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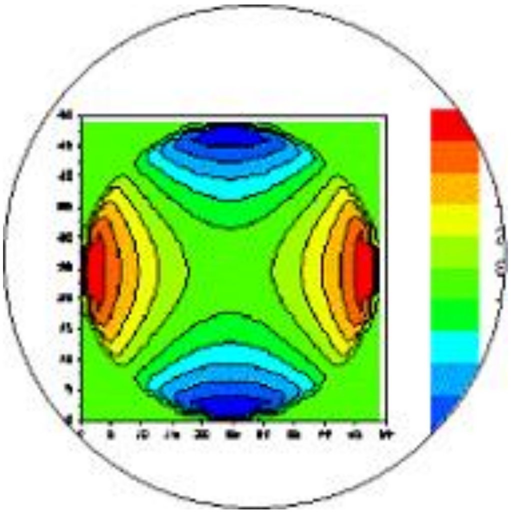
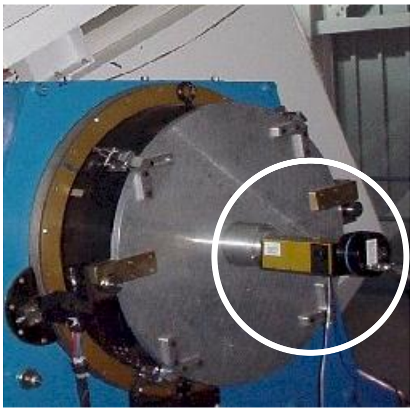
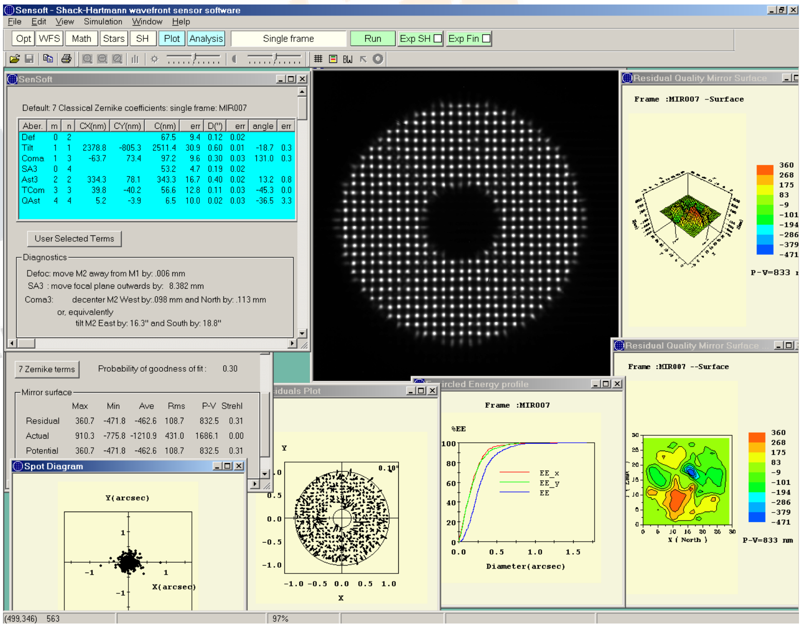
Puntino

Shack-Hartmann wavefront sensor for optimizing telescopes







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A finely tuned telescope is the key to obtaining deep, high-quality astronomical images.

Puntino, our Shack-Hartmann wavefront sensor specially developed for telescopes, is based on our extensive 10-year experience of use at observatories around the world.

It gives you complete analysis of the optics, mechanics, mirror supports, mirror and dome seeing.

Based on the analysis, the software suggests corrective action to be taken, enormously simplifying maintenance work, enabling you to achieve in hours what would normally take longer.

In keeping with our philosophy of providing you with a full set of tools, we also provide a CCD-based system for alignment telescopes and autocollimators.

Optimize telescope performance

With a powerful set of tools

PuntinoPro

Designed for the professional observatory, for permanent mounting

In a professional astronomical telescope, it is not practical to mount and dismount the sensor frequently, as it interferes with regular observations. PuntinoPro is completely automated, with a motorized remote control for the calibration system. It also comes with two cameras, and advanced hardware and software functions

Puntino minisensor

Designed for the small observatory, for mounting on the axis of the telescope

It is mounted on the telescope only when the SH test is to be done, as part of a periodic maintenance schedule.

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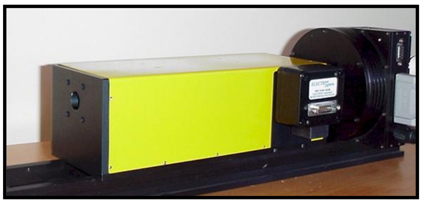
Puntino

Two models for different needs



Puntino Pro

Designed for the professional observatory, it can be mounted permanently on the telescope for a daily check on the image quality. Even during the night.

Basic features

- Measure the aberrations of any optical system (up to 34 terms of the Zernike polynomials).
- Estimate optical quality and Strehl ratio.
- Inspect the wavefront corresponding to any aberration.
- Use the diagnostics given by the program to focus any system. The program gives the magnitude (in mm) *and* the direction for effecting the correction.
- Use the indications given by the software to align the optical system in minutes (instead of hours). Use the indications given by the software (magnitude and direction) to move the optical element for effecting the alignment. It takes the guesswork out of alignment.
- Find out the correct focal plane using the spherical aberration measured by PuntinoPro. The program again gives you the magnitude and direction in which to move the element or the focal plane.
- Use this information in a feedback loop during manufacturing.
- Use it for identifying support errors by shown by the wavefront map after mathematically subtracting the lower order aberrations.
- Identify air turbulence by inspecting the plots of the residuals.
- See *on-line* how the aberrations change during the night.
- Build/refine a sophisticated pointing model for the telescope using the indications given by PuntinoPro of the shift of image in the focal plane of the telescope for different positions in the sky.
- The program can accept temperature measurements provided by the user using a special software module. This provides an important check on the correlation of temperature with any of the aberration coefficients.

In the next sections, we give an overview of our instruments. A more detailed list of the hardware and software features of PuntinoPro can be found in the section ***Features of the Shack-Hartmann analysis software Sensoft Version 5.1 for PuntinoPro***

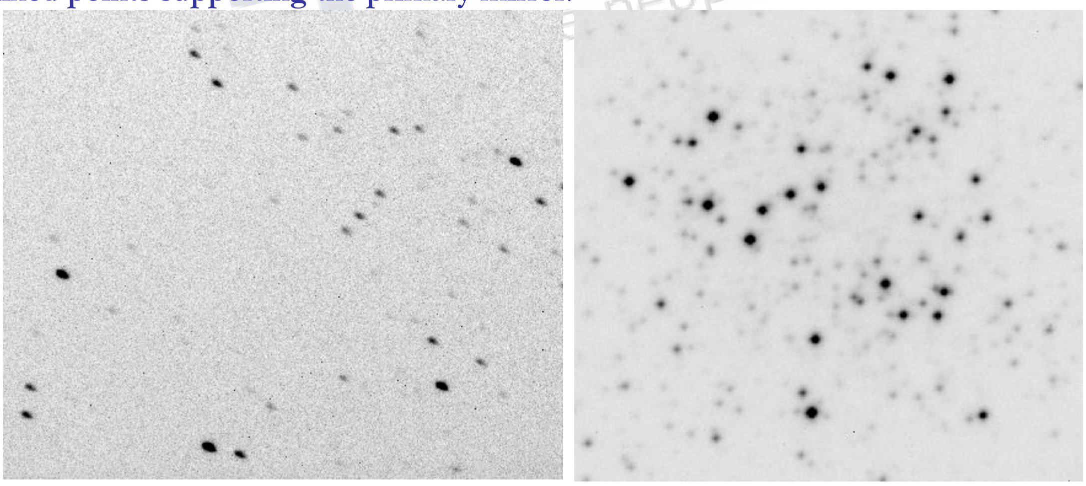
Gain up to 1 magnitude by fine tuning

Adjusting a telescope is a delicate and time-consuming process, which, if not done frequently, can lead to images affected by aberrations. This not only results in loss of efficiency (up to 1 magnitude), but can also give rise to images that are non-regular, and hence difficult to analyze.

Moreover, if the focal plane that is being used is not correct, it will result in the image having spherical aberration, which will enlarge the image symmetrically (since it is a symmetric aberration), and it will be mistaken for the effect of seeing.

With the help of PuntinoPro, the telescope can be adjusted quickly. Some examples are shown below.

The pupil of two telescopes (taken with the finder CCD of PuntinoPro) which had astigmatism (center and left) and triangular coma (right). The two images at left are intra and extra focal, and show the elongation of the image due to astigmatism, as well as the 90-degree inclination between the two. The image on the right shows the triangular image caused by the wrong adjustment of the three fixed points supporting the primary mirror.



The images from a telescope that has astigmatism (left) that is slightly out of focus. Note the elongation of the images due to astigmatism. The elongation was not caused by telescope tracking errors, as the EW direction is horizontal. The picture at right is of the central part of the cluster M53, after the telescope aberrations were corrected.

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A complete set of tools for the analysis and optimization of telescope performance

Initial setup of telescope with an alignment telescope using the CCD-based software package : Alisa

- Identification of the two axes of the telescope (ALT-AZ, or HA-DEC).
- Alignment of primary mirror axis with center of cell.
- Alignment of primary mirror axis with the axis of rotation of telescope.
- Align drive of M2 with optical axis.
- Initial alignment of primary and secondary mirrors axes.

