Closed-Loop Active Optics with and without wavefront sensors

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Telescopes with Active Optics

Telescope (monolithic mirror)	Diameter [m]
VST	2.6
WIYN	3.5
NTT - TNG	3.5
SOAR	4.1
VISTA	4.2
DCT	4.3
MMT-MAGELLAN	6.5
GEMINI	8.0
VLT	8.2
SUBARU	8.2
LBT	2x8.4

+ Keck, GTC (10-m segmented)

- Mature technology… but still room to improve
- Recent class of **wide-field telescopes with AO** (VISTA, VST, Pan-STARRS, LSST yet to come). New wavefront control strategy can still be explored

Wide-field telescopes vs AO

Examples:

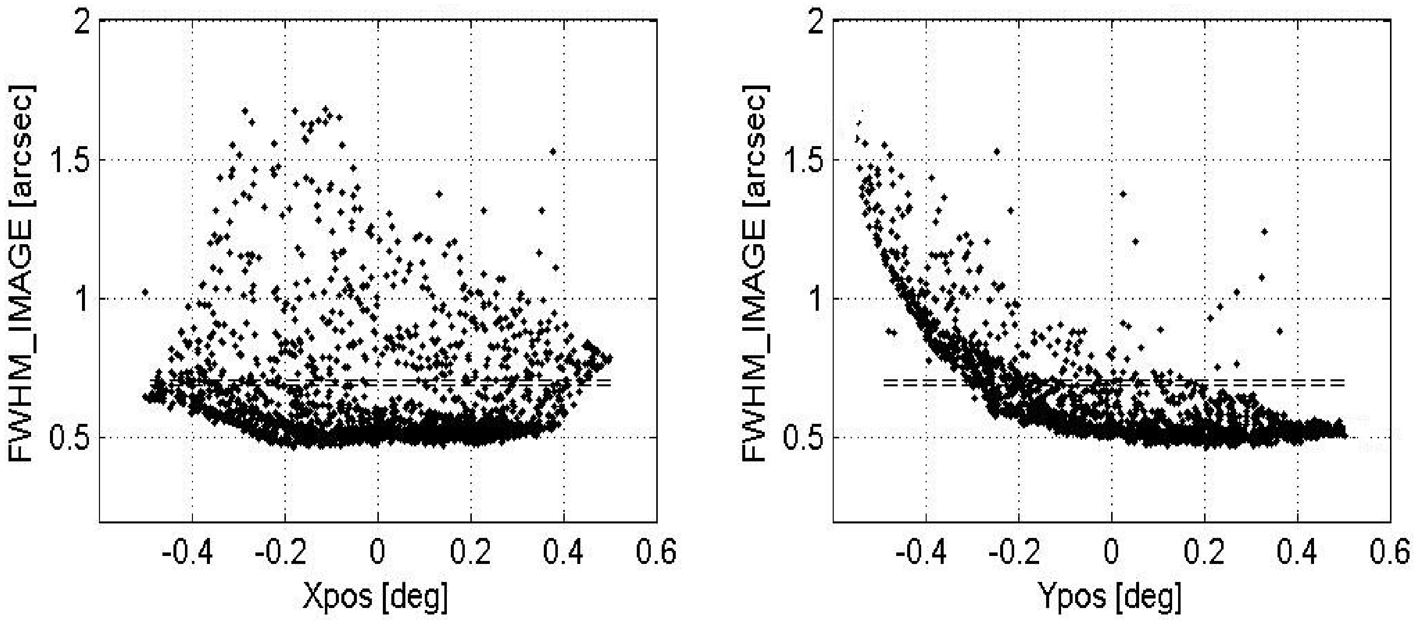
- VST (2.6m, 1° FoV, visible, Cerro Paranal, Chile)
- Vista (4.1m, 1.65°, near-IR, Cerro Paranal, Chile)
- Pan-STARRS (1.8m, 3°, Hawaii)
- LSST (planned: 8.4m, visible/NIR, Cerro Pachón, Chile)

Challenges: Tight alignment tolerances, strong field dependence

Claim for optimized closed-loop active optics to minimize PSF degradation

Active Optics in Wide-Field Telescopes

- Usually uses N out-of-focus technical wavefront sensors at edge of science field (curvature sensing, “donut” method)
- Alignment challenges of wide field telescopes often underestimated
- No widely accepted control approach



