20 μ (the difference between the center of the reference and test images). A smaller value should be used if you are making very accurate measurements



5.4.6 Examples of Align procedure

5.4.6.1 Mirror image misaligned wrt center of the reference

The center of the reference is the center of the green circle
The center of the test image is the center of the red circle



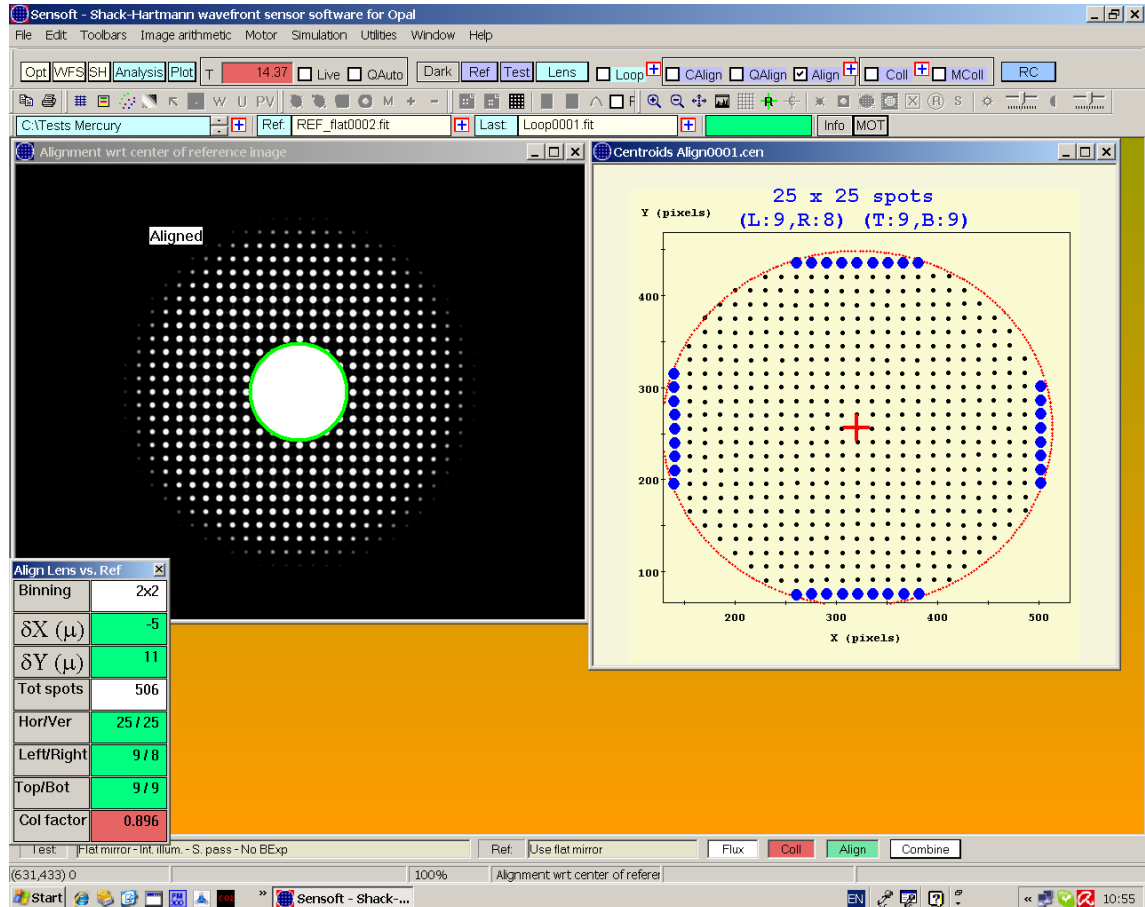
Condition 1: Not OK. δX and δY outside the tolerances defined for alignment

Condition 2: OK. Number of rows = columns

Condition 3: OK. Difference in number of spots between first and last column (Left/Right) is 2

Condition 4: OK. Difference in number of spots between first and last row (Top/Bottom) is 2

5.4.6.2 Mirror image aligned wrt center of the reference

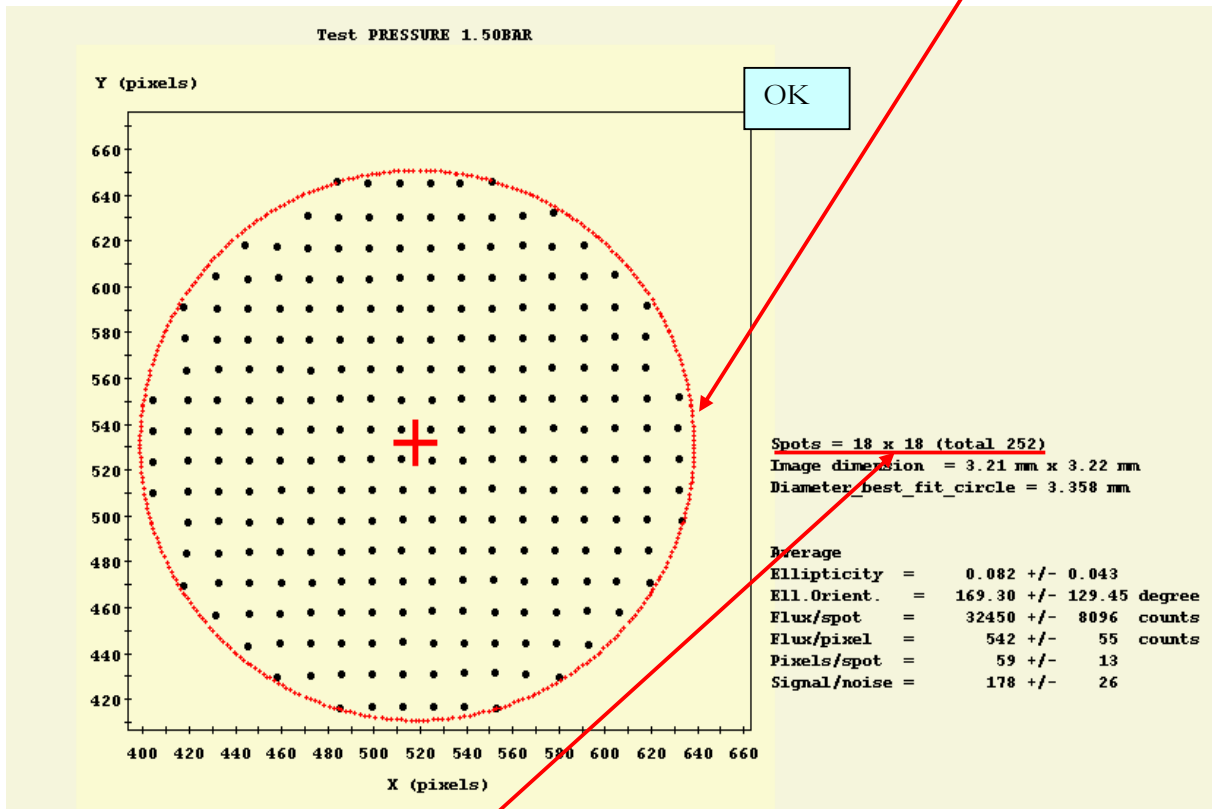


Condition 1: OK. δX and δY inside the tolerances defined for alignment

Condition 2: OK. Number of rows = columns

Condition 3: OK. Difference in number of spots between first and last column (Left/Right) is 1

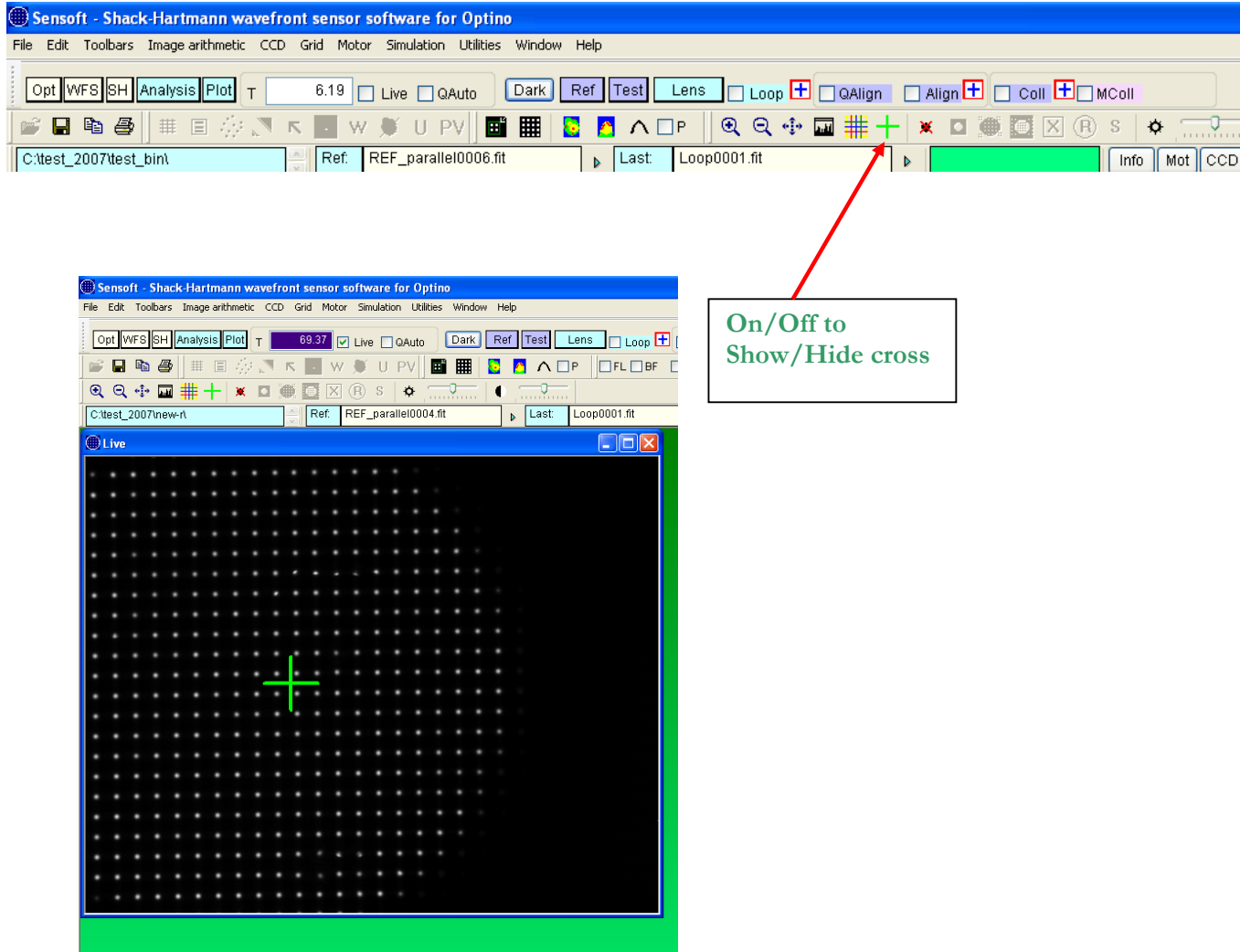
Condition 4: OK. Difference in number of spots between first and last row (Top/Bottom) is 0



Sensoft detects symmetry in the image above (number of rows equal to number of columns). Also, no of spots for first and last rows as well as first and last column is > 1

5.4.7 Cross on center of reference during Align/Coil/Live

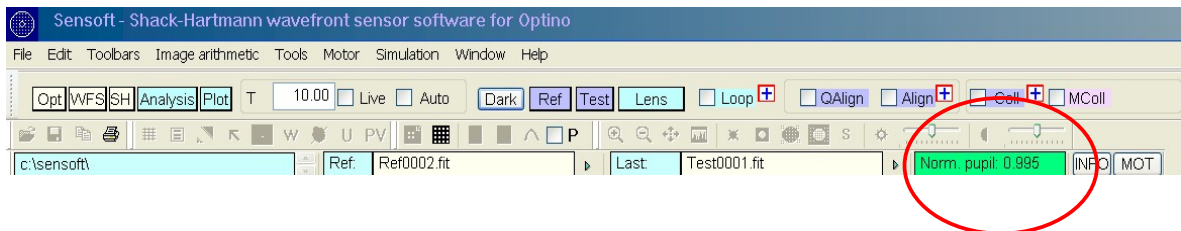
A cross representing the center of the last analyzed reference image can be displayed on the Shack-Hartmann image during the Live, Align, Collimate tasks. The cross can be enabled/disabled by clicking on the green cross



5.4.8 Do a Test analysis

Once above steps have been followed, click the Test button to obtain the first results.

-  *Check the value of the normalized radius: it should be between 0.98-1.02.*



- *If it is not, one or all of the following are true:*
 - 1. The light is not collimated (e.g. use the Coll command to check this)*
 - 2. If the light is collimated, then the optical parameters of the Test element entered in [OPT] are not correct (aperture and focal length - or distance to the image)*
 - 3. The focal length of the collimator has not been correctly entered*
- You will be presented with the following dialog box where you can change the optical parameters and recalculate the normalized radius. When you click OK to exit the dialog, the new optical parameters are automatically saved. You will have to run off-line analysis (or redo Test) to get the output results

Recompute normalized pupil ✕

Normalized pupil is outside the recommended range
(0.98->1.02)

Normalized pupil computed with current parameters	<input type="text" value="0.823"/>
F/# computed with current parameters	<input type="text" value="11.11"/>
Recommended F/# of optical system	<input type="text" value="13.50"/>

Please change the aperture and/or the focal length(s) to get the correct F/# indicated above

Aperture of test optic (mm)	<input type="text" value="9.00"/>
Effective focal length/distance to image plane (mm)	<input type="text" value="100.00"/>
Focal length of collimator (mm)	<input type="text" value="100"/>

- You can use the filename Test001 (it is continuously overwritten), or give the file the name of your choice
- Check that the spots of the reference and test images have combined well (no obvious double spots etc.)
- For highly aspherical elements or for elements with spurious spots (e.g. at the edges), you may need to change the automatic threshold found by Sensoft, as well as the ellipticity cutoff (lower it towards ~ 0.5) and the Combine factor (lower it from the default value of 8. Minimum ~ 2) in case the combination is showing double spots or other problems
- During the Test analysis, Sensoft will check if the test image:
 - Has the correct flux
 - Is taken in parallel light (Collimation)
 - Is aligned with respect to the reference image

If the check is OK, the boxes Flux, Collimation and Alignment at the bottom of the screen will turn green; otherwise, they will turn red.



5.4.9 Do a detailed analysis

- Once you are satisfied with the Test analysis, you can click the Analysis button to do a more detailed analysis and see the different graphs that you have chosen in the [SH/Graphics] section
- You can rename the file Test0001 in [SH/Directories] by selecting the Test0001 image (or the name that you have chosen) under Select Lens image, and do the analysis again
- During the analysis, Sensoft will check if the test image:
 - Is taken in parallel light (Collimation)
 - Is aligned with respect to the reference image

If the check is OK, the boxes Collimation and Alignment at the bottom of the screen will turn green; otherwise, they will turn red.

- Note: unlike for on-line analysis under Test, the flux is not checked



5.5 Off-line analysis

- You can load old files and redo the analysis. Choose the Reference and Lens files under [SH/Directories] and click Analysis
- You can also reload old results by loading the appropriate file with the .cof extension from the File menu
- During the analysis, Sensoft will check:

- Was taken in parallel light (Collimation)
- Was aligned with respect to the reference image

If the check is OK, the boxes Collimation and Alignment at the bottom of the screen will turn green; otherwise, they will turn red.

- Note: unlike for on-line analysis under Test, the flux is not checked



5.6 Testing a series of lenses

- You can test a series of lenses (or other optical elements) by using the Lens command. It will take the prefix for the file that you have specified in [SH/Directories]. This will create a series of files with suffix file0001, file0002 etc.
- All the important results for the batch (like the Zernike coefficients) are stored in an Excel file in the main working directory [WD]

5.7 Computation of M^2 for laser

At the end of the Shack-Hartmann analysis the table containing the Zernike coefficients and the wavefront analysis results is shown on the screen. The M^2 analysis can be done by clicking on the MSquare button that is enabled on this table.

The screenshot shows the Sensoft software interface. The 'MSquare' button is highlighted with a red arrow pointing to a callout box that says 'Click to launch/Display MSquare analysis'. Below the button are three tables: 'SH analysis of: Test single image', 'Standard Zernike coefficients', and 'Wavefront (values in nm)'. At the bottom, there are statistics for 'Actual Quality' and 'Probability of goodness of fit'.

Image	Date	Time	Exp.time	Thresh.	Ellip...
Test: HENE LASER WITH BE12-60	2007-12-13	11:23:36	.001 sec	.073	.70
Ref: REF_PARALLEL LIGHT_BE12-...	2007-12-13	10:52:14	.012 sec	.178	.40

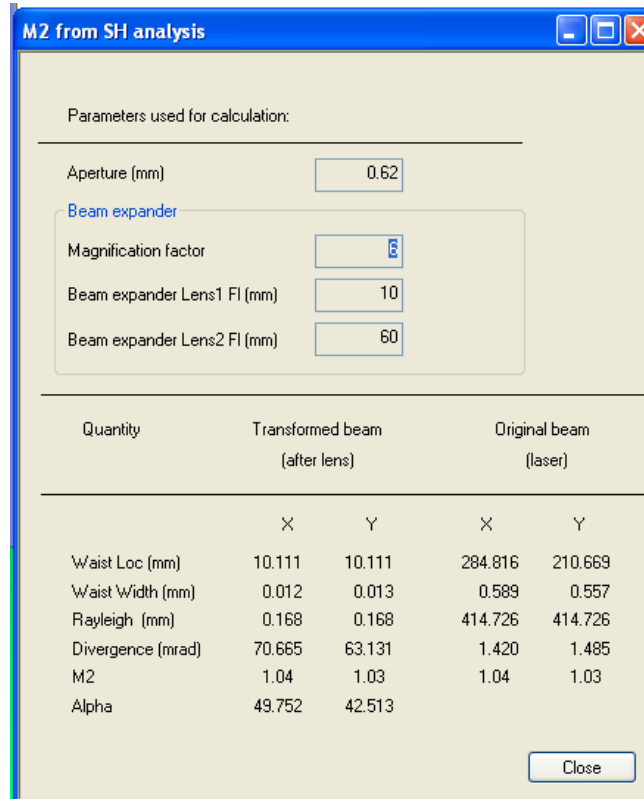
Aber	m n	Cx(nm)	Cy(nm)	C(nm)	Angle
Def	0 2			15.4	
Tilt	1 1	8234.3	553.7	8252.9	3.8
Coma	1 3	0.4	0.0	0.4	-1.4
SA3	0 4			2.2	
Ast3	2 2	4.2	-9.0	9.9	-64.9
TCom	3 3	4.9	-2.8	5.7	-29.6
QAst	4 4	2.3	-1.3	2.7	-28.4

Quality	Max	Min	Average	P-V	Rms	Strehl
Residual	50.6	-35.6	-40.1	86.2	16.6	0.973
Actual *	62.5	-42.3	-58.1	104.8	19.4	0.964
Potential	50.6	-35.6	-40.1	86.2	16.6	0.973

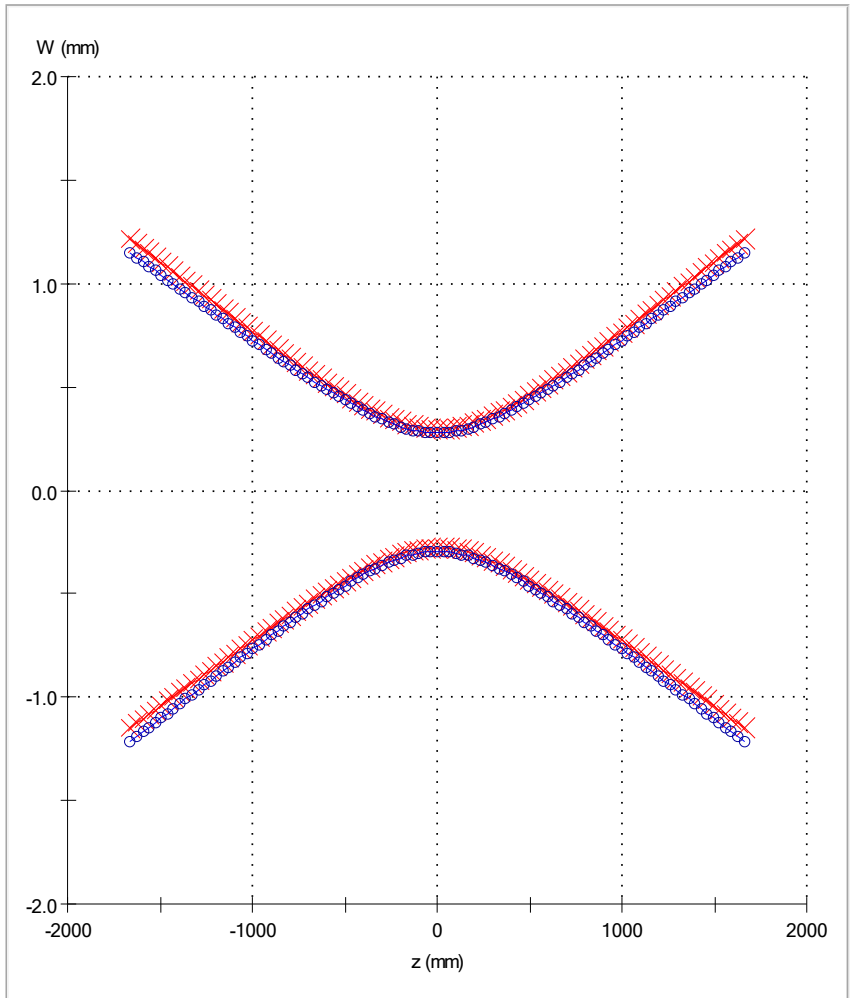
* Actual Quality: tilt and defocus subtracted
 Normalized pupil: 0.997 No of spots used: 239 Probability of goodness of fit: 1.00

The results are given in numerical form in a dialog and as graphs with the M^2 computed after lens and before lens

By clicking on the Close button the dialog is closed.



HeNe laser with BE12-60 - (laser)		
	X	Y
Alpha	49.752	42.513
Waist Width (mm)	0.589	0.557
Rayleigh (mm)	414.726	414.726
Divergence (mrad)	1.420	1.485
M2	1.04	1.03



5.8 Using the loop command for seeing results in real-time

You can see the results also in a loop. Not all options may be available for your version of Sensoft.

See also chapter about on-line and off-line analysis.

Loop param
✕

Range of alert values for aberration coefficients

		From	To
Defocus	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
Tilt	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
Coma	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
Sa3	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
Ast	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
Tricoma	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
QAst	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
Coma5	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
SA5	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>
Ast5	(nm)	<input type="text" value="0"/>	<input type="text" value="50"/>

Select type of plot for loop

Contour
 3D
 Aberrations
 Align (Coma/Ast)
 Spot diagram
 Residuals
 Mtf

SH image

Display
 Image stretching factor
 2x2
 3x3


Archive results of analysis

Save coefficients in log file

Serial communication of coefficients


Without sending coefficients
 Send coefficients to:
 COM1
 COM2

5.9 Make a comparison using the Excel file

- An Excel file is created in the Directory that you have chosen that contains the results for all the lenses tested (except for the Test0001 image created with the Test command and the file Loop0001 created with the Loop command)
-  This file can be accessed only when Sensoft is not analyzing any new image. Sensoft will ask to close the file before starting a new analysis

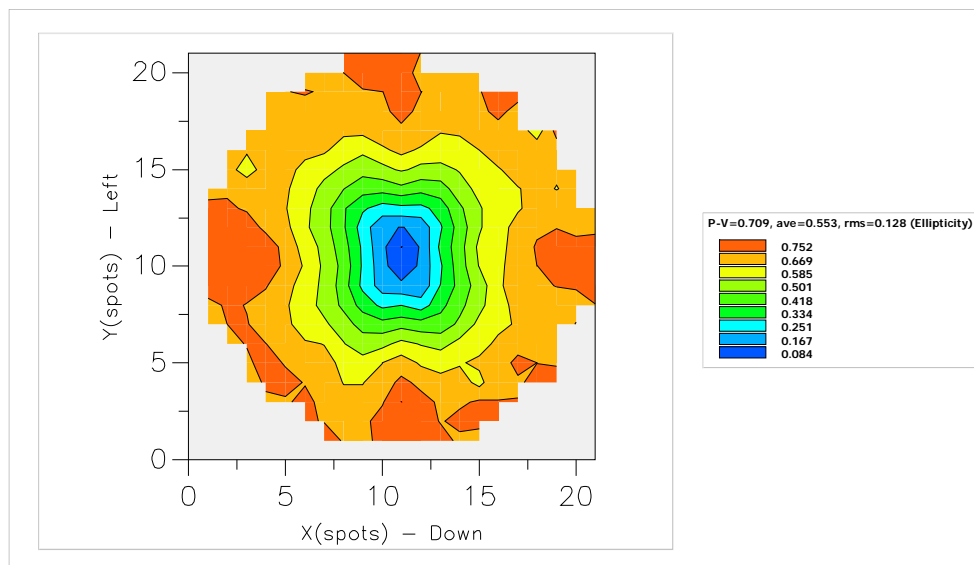
Chapter 6: On-line analysis and adjustment of optical systems

6.1 Using Sensoft for on-line analysis of an optical system

- Enter the optical parameters in [Opt]
- Do the optical setup for taking the reference image
- Optimize the exposure time using [Live] and [QAuto]; take the reference image with [Ref]
- Do the optical setup for taking the Test image
- Click [Live] and align the Test image with the reference image, using the [Align] command
- Click the [Test] button. This will take the image of the Test element, and do a full analysis with the first 7 Zernike terms
- Check the normalized pupil and the combination of the spots, as well as other parameters that result from the analysis
- Click on the  button close to the [Loop] check box on the dialog bar. The Loop param dialog will be displayed on the PC screen.
- Select the graphics that you would like to display and the other parameters as described in section 3.8.3
- You are now ready to run the analysis in a Loop
- Check the Loop box; the Shack-Hartmann image will be displayed on the PC screen together with the graphics that you selected


6.2 Using Sensoft for checking the alignment

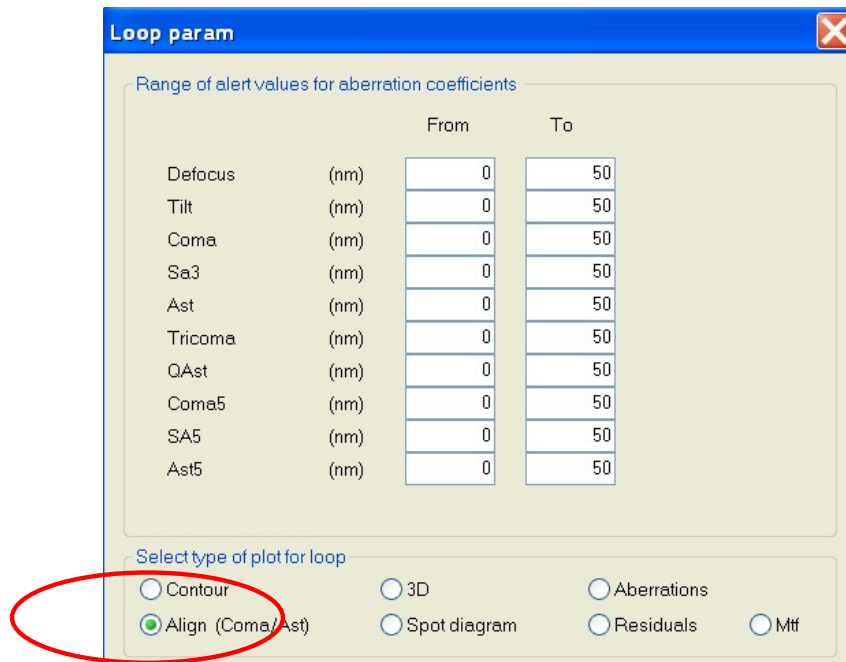
Sensoft computes the ellipticities of the spots and plots it as a 3D distribution or as a contour plot. If the test system is not correctly aligned with respect to the fiber, then you will get a plot that will show an asymmetry (see below). You should adjust the fiber until you get a symmetrical plot.