Fine alignment and adjustment using PuntinoPro and Sensoft

- Alignment of M1 and M2 axes using the indications given by Sensoft (coma measurement).
- Identification of correct focal plane (zero spherical aberration) using the diagnostics of Sensoft.
- Optimization of support systems near zenith using the values of astigmatism, triangular coma, quadratic astigmatism and map of the mirror surface after subtraction of lower-order aberrations.
- Optimization of dome and mirror seeing using maps of the residuals over the pupil.

Variation of aberrations with zenith distance and creation of look-up table

- Calibration of aberrations with zenith distance using the in-built star selection section.
- Optimization of support system with zenith distance using the in-built star selection section.

Use of second CCD camera for examining telescope pupil

- Examination of out-of-focus pupil obtained with the second CCD camera.
- Check of linearity of the M2 drive using the second CCD without mounting the alignment telescope.
- Measurement of combined external seeing, dome and mirror seeing using the second CCD camera.

Active optics: correction of coma and defocus by moving secondary mirror

- Coma and focus can be corrected by passing the values of the movement computed by Sensoft to the control system of M2 via Ethernet or serial cable.

Active optics: correction of aberrations of primary mirror

- Full active optics on the shape of the primary mirror using the coefficients computed by Sensoft. The values can be passed to the control system via Ethernet or serial cable.

Advanced optical analysis

- Based on the Shack-Hartmann data, the MTF of the telescope can be computed.

Simulations

- Generation of Zernike wavefronts, Telescope design and diffraction analysis (MTF due to aberrations, ripple, micro ripple, seeing, telescope pointing, pixel size of CCD).

Sensoft: not only Zernike coefficients

Sensoft combines the full control of PuntinoPro (including the CCD cameras), as well as the Shack-Hartmann analysis. It not only gives the Zernike coefficients, but also the diagnostics for adjusting the telescope.

Designed for easy interpretation of the results	Sensoft not only gives the aberration coefficients of the wavefront in nanometers, but also the corresponding size (in arcseconds) due to the aberrated image in the focal plane, making it easier to interpret the results.
Detailed computations	3 SH loops are computed automatically at every run: one for Actual Quality (only tilt and defocus removed), Real Quality (user selected Zernike aberration terms removed), and Potential Quality (first 7 Zernike terms removed). It is thus possible to have a clear idea of the current telescope quality, the potential telescope quality, and information on any single aberration.
Error analysis	The errors of the coefficients and probability of goodness-of-fit are computed.
Correcting defocus	Sensoft gives a very precise measure of the defocus, in terms of the movement of the secondary mirror.
Alignment: using the value of coma to correct it	Based on the telescope parameters, Sensoft gives you the movements of the secondary mirror (decentering or tilt) required for correcting coma - both magnitude and direction.
Measure the conic coefficient	The high dynamic range of the instrument (~100λ of spherical aberration) can give the conic coefficient of the (hyperbolic) primary mirror.
Finding the correct focal plane from the measured spherical aberration	At the Cassegrain focus, Sensoft can be used to find the correct focal plane, defined as the plane where spherical aberration is zero. Based on the telescope parameters, it gives you the magnitude and the direction by which the focal plane must be shifted to get zero spherical aberration.
Astigmatism, Triangular coma and Quadratic astigmatism	The presence of these aberrations indicates the presence of support errors. Using the values of these coefficients in conjunction with the surface map of the mirror, mirror supports can be optimized.
High-resolution map of the support imprints	The sampling of 22x22 spots on the pupil gives a high-resolution map of the mirror surface after removing the lower order Zernike terms. In conjunction with the measured

	astigmatism, triangular coma and quadratic astigmatism, mirror supports can be optimized.
Extensive graphs for ease of interpretation	Sensoft is rich in graphs: 37 in the full version.
Averaging to reduce noise due to air effects	The coefficients of multiple SH frames can be averaged to reduce noise due to air turbulence as well as dome seeing effects.
Fast computation loop	The full set of computations takes less than 2 seconds.
Optimization of dome and mirror seeing	A plot of the residuals over the pupil after the Shack-Hartmann analysis can be used to investigate dome and mirror seeing. The pupil image from the second CCD camera can also be used.
Detailed Help	An extensive Help (over 20MB), with very detailed explanations of the most basic concepts.

Mounting PuntinoPro and the frequency of tests

It is desirable to check the state of the telescope every evening before starting observations. It has been designed to allow it to be mounted off-axis, so that the regular observing schedule is not disturbed. It comes equipped with a remote control for the calibration source, which enables the reference frame (for calibrating the instrumental aberrations) to be taken as frequently as required to compensate for temperature and telescope position changes during the night.

Permanent mounting of PuntinoPro off-axis	
Using a flat-mirror	PuntinoPro can be mounted off-axis, and the light from the telescope can be directed to it by flipping in a flat-mirror (which is removed after the tests are done). This enables the test to be done every evening, before observations start.
As part of the guider	Using appropriate optics, PuntinoPro can be made part of the guiding unit of the telescope, and can thus be used even during the night. Since the guider is used off-axis, the off-axis (field) aberrations of the telescope need to be removed. In the case of a classical Cassegrain telescope these are coma and astigmatism, and in the case of a Ritchey-Chretien telescope, only astigmatism. These values depend on the telescope parameters, and can be input into Sensoft, which removes the effect of these aberrations.

Frequency of SH tests

Ideally the tests should be done continuously throughout the night. However, if this is not possible, the tests should be done at the beginning of the night.

Frequency of acquisition of calibration reference frames

The calibration frame of PuntinoPro should be taken whenever the temperature changes by a few degrees, or when the telescope is moved by a large angular distance.

Advanced features

- ## Two-CCDs for a complete analysis: examine the pupil for more details

PuntinoPro is equipped with 2 CCDs: one for the SH frame, the other for acquiring a direct image of the star. The out-of-focus pupil of the telescope can be examined, giving additional information, like alignment of the spiders of the primary and secondary mirrors, zones on the mirror surface, support problems etc.

- ## Seeing monitor

The second CCD can be used as dome seeing monitor. It is capable of giving up to 100 frames per second in sub-frame readout mode (exposure time of 10ms).

- ## Active optics

Using appropriate optics, it can be used even on-line (e.g. in conjunction with the autoguider) for measuring and correcting the aberrations (e.g. active control of the primary and secondary mirrors), for checking the quality of air conditions, temperature effects etc. during the night. The Zernike coefficients computed by Sensoft can be passed to an external control computer of the telescope via the serial port or Ethernet.

- ## MTF, PSF and EE based Diffraction analysis

The MTF, PSF and EE of the telescope based on diffraction analysis can be computed from the data obtained from SH analysis.

- ## Simulations

Generation of Zernike wavefronts, Telescope design and diffraction analysis (MTF due to aberrations, ripple, micro ripple, seeing, telescope pointing, pixel size of CCD).

- ## High sampling for a more reliable determination of spherical aberration

PuntinoPro has a high sampling of spots to determine spherical aberration reliably.

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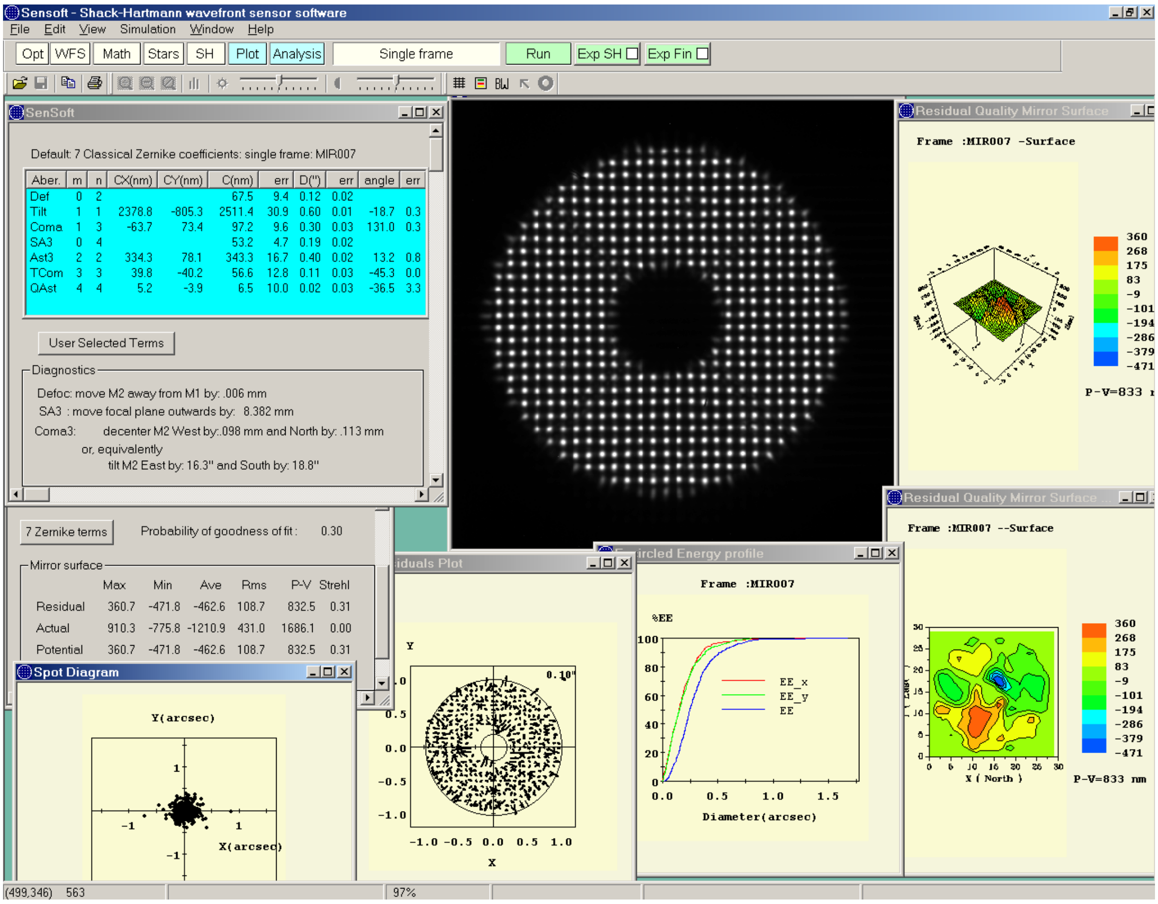
Sensoft: instrument control and analysis

Sensoft integrates the full control of PuntinoPro.