Misalignment

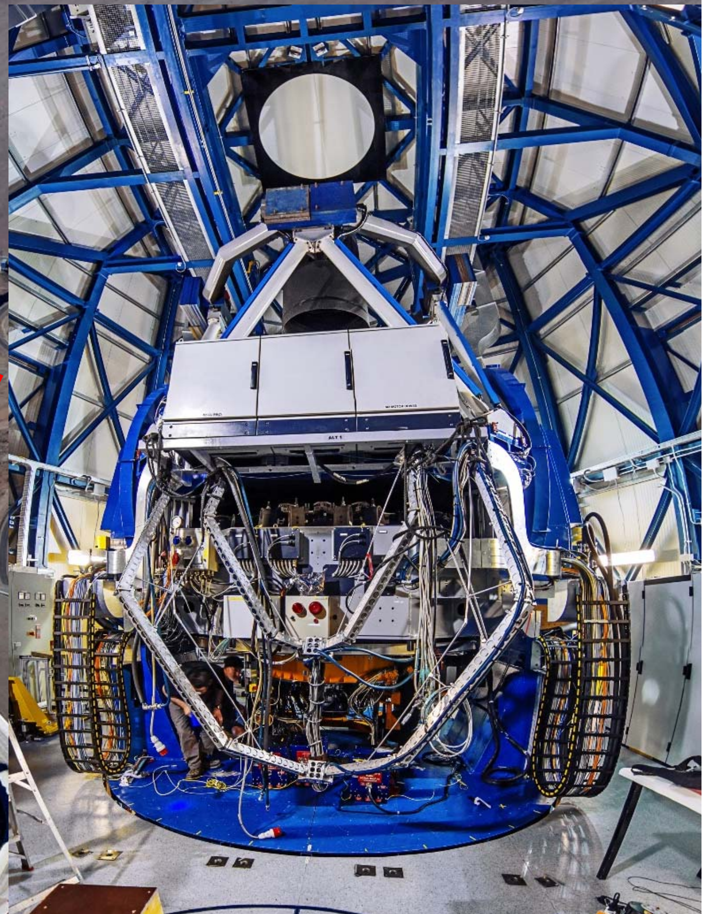
↓

FWHM degraded

On a (much) smaller field the effect of the same misalignment would likely be negligible