Contour plot of ellipticity. Note the four read areas on the edges. These are due to the stress caused the screws holding the fiber.

6.3 On-line alignment of multi-component systems using coma and astigmatism

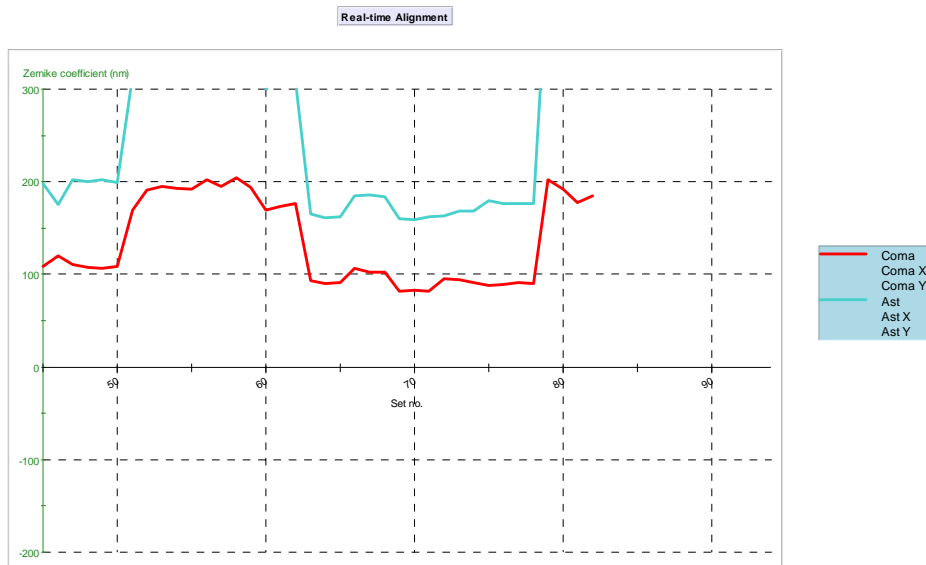
- Enter the optical parameters in [Opt]
- Do the optical setup for taking the reference image
- Optimize the exposure time and take and store the reference image, using [Live] and [QAuto] and [Ref]
- Do the optical setup for taking the Test image
- Click [Live] and align the Test image with the reference image, using the [Align] command
- See that you have chosen to fit the first seven terms (default) in the [SH/Zernike] section
- Click the [Test] button. This will take the image of the Test element, and do a full analysis with the first 7 Zernike terms
- Check the normalized pupil and the combination of the spots, as well as other parameters that result from the analysis
- Click on , and select the Align (multi-component system) type of graphic
- Now check [Loop] on the toolbar. This will start the analysis, and produce a real-time graph with the total values of coma and astigmatism (and their x- and y-components)
- The optical system can now be aligned using these graphs (reduce coma and astigmatism to minimum)



- Start the Loop from the dialog bar.



- The analysis will start and you will see a graph shown below



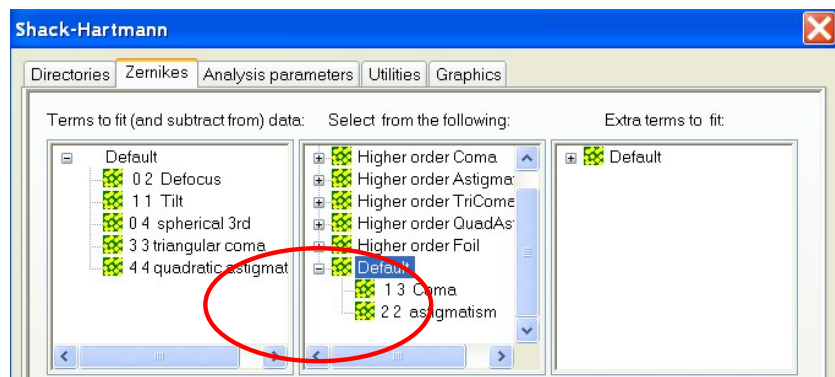
On-line alignment using coma and astigmatism

You can choose to focus on the total coma and astigmatism and/or the components by clicking on the Align toolbar that appears once the loop is started.



The align toolbar

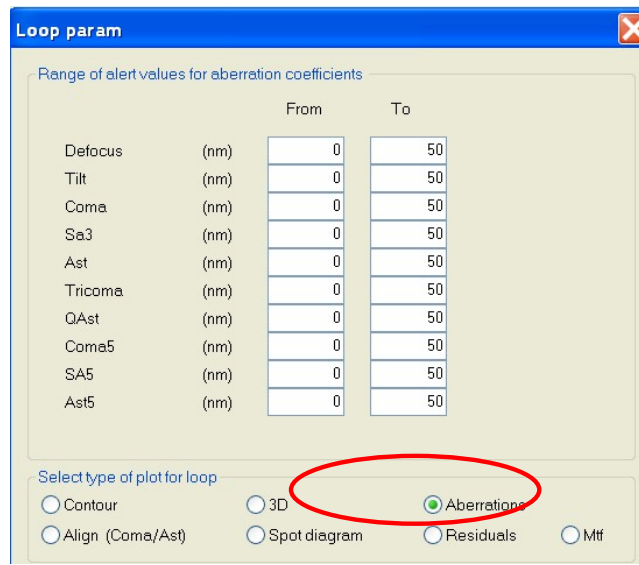
If desired, you can also look at the spot diagram and the wavefront/contour plot. In that case, do not fit coma and astigmatism in [SH/Zernikes].



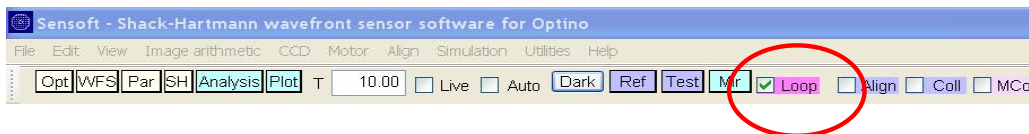
6.4 Adjustment of spacing between the elements (SA3 and defocus)

You can use the measurement of SA3 and defocus to optimize the separation between the elements.

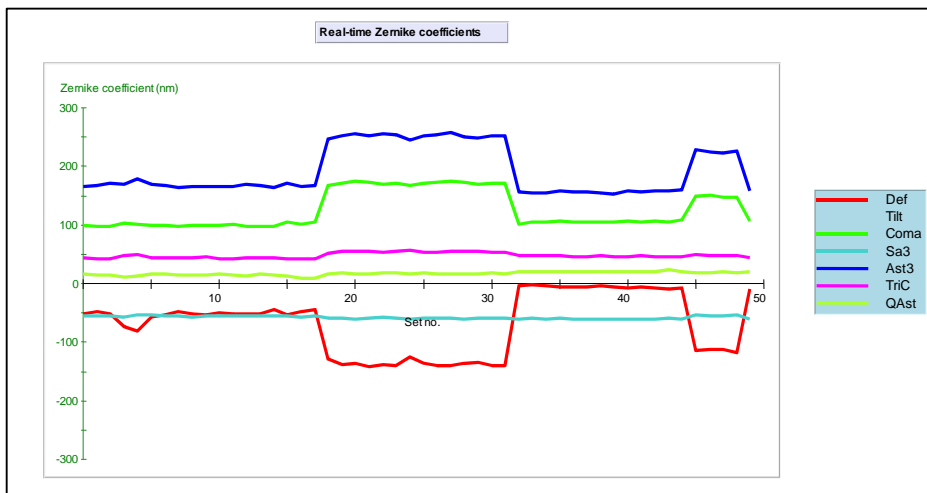
- See that you have chosen to fit the first seven terms (default) in the [SH/Zernike] section
- In the Loop param dialog, choose the [Aberration] plot option



- Start the Loop from the toolbar



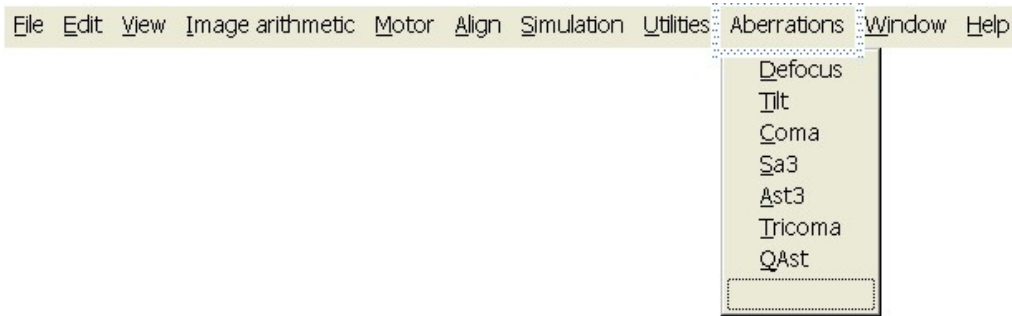
The analysis will start and you will see a graph shown below:



On-line display of aberrations

You can choose to focus on SA3 and Defocus by using the Aberrations Menu. By clicking on one aberration, the correspondent

line/aberration will disappear from the plot above.



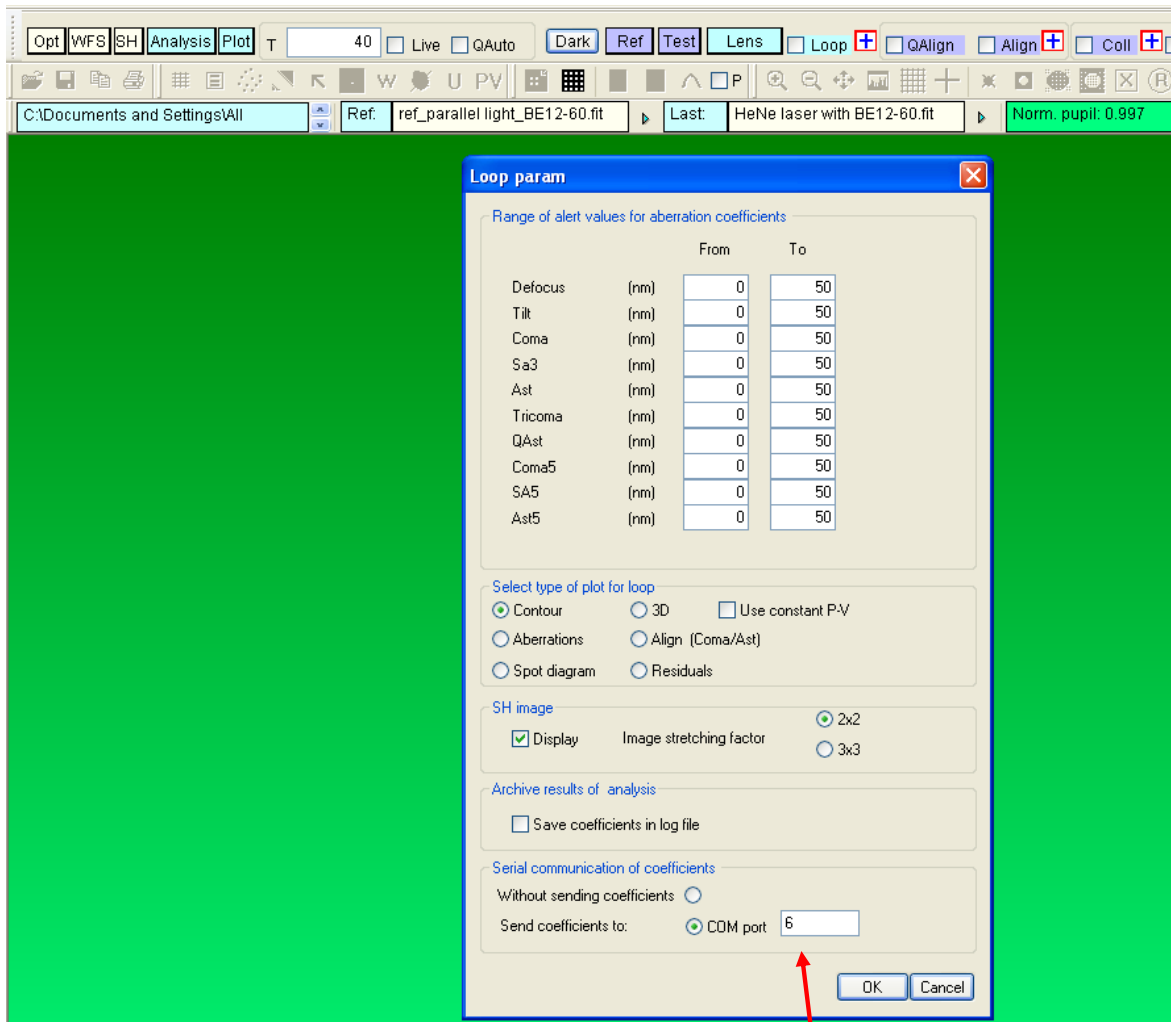
Aberrations menu

The values of the default coefficient aberrations will be displayed on a toolbar that will appear on the screen only during the loop. The values of the coefficient will appear on a red or green background, depending if the value is outside or inside the tolerance defined in the Loop param dialog. If desired, you can also look at the spot diagram and the wavefront/contour plot. In that case, do not fit SA3 and defocus in [SH/Zernikes].

6.5 Sending coefficients on the serial port

This task is in Sensoft Professional and Engineering version only.

When Sensoft is launched there is no remote communication port predefined in the software. Clicking on the cross close to the Loop box the communication port can be selected.



On the receiving PC launch the HyperTerminal program

Set the parameters of the COM port

Baud rate 9600

8bit

Parity NONE

Handshaking Xon/Xoff

When the Analysis is launched in a loop in the HyperTerminal window the sequence of the coefficients will be received at the end of every analysis.

In the present version of the software, the PC controlling the instrument is not working in close loop with the remote PC. In this case a maximum of 10 selected coefficients is sent every time the continuous SH analysis loop is performed, without waiting for any acknowledgement message from the remote computer.

For each generic message the protocol is as follows:

SEND

[STX] [String][ETX]

where

[STX] is the "start of data block" character ^B

[ETX] is the "end of data block" character ^C

The message is as follows:

"C,nnn,r1,m1,c1x,c1y,c1,a1,[Y/N],r2,m2,c2x,c2y,c2,a2,Y[N],r3,m3,c3x,c3y,c3,a3,[Y/N],.....,rn,mn,cnx,cny,cn,an,[Y/N]"

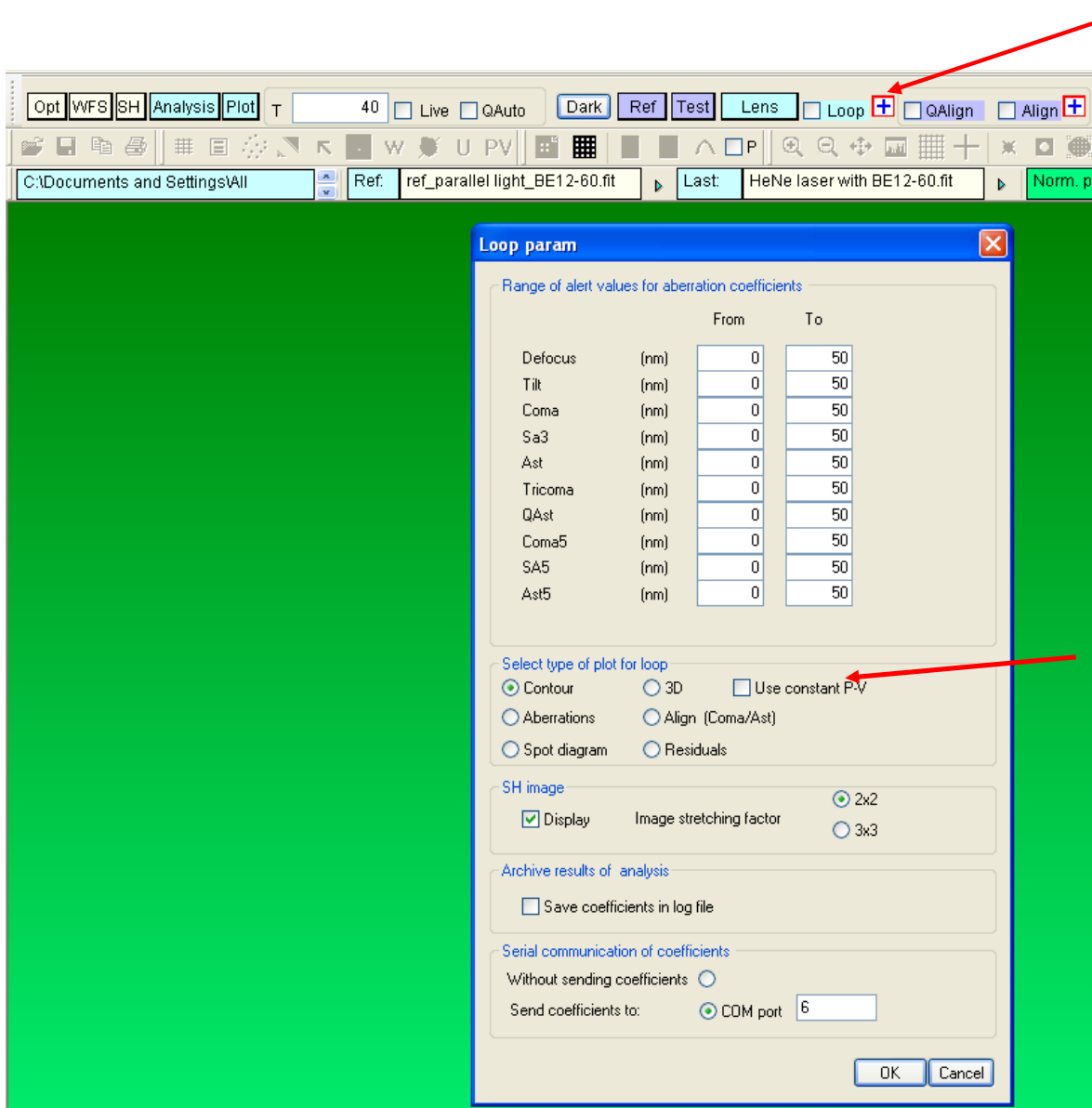
where:

1. C is the message identifier (character)
2. nnn is the number of coefficients following in the message (integer)
3. r1,m1,c1x,c1y,c1,a1,[Y/N]... rn,mn,cnx,cny,cn,an,[Y/N] is the sequence of nnn coefficients; each coefficient:
 1. rn radial dependence for nth coefficient (integer)
 2. mn azimuthal dependence for nth coefficient (integer)
 3. cnx, x component for nth coefficient (integer)
 4. cny, y component for nth coefficient (integer)
 5. cn, nth coefficient value from analysis (integer)
 6. an, angle for nth coefficient .
 7. The Y/[N] implying that the nth coefficient is [is not] inside the tolerance established by the user in the Wfs folder.

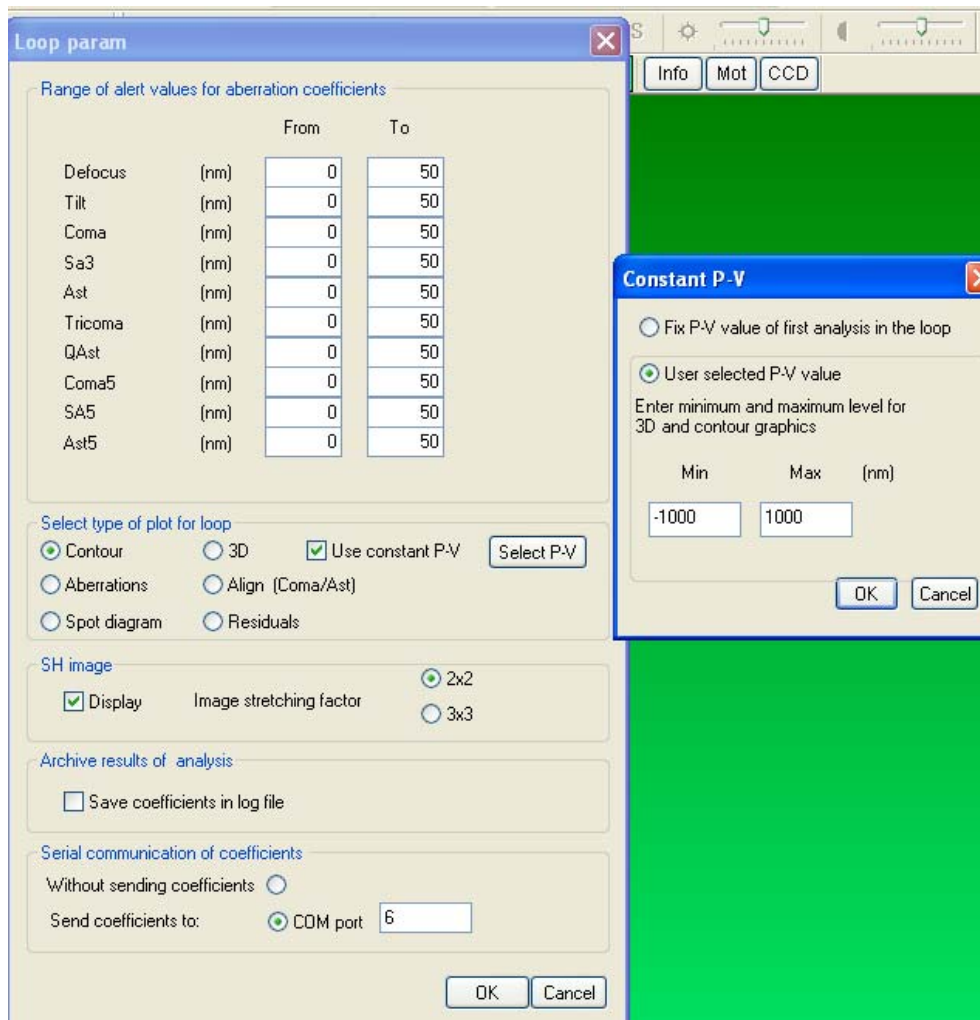
In case of coefficients without azimuthal dependence (defocus, spherical, etc. where mn=0) the angle is 0 and the cx and cy components of the coefficients are not evaluated.

6.6 Using constant P-V value for displaying 3D and contour of wavefront in a loop

When the Shack-Hartmann analysis is done in a loop the user can select to use a constant P-V interval for displaying the 3D and contour of the wavefront. The P-V interval can be selected in the Loop parameters dialog.