- Control of CCD cameras and stepper motor
- SH analysis

By specifying a few parameters when you run the program for the first time, you are set for the full night. Analysis of the Shack-Hartmann frame is again a matter of one click of the mouse.

You can get a good Shack-Hartmann frame, analyze it and get the first results in less than a minute.



The graphical user interface of Sensoft, with some of the graphs shown

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Summary of features of PuntinoPro

Hardware

Number of spots: about 22x22 (standard). Higher number can be used if desired.

High sampling over pupil for a more reliable determination of spherical aberration.

2 cameras (one for SH images, the other for direct images). The camera for obtaining SH images is a CCD camera and can be selected by the user (e.g. a cooled camera). The camera for direct imaging is a CMOS camera with 1280x1024 pixels of size 6.7μ.

Remote control of stepper motor from PC for the calibration light source.

Shape of instrument: box with 6 M-6 holes on front flange for mounting.

Software: control and analysis

CCD and motor control integrated into software.

Coefficients of up to 34 Zernike terms (Seidel, Standard, Fringe and Annular) – user selected.

Wavefront (P-V, rms), Strehl Ratio.

Software indication for correcting measured defocus, coma and spherical aberration.

Advanced image analysis.

Intra-focal and extra-focal images recorded with second CCD.

Measurement accuracy of Zernike in the presence of noise (seeing dependent): ~0.1”.

Averaging of coefficients obtained from SH analysis to reduce effect of noise due to air effects.

Plots of variation of aberrations during the night.

Star catalog in program for calibration of aberrations with zenith distance.

Optional features for PuntinoPro

Computation of MTF, PSF and EE from Shack- Hartmann data.

On-line control for active optics.

Measurement of total seeing (external, dome and mirror) using the second camera.

Calibration of the linearity of the focusing drive of the secondary mirror.

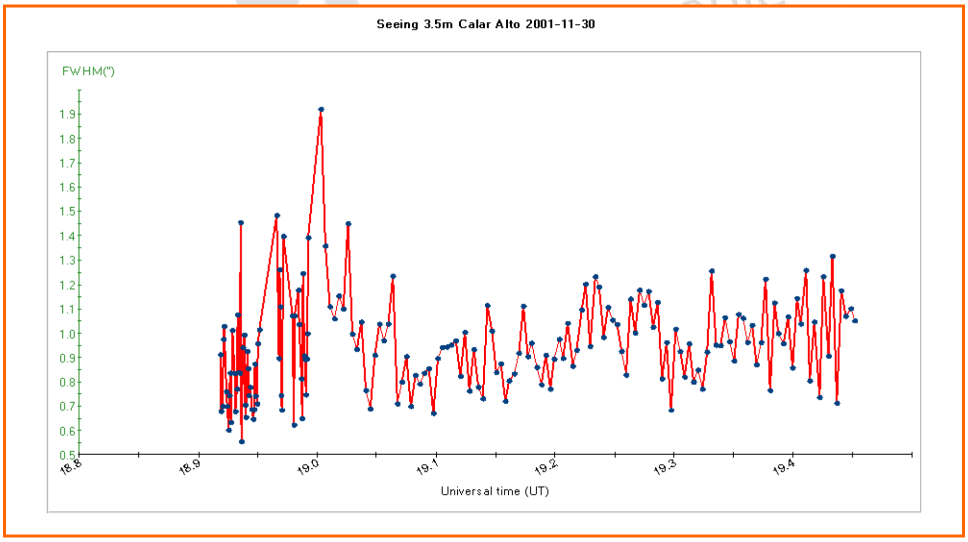
Simulations: Generation of Zernike wavefronts, Telescope design and diffraction analysis (MTF due to aberrations, ripple, micro ripple, seeing, telescope pointing, pixel size of CCD).

Fast (50Hz) tip-tilt corrections.

MIMMsoft: for seeing measurement

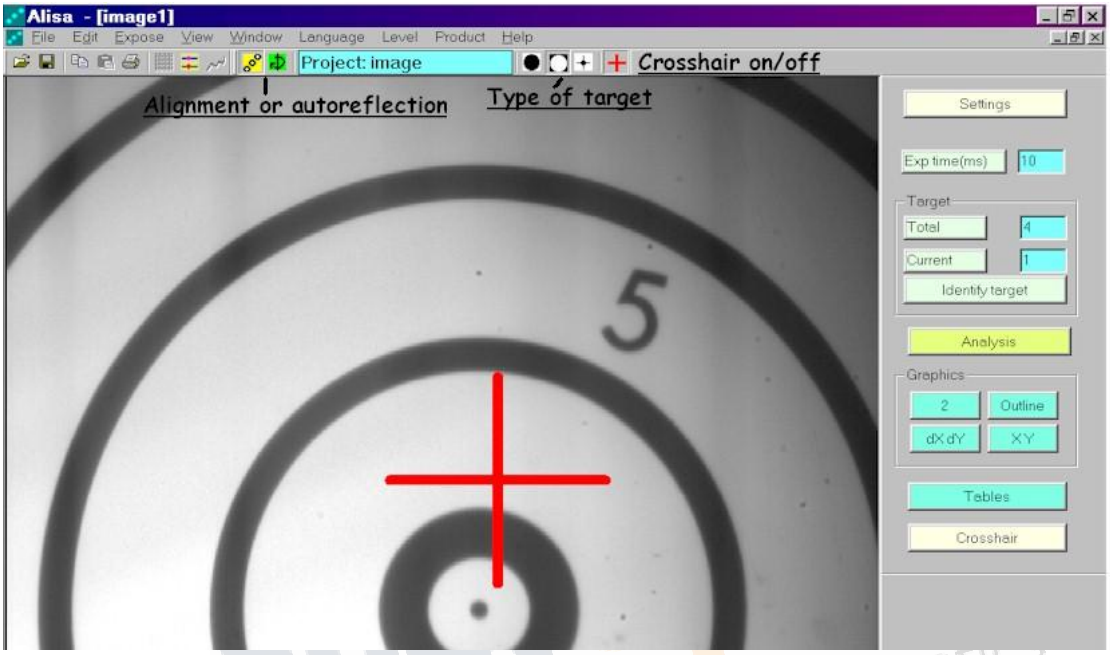
MIMMSoft is a software package for measuring astronomical seeing. Its highlights are:

- ✓ Can be used to measure seeing using a single aperture (like at the focus of a large telescope so that windshake is not a problem) or with a DIMM (dual image motion monitor).
- ✓ Can be used with the finder camera of Puntino, the Shack-Hartmann wavefront sensor made by Spot-optics s.r.l. for testing telescopes. Thus, in combination with the detailed information on the aberrations obtained from Shack-Hartmann analysis, a complete picture of the telescope performance can be obtained, which includes the effect of dome and mirror seeing.
- ✓ Measures and displays, in real-time, the measured value of the FWHM (the seeing), □ (the 2D variance of the image motion), or r_0 (Fried's parameter).
- ✓ The data can be saved and retrieved and plotted at a later time.
- ✓ Up to 1000 frames can be used for computing the value of □□
- ✓ A minimum exposure time of 0.01ms can be used (with bright stars, of course), leading to a very large bandpass of 1MHz for the computation of Scintillation Index.
- ✓ Automatic optimization of exposure time for precise centroiding.



Alisa: software for micro-alignment

In line with our philosophy of providing you with a complete solution, we also offer the Alisa software and camera for use with an alignment telescope and autocollimator. This can be used for initial alignment and setup of the telescope, and helps reduce the tedium of alignment by substituting the eyepiece by a digital camera: the image of the target is obtained and analyzed by software.



About the firm

Spot-optics was founded in 1996. We offer complete solutions in the field of optics and software, covering any phase from the design of optics and software analysis to the fully developed end-user product.

We have about two decades experience in the field of optical design and software analysis and development. Our software specialization is in the development of software for image processing as well as industrial process control.

Our main product is a wavefront sensor based on the Shack-Hartmann principle. Our Shack-Hartmann wavefront sensors give the optical quality of a large sample of different optical surfaces: from the astronomical telescopes with diameters of several meters, to the DVD lenses and mobile phone with diameter of a few millimeters, to the human eye.

The use of our instruments is made very simple because of the advanced compact optical design and the degree of automation. The control software specifically developed by us allows the full control of the instrument, and our Shack-Hartmann analysis software gives you very precise indications about the quality of the optical element under test. Finally a detailed diagnostics suggests how the optical quality can be improved. All the results from the software are available in a few seconds.

Our first Shack-Hartmann sensor was developed for the test of mirrors of astronomical telescopes. Our Shack-Hartmann wavefront sensor for astronomy PuntinoPro is now operative on several telescopes in Italy, Spain, India and USA. We have been consultants for a number of observatories and firms (including Zeiss) for the alignment and quality control of telescopes. Thus PuntinoPro has been also mounted on several additional telescopes in Europe, Africa and USA.