Wide-field telescopes

ESO - Paranal



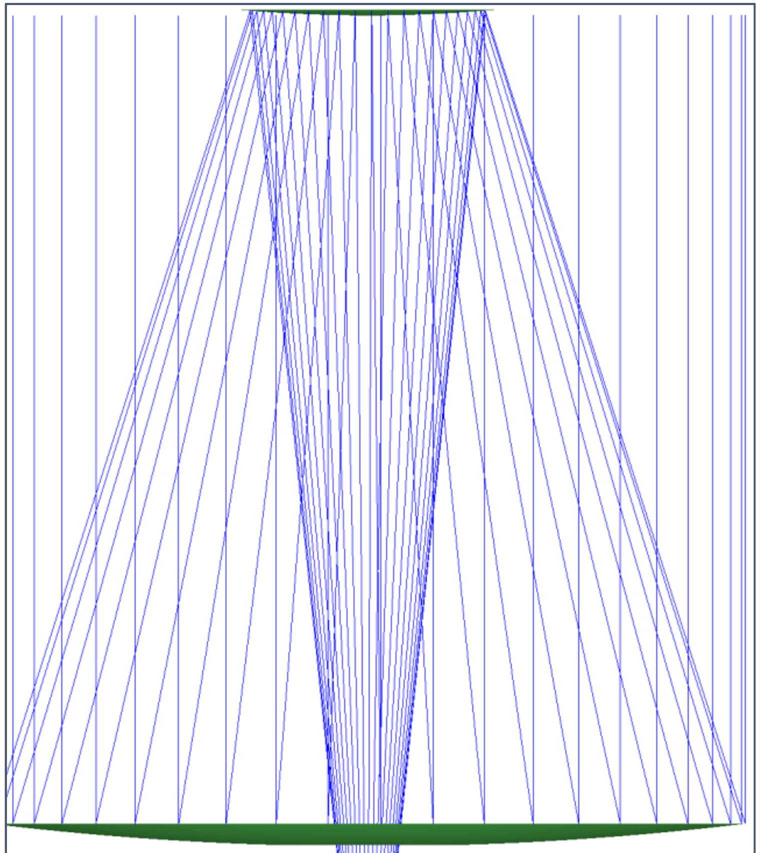
Seeing-limited

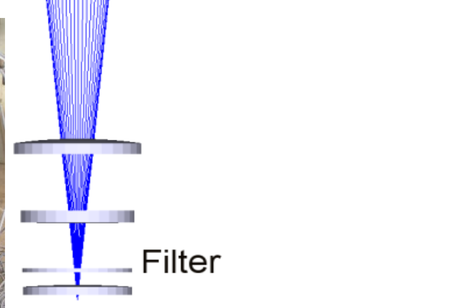
but with some

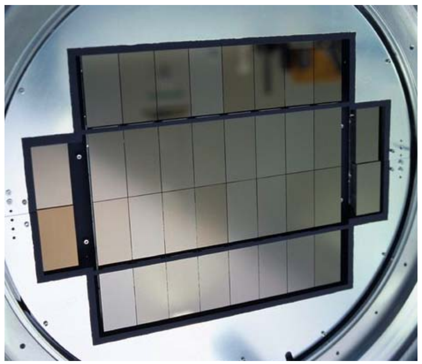
ADONI inside

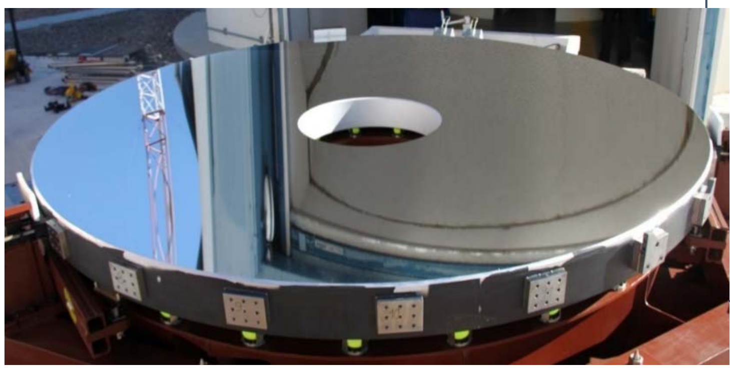
Optical System

- Primary mirror: 2.6-m
- Secondary mirror: 0.9-m
- F# 5.5
- Field corrector with 3 lenses (2 in the telescope + 1 in the camera)
- Field: 1° x 1°
- Curvature Wavefront Sensor with in- and out-focus CCDs (or Shack-Hartmann)
- Active M1 shape control (81 active axial support + 3 axial fixed points)
- Active M2 positioning in 5 dof (hexapod)