When the 'Use constant P-V' is checked the dialog with the P-V selection is displayed



There are two possible choices:

- The P-V scale can be fixed on the P-V value of the first image analysed in the loop
- The P-V interval can be user selected

The entered values will be stored in the computer memory and used until the 'Use constant P-V' is unchecked

Chapter 7: Zonal and Modal Wavefront reconstruction in Sensoft

7.1 How Sensoft is reconstructing of Zonal and modal wavefront

7.1.1 Zonal wavefront computation

- What is measured is the displacement on the CCD after it passes through the lenslet (let us call it dx, dy - called $\square x$ and $\square y$ in the paper as they are partial derivatives)
- dx and dy are the derivatives of the WF
- So if you numerically integrate the derivatives of the WF (i.e. dx, dy for all the spots) you get back the WF
- Sensoft uses sophisticated algorithms for the numerical integration to give detailed structure on the WF
- The algorithm also increases the effective sampling by about a factor of 3. So instead of 50x50 spots, you effectively get 150x150 spots.

Note that we have not talked about the Zernikes at all. For Zernikes we go as follows:

7.1.2 Modal (or sum of the Zernikes) wavefront computation

- We measure (dx,dy) like above
- We mathematically express the wavefront WF_Zer in terms of Zernike polynomials $WF(x,y)=a_0 + a_1 \times \text{Tilt} + a_2 \times \text{defocus} + a_3 \times \text{coma} + a_4 \times \text{Sa}_3 + a_5 \times \text{Ast}_3 + \text{other higher order terms}$ (Eqn. 1)
- We find MATHEMATICALLY the derivatives of the WF_Zer on Eqn. 1. They should be connected with the measured (dx,dy) for all spots
- We fit the derivatives to the real data (dx,dy) and compute a1, a2, a3 etc.
- By adding a1, a2 etc. with the correct phase for each aberration, we get the WF_Zer
- It is very important to note that this is only valid if you can express the WF in terms of Zernikes. However, any WF will have some part which is WF_Zer and some part which is not
- This is called modal WF and is given by most people

The computation of the Modal Wavefront is mathematically easier and thus the computation is faster than in the case of the Zonal Wavefront.

The computation of the Zonal Wavefront is mathematically heavy and very difficult to compute accurately. The computation takes longer than the Modal Wavefront one but gives much more information on the real detailed structure of the test element. This is very clear in the example given in the next section.

The Modal wavefront is to be preferred when the interest is in fast computation and in the aberration coefficients only

The Zonal wavefront is to be preferred when the interest is in the detailed structure of the test elements and its support/mounting system

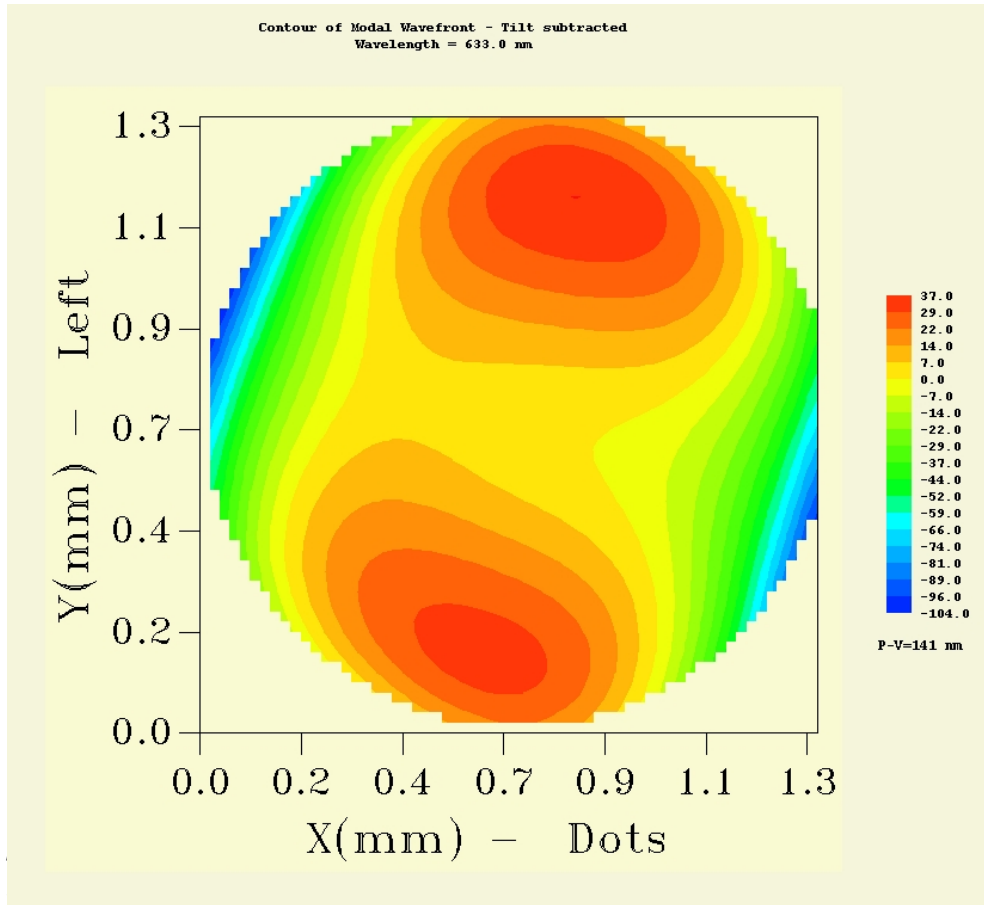
7.2 Examples of Modal and Zonal Wavefronts

The aberration coefficient, modal and zonal wavefront computed from the Shack-Hartmann analysis for a test lens is given in this section

Aberration coefficients of test lens

Aber	m n	Cx(nm)	Cy(nm)	C(nm)	Angle
Def	0 2			-11.8	
Tilt	1 1	-5835.1	1003.0	5920.7	170.2
Coma	1 3	1.5	-2.0	2.5	-52.2
SA3	0 4			-7.7	
Ast3	2 2	6.6	22.2	23.1	73.6
TCom	3 3	1.0	1.4	1.8	54.3
QAst	4 4	3.4	1.4	3.7	21.9

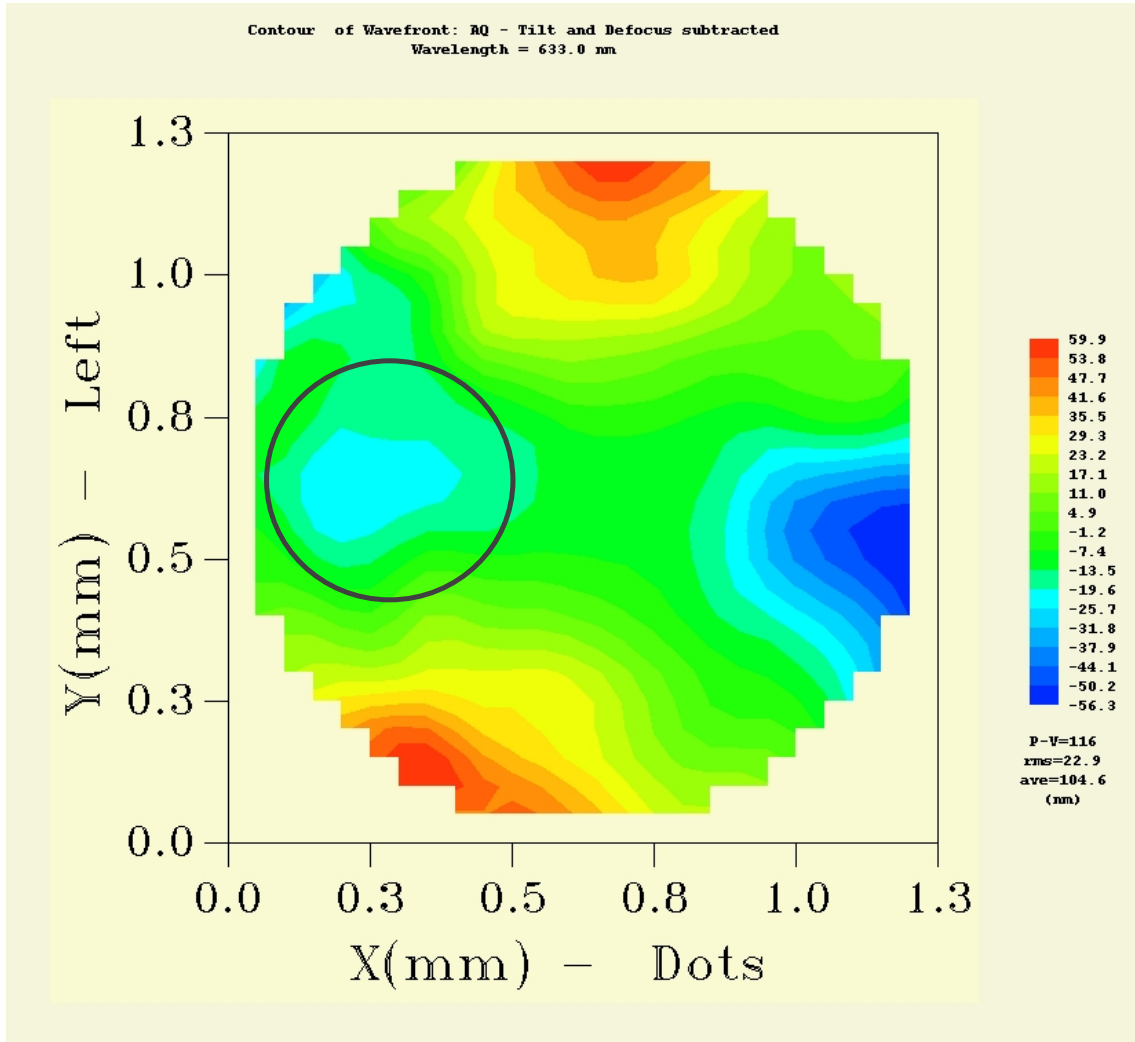
7.3 Examples of Modal Wavefront



putation of

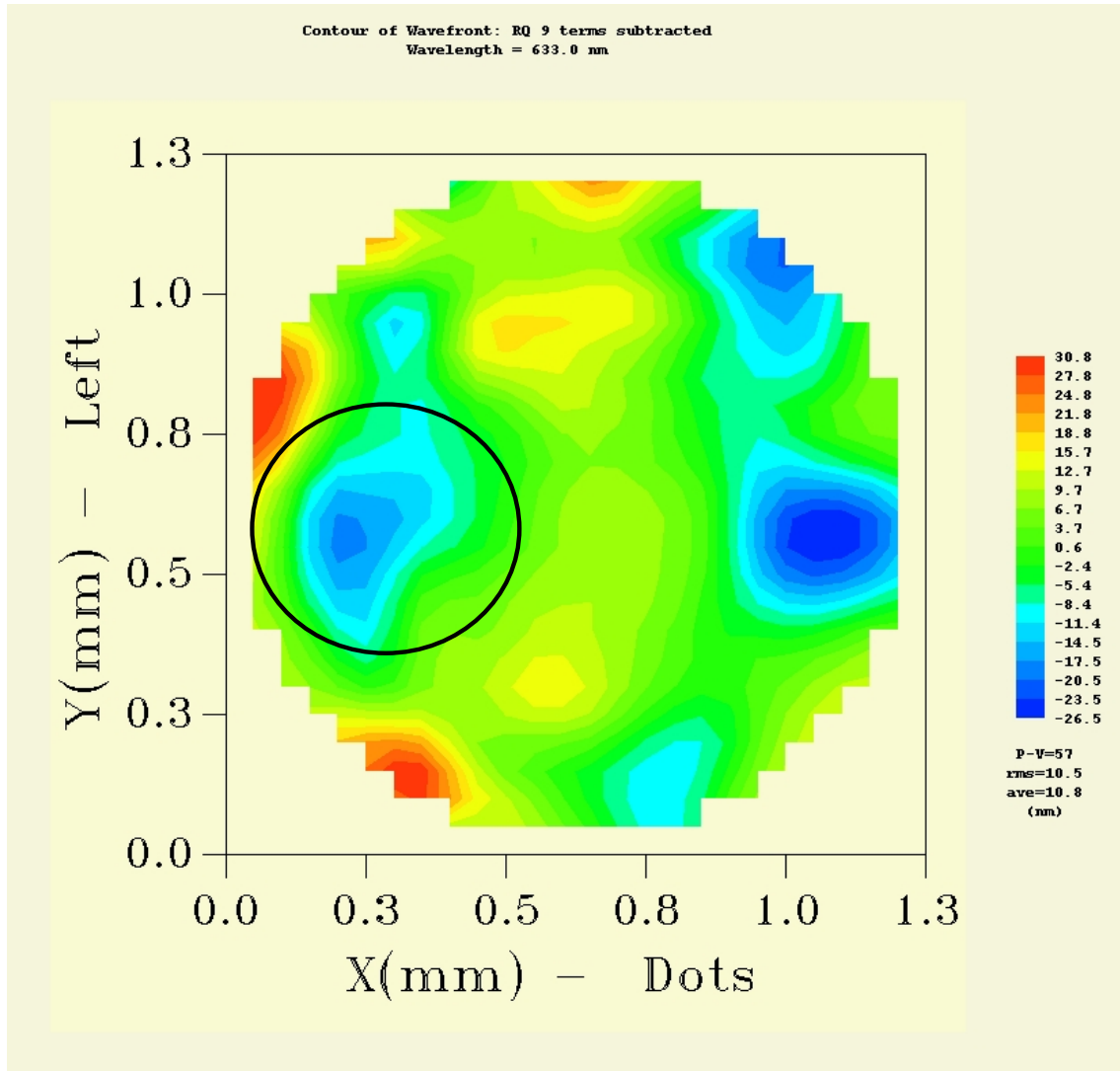
7.4 Examples of Zonal Wavefront

Zonal wavefront for Actual Quality of test lens



The Zonal wavefront for Actual Quality (tilt and defocus contributions mathematically subtracted from the derivatives dx,dy) is also dominated by 3rd order astigmatism, but it shows some asymmetrical structures (in the black circle). The Zonal Wavefront for Residual Quality (contributions from all of the fitted aberration subtracted from the derivatives dx,dy) confirms that the structures are real. They are due to effects that cannot be represented in terms of Zernike coefficients.

Zonal wavefront for Residual Quality of test lens



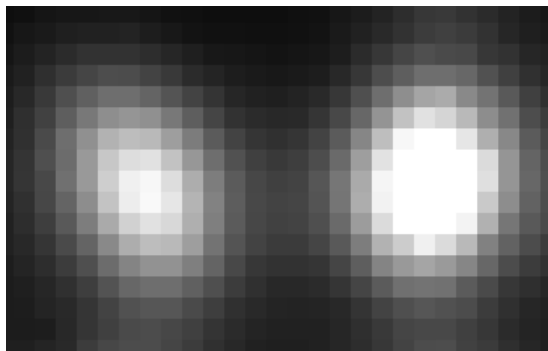
The Zonal Wavefront for Residual Quality (contributions from all of the fitted aberration subtracted from the derivatives dx,dy) confirms that the structures (in the black circle) are real. They are due to effects that cannot be represented in terms of Zernike coefficients. **This information cannot be obtained from the Modal Wavefront.**

Chapter 8: Analysis of results 1: the shapes and intensity of the spots

8.1 Introduction

All the computations done by Sensoft (computation of surface, computation of Zernike coefficients etc.) are based on the computations of the centroids of the spots. However, the *shape* of the centroids themselves can be used to obtain information on the surface of the optical system from which they are reflected.

- An irregular shape will give rise to an elongated spot, while a regular shape will give a spot that is almost circular (see Section 1.2.11 for the mathematical definition of ellipticity)
- Round spots have ellipticity $\varepsilon=0$, and elongated ones $\varepsilon=1$
- A surface that has less reflectivity will give spots with lower intensity



An elliptical spot (left) and a regular spot (right). The intensity of the elliptical spot is lower, indicating that the area of diameter 300μ - (that of one lenslet array) from which it was reflected had a lower reflectivity compared to that on the right

Of course, not only can individual spots be studied, but the distribution over the whole surface can also be studied.

i While this chapter explains the use of the centroids for understanding the surface quality of the optical system, it is to be noted that these parameters have also a role to play in the analysis of the images. For example, in general, for a good SH analysis, all spots with ellipticity $\varepsilon > 0.7$ are rejected. Thus, if you wish to see the distribution of ellipticity for the very highly elongated spots also, set the rejection limit for $\varepsilon=1$ and retry the analysis. If the combination of the spots from the reference and optical system fails, lower the rejection limit of ε and try again. Please see Chapters 1 and 4 for more details.

8.2 The various plots available

8.2.1 Distribution of the individual centroids over the pupil

The following graphs are available both for the reference and for the lens image:

- Distribution of the centroids of the spots (used for computing the shape of the surface and the coefficients of the Zernike terms)

- Ellipticity distribution of the spots (used for identifying irregular shape of the area (200-300 μ according to the lenslet array D(iiameter) parameter) from which the spot originates)
- Intensity distribution of the spots (used for measuring reflectivity)
- S/N (Signal-to-Noise) ratio distribution of the spots (same as intensity distribution, but takes into account also the noise of the camera)

8.2.2 3D and contour plots

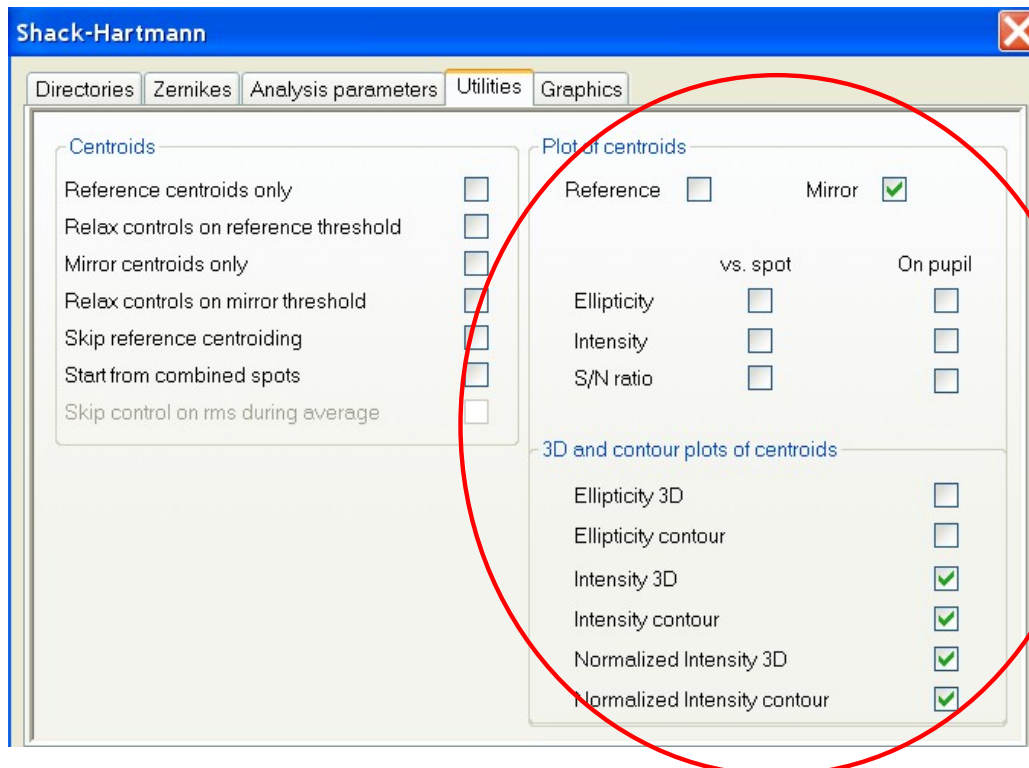
The intensity and ellipticity distribution better represent the form of 3D and contour plots. They can be plotted to look for any variation.

Furthermore, after the combination of the lapping plate vs. reference centroids (the second step in the Shack-Hartmann analysis), a 3D and contour of intensity of the spots normalized with respect to the image assumed as reference for the analysis. The normalization takes into account any non-uniformity in the calibration light source and Optino.

8.3 Choice of plots to display

The first step of the analysis of the Shack-Hartmann image consists in computing the center of gravity of the spots in the image. At the end of this analysis, Sensoft creates a file with extension .cen that contains information about the position of the spots, their ellipticity, intensity, Signal/Noise (called S/N) ratio.

In Sensoft you can select among these different graphs in the [SH/Utilities] page.

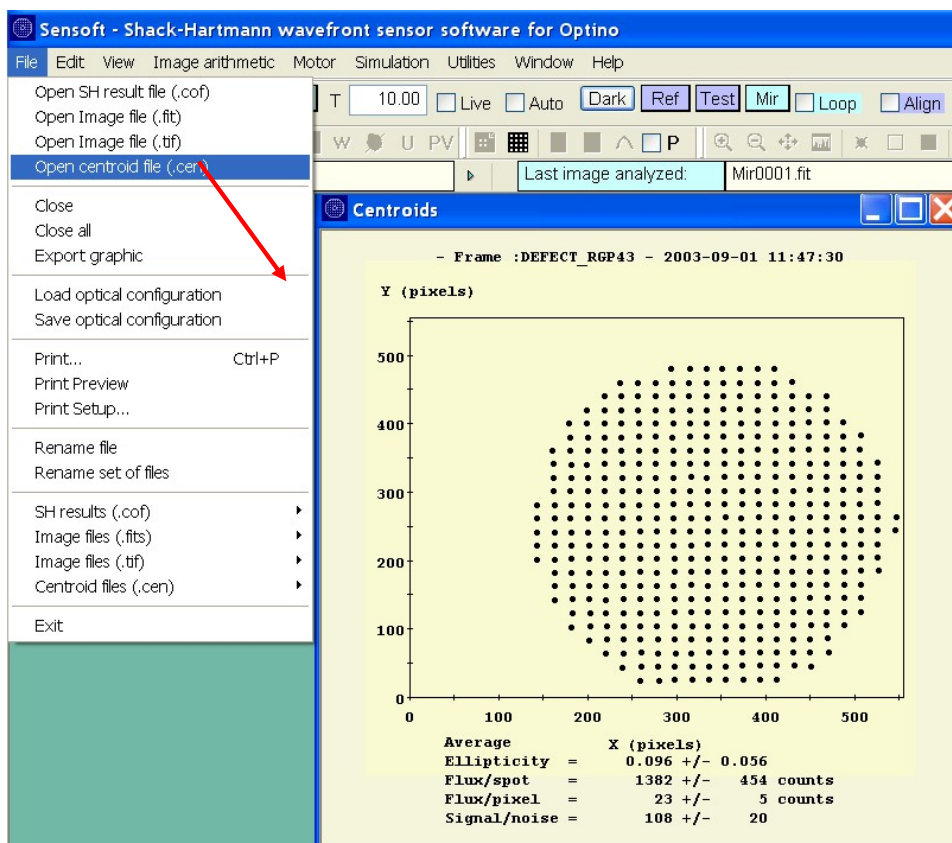


Note: The plots for the reference image are shown only if the 'Reference' box is checked, and that for the lens image only if the 'Lens' box is checked.

8.4 On-Line and off-line display of the plots

The graphs selected in [SH/Utilities] are automatically displayed in one of the two following ways:

- **On-Line:** at the end of the analysis (when the [Ref], [Test], [Lens] or [Analysis] buttons are clicked)
- **Off-line:** by opening the centroid file (file with .cen extension) of an image that has been already analyzed from the File Menu and clicking the Plot button in the dialog bar.



8.5 Examples of the various plots

8.5.1 Positions of the centroids

This graph gives the computed position of the center of gravity of the spots in the image. An example is given below for a reference image. For the absolute reference image these points have a


regular distribution on a grid, while for the image of the optical system under test, their positions are on an irregular grid due to the aberrations of the optical surface (see section 6.1).

8.5.2 Distribution of intensity of the spots over the image

This graph gives the total intensity of each of the spots displayed in the centroid graph. The variation of intensity is due either to the illumination/optical setup or to defects in a certain region of the optical surface under test. Ideally, the distribution of intensity should be uniform over all the spots. This is mostly true for the reference image. For the image of the optical system under test, the distribution is not uniform due to variation in the reflectivity of the surface.

If the same pronounced effect is present in the same area in the distribution of intensity for both reference and lapping plate image, it is possible that the calibration light source is not giving a uniform illumination (e.g. if the fiber is not inserted correctly).

If the non-uniformity condition in the image of the lapping plate persists despite these precautions, or it is not present in the reference image, it means that there is a real variation in reflectivity over the area of the lapping plate being tested.

 We recommend that you use the normalized 3D and contour plots of the intensity distribution. In these plots, the non-uniformity in the reference image has been corrected using software by normalization, thus the variation that you see is due to the lapping plate only.

The average values for the ellipticity ϵ , intensity and the S/N ratio are shown in the graphs in the following pages, with their respective standard deviation σ ; these values give already an indication of the quality of the image.