While **Puntino** has been developed specially for astronomical telescopes, **Optino/Opal/Lentino** are Shack-Hartmann wavefront sensors designed and realized for the optical test in the laboratory and in the production environment and can test a large variety of optical elements both in transmission and reflection. **Laserino** is the sensor designed and realized for the test of lasers. We can test laser at practically any wavelength from UV to 10.6µ (LWIR, CO2).

Finally we have developed a series of sensors for testing optical elements both on-axis and off-axis. **Sfera** can test small lenses like mobile phone lenses, **Stella** can test large lenses like telecentric lenses and 5Star can test objective lenses like zoom lenses mounted on digital cameras

We have developed further products in the field of optical alignment and in the medical field.

For further details on our products we address you to our website: www.spotoptics.com.

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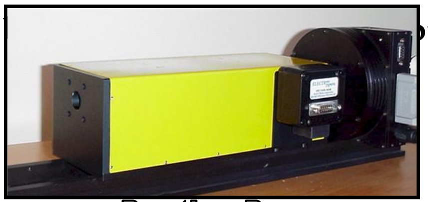
We can be contacted  tics.com

Puntino Pro

Features of the Shack-Hartmann analysis software Sensoft Version 5.1 for PuntinoPro

PuntinoPro: technical specifications (February 2011)

1	Type of elements that can be tested	Astronomical telescopes (at Cassegrain, prime and Newtonian focus). Telescopes in the laboratory. Lenses.
2	Focal ratios covered	f/1.8 to f/300 standard. Faster focal ratios can be tested with special setup.
3	Diameter of optical element that can be tested	Practically any diameter.
4	Diameter of lenslets	0.3mm.
5	Focal length of lenslets	41mm.
6	Standard sampling on the pupil	About 22x22
7	Maximum sampling	Up to 65x65 spots can be used (camera dependent).
8	Analysis Software	Sensoft.
9	Precision of Zernike polynomials coefficients (laboratory)	$\lambda/300$.
10	Precision of Zernike polynomials coefficients (telescope)	0.01”
11	Precision with which the wavefront is computed	$\lambda/150$ rms.
12	Wavelength range	With standard camera from 0.375 up to 1.1μ. With IR camera up to 2μ.
13	Reference source	White light fiber optic source with standard uncooled camera. LED with cooled camera. Remotely controlled.
16	Distance from flange to instrument focus	54.8mm.
17	Height of optical axis from base	61.5mm.
18	Camera for SH	10-bit uncooled CMOS or 14 or 16-bit cooled CCD.
19	Camera for Finder	10-bit uncooled CMOS, 1280x1024pixels, 6.7μ pixel size or 14 or 16-bit cooled CCD.
20	Dimensions (approximate)	9 (Height) x 22 (Length) x 9 (Width) cm.
21	Power requirement (Fiber optic light source).	120V or 220V, 200VA.

22	Power requirement (stepper motor)	12V. 500mA

NOTES AND EXPLANATIONS:

4. Lenslets with different diameters available on request.
5. Lenslets with different focal length available on request.
6. With the standard CMOS camera, which has a chip size of 6.8x8.5mm^2. Pixel size: 6.7µ.
7. For a chip-size of 19mm. This is a slow read-out cooled CCD.
9. Repeatability of measurement obtained by combining two SH frames taken in succession. The error of this coefficient depends on the sampling used for obtaining the SH frame.

10, 11 and 12. Depends on the noise due to the ambient air conditions.

18. We support SBIG cameras. Other cameras can be integrated upon special request.

Details of features: PuntinoPro and Sensoft

Test configuration	
Telescope at cassegrain focus	✓
Telescope at Newtonian	✓
Single lens	✓
Multiple component lens	✓
Calibration for correcting aberrations	
Calibration for correcting aberrations measured by Puntino (empirical, from ray-tracing or analytic)	✓
Wavefront sensor configuration	
Operating system supported (with SBIG and Luemenra cameras)	WXP/W7
Number of CCD cameras	2
Number of bits for A/D conversion (camera dependent)	8,10 or16
CCD cameras supported: SBIG (thermoelectrically cooled), CMOS camera Lumenera	✓
Shack-Hartmann CCD selection and setup - acquisition, automatic dark subtraction, binning, temperature control where applicable.	✓
Specification of orientation of SH CCD frame – used in defining directions for the correction of coma. Also for defining directions on wavefront map.	✓
Finder CCD selection and setup - acquisition, automatic dark subtraction, binning, temperature control where applicable.	✓
Other CCDs on request (where possible)	✓
Remote control of reference light source	✓
Stepper motor movement	✓
Stepper motor diagnostics	✓
Image analysis	
Display of frames, save in TIFF/FITS format, contrast enhancement, brightness enhancement, zoom	✓
Image arithmetic (addition, subtraction, multiplication and division of frames)	✓
SH analysis	
Computation of Zernike coefficients, wavefronts & Strehl ratio	✓
Selection of mirror or wavefront surface for computation	✓
Automatic threshold for computation of centroids	✓
Selection of annulus on pupil	✓
Diameter containing 80% and 50% Encircled Energy values	✓
Rms values of the residuals	✓
Rejection of spots based on ellipticity	✓
Selection of Seidel, Standard, Fringe or Annular Zernike terms to fit to data	✓
Maximum number of Seidel, Standard, Fringe or Annular Zernike terms	34
Selection of extra Zernike terms for least squares fit	✓
Average values computed from multiple SH frames	✓
Computation of displacement of optical axis of Puntino with respect to that of the telescope	✓
Plots for checking the ellipticity, S/N ratio and flux distribution of spots over the pupil.	✓

3 computational loops during analysis: Actual Quality, Potential Quality and Real Quality	✓
Star selection for calibration of aberrations with zenith distance	
Selection of stars for SH analysis based on zenith distance or (hour angle, declination)	✓
Theoretical or empirical calibration of flux from telescope	✓
Plots	

Optional: Simulations

Generation of Zernike wavefronts

Seidel, Classical, or Annular Zernikes polynomials
Selection of term or terms to add (coefficient and angle)
Selection of kind of noise to add: Gaussian or Random
Average of several frames
Number of spots (up to 70)
Optical parameters of optical element and Shack-Hartmann grid

Plots

Combined frame
Encircled Energy profile
Residuals
Spot diagram
Wavefront contour and 3D plot

Telescope design based on analytic theory

Cassegrain or Gregorian (Ritchey-Chretien, Classical or Dall-Kirkham)

Plots: Field aberrations

Coma
Astigmatism
Sag
Defocus
Distortion

Plots: despace aberrations

Coma due to misalignment
Spherical aberration due to wrong focal plane

Diffraction computations based on analytic theory: MTF, PSF

Aberrations: defocus and spherical aberration
Pixel size of detector
Ripple on optical surface
Micro ripple on optical surface
Pointing accuracy of telescope
Atmospheric seeing

Plots

MTF as a function of normalized frequency or lines/mm
PSF and EE as a function of angular or dimensionless radius
Computation of MTF, PSF and EE from the spot diagram generated for the al

MTF, PSF and EE computed from the SH analysis

Plots

MTF as a function of normalized frequency or lines/mm
PSF and EE as a function of angular or dimensionless radius

Optional features for PuntinoPro and Sensoft

MTF, PSF and EE from Shack-Hartmann analysis	
MTF, PSF and EE computed from the SH analysis	✓
Plots	
MTF as a function of normalized frequency or lines/mm	✓
PSF and EE as a function of angular or dimensionless radius	✓
Calibration of linearity of M2 drive	
On-line control for active optics	
Values for the movement of M2 for correction coma and defocus passed to the M2 motor control (on the same PC or another PC - via serial port or Ethernet)	✓
Values of Zernike coefficients passed to active optics control loop via Ethernet	✓
Tip-tilt measurements at a frequency of 50Hz using a fast-readout	
Seeing	
Computation of r0, seeing and scintillation index using the finder CCD	✓
Plots	
r0, seeing and scintillation index as a function of time	✓

The wavefront: its measurement

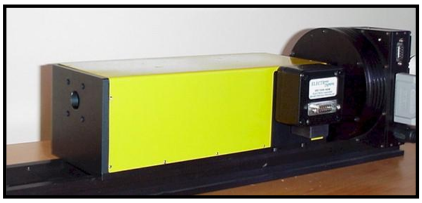
Wavefront W=	A1 x Focus
	+ A2 x Tilt
	+ A3 x Coma
	+ A4 x Spherical aberration
	+ A5 x Astigmatism
	+ A6 x Triangular coma
	+ A7 x Quadratic astigmatism
	+ An..x Higher order Zernike aberrations
	+ Noise (air effects)

Sensoft measures the derivative of the aberrated wavefront *W*, and estimates the values of the coefficients (A0, A1, A2, A3, A4, A5, A6, and An..) of the aberrations (Zernike coefficients).