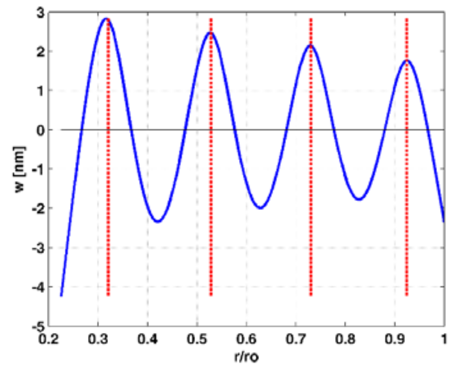


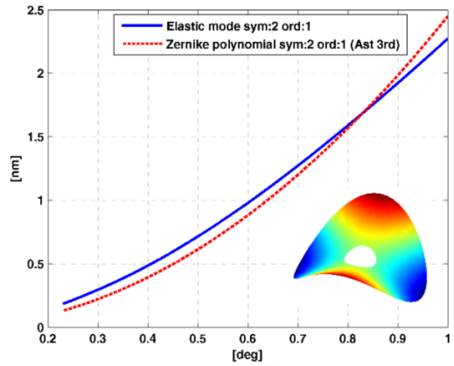


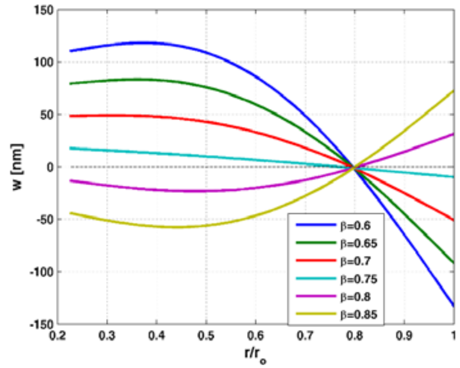


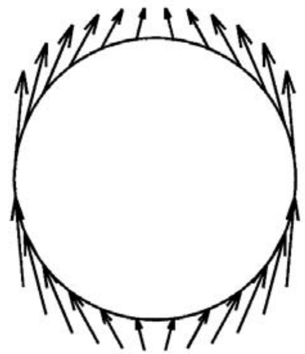
The AO System

- Axial Support System Geometry: result of optimization problem for a four rings continuous support over the full aperture
- 84 axial supports in 4 rings (*small* mirror, the highest density), 3 hard points
- M1 Elastic Modes adopted rather than Zernikes (much smaller correction forces)
- Calibration forces for the correction of the aberration modes computed solving an optimization problem: minimization of the difference between the r.m.s. values of the desired deformation and the one generated by the support forces.
- Lateral Support System (Schwesinger) Optimized with β=0.75, forces with X-Y-Z components.
- Lateral fixed points
- M2 actively corrects defocus, coma, linear astigmatism

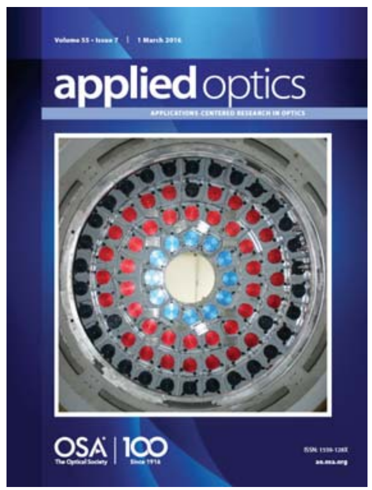


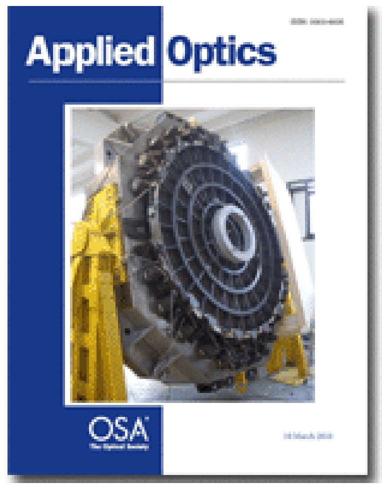






System (pictures?) appreciated by OSA

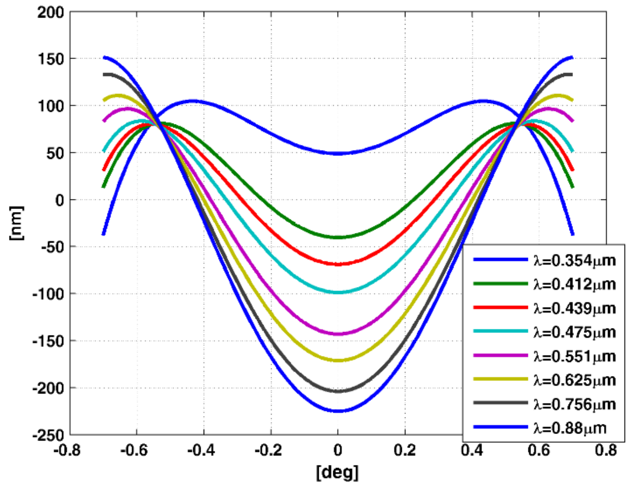




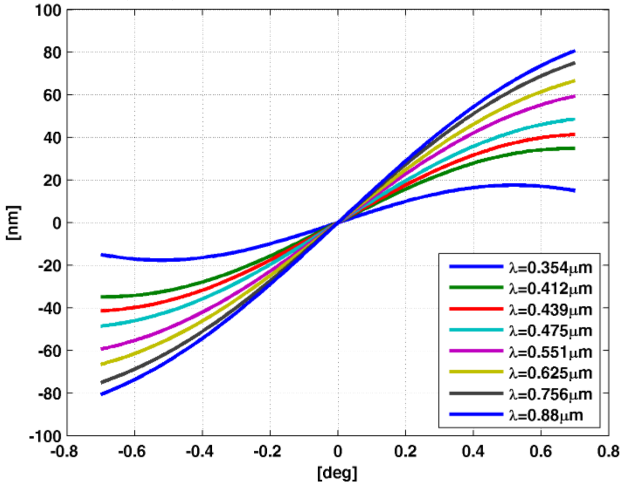
Field Aberrations

- Not a pure Ritchey-Chretien
- Dependencies of defocus (Z4) and the cosine components of third-order coma (Z8) and third-order astigmatism (Z6) on the radial field coordinate σ (Zemax[TM] numbering of Zernike standard modes)
- They strongly deviate from the classical linear (for coma) and quadratic (for defocus and astigmatism) dependencies, based on 3rd order aberration theory
- Well described adding higher order terms in the radial field coordinate