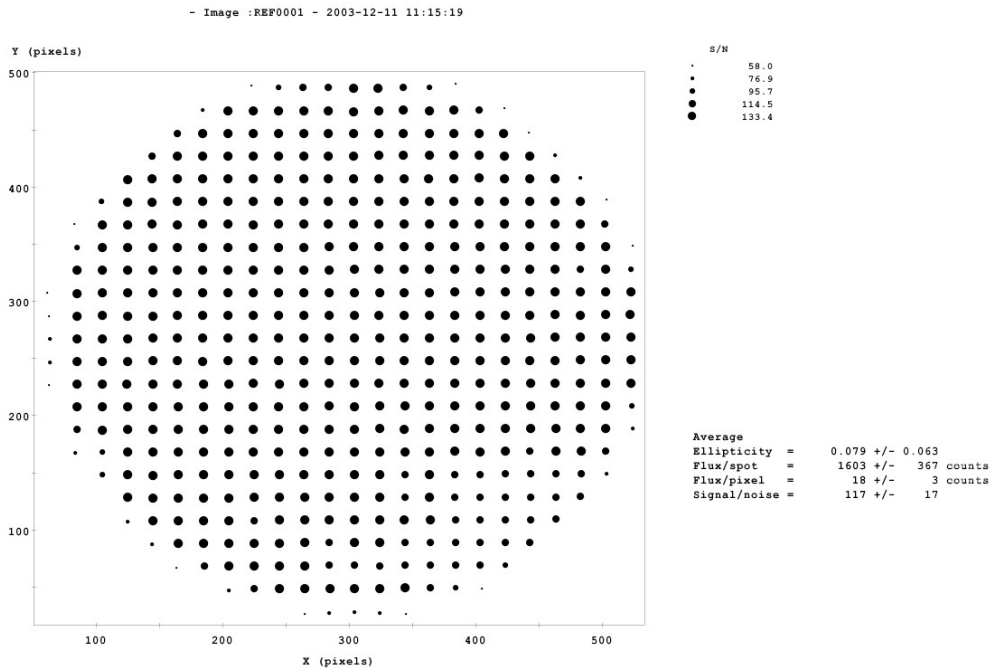
A low value for the ellipticity ϵ indicates that the spots are regular and rounded. A reasonable value of σ for the intensity means that there is little variation over the image
A high S/N ratio (~ 100) means that the centroid intensity is sufficient to compute the various parameters of the spots accurately

8.5.3 Distribution of ellipticity ϵ of the spots over the image

This graph gives the ellipticity ϵ of each spot displayed in the centroid graph. As mentioned earlier, some of spots may be elongated due to the irregularity of the surface being tested. However, a low intensity of the spots can also cause elongation of the spots. Thus, if it is found that the S/N ratio of the spot is high enough ($> \sim 50$), then the elongation of the spot is due to an irregular surface.

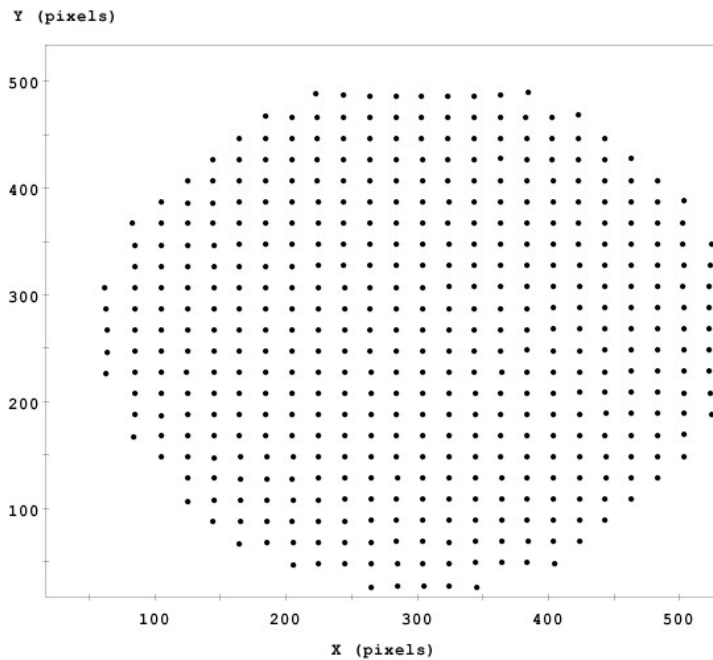
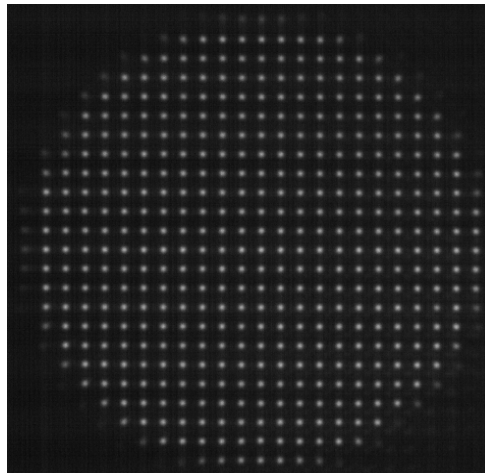
8.5.4 Distribution of Signal-to-Noise (S/N) ratio of the spots over the image

See the discussion for the distribution of the intensity above. The Signal-to-Noise ratio takes into account the various sources of noise in the camera. A S/N ratio of >100 is required for an accurate computation of the centroid parameters.



Plot of signal to noise distribution over the image of a reference

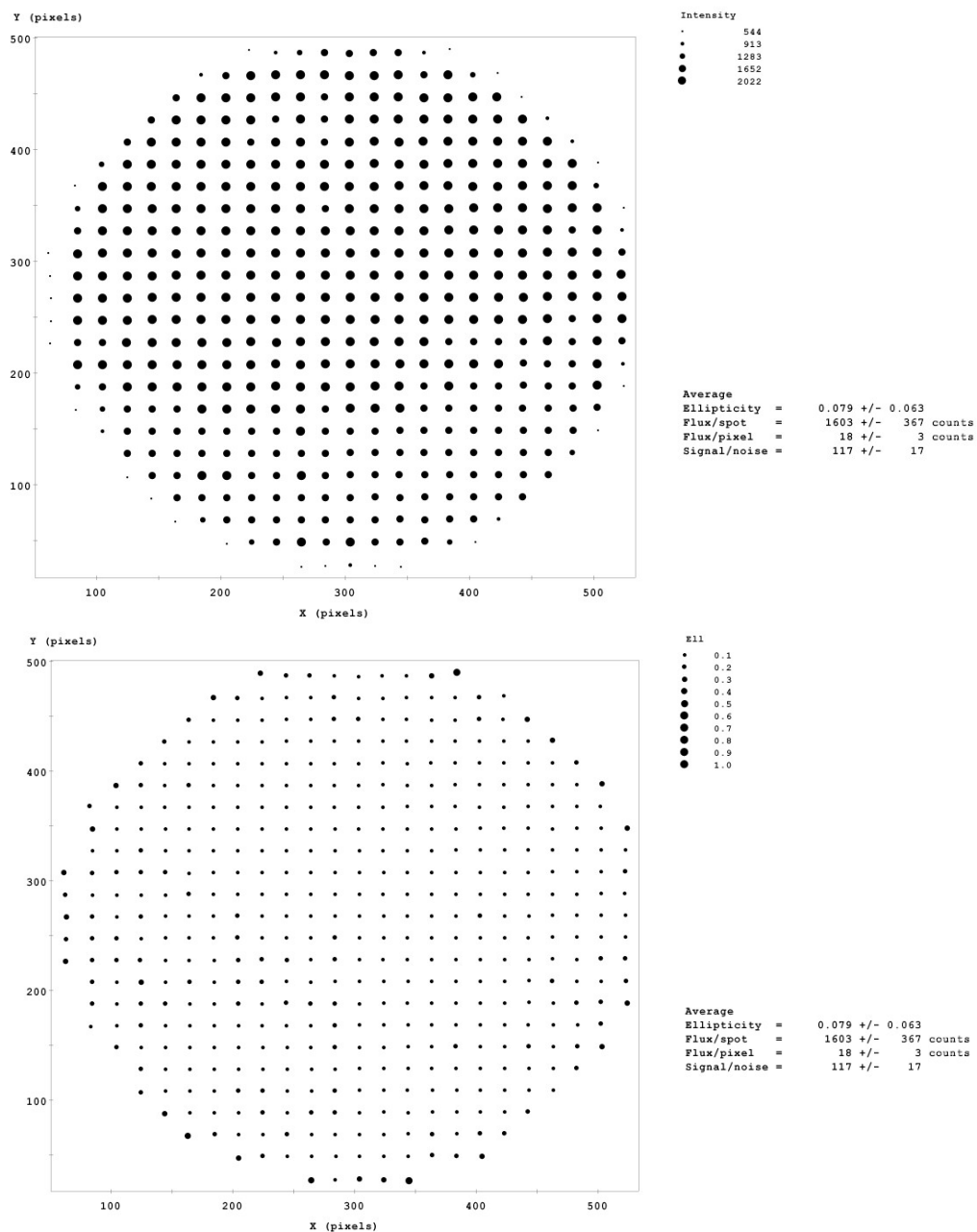
The spots with higher S/N are displayed with dots of increasing diameter. A S/N ratio of at least 100 is required for obtaining good results. If you have a low S/N ratio, increase the exposure time up to about 50ms. Alternatively, increase the light intensity of the fiber-optic light source.



```

Average
Ellipticity = 0.079 +/- 0.063
Flux/spot = 1603 +/- 367 counts
Flux/pixel = 18 +/- 3 counts
Signal/noise = 117 +/- 17
    
```

Plot of centroids for the reference image shown on top. As expected, the average value and the rms value of the ellipticity ϵ are small. The Signal/Noise (per spot) ratio is > 100

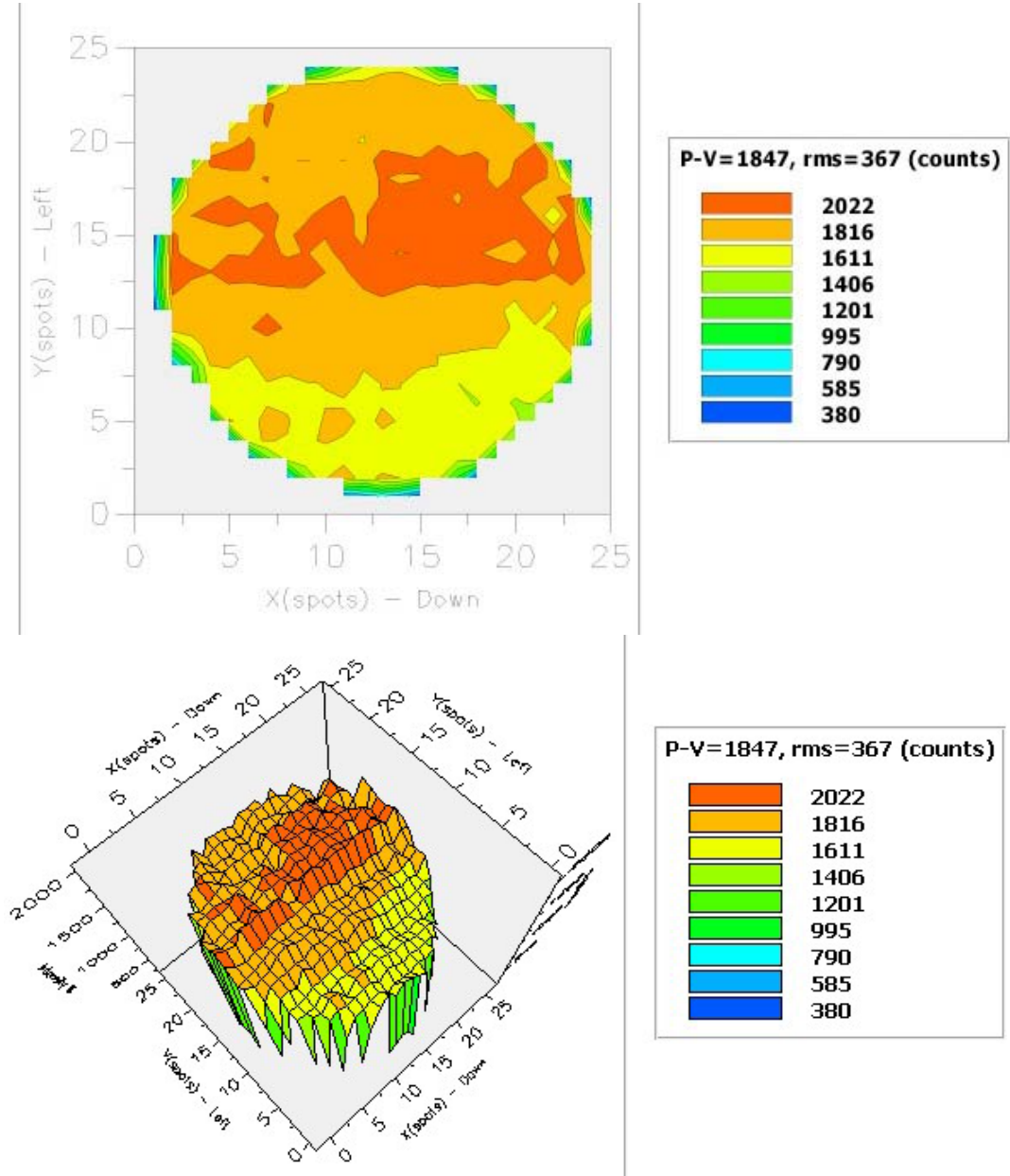


Plot of intensity (top) and ellipticity (bottom) distribution for the reference image shown above. Compare with the 3D and contour plots later in this chapter

8.6 Examples of 3D and contour plots of distribution of centroids

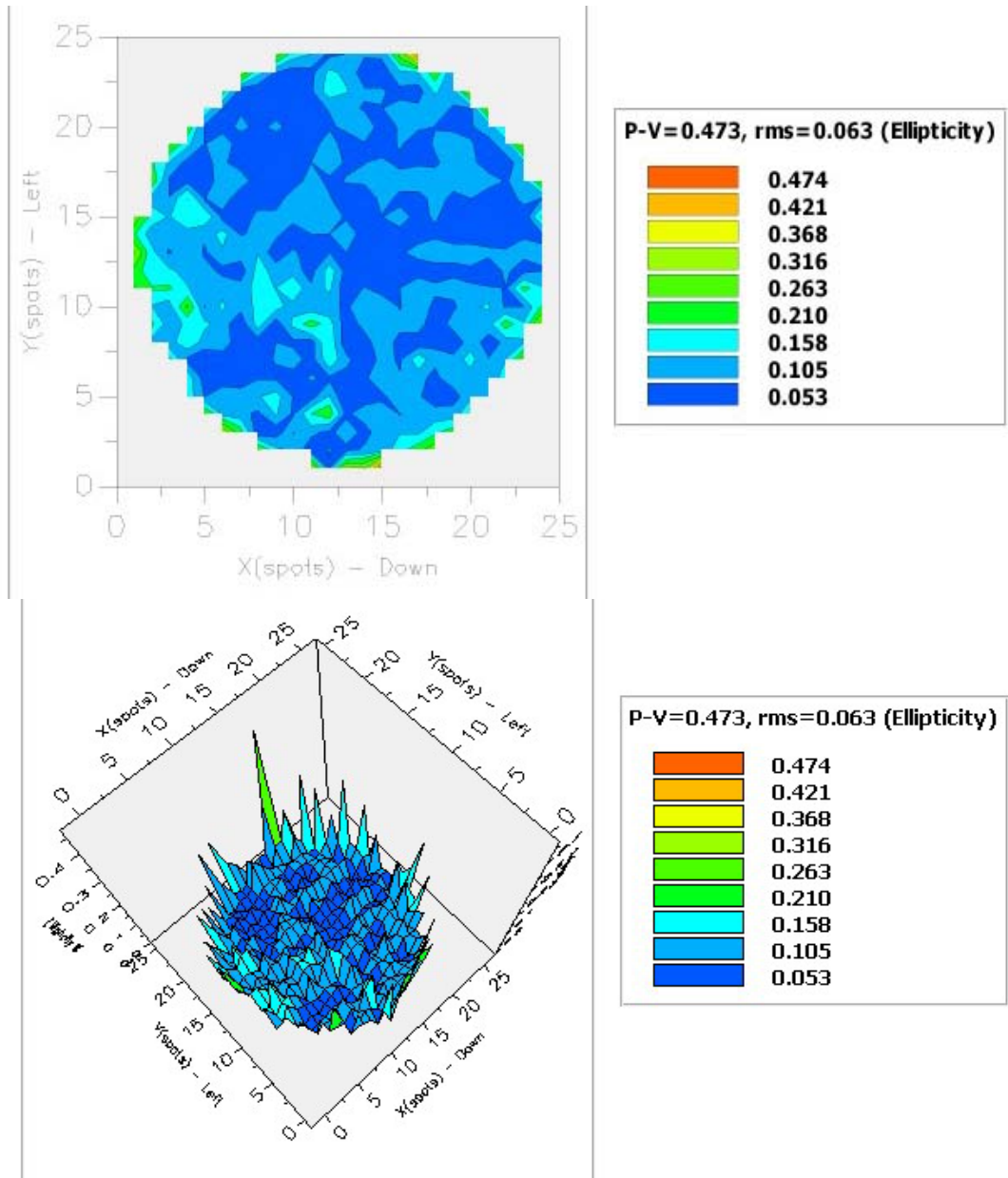
This graph gives the total intensity of each of the spots displayed in the centroid graph in a contour form. An example is given in the figure below for a reference image.

When the distribution of intensity should be uniform on the image, the value of the contour levels on the graphs are very close.



Intensity distribution: 3D (bottom) and contours (top) over the reference image. The variation in intensity is small. The edges are affected by the presence of weak spots due to diffraction effects.

In the analysis of the image of the optical system under test, the software automatically compensates for this variation



Ellipticity: 3D distribution (bottom) and contour plot over the reference image. Except for the edges, where the ellipticity is high due to diffraction effects (see contour map of the intensity distribution above), there is a very small variation in ellipticity

Chapter 9: Frequently asked questions

1. I am not getting enough flux for the tests (e.g. when testing uncoated surfaces)

Try the one or more of the following:

1. Use a fiber of shorter length. The standard fiber has a length of 91cm. A shorter fiber of 61cm is available
2. Increase the gain of the camera. This will increase the noise slightly
3. Use a brighter source. The standard illuminator comes with a light source of 150W. Light sources of up to 250W are available
4. Use a cooled camera. Please ask Spot-optics

2. How do I recompute the Reference centroids?

It can happen that you choose an old reference image and want to do the tests against this reference image. In the property page [SH/Directories], choose the reference image that you wish to use. Then go to the [SH/Utilities] page, and check the Compute Reference centroids only box. The new centroids are computed and used for the subsequent analysis.

3. Where are all the results stored?

1. The images, the output analysis file (‘.sha’ extension) and the Excel file are stored in the main **working directory [WD]** specified in [SH/Directories]
2. All the results are stored in [WD]/single subdirectory
3. All the log files are stored in [WD]/log subdirectory
4. All the results for the average files are stored in [WD]/average subdirectory

4. How do I see the results in off-line mode?

You can see the results for any analysis by opening the appropriate file with the ‘.cof’ extension in [WD]/single subdirectory from the File menu

5. Are the results available in text format?

You can see the results for any analysis by opening the appropriate file with the ‘.sha’ extension in main directory [WD]

6. How do I print the results?

You can see the results for any analysis by opening any coefficient file with the ‘.cof’ extension in [WD]/single subdirectory. Then use the Print command to print the file. You can also use the Print Preview command to see the file

7. How do I see the graphs for the analysis in off-line mode?

You can see the graphs for any analysis by opening any file with the '.sha' extension in [WD]/single subdirectory. Then click the Plot button on the toolbar. It will show all the graphs that have been selected in [SH/Graphics]

8. How do I see the graphs for the centroids?

You can see the graphs for the centroids by opening any file with the '.cen' extension in the working directory under the WD/single subdirectory

9. How do I use the Loop command?

You can use the Loop command to see a number of graphs in a loop. The parameters are set by clicking the + sign next to the loop.

10. What is the difference between QAlign and Align?

QAlign uses a weighted mean of all the pixels for the alignment, and is fast. Align is more precise and uses the centroids. It is recommended that Align be used in most cases. QAlign is particularly suited for the large-format cooled cameras

11. What is normalized radius?

- Sensoft measures the radius of the image on the camera
- It then divides this by the radius entered by the user
- If additional elements are used in the optical train (like a collimator or beam expander), Sensoft takes their effect into account



It is strongly recommended that the correct parameters be entered to get a normalized radius between 0.98-1.02.

12. I am not getting a normalized radius between 0.98-1.02. What should I change?

If it is not, one or all of the following are true:

- The light is not collimated (e.g. use the Coll command to check this)
- If the light is collimated, then the optical parameters of the test element entered in [OPT] are not correct (aperture and focal length – or distance to the image)
- The focal length of the collimator has not been correctly entered

13. What is the precision that I can expect from the analysis?

- The repeatability (taking two images in continuation – first the reference image and then the test image) of the rms value of the wavefront is better than 3-4nm. The standard Zernike coefficients are determined to better than 2-3nm (expect tilt)
- If the alignment between the reference and the test image is not perfect (which is the case in reality), the rms is of the order of 7-8nm, and the Zernike coefficients of the order of 5nm

14. What are AQ, PQ and RQ?

- **AQ: Actual Quality.** The quality of the wavefront after the subtraction of tilt (or tilt and defocus) from the data. This is chosen in [SH/Zernikes]
- **PQ: Potential Quality.** The quality of the wavefront after the subtraction of 7 Zernike terms (tilt, defocus, coma, SA3, Ast3, TComa and QAst) from the data. This applies also the computation of the Strehl ratio, spot diagram, Encircled Energy, and residuals.
- **RQ: Residual Quality.** The quality of the wavefront after the subtraction of the user- selected Zernike terms. This is chosen in [SH/Zernikes]. This applies also the computation of the Strehl ratio, spot diagram, Encircled Energy, and residuals



The program will display the wavefront corresponding to these three cases after Analysis or Test or Lens. However, the wavefront, spot diagram and the residuals shown during the computations in a loop correspond to RQ

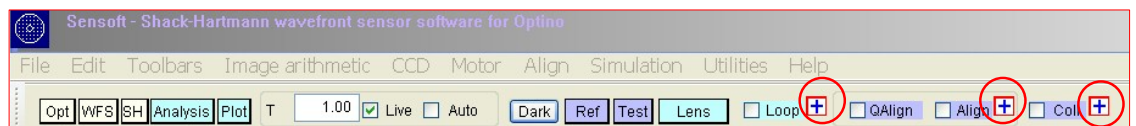
15. Which Zernike polynomials should I use?



It is strongly recommended that Seidel polynomials not be used because of non-orthogonality issues. Please use any of the Zernike polynomials (Annular, Standard or Fringe) according to the element being tested

16. Where are the parameters for the Loop, Align and Coll defined?

They are found under the cross sign next to the respective buttons:



17. The Info toolbar

A useful feature of Sensoft is the Info toolbar where all the relevant information about the settings used for the test element are reported

Test	Lens D	Illum.	Internal
D (mm)	9.50	FL (mm)	100.00
CFL (mm)	100.00	F#	-
Ref Th.	0.16	Ref El.	1.00
Lens Th.	0.19	Lens El.	1.00
Comb. F.	8.0	Annulus	Full

- D: Diameter (or free aperture) of test element (mm)
- FL: Focal length of test element (mm)
- CFL: Collimator focal length (mm)
- F#: Focal ratio or F-number of test element
- Ref Th.: Threshold for Reference spots found by Sensoft. It can be overridden by the user under [SH/Analysis parameters]
- Ref El.: Ellipticity cutoff for Reference spots. Parameter used for rejecting elliptical spots. Specified in [SH/Analysis parameters]. Default value: 0.7
- Lens Th.: Threshold for Lens spots found by Sensoft. It can be overridden by the user under [SH/Analysis parameters]
- Lens El.: Ellipticity cutoff for Lens spots. Parameter used for rejecting elliptical spots of test element. Specified in [SH/Analysis parameters]. Default value: 0.7
- Comb. F.: Combination factor for Lens and Reference spots. The default value is 8. A lower value may be required if you have difficulty in combining the Reference and Lens centroids. Specified in [SH/Analysis parameters]
- Annulus: If the full or part of the pupil is used in the analysis (range 0->1.0). Specified in [SH/Analysis parameters]. Not to be confused with the central obscuration of the pupil due to obscuration in the optical system

18. How do I save the optical parameters that I have used for a particular test?

The user-defined parameters can be saved and reloaded later by using the Save/Load configuration option under the File menu.

Chapter 10: Examples from Sensoft

10.1 Wavefront and spot diagrams

In this section, we give examples of the various figures obtained using Sensoft for an $f/14$ system. For the six aberrations, the figures were obtained by fitting six of the seven default terms, excluding the aberration of interest. Thus, it is possible to see the effect of that particular aberration. Defocus is not shown, as its value was insignificant for this particular image. Note that since these figures were obtained from real data, and they include the effects of higher order aberrations, as well as noise due to air turbulence.

The angle and peak of the wavefront correspond to the aberration coefficient obtained from the SH analysis for the Seidel polynomials. This is true except for coma, where fitting higher order coma (along with third order coma) gives the correct wavefront. This underscores the fact that the analysis has to be done carefully, especially if it is suspected that higher order aberrations are present.

The mirror surface is also shown for tilt. Note that the mirror surface is half the wavefront, with the opposite sign. By the convention, when the wavefront is retarded with respect to the ideal wavefront, it is **positive**.