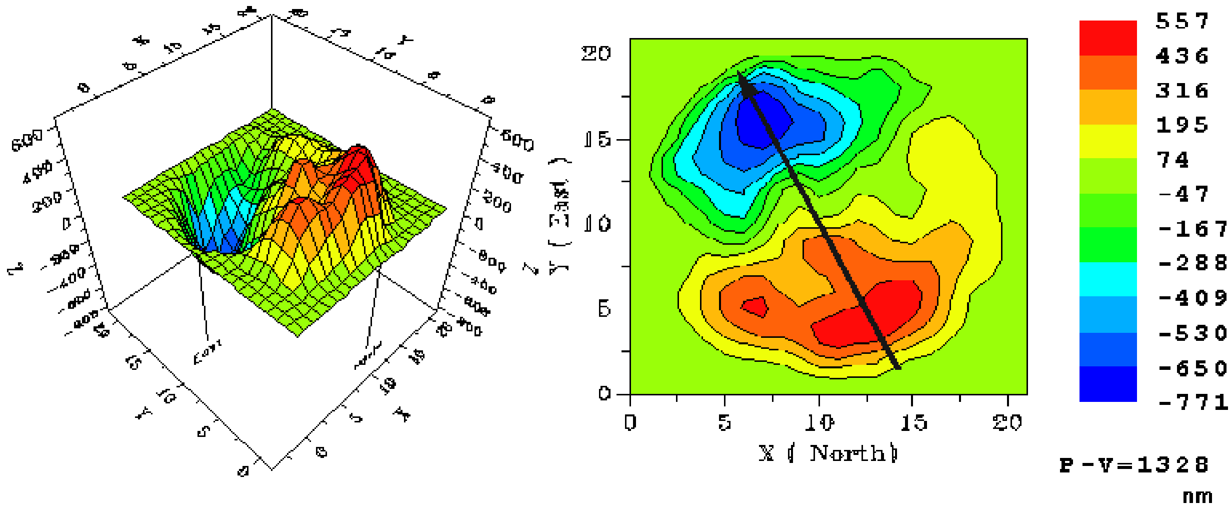
The form of the various aberration terms is given later separately. Sensoft is capable of fitting up to 34 terms.

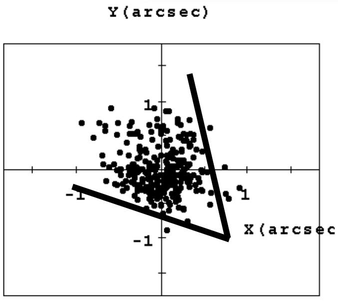
The next few pages show examples of:

- ✓ ***Alignment of the telescope mirrors by measuring and correcting coma.***
- ✓ ***Astigmatism and Triangular Coma: indicators of support problems.***
- ✓ ***Identifying individual supports of optical mirrors that have problems.***
- ✓ ***Check if the dome and mirror seeing (astronomical telescopes) or air-currents (laboratory/workshop) are optimized.***
- ✓ ***Maintaining the optimal setup by monitoring the aberrations on-line.***
- ✓ ***Results given by Sensoft.***



Telescope alignment





The wavefront and the spot diagram for coma
of a 1.5m telescope as measured by Puntino.
The lines define the cone of the comatic image.
The size of the comatic given by Sensoft is 1.1″,
with an angle of 116 degrees. The spot
diagram is affected by the presence of higher order
aberrations.
Using a calibration based on the telescope
parameters, Sensoft gives you the movements of
the secondary mirror (decentering or tilt) required for correcting it - both in magnitude and direction. The alignment can be achieved in a few iterations, the precision being limited only by the mechanics of the telescope. If the exact parameters of the telescope are not known, approximate parameters can be used. In any case, the correct alignment is achieved when the measured coma is zero. Once this is done, this empirical calibration can be used subsequently.

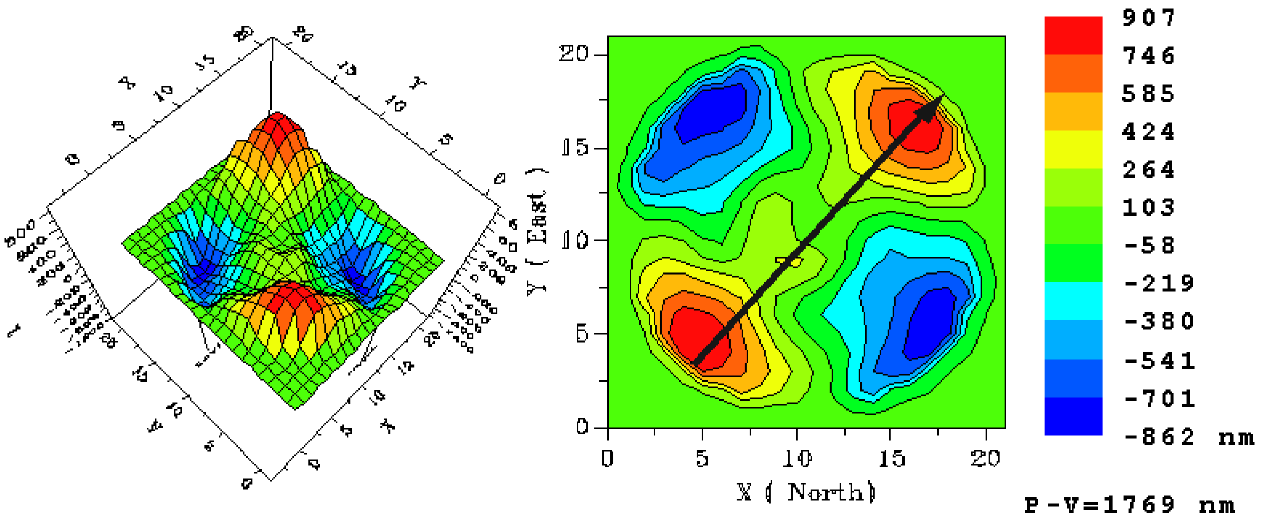
The following is an example of the output given by Sensoft with the indications to correct the measured coma. These values can be used for a manual adjustment of the telescope, or if the secondary mirror is actively controlled, can be passed to the control system:

- Decenter: M2 West by: 1.389 mm and North by: 3.145 mm

  Or, equivalently

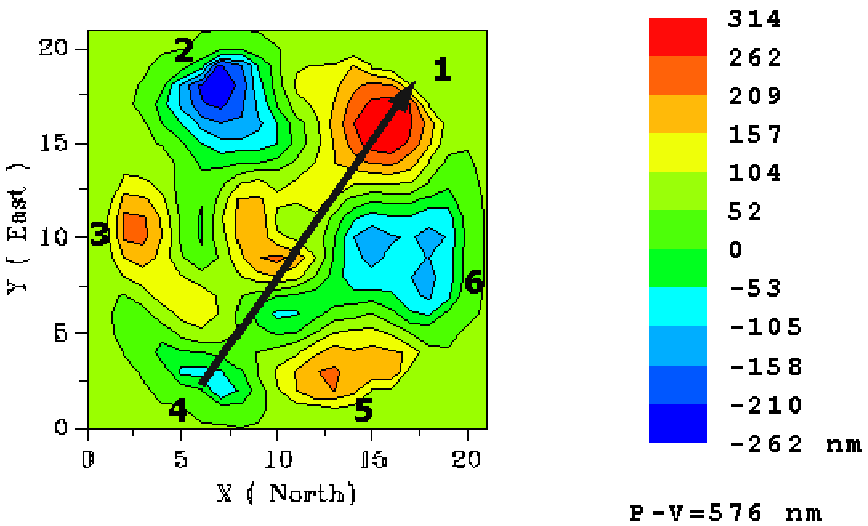
- Tilt: M2 East by: 100.6" and South by: 227.7".

Astigmatism and triangular coma

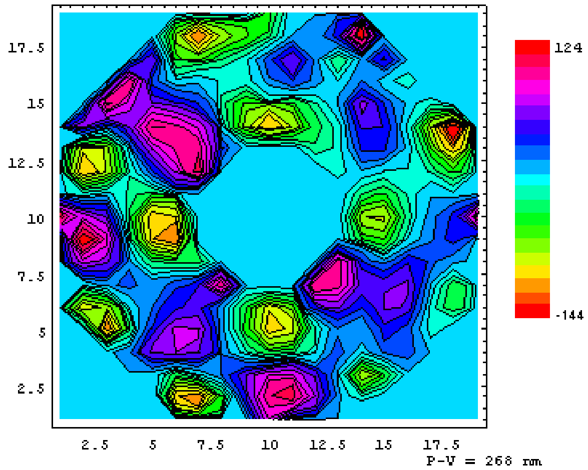


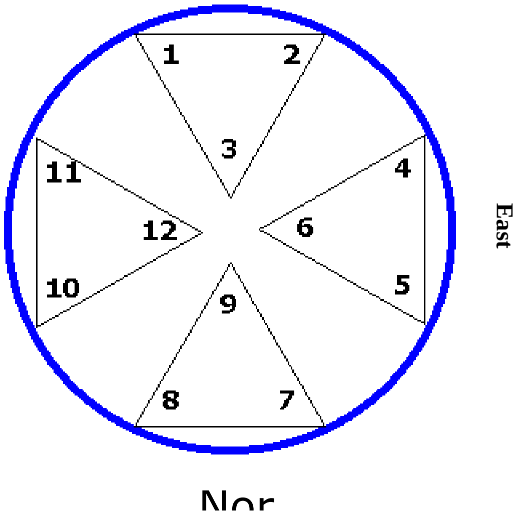
Astigmatism can arise as a field aberration or due to the shape of the mirror (in which case its shape and magnitude is constant over the field). A mirror can take an astigmatic shape during polishing, and/or due to the wrong forces applied by the mirror mounting system. The above figure shows the wavefront of the 1.5m telescope as measured by Puntino, for astigmatism alone. It had an orientation of 45 degrees, and was caused by the support errors.

The following figure shows the presence of triangular coma, again caused by support errors.