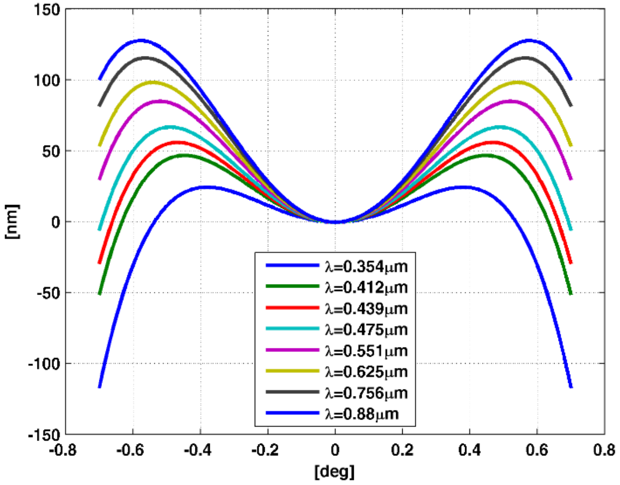
$$Z_4(\sigma) = c_{40} + c_{42}\sigma^2 + c_{44}\sigma^4$$



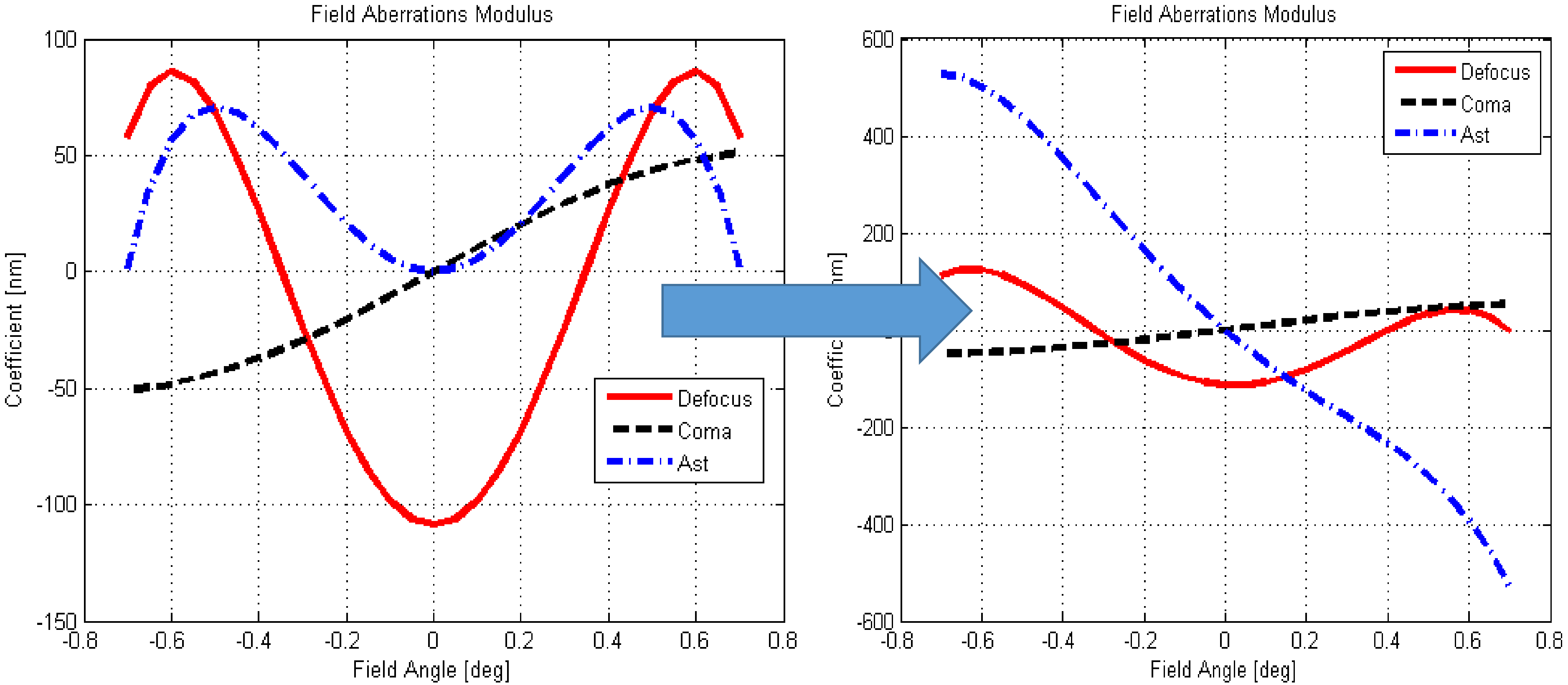
$$Z_8(\sigma) = c_{81}\sigma + c_{83}\sigma^3 + c_{85}\sigma^5$$