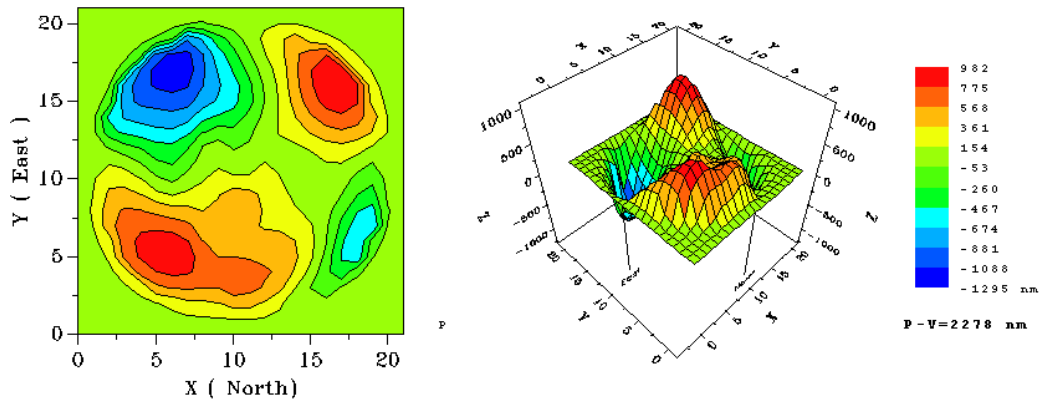
See Zernike polynomials - explanation and theoretical examples of wavefronts, spot diagrams and residuals.

The coefficients for the Annular Zernike polynomials, as well as the total coefficient for the Seidel polynomials are shown in the plots. The diameter containing the 100% Encircled Energy is also shown (in arcsec).

Wavefront	Residuals and spot diagrams	Mirror surface
Examples with following aberrations removed from data		
Only tilt removed	Only tilt removed	
Examples with following aberrations left in the data (all other terms removed)		
Tilt	Tilt	Tilt
Coma	Coma	
Coma higher order		
3rd spherical aberration	3rd spherical aberration	
Astigmatism	Astigmatism	
Triangular coma	Triangular coma	
Quadratic astigmatism	Quadratic astigmatism	
After subtraction of 7 terms	After subtraction of 7 terms	

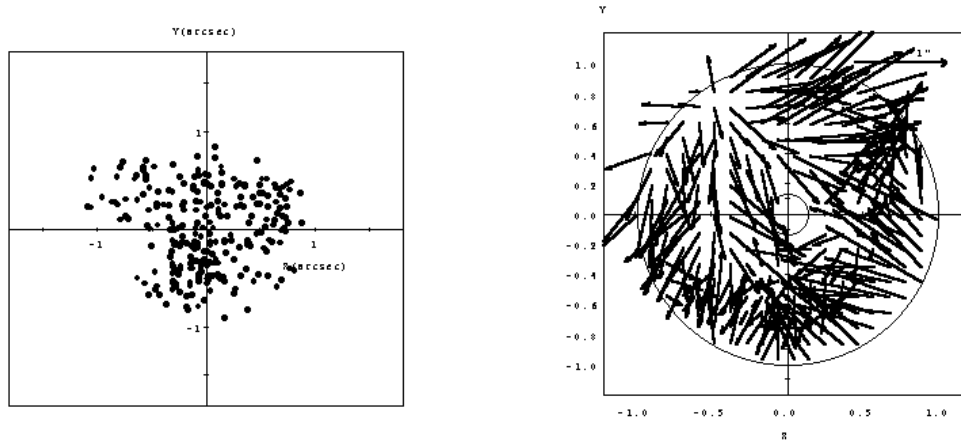
Note: Along with the aberrations left in the data, the wavefront will also show the presence of higher-order aberrations and other sources of noise

10.1.1 Only tilt removed (wavefront)



The effect of the dominant aberration, astigmatism, is seen here.

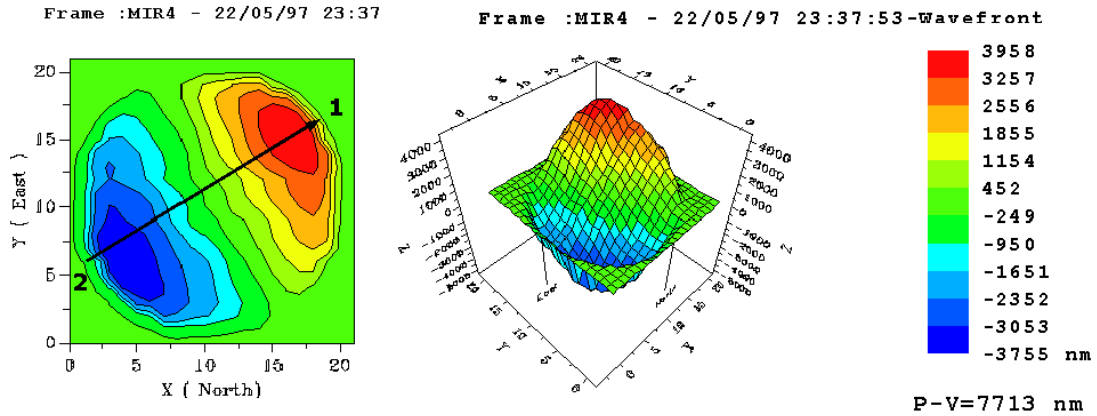
10.1.2 Only tilt removed (spot diagram and residuals)



The effect of the dominant aberrations, coma and astigmatism, is seen here.

10.1.3 Tilt (wavefront)

Zernike coefficients: Annular: $C_x=2087\text{nm}$, $C_y=1250\text{nm}$, $C=2433\text{nm}$
Seidel: 4868nm
Angle= 31°

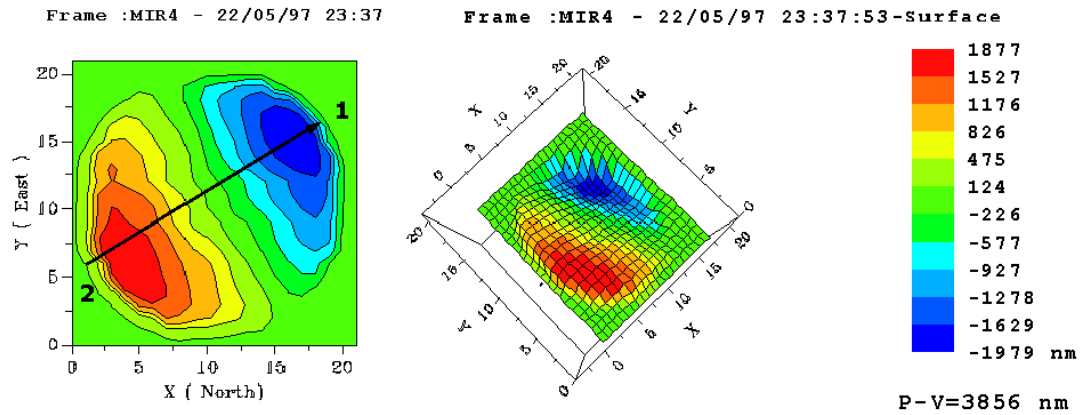


The single peak and single trough (marked by numbers) corresponding to the nature of this aberration (since it has a $\cos \varphi$ dependence) are clearly seen (see section on *Zernike polynomials*).

Also, see the plot of the mirror surface.

10.1.4 Tilt (mirror surface)

Zernike coefficients: Annular: $C_x=2087\text{nm}$, $C_y=1250\text{nm}$, $C=2433\text{nm}$
Seidel: 4868nm
Angle= 31°

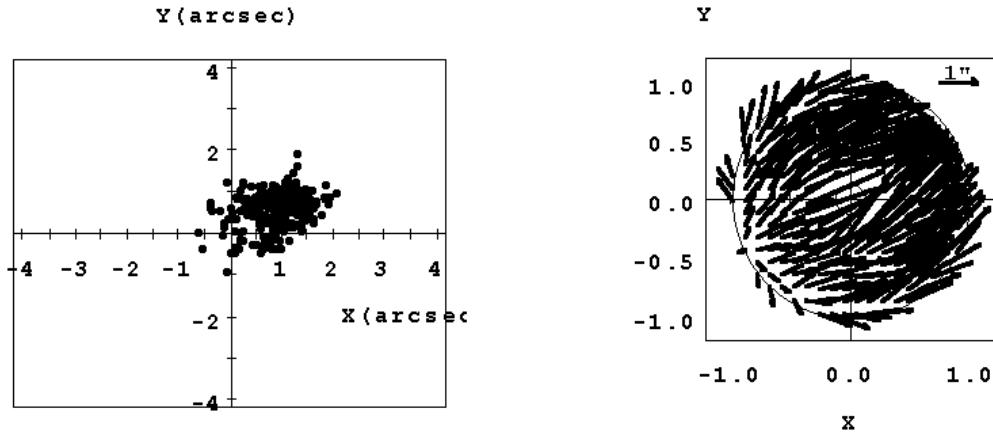


The single peak and single trough (marked by numbers) corresponding to the nature of this aberration (since it has a $\cos \varphi$ dependence) are clearly seen (see section on *Zernike polynomials*).

Since this is the mirror surface, the peak and trough are half that for the wavefront, and of the opposite sign.

10.1.5 Tilt (spot diagram and residuals)

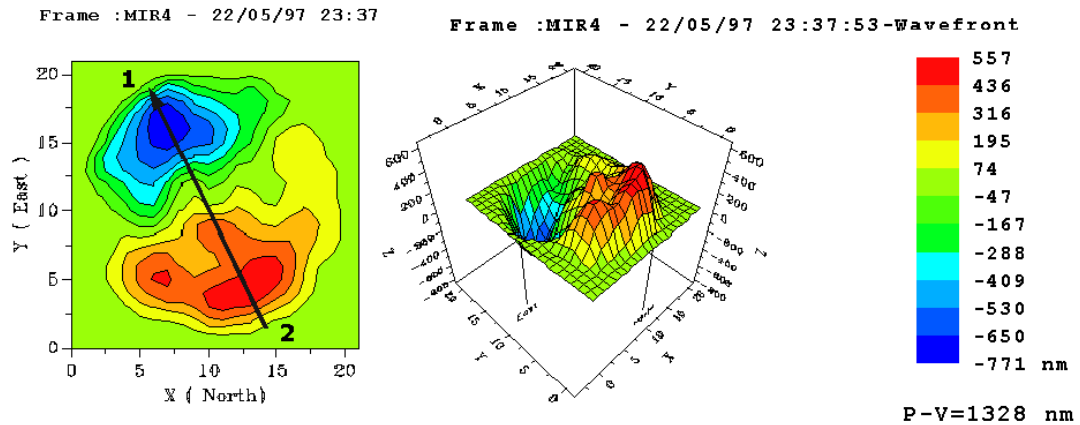
Zernike coefficients: Annular: $C_x=2087\text{nm}$, $C_y=1250\text{nm}$, $C=2433\text{nm}$
Seidel: 4868nm
Angle= 31°



The spot diagram is shifted in the direction of the tilt (31°). The residuals also show the same effect.

10.1.6 Coma (wavefront)

**Zernike coefficients: Annular: $C_x=-74\text{nm}$, $C_y =133\text{nm}$, $C=152\text{nm}$
Seidel: $C=1278\text{nm}$
Angle= 119°**

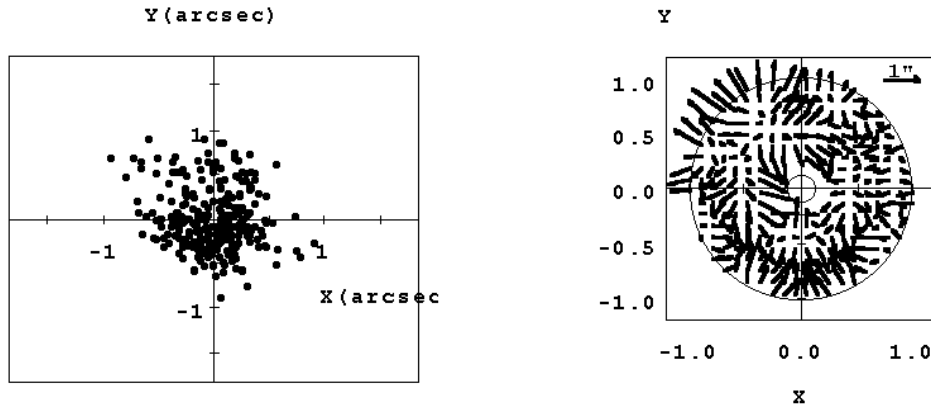


The single peak and single trough (marked by numbers) corresponding to the nature of this aberration (since it has a $\cos\phi$ dependence) are clearly seen (see section on *Zernike polynomials*).

Note that the peak of the wavefront does not correspond to the angle of 119° , but is found to be at $(119+180)^\circ$. This is due to the presence of higher order coma, which when removed, gives the correct orientation.

10.1.7 Coma (spot diagrams and residuals)

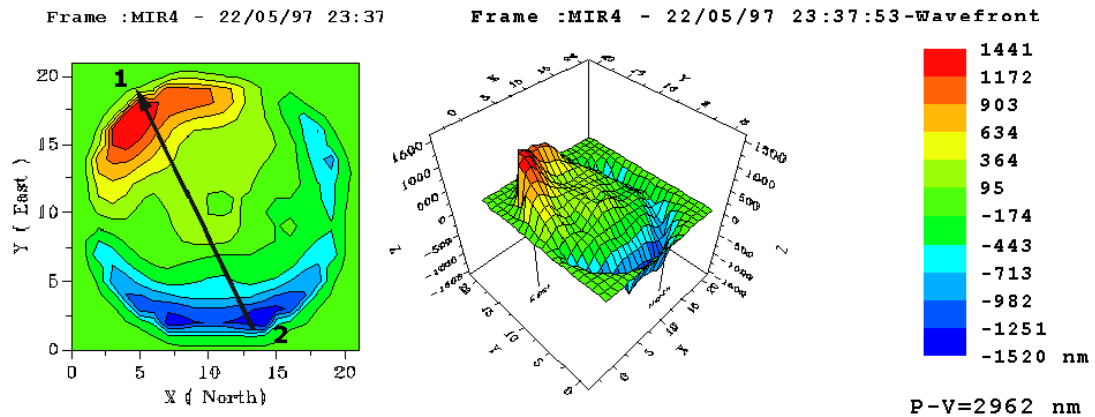
Zernike coefficients: Annular: $C_x=-74\text{nm}$, $C_y=133\text{nm}$, $C=152\text{nm}$;
Seidel: $C=1278\text{nm}$
Angle= 119°
D100= $1.06''$



The spot diagram at left shows that the point of the spot diagram is aligned along a line with an angle of approximately 119° , with the coma flare in the 2nd quadrant (see section on *Zernike polynomials*).

10.1.8 Coma (wavefront, with higher order fit)

Zernike coefficients: Annular: $C_x=-74\text{nm}$, $C_y=133\text{nm}$, $C=152\text{nm}$
Seidel: $C=1278\text{nm}$
Angle= 119°

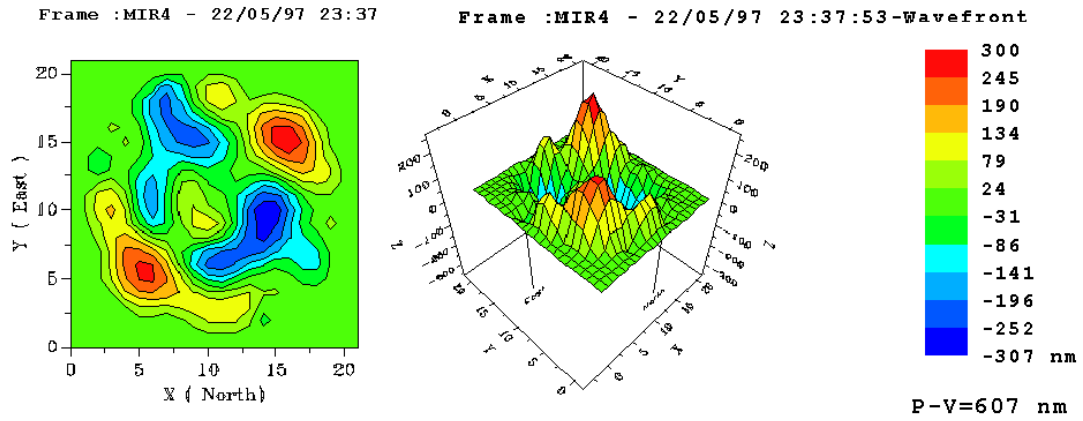


The single peak and single trough (marked by numbers) corresponding to the nature of this aberration (since it has a $\cos\phi$ dependence) are clearly seen (see section on *Zernike polynomials*).

Note how the angle coincides with the peak of the wavefront (red). This was not the case when only 3rd order coma is fitted to the data. In addition, the Seidel coefficient is closer to that shown by the peak of the wavefront.

10.1.9 Spherical aberration (wavefront)

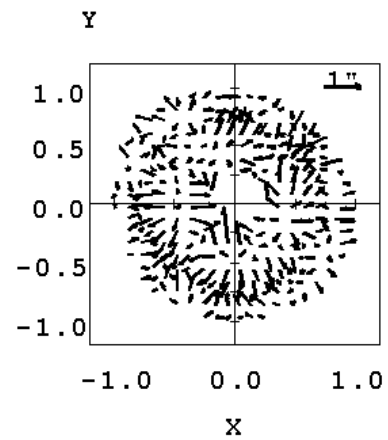
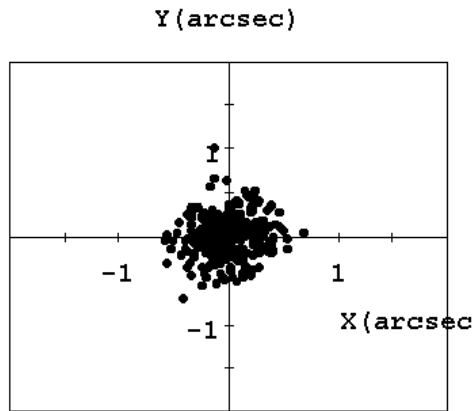
Zernike coefficients: Annular: C=-35nm
Seidel: C=-487nm



The wavefront is not that one would expect for pure spherical aberration due to support errors. Also, see Wavefront after subtraction of 7 terms.

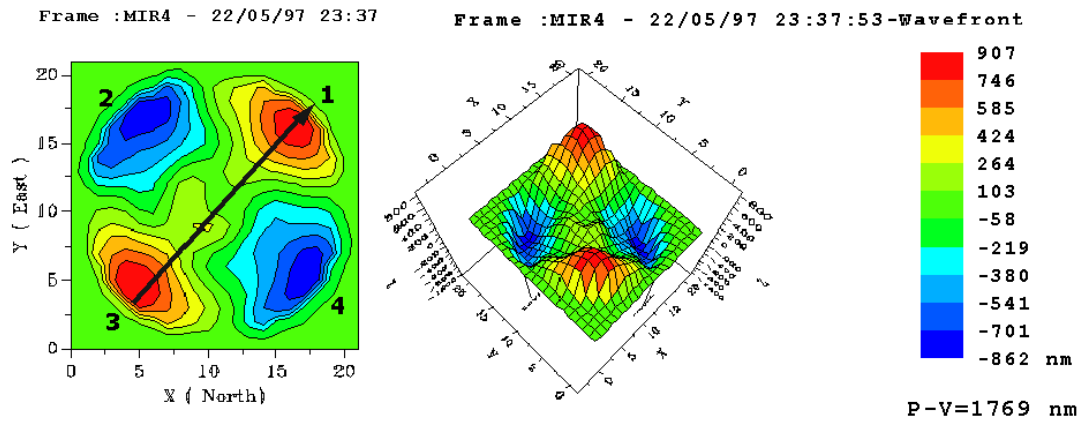
10.1.10 Spherical aberration (spot diagram and residuals)

Zernike coefficients: Annular C=-35nm
Seidel: C=-487nm
D100=0.27"



10.1.11 Astigmatism (wavefront)

Zernike coefficients: Annular: $C_x=276\text{nm}$, $C_y=363\text{nm}$, $C=347\text{nm}$;
Seidel= 881nm
Angle= 49°

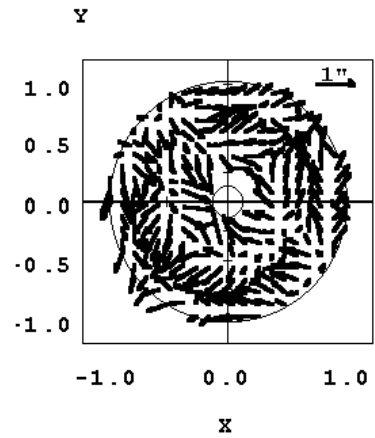
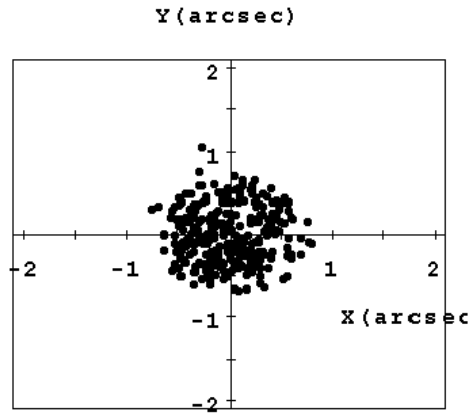


The two peaks and two troughs (marked by numbers) corresponding to the nature of this aberration (since it has a $\cos 2\varphi$ dependence) are clearly seen (see section on *Zernike polynomials*).

The wavefront after subtraction of the first 7 Zernike terms shows that the peak here corresponds to one of the supports of the optical element.

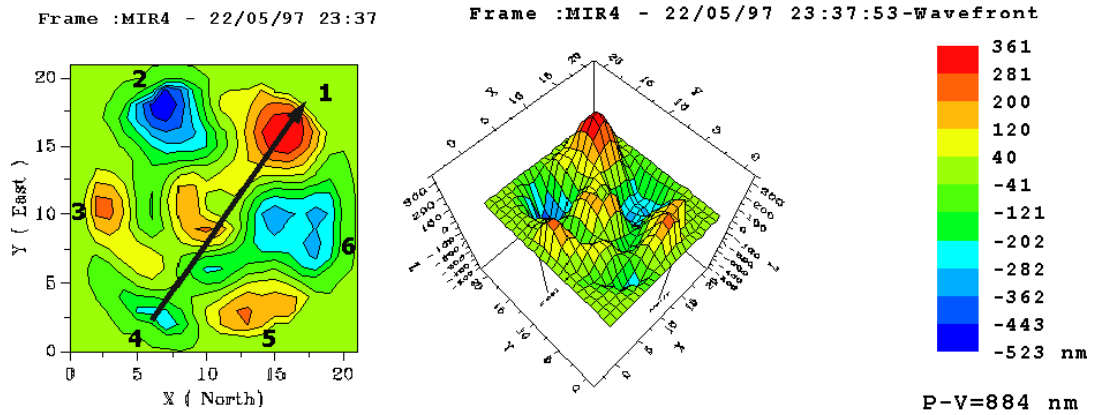
10.1.12 Astigmatism (spot diagram and residuals)

Zernike coefficients: Annular: $C_x=276\text{nm}$, $C_y=363\text{nm}$, $C=347\text{nm}$
Seidel=881nm
Angle=49°
D100=0.98"



10.1.13 Triangular coma (wavefront)

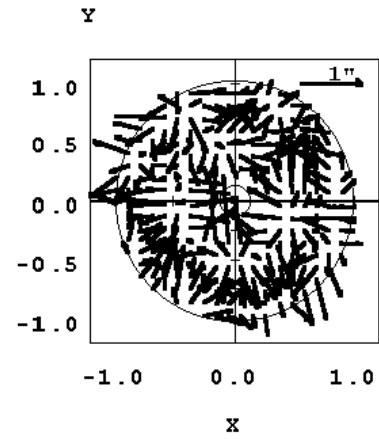
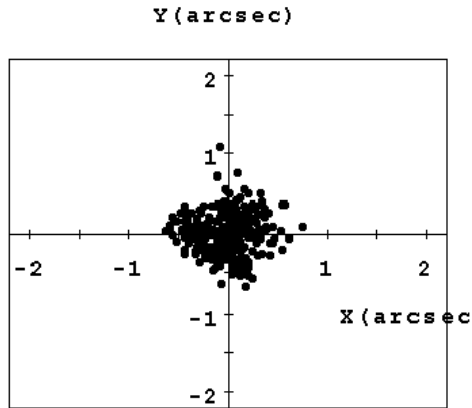
Zernike coefficients: Annular: $C_x=68\text{nm}$, $C_y=91\text{nm}$, $C=114\text{nm}$
Seidel= 318nm
Angle= 53°



The three peaks and three troughs (marked by numbers) corresponding to the triangular nature of this aberration (since it has a $\cos 3\phi$ dependence) are clearly seen (see section on *Zernike polynomials*).

10.1.14 Triangular coma: spot diagram and residuals

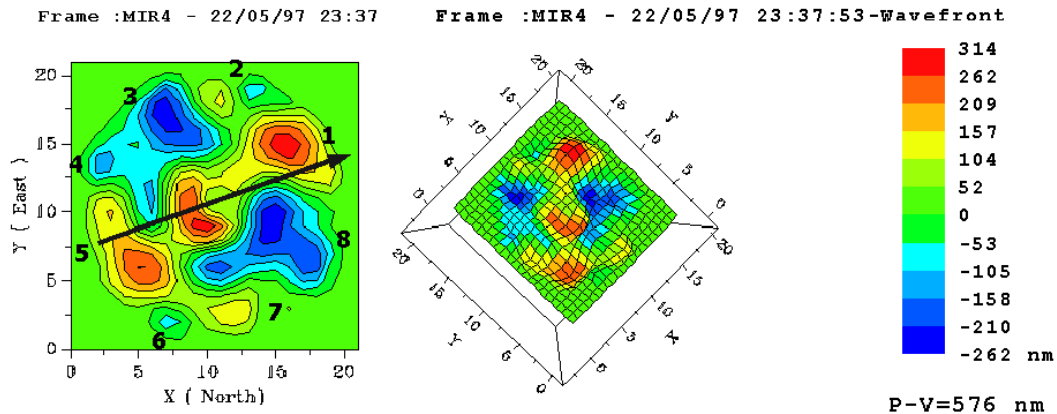
Zernike coefficients: Annular: $C_x=68\text{nm}$, $C_y=91\text{nm}$, $C=114\text{nm}$
Seidel= 318nm
Angle= 53°
D100= $0.53''$



The triangular nature of the image is clearly seen.