Support problems





The wavefront plot at left was obtained by mathematically subtracting out the lower order aberrations measured by Puntino/Sensoft. It shows the presence of support problems in the 1.5m mirror (which is particularly thin: it had an aspect ratio (diameter/thickness) of 45. On the right is the map with the distribution of the supports. The imprint of the supports is clearly seen in the figure at left.

It is the presence of these support errors that gives rise to the large amount of astigmatism as well as triangular coma shown above. Knowing the shape of the wavefront (high and low) and taking into account the orientation information, the supports can be adjusted quickly.

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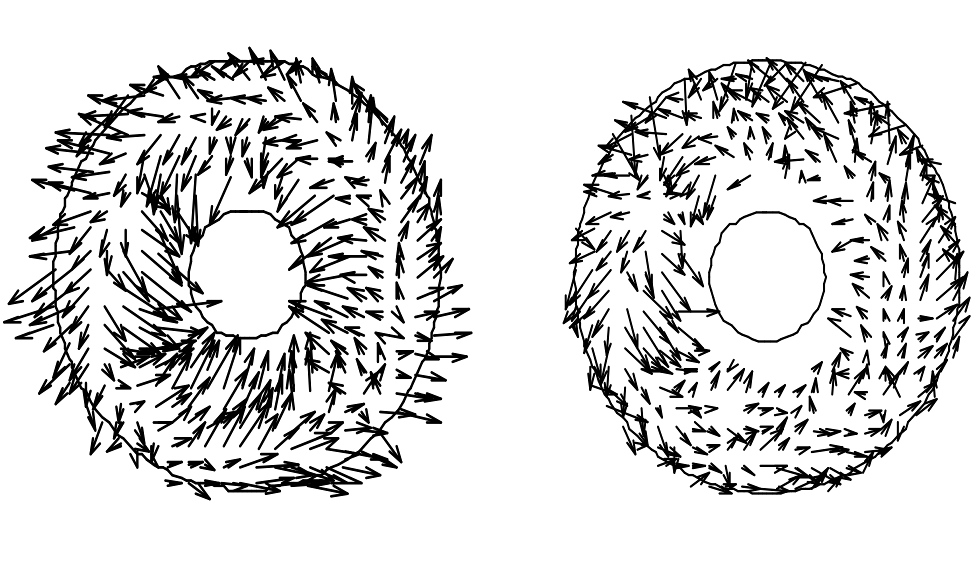
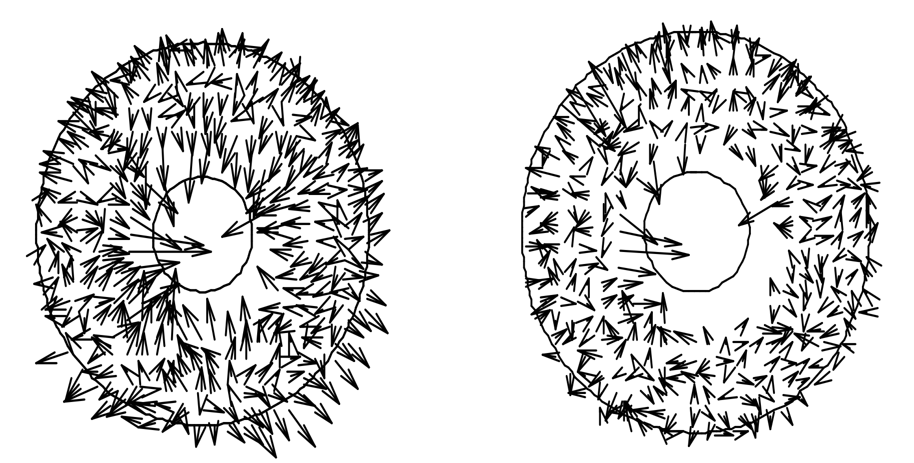
Dome and mirror seeing

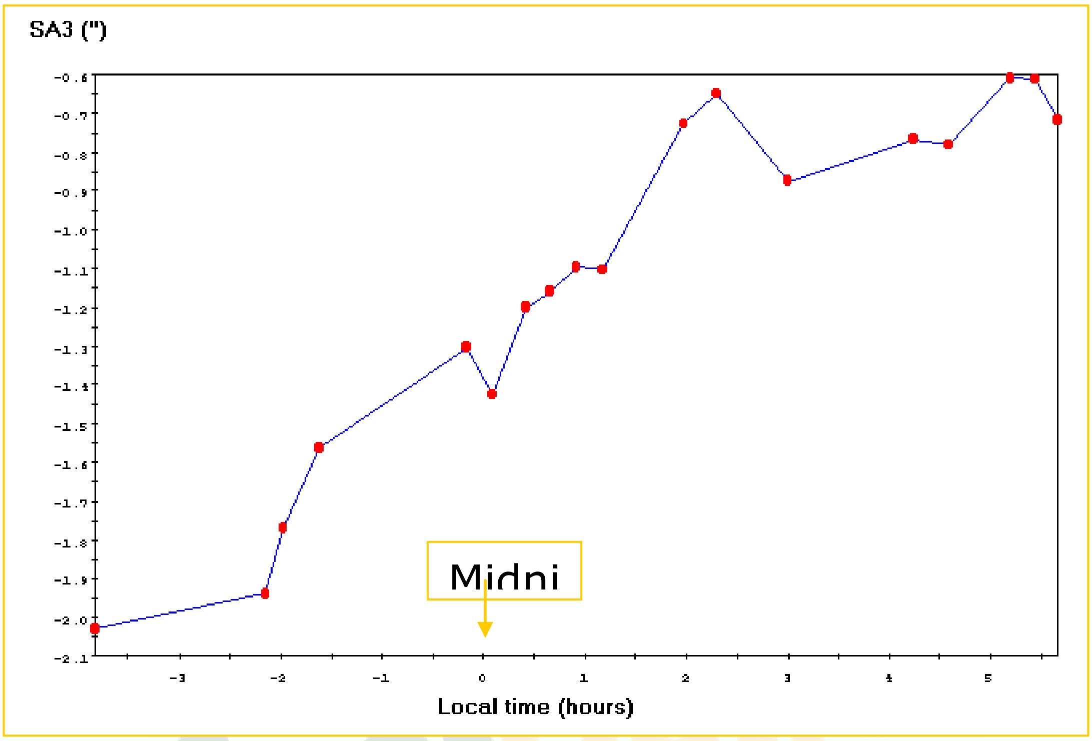
A plot of the residuals at the points where the mirror wavefront is sampled by the SH grid for a 1.2m telescope. The residuals at left have been plotted after the mathematical removal of two Zernike terms: defocus and tilt. At right, the plots after the removal of 7 Zernike terms. In both cases, it is evident that hot air on the mirror was funneling up, causing a vortex on the mirror, as the hot air wrapped itself around the baffle of the primary mirror. The coefficient of SA in this case was 83.8±4.7 nm, or equivalently, 0.89±0.05´´.



Now the telescope was pointing in a different direction, with a strong wind blowing into the dome. This clearly had the effect of blowing away the hot air on the mirror. The coefficient of SA in this case was 73.7±4.7 nm, or 0.78±0.05´´, similar to the case above, showing that it is possible to obtain reliable estimates for the aberration coefficients despite the present of air effects.



Temperature effects



The above plot shows the variation of spherical aberration during the night: it changed from about –2.1″ to –0.6″ (the diameter of the image due to spherical aberration alone). This was due to the change of dome temperature, causing a change in the shape of the mirror.

Plots like these are available from PuntinoPro/Sensoft for the 7 basic aberrations. This is a powerful diagnostic tool for analyzing and optimizing the performance of a telescope.

Output from Sensoft

CLASSICAL ZERNIKES COEFFICIENTS AND THEIR ANGLES

Aberration	c_x (nm)	c_y(nm)	Cf(nm)	D('')	angle(ø)
Def 0 2			**1±16**	**.01±.06**	
Tilt 1 1	**2056±40**	**1190±38**	**2375±54**	**1.31± .03**	**30±1**
Coma 1 3	**-66±9**	**150±10**	**164±13**	**1.15± .09**	**113±2**
SA3 0 4			**-33±7**	**-.26± .05**	
Ast3 2 2	**228±19**	**250±19**	**338±20**	**.91 ±.06**	**47±0**
TCom 3 3	**67±13**	**97±13**	**118±16**	**.55 ±.07**	**55±1**
QAst 4 4	**18±10**	**8±10**	**20±11**	**.14 ±.08**	**25±3**

WAVEFRONT (in nm)

Max	Min	Peak-Valley	Rms	Strehl ratio	
311	-289	599	109	.31	

Probability of goodness-of-fit: 1.000

ORIENTATION OF CCD FRAME (used for direction calibration)