$$Z_6(\sigma) = c_{62}\sigma^2 + c_{64}\sigma^4$$



Linear Astigmatism

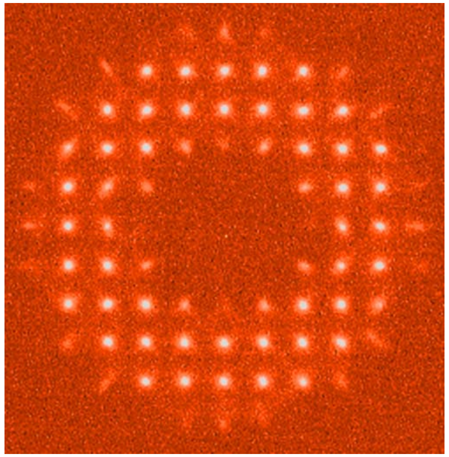


(3 arc min) rotation around CFP
Linear Astigmatism becomes critical… linearly

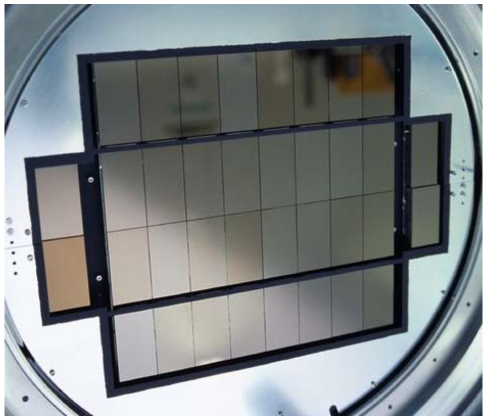
- ❑ Necessity to control linear astigmatism
- ❑ M2 NOT used only to correct coma (but pointing corrections needed)
- ❑ Disentanglement of M1 figure astigmatism and linear astigmatism needed
- ❑ Wavefront sensing in at least 2 field points