10.1.15 Quadratic astigmatism (wavefront)

**Zernike coefficients: Annular: Cx=24nm, Cy=9nm, C=26nm
Seidel=81.4nm.
Angle=20°**



Higher order terms (in this case support problems - see Wavefront after subtraction of 7 terms and astigmatism). These cause a local the four peaks and four troughs (marked by numbers), 45° apart, corresponding to the quadratic nature of this aberration (since it has a $\cos 4\phi$ dependence) are clearly seen (see section on *Zernike polynomials*).

Note:

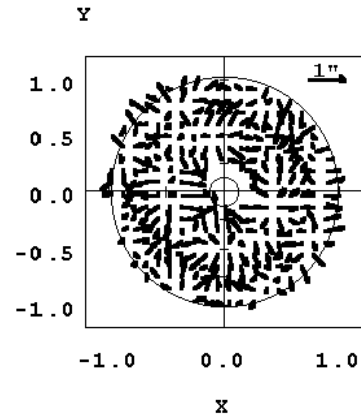
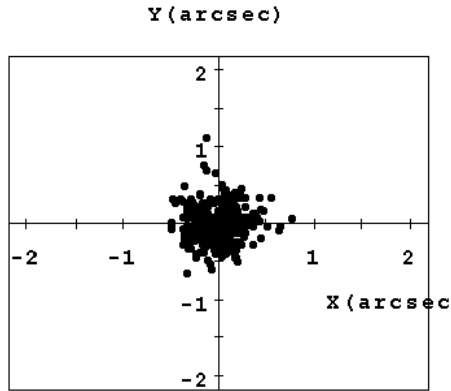
- Number 1 does not correspond exactly to the angle of 20° found from the analysis.
- Number 3, which should actually have been a peak, is here seen to be a trough.

Recall that the wavefront seen here is that due to quadratic astigmatism plus the effect of deformation of the mirror surface, and mask some of the features of quadratic astigmatism.

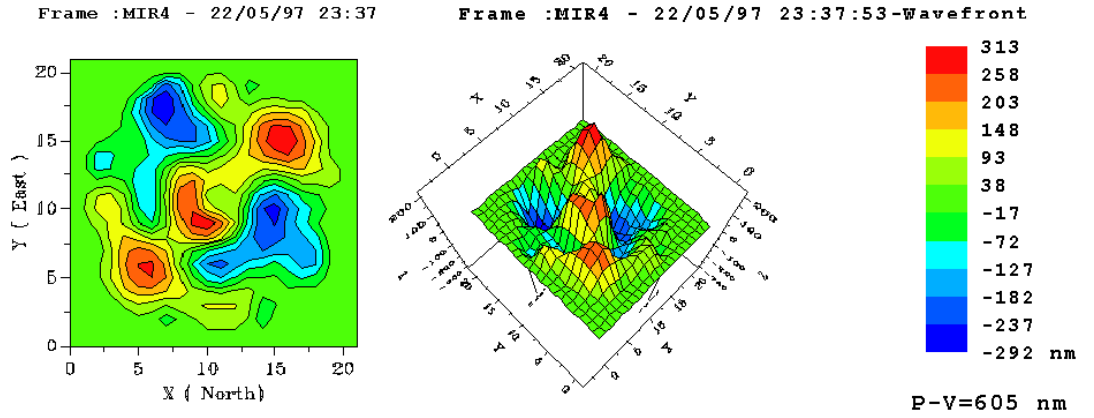
This conclusion is also supported by the fact that unlike for the other aberrations (for example coma) the Seidel coefficient is not half the P-V of the wavefront, indicating that support problems are distorting the wavefront.

10.1.16 Quadratic astigmatism (spot diagram and residuals)

Zernike coefficients: Annular: $C_x=24\text{nm}$, $C_y=9\text{nm}$, $C=26\text{nm}$
Seidel= 81.4nm .
Angle= 20°
D100= $0.18''$

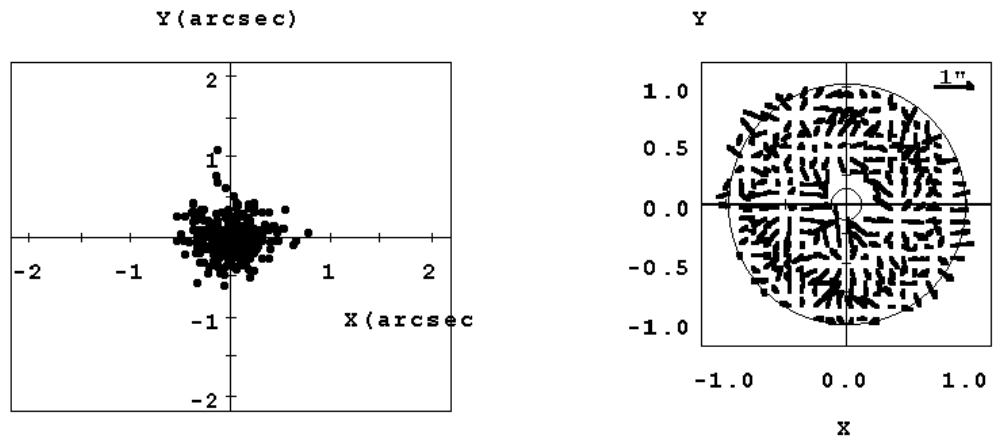


10.1.17 7 terms removed (wavefront)

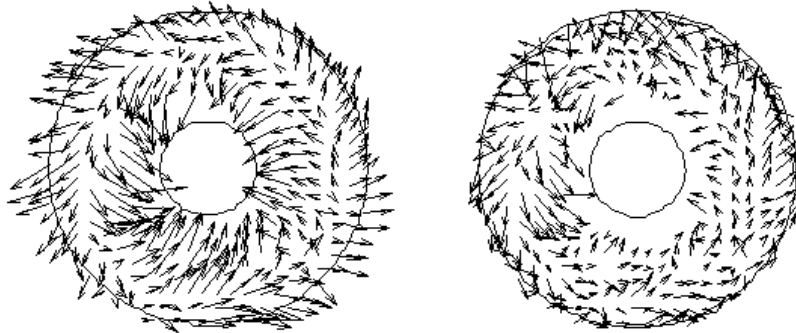


See the correspondence with the wavefront for astigmatism.

10.1.18 7 terms removed (spot diagram and residuals)

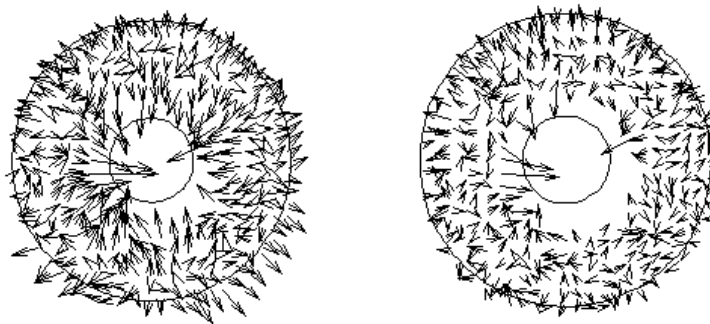


10.2 The problem of air turbulence in a telescope



A plot of the residuals at the points where the mirror wavefront is sampled by the SH grid for a 1.2m telescope

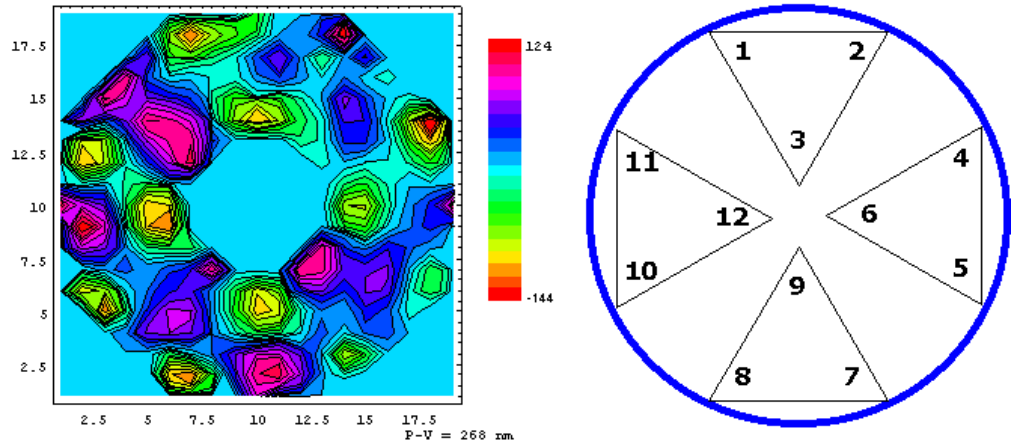
The plot at left show the residuals after the mathematical removal of two Zernike terms: defocus and tilt, while that at right after the removal of 7 Zernike terms. In both cases, it is evident that hot air on the mirror was funneling up, leading to the formation of a vortex on the mirror, as the hot air wrapped itself around the cooler baffle of the primary mirror. The coefficient of SA in this case was 83.8 ± 4.7 nm, or equivalently, $0.89 \pm 0.05''$.



Same as above, but with the telescope pointing in a different direction

There was a strong wind blowing into the dome. This clearly had the effect of blowing away the hot air on the mirror, as the residuals are more randomly distributed now. The coefficient of SA in this case was 73.7 ± 4.7 nm, or $0.78 \pm 0.05''$, similar to the case above. This shows that it is possible to obtain reliable estimates for the aberration coefficients despite the present of air turbulence.

10.3 Mirror support problems



The figure at left shows the mirror surface of a 1.5m telescope after the removal of the first 7 Zernike terms. The imprints of the primary mirror supports are clearly seen (down to a level of about 10nm). This can be confirmed from the figure at right, which shows the layout of the supports.

The SH image also had a very high astigmatism, which clearly was due to these supports not being well adjusted.

Chapter 11: Test configurations

11.1 General comments on the optical setup for testing with Optino, OMI, Puntino Lentino, Sfera, Stella and Opal

The general principle of the SH method consists of forming an image of the exit pupil of the optical element (or system) being tested on the SH grid. Puntino, Optino, OMI, Lentino, Sfera, Stella and Opal follow this design constraint for a standard optical setup.

Strictly speaking, this condition is generally required only when imaging an off-axis object. If it is important for your application, special optical attachments can be provided for reimaging the pupil exactly on the SH grid.

Various configurations which can be used for the SH test are described in this section. The two modes of illuminating the test element are:

- **External illumination:** Optino/OMI/Lentino/Puntino/Sfera/Stella/Opal
- **Internal illumination:** Optino/Opal

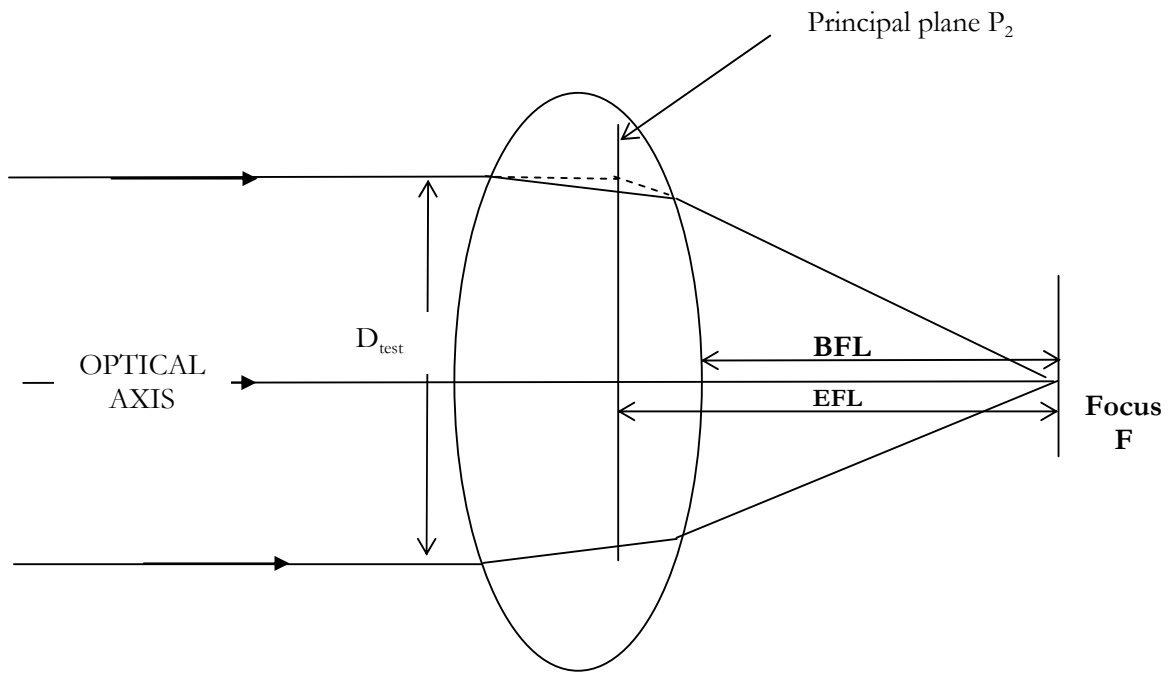
We have made every effort to cover all the possible test setups, but the user may wish to use other setups (e.g., for diverging and cylindrical lenses). Special setups can also be devised for elements that cannot be tested using the setups described here.

Please contact SpotOptics if you require any clarification.

A whole range of accessories (including mountings) is available from SpotOptics. Some of them are mentioned in this manual

The reference flat **RF** and reference sphere **RS** define the ultimate accuracy achieved

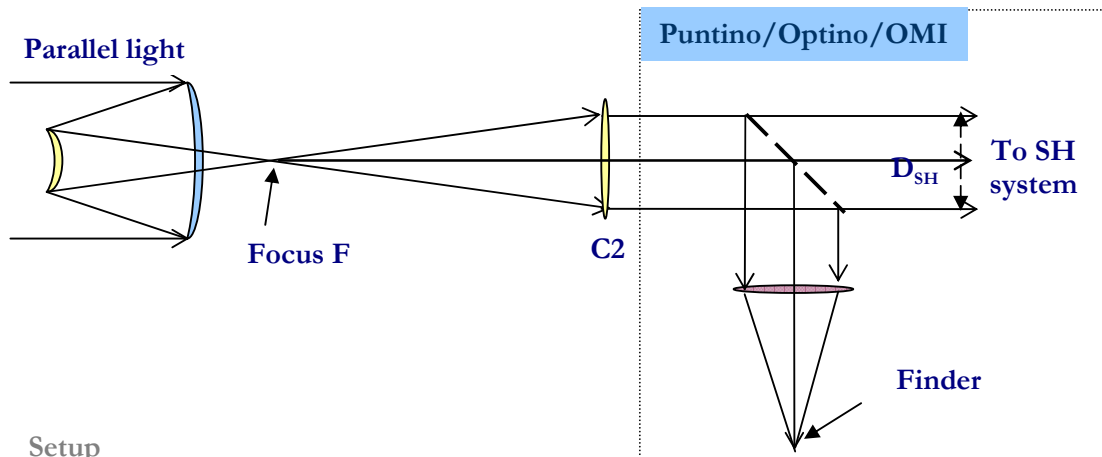
11.2 Terminology



1. The above figure shows parallel light falling on a lens of free aperture D_{test} . It comes to a focus F
2. The effective focal ratio is defined as $F_{eff} = D_{test} / f$, where D_{test} is the free aperture, and f the effective focal length
3. When the optical element is illuminated with the object at a finite distance o the image is formed at a distance i , and $F_{eff} = D_{test} / i$
4. It is also possible to use the diameter of the exit pupil instead of the aperture. Then f or i are measured from the position of the exit pupil

11.3 Tests using external illumination

Setup 1: Test of telescope at Cassegrain focus



Setup

The telescope is illuminated with parallel light (**Cal25** or **ECM25**), which comes to focus at **F**. **C2** collimates this light which is used for analysis. The collimator **C2** can be changed to match the focal ratio of the telescope.

In the case of an astronomical telescope, a natural star is used, with the aberrations due to the earth's atmosphere being removed by integrating the SH image for at least 30 seconds.

It is not necessary to use parallel light for the test. The measured aberrations will then no longer refer to those for parallel light, but to one particular optical configuration that is used for the test.

In **Puntino**, a beam-splitter is used to divert part of the parallel light to a camera lens and a second camera. This is used to acquire the star, as well as to get out-of-focus images of the telescope pupil. It gives additional information on the telescope quality (like zones on the mirror surface) and seeing.

In **Optino**, the filter holder can be replaced with an optional camera.

Instrument

Puntino/Optino/OMI

Calibration

The aberrations of the **Optino/OMI** and the collimator **C2** are removed by using **PH50** placed at the focus of **C2**. With **Puntino**, the calibration is done with a remotely controlled calibration unit inside the instrument.

Input values for wavefront analysis

D_{test} (free aperture of primary mirror), fl_{test} (focal length of telescope), fl_{col} (focal length of collimator). If the aperture stop is defined by the secondary mirror, then the size and distance of the exit pupil should substitute D_{test} and fl_{test} .

Other input values

β : The back focal distance in units of the focal length of the primary mirror (used in the computations for the coma correction).

K_2 : Conic coefficient of the secondary mirror. Used in the computation of coma and spherical aberration correction.

For the sake of completeness, other values of the telescope are also requested. They are not used in the analysis of the wavefront.

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus (by changing the separation between the mirrors), coma (alignment of the two elements) and spherical aberration (by changing the separation between the mirrors and shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user for any optical element in the system.

Defocus and spherical aberration are corrected by moving the secondary mirror. The spherical aberration measured by Sensoft refers to the best focal plane.

Information can be obtained of dome and mirror seeing by examining the plot of the residuals.

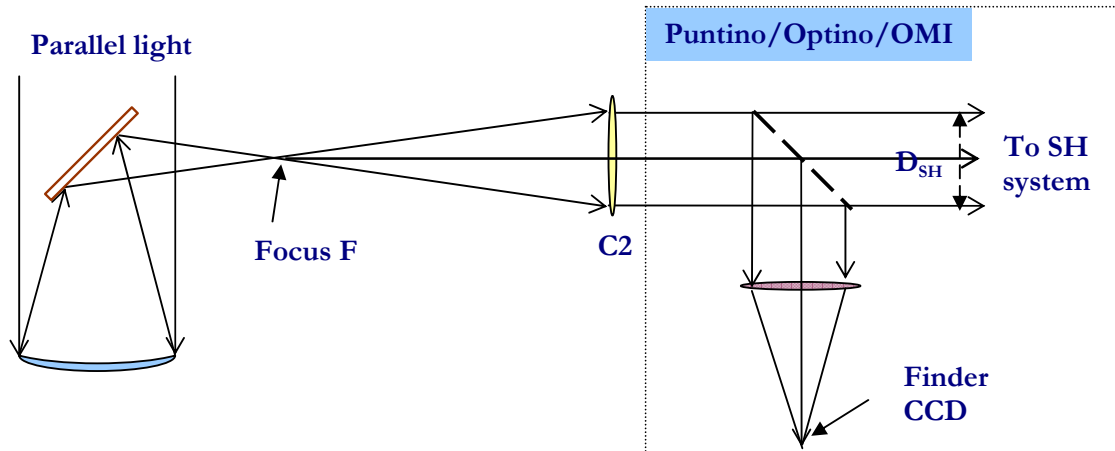
Single or double pass

Single pass. Note that since reflection doubles the aberrations, the mirror surface is half the wavefront computed by Sensoft, and has opposite sign.

Components required

1. Test telescope
2. **Cal25** or **ECM25** for illuminating telescope in lab or a natural star
3. Collimator **C2** to match focal ratio of telescope
4. **Optino/OMI: PH50** for calibration of collimator **C2**
5. **Puntino**: Internal calibration light source for calibration of collimator **C2**
6. Mountings

Setup 2: Telescope at Prime/Newtonian focus



Setup

The telescope is illuminated with parallel light (**Ca125** or **ECM25**), which comes to focus at **F**. **C2** collimates this light which is used for analysis. The collimator **C2** can be changed to match the focal ratio of the telescope.

In the case of an astronomical telescope, a natural star is used, with the aberrations due to the earth's atmosphere being removed by integrating the SH image for at least 30 seconds.

It is not necessary to use parallel light for the test. The measured aberrations will then no longer refer to those for parallel light, but to one particular optical configuration that is used for the test.

In **Puntino**, a beam-splitter is used to divert part of the parallel light to a camera lens and a second camera. This is used to acquire the star, as well as to get out-of-focus images of the telescope pupil. It gives additional information on the telescope quality (like zones on the mirror surface) and seeing.

In **Optino**, the filter holder can be replaced with an optional camera.

Instruments

Puntino/Optino/OMI

Calibration

The aberrations of the **Optino/OMI** and the collimator **C2** are removed by using **PH50** placed at the focus of **C2**. With **Puntino**, the calibration is done with the remotely controlled calibration unit inside the instrument.

Input values for wavefront analysis

D_{test} (free aperture of primary mirror), fl_{test} (focal length of test element), fl_{col} (focal length of collimator).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (by moving **M2** and shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user for any optical element in the system.

Information can be obtained of dome and mirror seeing by examining the plot of the residuals.

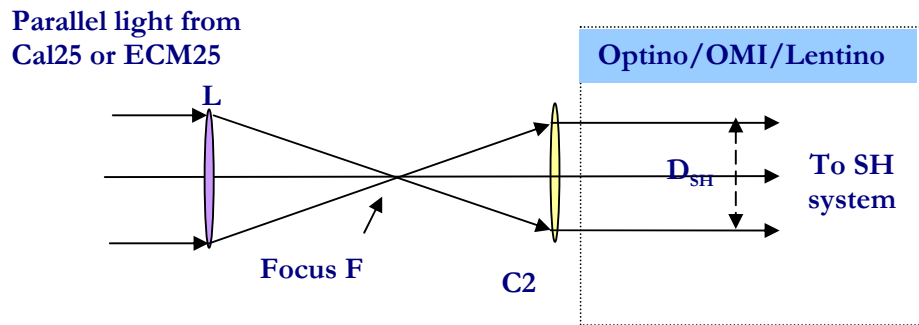
Single or double pass

Single pass. Note that since reflection doubles the aberrations, the mirror surface is half the wavefront computed by Sensoft, and has opposite sign.

Components required

1. Test telescope
2. **Cal25** or **ECM25** for illuminating telescope in lab or a natural star
3. Collimator **C2** to match focal ratio of telescope
4. **Optino/OMI: PH50** for calibration of collimator **C2**
5. **Puntino**: Internal calibration light source for calibration of collimator **C2**
6. Mountings

Setup 3: Single lens in parallel light (infinite-finite conjugates)



Setup

Parallel light from **Cal25** or **ECM25** falls on the lens **L** being tested, and comes to a focus at **F**. After passing through the focus, it is made parallel by the collimator **C2** (which can be changed to match the focal ratio of the lens **L**) and falls on **Optino/OMI/Lentino/Stella/Sfera/Opal**.

It is not necessary to use parallel light for the test. The measured aberrations will then no longer refer to those for parallel light, but to the particular optical configuration that is used for the test. See next section.

Instruments

Optino/OMI/Lentino/Stella/Sfera/Opal

Calibration

The aberrations of the **Optino/OMI/Lentino/Stella/Sfera/Opal** together with that of the collimator **C2** are removed by using **PH50** placed at the focus of **C2**.

Input values for wavefront analysis

D_{test} (free aperture of test element), $f_{l_{test}}$ (focal length of test element), $f_{l_{col}}$ (focal length of collimator).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (shift of focal plane of the lens). These corrections are based on analytical formulae, or on a lookup table provided by the user.

Single or double pass

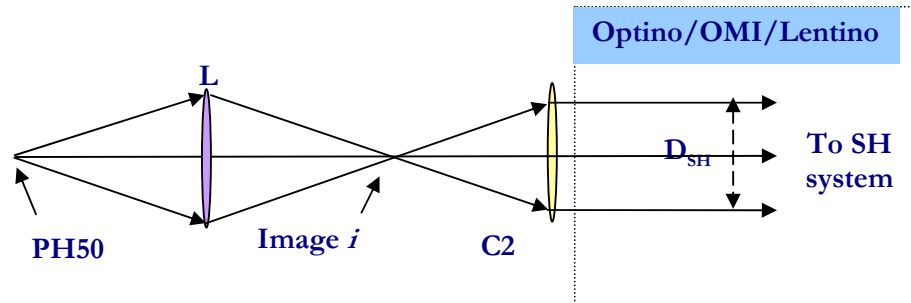
Single pass

Components required

1. Test lens
2. **Cal25** or **ECM25** for illuminating test lens
3. Collimator **C2** to match focal ratio of lens
4. **PH50** for calibration of collimator **C2** and **Optino/OMI**

5. Mountings

Setup 4: Single lens in diverging light (finite-finite conjugates)



Setup

PH50 is placed at a finite distance from the lens, which forms an image i . This is also the focus of the collimator **C2**, which illuminates **Optino/OMI/Lentino/Stella/Sfera/Opal** with parallel light. **C2** can be changed to match the effective focal ratio F_{eff} of the lens **L**

Instruments

Optino/OMI/Lentino/Stella/Sfera/Opal

Calibration

The aberrations of the **Optino/OMI/Lentino/Stella/Sfera/Opal** and the collimator **C2** are removed by using **PH50** placed at the focus of **C2**.