+X	-X	+Y	-Y
West	East	South	North

Shift of optical axis of instrument

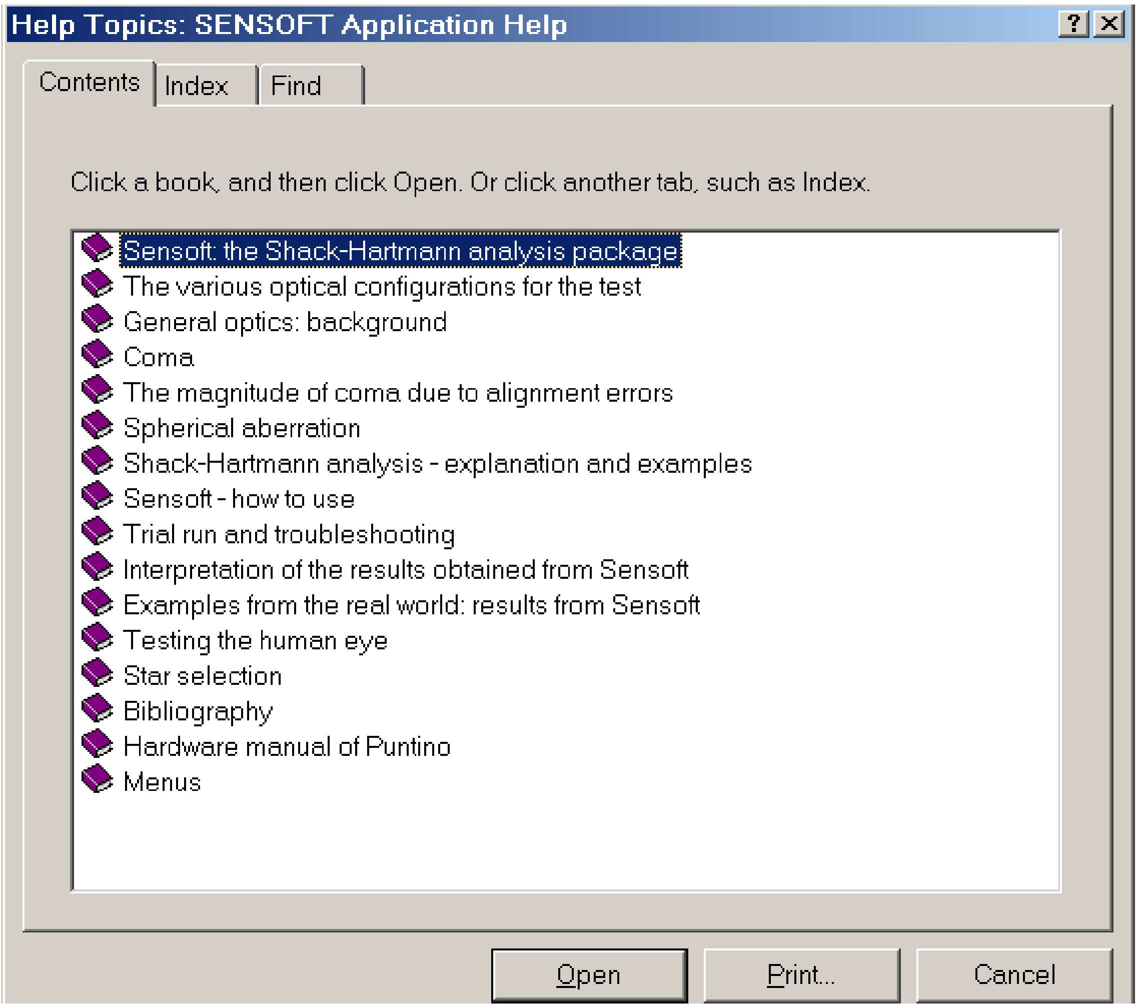
3.543 mm West .061 mm South

DIAGNOSTICS (for correcting three of the measured aberrations)

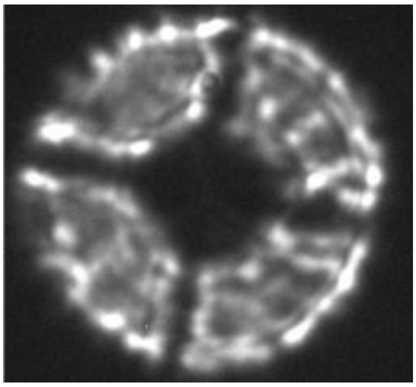
Aberration	Action	Movement
Defocus	move M2 away from M1	0.000 mm
Spherical (SA3)	move focal plane outwards	143.205 mm
	decenter M2	1.389mm (WEST)
Coma		3.145mm (NORTH)
	or equivalently	
	tilt M2	100.6" (EAST) 227.7" (SOUTH)

Detailed on-line help

Sensoft comes with a very detailed on-line Help:



Analysis of telescope pupil



Pupil of a telescope obtained with the second CCD of PuntinoPro. The presence of zones and air currents (bright spots) is clearly seen. The image is also slightly elongated, suggesting the presence of problems with the lateral supports: this was indeed confirmed by the high value of astigmatism measured for this telescope.

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Telescopes tested with Puntino

	Telescope	Where
1.	3.5m TNG primary mirror at Zeiss	Oberkochen (Germany)
2.	1.82m Asiago	Cima Ekar (Italy)
3.	1.5m Loiano	Loiano (Italy)
4.	1.2m Crete	Crete (Greece)
5.	2.5m Nordic Optical Telescope (NOT)	La Palma, Canary Islands
6.	**1.5m Sanchez***	**Tenerife, Canary Islands**
7.	1.5m TT1 of the Observatory of Napoli	Potenza (Italy)
8.	1.2m Yerkes Observatory	Williams Bay, USA
9.	0.75m Yerkes Observatory	Williams Bay, USA
10.	1m San Diego	San Diego (USA)
11.	**3.5m Apache Point Observatory***	**New Mexico, USA**
12.	1m Apache Point Observatory	New Mexico, USA
13.	1.8m Kottamia	Kottamia, Egypt
14.	**1m University of Virginia***	**Charlotteville (USA)**
15.	**2.5m VBT***	**Bangalore (India)**
16.	1m Zeiss	Bangalore (India)
17.	2m HIROT at EOST	Tucson, (USA)
18.	**2m HIROT***	**Hanle, Himalayas (India)**
19.	**2m MAGNUM***	**Maui,Hawaii (USA)**
20.	3.5m Calar Alto	Almeria (Spain)
21.	**2.3m Aristarchos telescope**	**Athens, (Greece)**
22.	**1m Catania Telescope***	**Catania (Italy)**
23.	**Multi Mirror Telescope (MMT)***	**Tucson, (USA)**
24.	**Mount Abu 1.2m IR telescope***	**Mount Abu, Rajasthan (India)**
25.	**4m Vista Telescope***	**La Silla (Chile)**
26.	**Las Cumbres Telescope ***	**USA**
27.	**Telescope Technology Ltd***	**UK**
28.	**1.8m Kottamia Telescope***	**NRIAG, Egypt**

*In regular use.

Perfect images and their degradation by aberrations

The two kinds of aberrations: same form but different origins

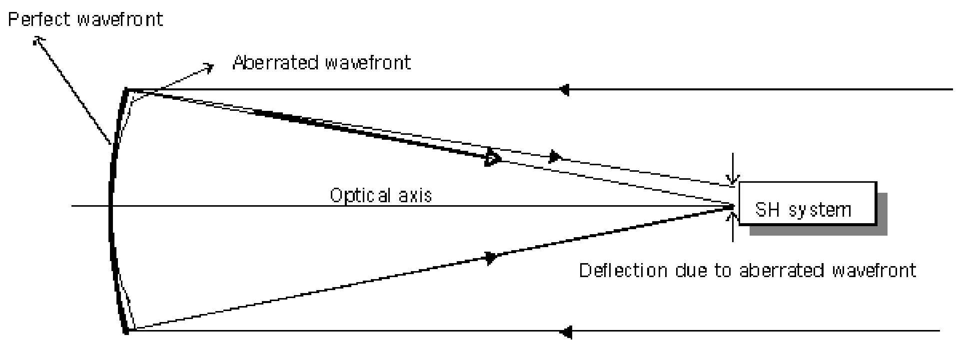
Aberrations (from the Latin aberrare, to deviate) cause the image to spread, leading to loss of resolution and telescope efficiency.

Aberrations like coma, astigmatism and spherical aberration are well known. These aberrations can arise due to two reasons:

Field aberrations that vary with field angle: An optical system which forms perfect images for objects on the optical axis will not do so for off-axis objects. These are called field aberrations, and vary according to some power of the angle of the incident ray with respect to the optical axis. For a particular optical system, their magnitude depends on the optical design.

Aberrations whose magnitude is constant over the field: It might seem surprising that aberrations can also be present for on-axis images. These aberrations have the same form as the classical off-axis aberrations, except that they do not depend on the field-angle.

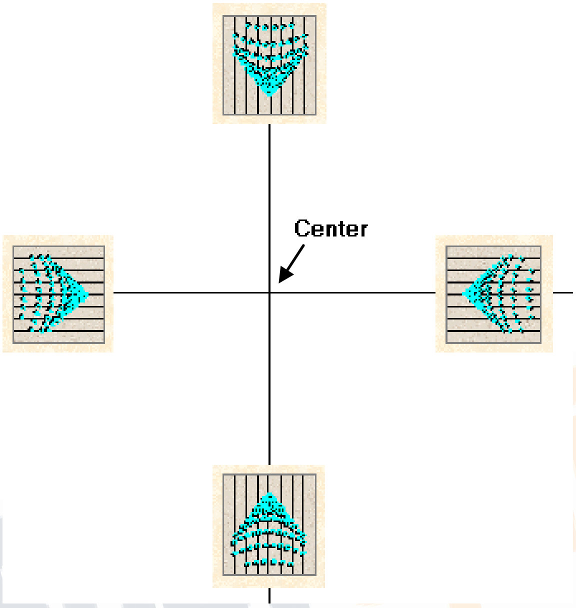
An aberrated wavefront and the corresponding displacement in the focal plane



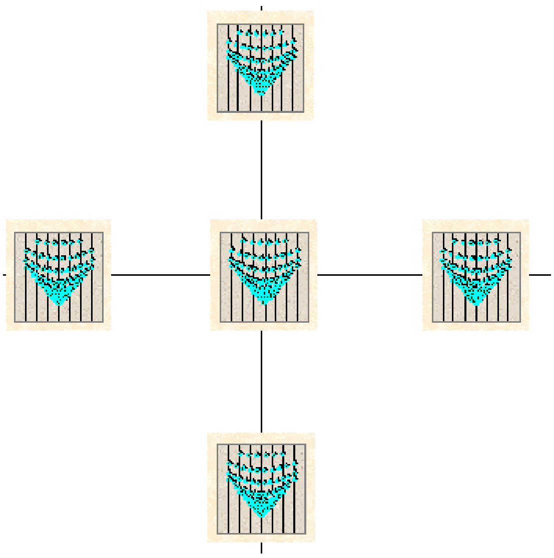
The aberrations are measured in the transferred pupil: a collimator placed after the focus makes the light parallel. A lenslet array placed at the position of the pupil forms images (spots) from individual points (zones) of the wavefront on a detector. If the wavefront were unaberrated, one would obtain a perfect matrix of spots. In the presence of aberrations, individual spots are deviated: one measures these deviations, and after fitting a mathematical function to these deviations (in terms of the Zernike polynomials), the coefficients of the aberrations are obtained.