Closed Loop with wavefront sensor

- ❑ Shack-Hartmann for commissioning

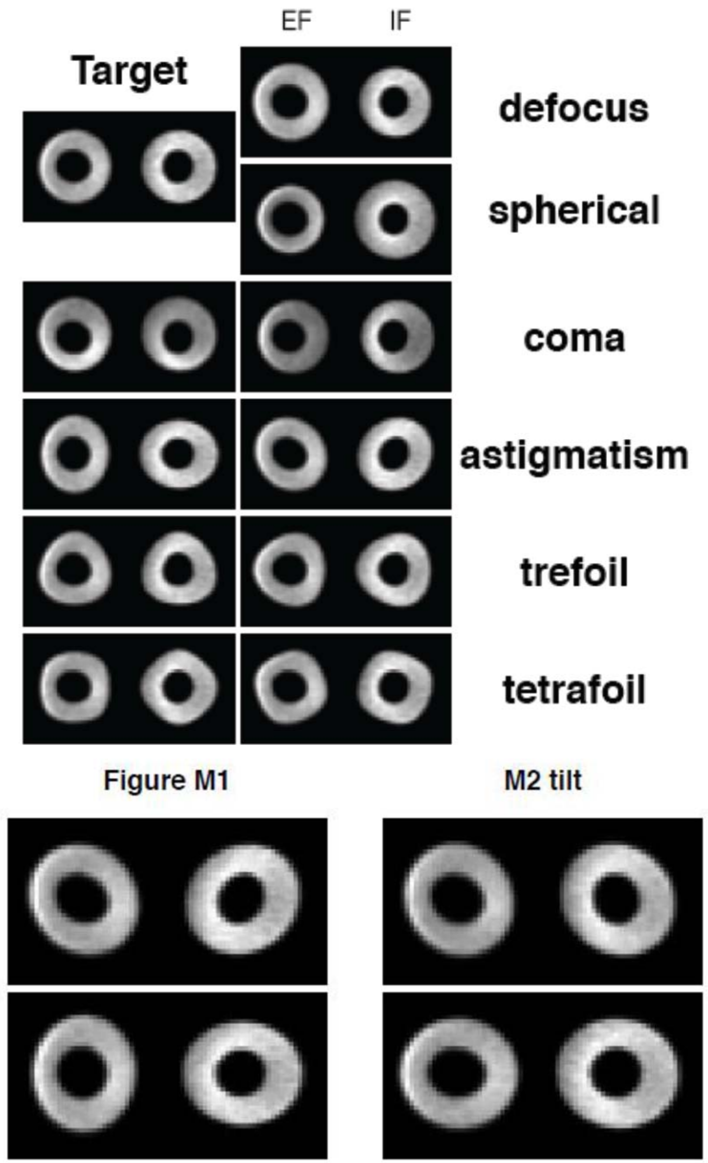


- ❑ Curvature sensor for operations. Two CCDs at the edge of the field intra-focal and extra-focal



- ❑ M1 figure astigmatism disentangled from linear astigmatism (misalignment) Pointing correction applied

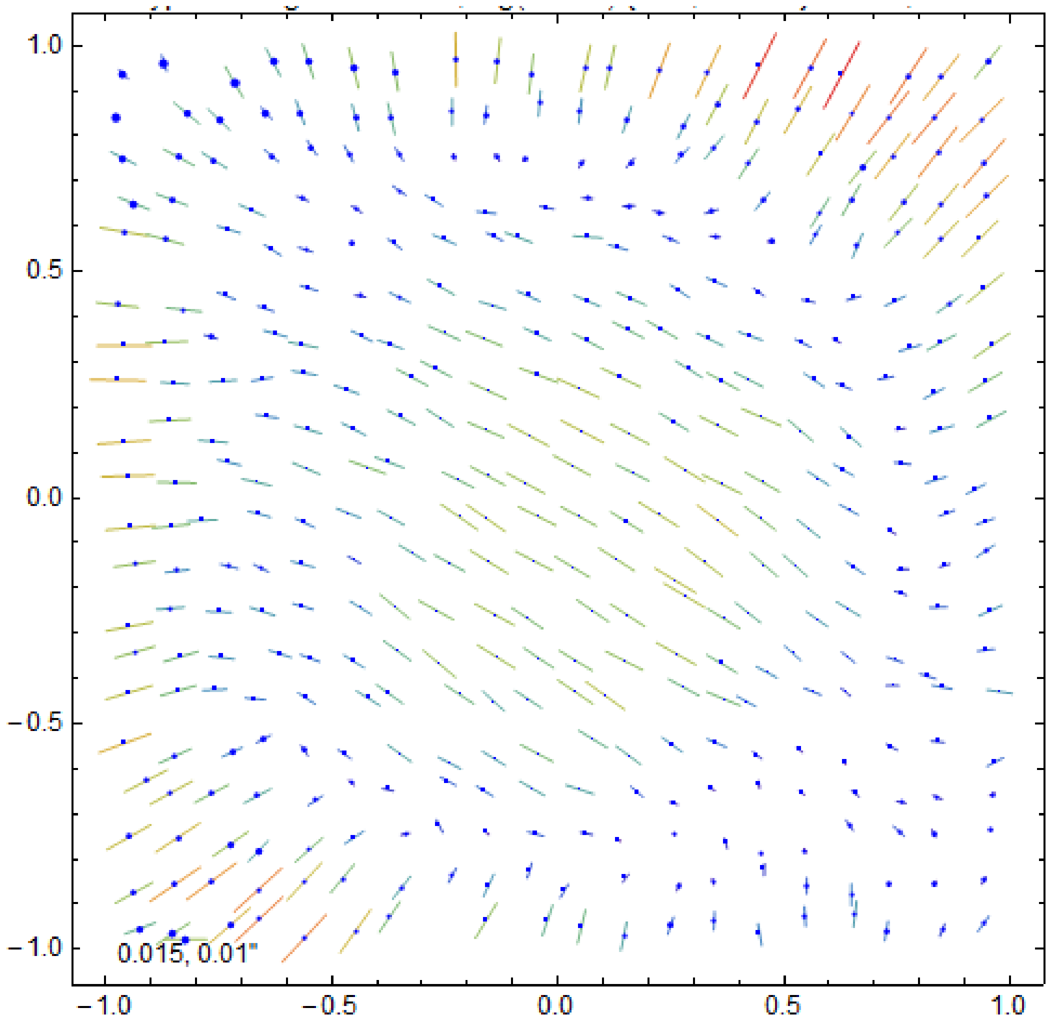
Basis functions



And without? Use of science images

Inverse problem: given a science image, how to correct the telescope aberrations?