Input values for wavefront analysis

D_{test} (free aperture of test element), i (image distance – measured from principal plane), f_{col} (focal length of collimator).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (which is minimized by shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user.

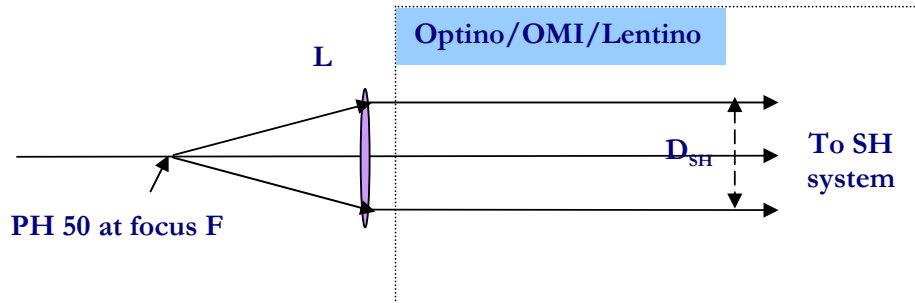
Single or double pass

Single pass

Components required

1. Test lens
2. **PH50** for illuminating test lens
3. Collimator **C2** to match the effective focal ratio $F_{eff} = D_{test}/i$ of lens
4. **PH50** for calibration of collimator **C2** together with **Optino/OMI/Lentino**
5. Mountings

Setup 5: Single lens at its focus (finite-infinite conjugates)



Setup

PH50 is placed at the focus of the lens **L**, which then illuminates **Optino/OMI/Lentino/Stella/Sfera/Opal** with parallel light.

Instrument

Optino/OMI/Lentino/Stella/Sfera/Opal

Calibration

The aberrations of **Optino/OMI/Lentino/Stella/Sfera/Opal** are removed by taking a calibration image with **Cal25** or **ECM25**.

Input values for wavefront analysis

D_{test} (free aperture of test element), i (image distance – measured from principal plane), f_{col} (focal length of collimator).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (minimized by shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user.

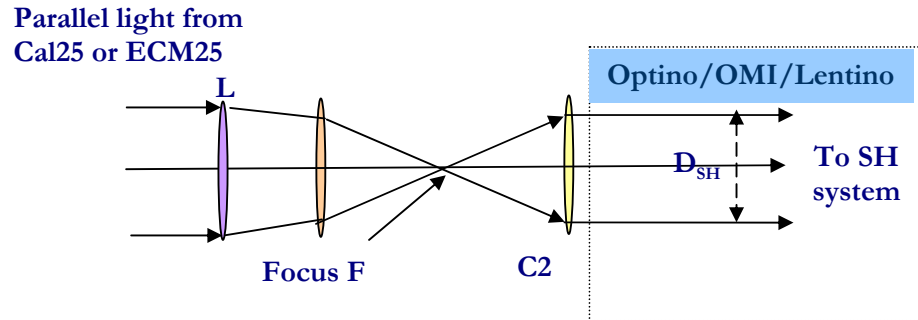
Single or double pass

Single pass

Components required

1. Test lens
2. **PH50** for illuminating test lens
3. **Cal25** or **ECM25** for calibration of **Optino/OMI/Lentino/Stella/Sfera/Opal**
4. Mountings

Setup 6: Multi-component lens in parallel light (infinite-finite conjugates)



Setup

Cal25 or **ECM25** is used to illuminate the two-lens system **L** with parallel light. The image is formed at the focus at the focus **F**, which is also the focus of the collimator **C2**, giving parallel light that illuminates **Optino/OMI/Lentino/Stella/Sfera/Opal**. Any number of elements that form a converging system can be tested together. The collimator **C2** can be changed to match the effective focal ratio F_{eff} of the lens **L**.

It is not necessary to use parallel light for the test. The measured aberrations will then no longer refer to those for parallel light, but to one particular optical configuration that is used for the test. See next section.

Instrument

Optino/OMI/Lentino/Stella/Sfera/Opal

Calibration

The aberrations of the **Optino/OMI/Lentino/Stella/Sfera/Opal** together with that of the collimator **C2** are removed by using **PH50** placed at the focus of **C2**.

Input values for wavefront analysis

D_{test} (free aperture of test element), f_{test} (focal length of test element), f_{col} (focal length of collimator).

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus, coma (by aligning the elements) and spherical aberration (by changing the separation between the elements and using a new focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user for any optical element in the system.

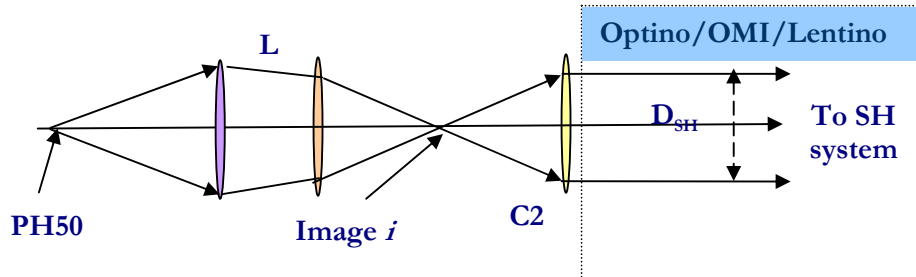
Single or double pass

Single pass

Components required

1. Test lens
2. **Cal25** or **ECM25** for illuminating test lens
3. Collimator **C2** to match focal ratio of lens
4. **PH50** for calibration of **C2** and **Optino/OMI/Lentino/Stella/Sfera/Opal**
5. Mountings

Setup 7: Multi-component lens in diverging light (finite-finite conjugates)



Setup

PH50 is placed at a finite distance from the two-lens system L, which forms an image *i*. This is also the focus of the collimator C2, which illuminates Optino/OMI/Lentino/Stella/Sfera/Opal with parallel light. C2 can be changed to match the effective focal ratio F_{eff} of the lens L

Any number of elements that form a converging system can be tested together.

Instrument

Optino/OMI/Lentino/Stella/Sfera/Opal

Calibration

The aberrations of the Optino/OMI/Lentino/Stella/Sfera/Opal and the collimator C2 are removed by using PH50 placed at the focus of C2.

Input values for wavefront analysis

D_{test} (free aperture of test element), *i* (image distance – measured from principal plane), f_{col} (focal length of collimator).

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus, coma (by aligning the elements) and spherical aberration (by changing the separation between the elements and using a new focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user for any optical element in the system.

Single or double pass

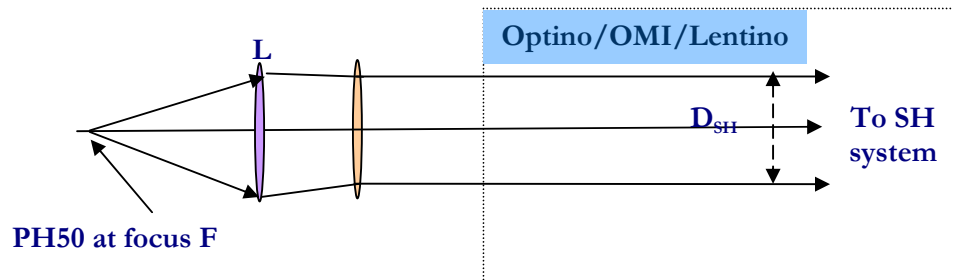
Single pass

Components required

1. Test lens
2. PH50 for illuminating test lens
3. Collimator C2 to match focal ratio of test lens

4. PH50 for calibration of C2 along with Optino/OMI/Lentino/Stella/Sfera/Opal

Setup 8: Multi-component lens at its focus (finite-infinite conjugates)



Setup

PH50 is placed at the focus of the two-lens system **L**, which then illuminates **Optino/OMI/Lentino/Stella/Sfera/Opal** with parallel light. Any number of elements that form a converging system can be tested together.

Instrument

Optino/OMI/Lentino/Stella/Sfera/Opal

Calibration

The aberrations of **Optino/OMI/Lentino/Stella/Sfera/Opal** are removed by taking a calibration image with **Cal25** or **ECM25**.

Input values for wavefront analysis

D_{test} (free aperture of test element), i (image distance – measured from principal plane), f_{col} (focal length of collimator).

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus, coma (by aligning the elements) and spherical aberration (by changing the separation between the elements and using a new focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user for any optical element in the system.

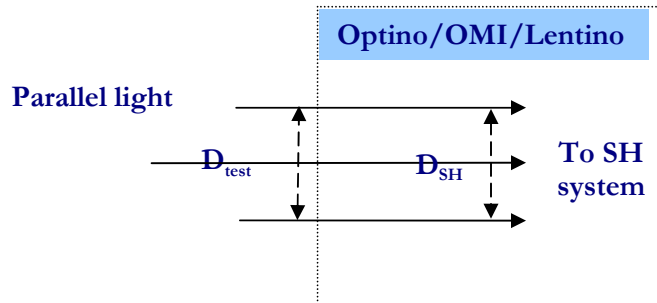
Single or double pass

Single pass

Components required

1. Test lens
2. **PH50** for illuminating test lens
3. **Cal25** or **ECM25** for calibration of **Optino/OMI/Lentino/Stella/Sfera/Opal**
4. Mountings

Setup 9: Parallel light (provided by user)



Setup

Parallel light provided by the user is used to illuminate **Optino/OMI/Lentino/Stella/Sfera/Opal**

Instrument

Optino/OMI/Lentino/Stella/Sfera/Opal

Beam expander

BE25 or **BE60** can be used to expand (or compress) the size of the output beam for optimum spot sampling (**Optino** and **OMI** only).

Calibration

Cal25 or **ECM25** is used to illuminate **Optino/OMI/Lentino/Stella/Sfera/Opal**.

Input values for wavefront analysis

D_{test} (diameter of test beam)

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus.

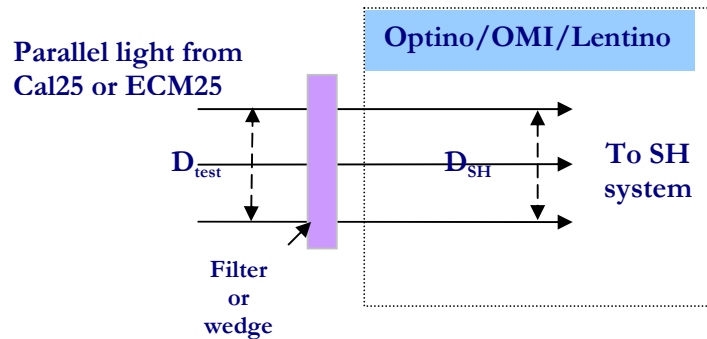
Single or double pass

Single pass

Components required

1. User supplied parallel light
2. **Cal25** or **ECM25** for calibration of **Optino/OMI/Lentino/Stella/Sfera/Opal**
3. Mountings

Setup 10: Filters, optical windows and wedges (single pass)



Setup

Cal25 or ECM25 illuminate **Optino/OMI/Lentino**. Optical elements like filters, optical windows and wedges can be tested by inserting them in the parallel optical beam.

Instrument

Optino/OMI

Beam expander

BE25 or BE60 can be used to expand (or compress) the size of the input beam for optimum spot sampling (**Optino** and **OMI** only).

Calibration

Cal25 or ECM25 is used to illuminate **Optino/OMI/Lentino** directly.

Input values for wavefront analysis

D_{test} (diameter of test beam)

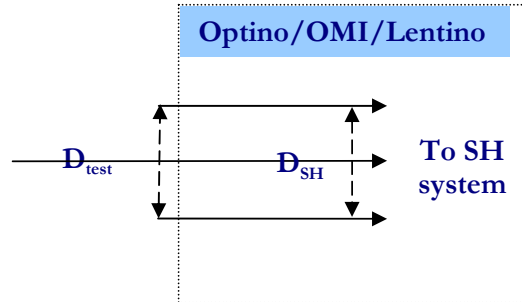
Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus.

Components required

1. Cal25 or ECM25 for illumination/calibration of **Optino/OMI/Lentino**

Setup 11: Lasers



Setup

A laser beam, appropriately attenuated, is fed into **Optino/OMI/Lentino**.

Instrument

Optino/OMI/Lentino

Beam expander

BE25 or **BE60** can be used to expand (or compress) the size of the laser.

Calibration

Cal25 or **ECM25** is used to illuminate **Optino/OMI** directly.

Input values for wavefront analysis

D_{test} (diameter of laser beam), θ (angle of divergence), M (magnification or compression factor of beam expander, if used).

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus. Other output: M^2 and θ .

Single or double pass

Single pass

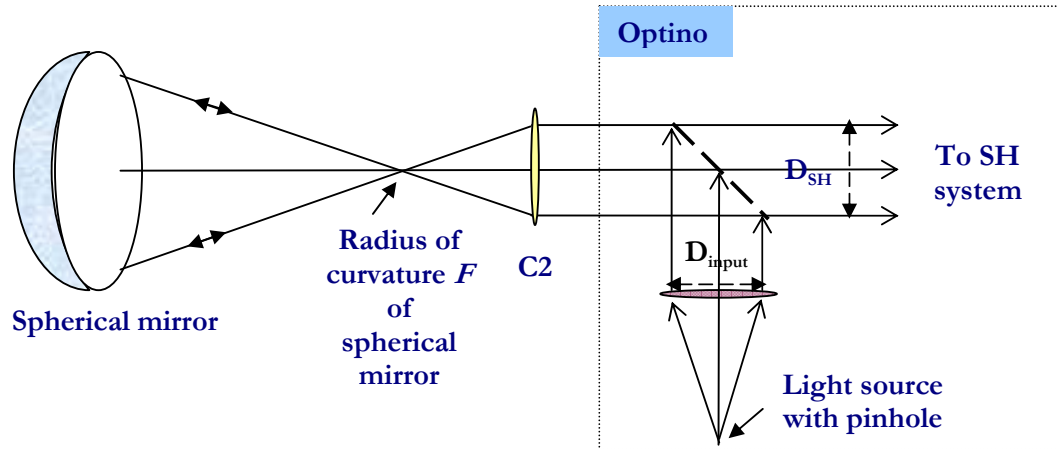
Components required

1. User supplied laser
2. **Cal25** or **ECM25** for calibration of **Optino/OMI** and **BE25/BE60** (if used)

11.4 Tests with internal illumination

All the tests done in double pass require the use of any of the models of Optino (OptinoUno, OptinoPro or OptinoEE)

Setup 12: Concave mirror



Setup

Parallel light from **Optino/Opal** passes through the collimator **C2** and comes to a focus at **F**, which is also the radius of curvature of the test spherical mirror. The focal ratio of the collimator **C2** should be twice that of the focal ratio of the spherical mirror, as it is being tested at its radius of curvature.

Instrument

Optino/Opal

Calibration

The aberrations of the collimator **C2** and **Optino** are removed by taking a reference image with the reference sphere **RS**.

Input values for wavefront analysis

D_{test} (free aperture of spherical mirror), f_{test} (focal length of test element), f_{col} (focal length of collimator **C2**).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (which is minimized by shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user.

The test can also be used to derive the conic coefficient K from the measured ASA . The spherical aberration of a mirror at its center of curvature is given by:

$$ASA = -K \frac{r^3}{2R^3}$$

Here ASA is the angular spherical aberration (diameter of image at best focus – in radians), K the conic coefficient of the mirror, r the ray height on the mirror, and R the radius of curvature. Spherical mirrors have zero ASA ($K=0$), while parabolic ($K=-1$) and hyperbolic ($K<-1$) mirrors have large positive spherical aberration. However, Sensoft is capable of testing mirrors with hundreds of wavelengths of aberrations.

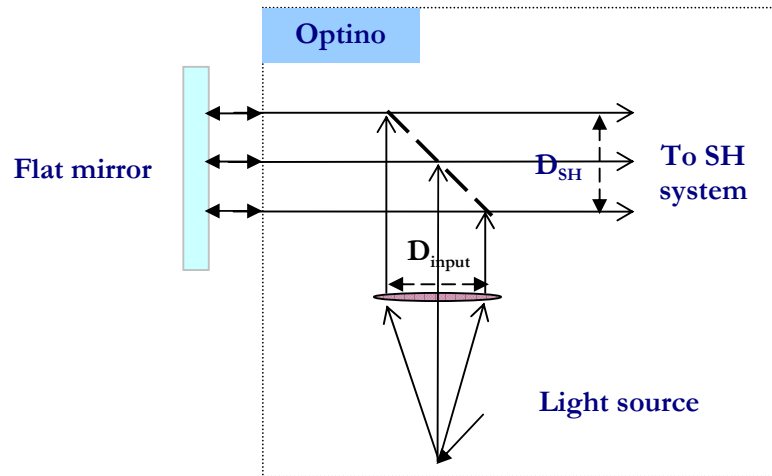
Single or double pass

Single pass

Components required

1. Test mirror
2. Collimator **C2**
3. Reference sphere **RS**
4. Mountings

Setup 13: Flat mirror (single pass)



Setup

Parallel light from **Optino/Opal** illuminates the test flat mirror, which reflects it back into **Optino/Opal**.

Instrument

Optino/Opal

Beam expander

BE25 or **BE60** can be used to expand (or compress) the size of the output beam for optimum spot sampling.

Calibration

The aberrations of **Optino/BE** or **Opal** are removed using the reference flat **RF** instead of the test mirror.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element),

M (magnification or compression factor of beam expander, if used).

Output information

Sensoft gives the Zernike coefficient, the wavefront and optical quality of the flat mirror.

Single or double pass

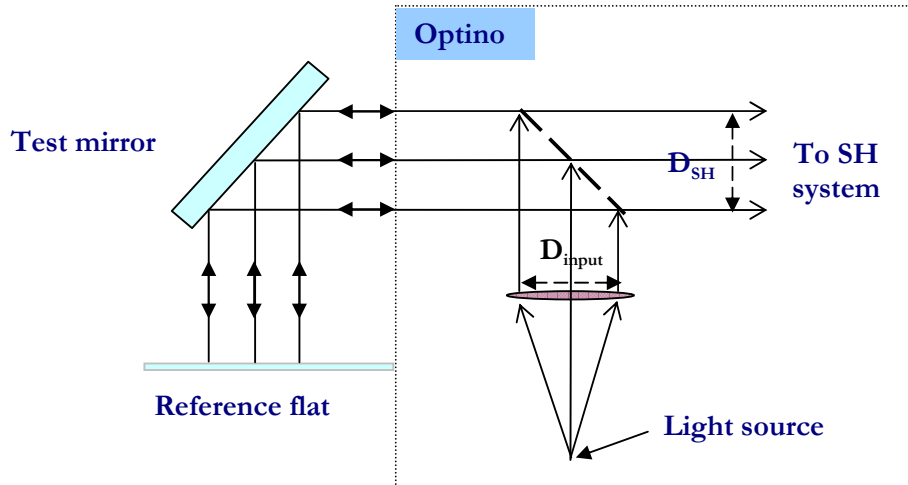
Single pass

Components required

1. Test mirror
2. Reference flat **RF**
3. Beam expander **BE25** or **BE60**

4. Mountings

Setup 14: Flat mirror (double pass)



Setup

Parallel light from **Optino/Opal** illuminates the test mirror mounted at 45° . Subsequently, the light falls on the flat mirror and is reflected back into **Optino/Opal**.

Instrument

Optino/Opal

Beam expander

BE25 or **BE60** can be used to expand (or compress) the size of the output beam for optimum spot sampling.

Calibration

The aberrations of **Optino/BE** or **Opal** are removed by using the reference flat **RF**. In principle, a standard flat mirror can also be used, as it is used for both the test and reference image. However, there is a greater chance that it will give a lower accuracy due to the same area not being exactly illuminated in both the images.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element),

M (magnification or compression factor of beam expander, if used).

Output information

Sensoft gives the Zernike coefficient, the wavefront and optical quality of the flat mirror.

Single or double pass

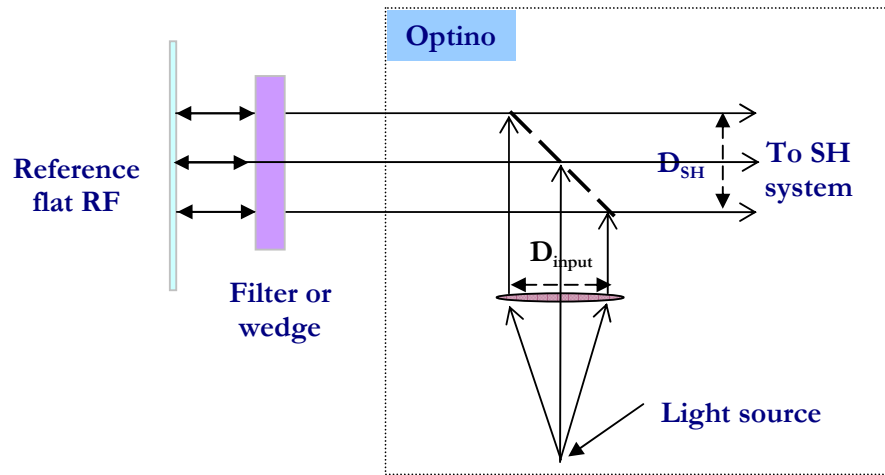
Double pass

Components required

1. Test mirror
2. Reference flat **RF**
3. Beam expander **BE25** or **BE60**

4. Mountings

Setup 15: Filters, optical windows and wedges (double pass)



Setup

Parallel light from **Optino/Opal** illuminates the reference flat **RF**, which reflects it back into **Optino/Opal**.

The test element (filter, optical window or wedge) is inserted before the flat mirror.

Instrument

Optino/Opal

Beam expander

BE25 or **BE60** can be used to expand (or compress) the size of the output beam for optimum spot sampling.

Calibration

The reference image is taken with the reference flat **RF** (without the test element).

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element),

M (magnification or compression factor of beam expander, if used).

Output information

Sensoft gives the Zernike coefficient, the wavefront and optical quality of the flat mirror.

Single or double pass

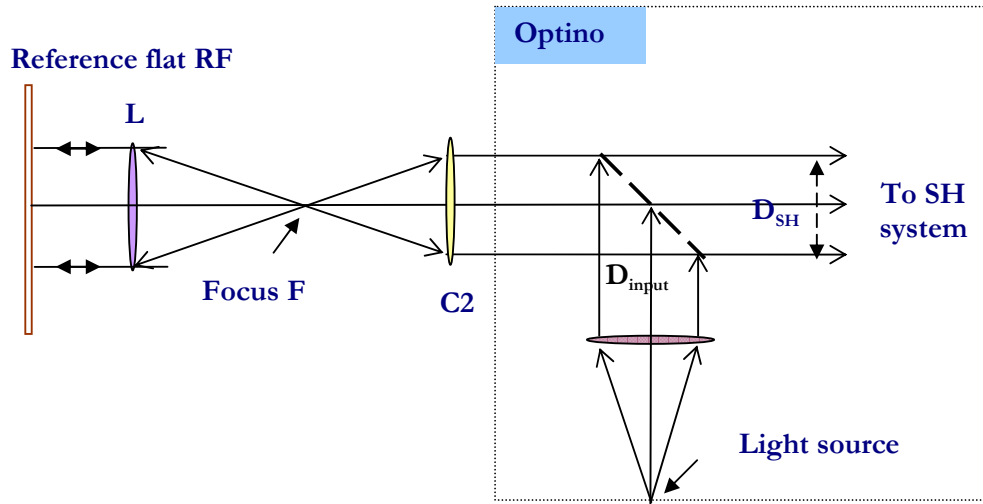
Single pass

Components required

1. Test element
2. Reference flat **RF**

3. Beam expander **BE25** or **BE60**
4. Mountings

Setup 16: Small single lens using collimator and flat mirror
(finite-infinite conjugates)



Setup

Parallel light from **Optino/Opal** passes through the collimator **C2** and comes to a focus at **F**, which is also the focus of the test lens **L**. Collimated light from **L** falls on the reference flat **RF**, and is reflected back into **Optino/Opal**. **RF** should have a minimum diameter equal to the aperture of the lens **L**, and the focal ratio of the collimator **C2** should match that of the lens **L**.

Instrument

Optino/Opal

Calibration

The aberrations of **Optino/Opal** as well as the collimator **C2** are removed by using the reference sphere **RS**.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), f_{test} (focal length of test element), f_{col} (focal length of collimator **C2**).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (which is minimized by shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user.