Coma due to collimation error

Coma as a *field aberration* is inherent in the optical design. For example, a classical cassegrain telescope (in which the primary mirror is parabolic, and the secondary mirror is hyperbolic) will have field coma, while a Ritchey-Chretein telescope (both primary and secondary mirrors are hyperbolic) will not. Note that the comatic images point to the center of the field.

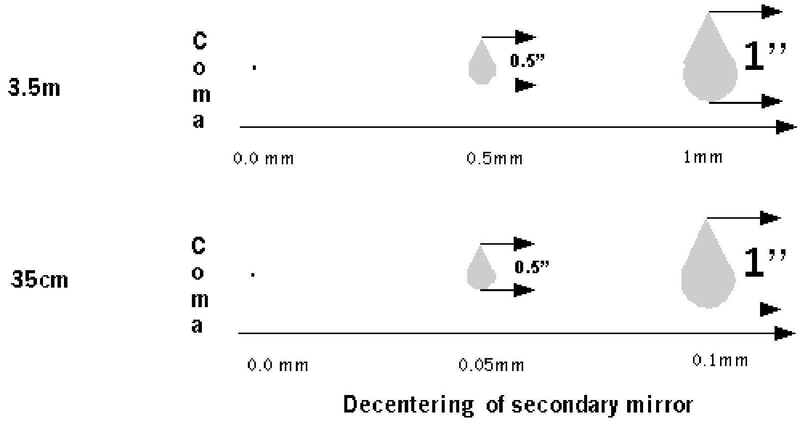


Coma due to misalignment (also called collimation error) originates in a two-mirror (or lens) system, when the primary and secondary mirrors are not aligned (one mirror tilted or decentered with respect to the other). In this case, comatic images of the same size, and pointing in the same direction, are formed all over the field, *including the center of the field.* While field coma is inherent in the optical design, coma due to misalignment can be removed if it can be measured. This is what is achieved with Puntino.



How important are these aberrations in normal telescopes? Magnitude of coma

We give the magnitude of coma for two typical f/11 telescopes of diameter 3.5m and 35cm. The aberrations are more for fast primary mirrors.

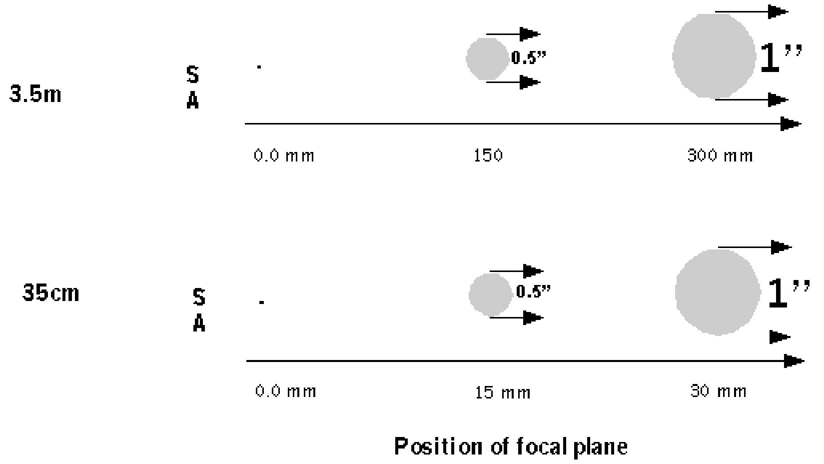


As a rule of the thumb, a standard f/10 telescope will have a 1″ comatic image for 1mm of decentering. On the other hand, an f/2 telescope (the other optical parameters being the same) will require a much tighter tolerance: a 1″ comatic image is obtained due to a misalignment of only $1/(10/2)^2$=0.04mm (40 microns) ! (See section on formulae.)

Spherical aberration

Spherical aberration can occur even if there is no defect in the optical design, if the focal plane is not at the correct position. Even if the optical design and the focal plane are correct, due to temperature changes, the shape of the primary and secondary mirrors change at different rates, leading to spherical aberration.

It is a common to think that the focal plane of a telescope can be simply can be changed by refocusing to accommodate different instruments. However, the refocused the image suffers from spherical aberration.



The magnitude of coma

The equation below shows how the length of the comatic image due to misalignment depends on the parameters of a two-mirror telescope:

$$\frac{l}{f}\frac{3(m-1)^3}{32F^2}\left[K_2-\left(\frac{m+1}{m-1}\right)\right]$$

Here *l* is the linear misalignment between the primary and secondary mirrors, *m* the magnification (f_{tel}/f_1) of the telescope, *F* the focal ratio of the telescope, and K_2 the conic coefficient of the secondary mirror. The value of coma is in radians.

It is clear from the equation that coma is higher for:

- ✓ **Faster telescopes (i.e. smaller F-ratios *F*).**
- ✓ **Telescopes with larger magnification *m*.**
- ✓ **Telescopes with shorter focal length *f*.**

As a rule of the thumb, a standard f/10 telescope will have a 1″ comatic image for 1mm of decentering. On the other hand, an f/2 telescope (the other optical parameters being the same) will require a much tighter tolerance: a 1″ comatic image is obtained due to a misalignment of only $1/(10/2)^2$=0.04mm (40 microns) !

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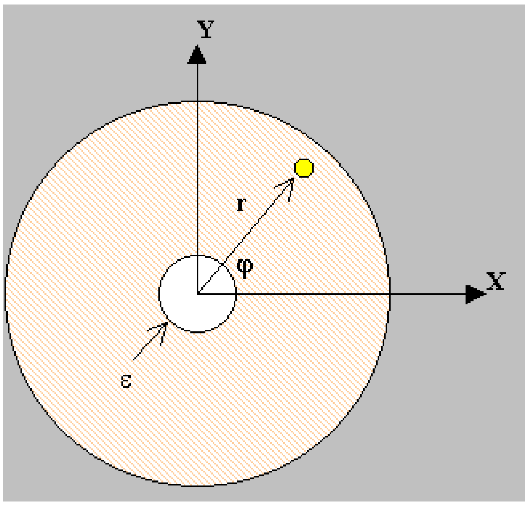
Expressions for 7 Zernike terms



r is the radius of the normalized pupil, ϕ the azimuthal angle, and the ϕ_n 's the zero point of the orientation of the aberration. ε is the normalized radius of the pupil.

NAME	CLASSICAL ANNULAR ZERNIKE POLYNOMIALS	SEIDEL POLYNOMIALS
Tilt	$2\frac{r\cos(\varphi+\varphi_0)}{(1+\varepsilon^2)^{1/2}}$	$r\cos(\varphi+\varphi_0)$
Defocus	$\sqrt{3}\frac{2r^2-(1+\varepsilon^2)}{(1-\varepsilon^2)}$	r^2
Coma	$\sqrt{8}\frac{\left[3(1+\varepsilon^2)r^3-2(1+\varepsilon^2+\varepsilon^4)r\right]\cos(\varphi+\varphi_1)}{(1-\varepsilon^2)\left[(1+\varepsilon^2)(1+4\varepsilon^2+\varepsilon^4)\right]^{1/2}}$	$r^3\cos(\varphi+\varphi_1)$
3rd order Spherical Aberration	$\sqrt{5}\frac{6r^4-6(1+\varepsilon^2)r^2+(1+\varepsilon^2+\varepsilon^4)}{(1-\varepsilon^2)^2}$	r^4
5th order Spherical aberration	$\sqrt{7}\frac{20r^6-30(1+\varepsilon^2)r^4+12(1+3\varepsilon^2+\varepsilon^4)r^2-(1+9\varepsilon^2+9\varepsilon^4+\varepsilon^6)}{(1-\varepsilon^2)^3}$	r^6
Astigmatism	$\sqrt{6}\frac{r^2\cos(2\varphi+\varphi_2)}{(1+\varepsilon^2+\varepsilon^4)^{1/2}}$	$r^2\cos(2\varphi+\varphi_2)$
Triangular coma	$\sqrt{8}\frac{r^3\cos(3\varphi+\varphi_3)}{(1+\varepsilon^2+\varepsilon^4+\varepsilon^6)^{1/2}}$	$r^3\cos(3\varphi+\varphi_3)$
Quadratic Astigmatism	$\sqrt{10}\frac{r^4\cos(4\varphi+\varphi_4)}{(1+\varepsilon^2+\varepsilon^4+\varepsilon^6+\varepsilon^8)^{1/2}}$	$r^4\cos(4\varphi+\varphi_4)$

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