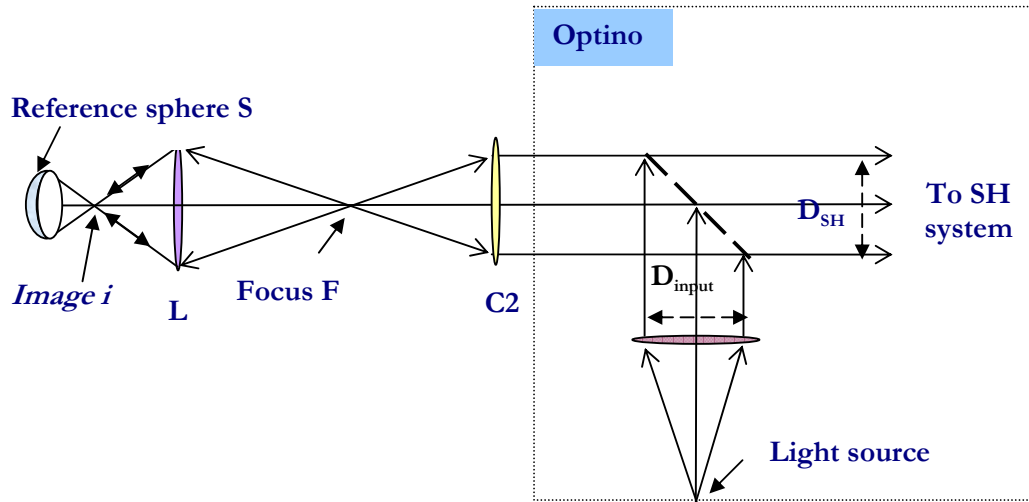
Single or double pass

Double pass

Components required

1. Test lens
2. Collimator **C2**
3. Reference flat **RF**
4. Reference sphere **RS**

Setup 17: Single lens using collimator and spherical mirror
(finite-finite conjugates)



Setup

Parallel light from **Optino/Opal** passes through the collimator **C2** and comes to a focus at its focus **F**, which is at an object distance o from the test lens **L**. The lens **L** forms an image at a distance i . The light then falls on the reference sphere **RS**, and is reflected back into **Optino/Opal**. The focal ratio of the collimator **C2** should match the effective focal ratio of the lens **L** used at a finite conjugate.

Instrument

Optino/Opal

Calibration

The aberrations of **Optino/Opal** and the collimator **C2** are removed by using the reference sphere **RS**.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), o (object distance from principal plane), i (image distance from principal plane), f_{col} (focal length of collimator **C2**).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (which is minimized by shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user.

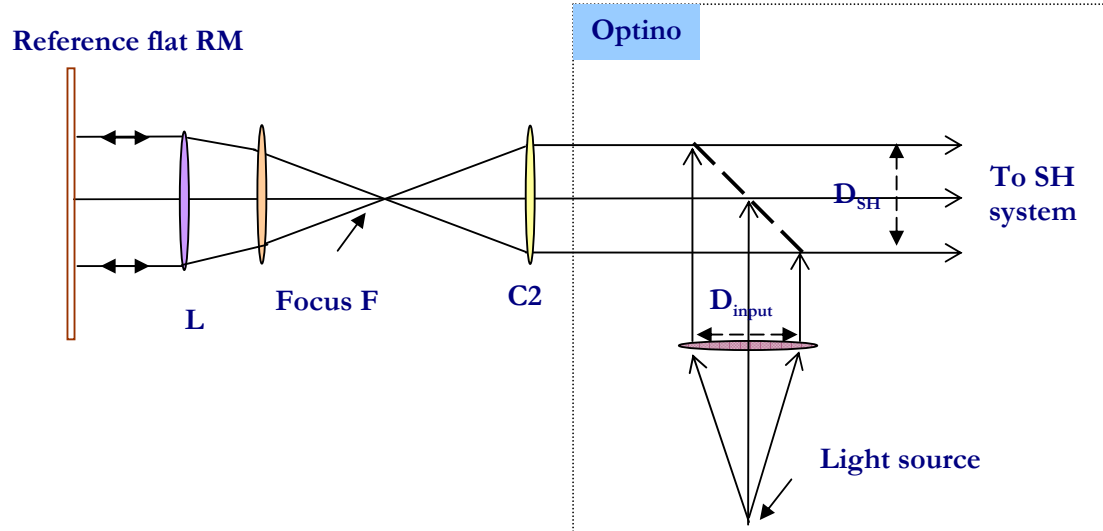
Single or double pass

Double pass

Components required

1. Test lens
2. Collimator **C2**
3. Reference sphere **RS**
4. Mountings

Setup 18: Multiple-component lens using collimator and flat mirror (finite-infinite conjugates)



Setup

Parallel light from **Optino/Opal** passes through the collimator **C2** and comes to a focus at **F**, which is also the focus of the multi-component test lens **L**. Collimated light from **L** falls on the reference flat **RF**, and is reflected back into **Optino/Opal**. **RF** should have a minimum diameter equal to the aperture of the lens **L**, and the focal ratio of the collimator **C2** should match that of the lens **L**.

Instrument

Optino/Opal

Calibration

The aberrations of **Optino/Opal** along with the collimator **C2** are removed by using the reference sphere **RS**.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), f_{test} (focal length of test element), f_{col} (focal length of collimator **C2**).

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus, coma (by aligning the elements) and spherical aberration (by changing the separation between the elements). These corrections can be based on analytical formulae, or on a lookup table provided by the user for any optical element in the system.

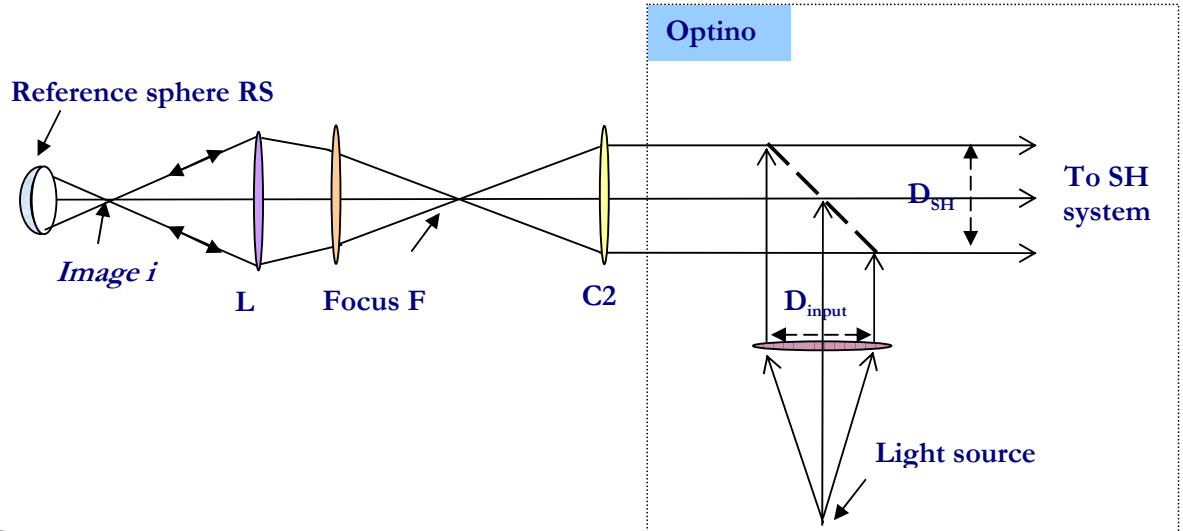
Single or double pass

Double pass

Components required

1. Test lens
2. Collimator **C2**
3. Reference flat **RF**
4. Reference sphere **RS**
5. Mountings

Setup 19: Multiple-component lens using collimator and spherical mirror (finite-finite conjugates)



Setup

Parallel light from **Optino/Opal** passes through the collimator **C2** and comes to a focus at its focus **F**, which is at an object distance o from the multi-component test lens **L**. The lens **L** forms an image at a distance i . The light then falls on the reference sphere **RS**, and is reflected back into **Optino/Opal**. The focal ratio of the collimator **C2** should match the effective focal ratio of the lens **L** used at a finite conjugate.

Instrument

Optino/Opal

Calibration

The aberrations of **Optino/Opal** as well as the collimator **C2** are removed by using the reference sphere **RS**.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), o (object distance from principal plane), i (image distance from principal plane), f_{col} (focal length of collimator **C2**).

It is also possible to use the diameter and position of the exit pupil. The object and image distances are then measured from the position of the exit pupil.

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus, coma (by aligning the elements) and spherical aberration (by changing the separation between the elements). These corrections can be based on

analytical formulae, or on a lookup table provided by the user for any optical element in the system.

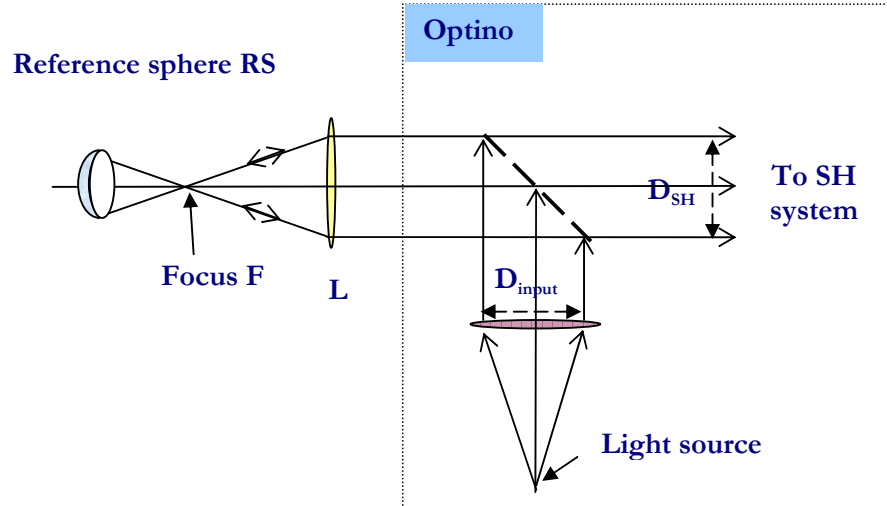
Single or double pass

Double pass

Components required

1. Test lens
2. Collimator **C2**
3. Reference sphere **RS**
4. Mountings

Setup 20: Single lens in parallel light using a spherical mirror
(infinite-finite conjugates)



Setup

Parallel light from **Optino/Opal** passes through the test lens **L** and comes to a focus at **F**, which is also the focus of the reference sphere **RS**, and is reflected back into **Optino/Opal**.

Instrument

Optino/Opal

Beam expander

BE25 or **BE60** can be used to expand (or compress) the size of the output beam for optimum spot sampling.

Calibration

The reference image is taken with **Optino/Opal** and the reference flat **RF**.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), f_{test} (focal length of test element), M (magnification or compression factor of beam expander, if used).

Output information

Along with the Zernike coefficients, the wavefront and optical quality, Sensoft gives diagnostics for correcting defocus and spherical aberration (which is minimized by shifting the focal plane). These corrections can be based on analytical formulae, or on a lookup table provided by the user.

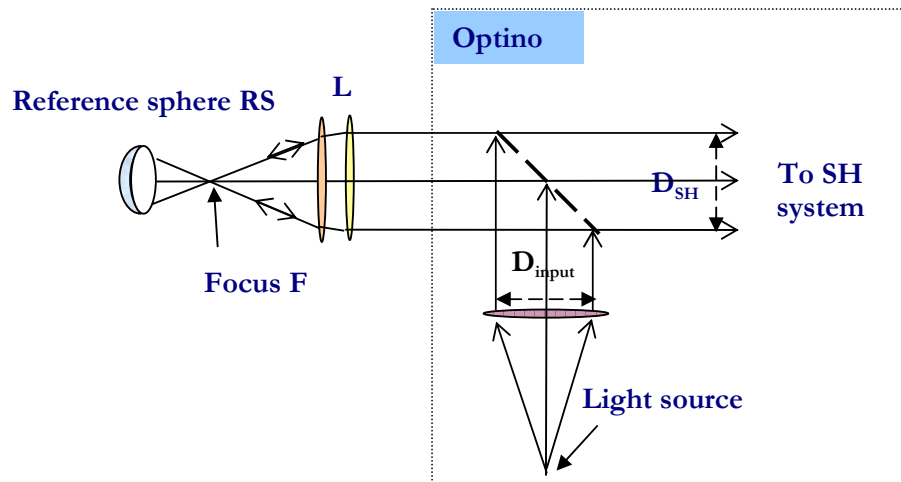
Single or double pass

Double pass

Components required

1. Test lens
2. Reference flat **RF**
3. Reference sphere **RS**
4. Mountings

Setup 21: Multi-component lens in parallel light using a spherical mirror (infinite-finite conjugates)



Setup

Parallel light from **Optino/Opal** passes through the multi-component test lens **L** and comes to a focus at **F**, which is also the radius of curvature of the reference sphere **RS**, and is reflected back into **Optino/Opal**.

Instrument

Optino/Opal

Beam expander

BE25 or **BE60** can be used to expand (or compress) the size of the output beam for optimum spot sampling.

Calibration

The reference image is taken with **Optino/Opal** and the reference flat **RF**.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), $f_{l_{test}}$ (focal length of test element), M (magnification or compression factor of beam expander, if used).

Output information

Along with the Zernike coefficients, wavefront and the optical quality, Sensoft gives diagnostics for correcting defocus, coma (by aligning the elements) and spherical aberration (by changing the separation between the elements). These corrections can be based on analytical formulae, or on a lookup table provided by the user for any optical element in the system.

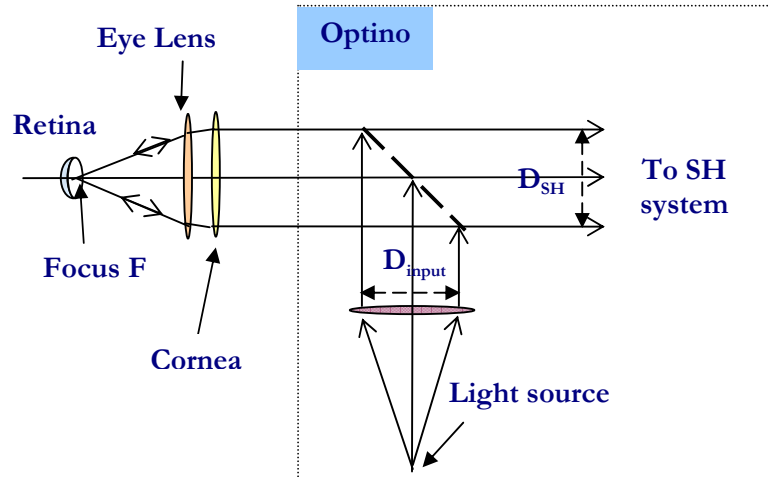
Single or double pass

Double pass

Components required

1. Test lens
2. Reference flat **RF**
3. Reference sphere **RS**
4. Mountings

Setup 22: Human eye



Setup

For testing the eye, the basic configuration is the same as that for the test of a test of single lens in parallel light. Note that in this situation, the eye acts as the optical element being tested **and** the collimator. Thus, the focal length of the collimator and optical element to be entered in the [Opt] section are the same.

Furthermore, if the diameter of the returning parallel beam from the eye is changed using additional optics, the factor (called the reduction factor) by which the beam is reduced (or enlarged) should be also entered in the [Opt] section. The value of reduction factor is 1 for no change in beam diameter, less than 1 for a reduced beam, and more than 1 for an enlarged beam.

Instrument

Optino

Calibration

The reference image is taken with **Optino** and the reference flat **RF**.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), f_{test} (focal length of eye), f_{col} (focal length of collimator **C2**=focal length of eye).

Output information

Sensoft gives the Zernike coefficient, the wavefront and optical quality of the flat mirror.

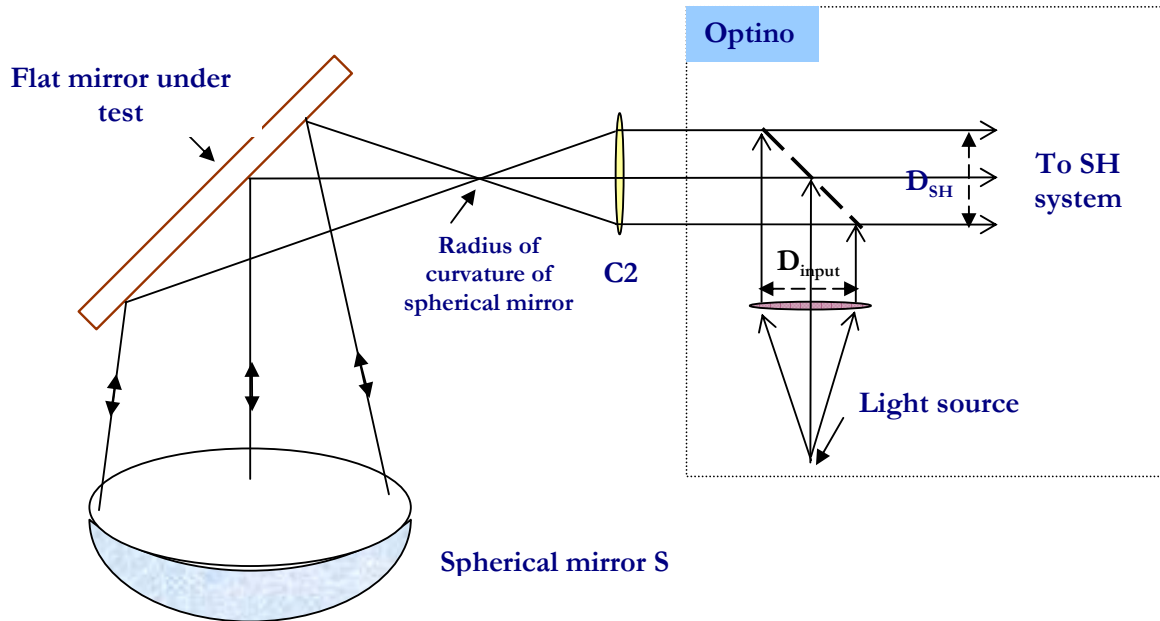
Single or double pass

Double pass

Components required

1. Eye
2. Reference flat **RF**
3. Mountings

Setup 23: Flat mirror in Ritchey-Common setup



Setup

The Ritchey-Common configuration is used for testing a flat mirror, in conjunction with a spherical mirror.

Parallel light from **Optino/Opal** passes through the collimator **C2** and comes to a focus at its focus **F** (which is also the radius of curvature of the spherical mirror **S**). It strikes the test and spherical mirrors, and is reflected back into **Optino/Opal**. The focal ratio of the collimator **C2** should match that of the radius of curvature of the spherical mirror.

In the above configuration, the spherical mirror has been placed at an angle of 90 degrees. Other angles can be also used.

Multiple measurements of the flat mirror are required after rotation to remove the effect of the astigmatism due to its curvature.

Instrument

Optino/Opal

Calibration

The reference image is obtained by illuminating the spherical mirror directly. Clearly, since the aberrations of the spherical mirror are removed by the calibration process, it does not need to be of a very high quality. A careful alignment is required to achieve this.

Input values for wavefront analysis

D_{input} (input diameter of beam from Optino), D_{test} (diameter of test element), f_{test} (focal length of test element), f_{col} (focal length of collimator **C2**).

Output information

Sensoft gives the Zernike coefficient, the wavefront and optical quality of the flat mirror.

The conic coefficient of the test mirror can also be computed: the spherical aberration of a mirror at its center of curvature is given by:

$$ASA = -K \frac{r^3}{2R^3}$$

Here **ASA** is the angular spherical aberration (diameter of image at best focus – in radians), **K** the conic coefficient of the mirror, **r** the ray height on the mirror, and **R** the radius of curvature. Spherical mirrors have zero **ASA** (**K**=0), while parabolic (**K**=-1) and hyperbolic (**K**<-1) mirrors have large positive spherical aberration. However, Sensoft is capable of testing mirrors with hundreds of wavelengths of aberrations.

Single or double pass

Double pass

Components required

1. Test flat
2. Collimator **C2**
3. Spherical mirror **S**
4. Mountings

11.5 Table of configurations: external illumination

Setup	Test type	Calibration	Limit on aperture	Def	SA	Coma
1	Cassegrain Telescope	At focus of C2 with PH50	None. $F\#(\text{Tel})=F\#(\text{col})$	Y	Y	Y
2	Newtonian Telescope	At focus of C2 with PH50	None. $F\#(\text{mir})=F\#(\text{col})$	Y	Y	N
3	Single lens in parallel light (infinite-finite conjugates)	At focus of C2 with PH50	Limit set by size of parallel beam	Y	Y	N
4	Single lens in diverging light (finite-finite conjugates)	At focus of C2 with PH50	None	Y	Y	N
5	Single lens at its focus (finite-infinite conjugates)	Parallel light with Cal25 or ECM25	6.9mm	Y	Y	Y
6	Multi-component lens in parallel light (infinite-finite conjugates)	At focus of C2 with PH50	Limit set by size of parallel beam	Y	Y	Y
7	Multi-component lens in diverging light (finite-finite conjugates)	At focus of C2 with PH50	None			
8	Multi-component lens at its focus (finite-infinite conjugates)	Parallel light with Cal25 or ECM25	6.9mm			
9	Parallel light	Parallel light with Cal25 or ECM25	6.9mm	Y	Y	N
10	Filters, optical windows and wedges (single pass)	Parallel light with Cal25 or ECM25t	6.9mm	Y	Y	N
11	Laser	Parallel light with Cal25 or ECM25	6.9mm	Y	Y	N

Notes

- All tests are done in single pass.

11.6 Table of configurations: internal illumination

Setup	Test type	Calibration	Limit on aperture		D/S	Def	SA	Coma
12	Concave mirror at R.C.	Sphere	None		S	Y	Y	N
13	Flat mirror (single pass)	Flat	6.9mm	58.5mm	S	-	-	-
14	Flat mirror (double pass)	Flat	6.9mm	58.5mm	D	-	-	-
15	Filters, optical windows and wedges (double pass)	Flat	6.9mm	58.5mm	D	-	-	-
16	Single lens using collimator and flat mirror (finite-infinite conjugates)	Sphere	None		D	Y	Y	N
17	Single lens using collimator and flat mirror (finite-finite conjugates)	Sphere	None	F#(lens)= F#(col)	D	Y	Y	N
18	Multiple-component lens using collimator and flat mirror (finite-infinite conjugates)	Sphere	None	F# (lens)= F#(col)	D	Y	Y	Y
19	Multiple-component lens using collimator and flat mirror (finite-finite conjugates)	Sphere	None	F# (lens)= F#(col)	D	Y	Y	Y
20	Single lens in parallel light using a spherical mirror (infinite-finite conjugates)	Flat	6.9mm	58.5mm	D	Y	Y	N
21	Multiple-lens in parallel light using a spherical mirror (infinite-finite conjugates)	Flat	6.9mm	58.5mm	D	Y	Y	N
22	Human eye	Sphere	6.9mm	F# (eye)= F#(col)	D	Y	Y	N
23	Flat mirror in Ritchey-Common setup	Sphere	None	F# (lens)= F#(col)	D	Y	Y	N

Notes

- Without the beam-expander, the maximum diameter tested (6.9mm) refers to the standard camera. It can go up to 24mm with the large format camera.
- Using special beam expanders, the maximum aperture tested is 400mm
- For flat mirrors, a collimator focal length of 100mm is assumed.
- F# denotes effective focal ratio
- D/S: S: Single pass. Wavefront is multiplied by a factor of 1. D: Double pass. Wavefront is multiplied by a factor of 0.5
- The last three columns refer to the correction for the calibration of the defocus, 3rd order spherical aberration and coma

Chapter 12: The equations of Shack-Hartmann analysis

The following is based on the paper presented at SPIE (Vol. 1994, 1993) (see *References*)

The deflection in the x -direction, or the x -derivative at any point (r,φ) , can be written as,

$$\delta_x = \frac{\partial W(r, \varphi)}{\partial x} = \frac{\partial W}{\partial r} \frac{\partial r}{\partial x} + \frac{\partial W}{\partial \varphi} \frac{\partial \varphi}{\partial x}$$

or,

$$\delta_x = \frac{\partial W(r, \varphi)}{\partial x} = \frac{\partial W}{\partial r} \cos \varphi - \frac{\partial W}{\partial \varphi} \frac{\sin \varphi}{r}$$

Similarly, in the y -direction

$$\delta_y = \frac{\partial W(r, \varphi)}{\partial y} = \frac{\partial W}{\partial r} \frac{\partial r}{\partial y} + \frac{\partial W}{\partial \varphi} \frac{\partial \varphi}{\partial y}$$

or

$$\delta_y = \frac{\partial W(r, \varphi)}{\partial y} = \frac{\partial W}{\partial r} \sin \varphi + \frac{\partial W}{\partial \varphi} \frac{\cos \varphi}{r}$$

For any optical element, δ_x and δ_y are the measured deviations on the CCD, and the parameters F, f_{lenslet} and f_{coll} are known. If we fix the form of $W(r,\varphi)$, then the coefficients of this aberration function can be computed using a least-squares fit. It is usual to express the wavefront aberration in terms of the Zernike coefficients.²

It is important to emphasize that δ_x and δ_y contain *all* the information regarding the telescope, i.e. not only the effects of low-order aberrations, but also other effects, e.g. due to air currents, mirror deformation etc. Once the dominant effects of lower order aberrations are removed, it is possible to see the other effects.

References

There are a number of excellent references in the literature. The following table lists some books that will be useful. It clearly is not a complete list.

Author	Title	Publisher	Comment
Born & Wolf	Principles of Optics	Pergamon Press	Standard reference
Hecht	Optics	Addison Wesley	
Mahajan	Aberration theory made simple	SPIE Optical Engineering Press	For Annular Zernike polynomials. See also the references to the original papers
Malacara	Optical Shop testing	John Wiley	The standard book for optical testing.
Schroeder	Astronomical Optics	John Wiley	Good reference for astronomical optics
Smith, Warren	Modern Optical Engineering	McGraw Hill	Excellent explanation of many optical concepts
Welford	Aberrations of Optical Systems	Adam Hilger	

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