- Quantify aberrations in the field by star ellipticities extracted from science image
- Ellipticities also derived from analytical WFE expression



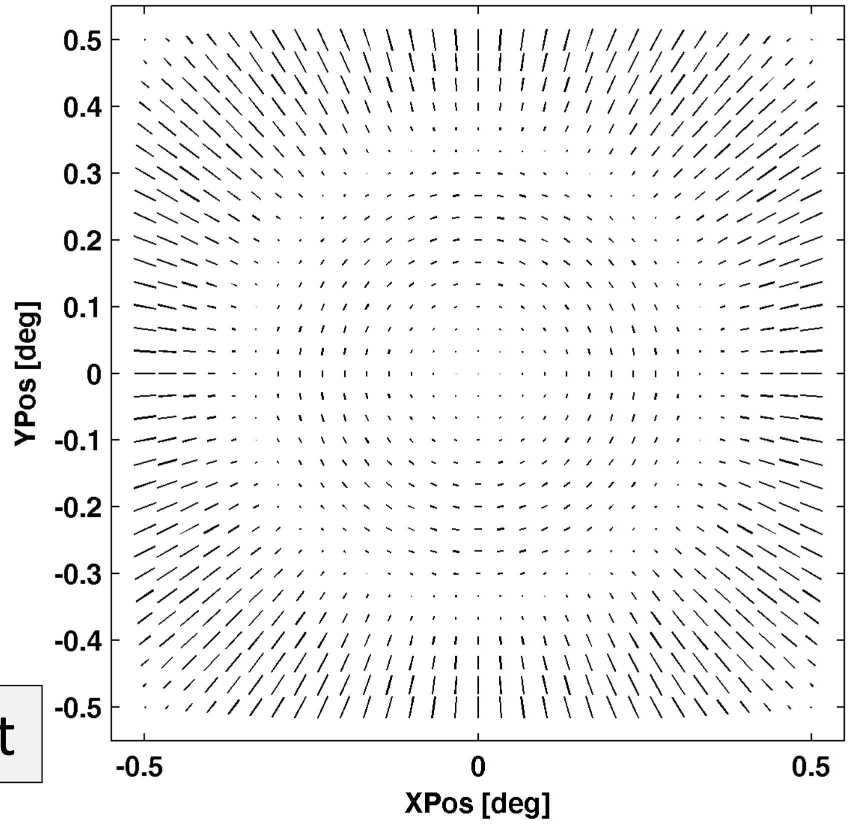
Ellipticities

- Symmetrical pattern of ellipticities in the field in the ideal condition of perfect alignment and mirrors shape
- The field is curved, the ideal condition is a compromise where the best focus (c_{def} =0) is not in the center but approximately half-way to the edge of the field
- The ring of zero ellipticity corresponds to the zero defocus condition
- The ellipticities inside the zero-defocus circle, are orthogonal to the ellipticities out of the circle
- The reason is the well-known property of an astigmatic image ellipse, that rotates by 90 degrees from intra- to extra-focal position

$$\varepsilon = 1 - \frac{\sigma_s}{\sigma_l}$$

$$\sigma_l = \sqrt{\left(k\sigma_{seeing}\right)^2 + \left(\frac{c_{ast} + c_{def}}{r_m}\right)^2}$$

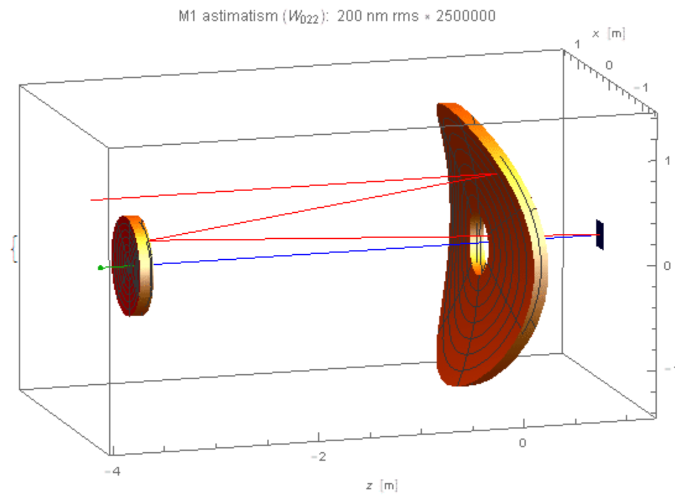
$$\sigma_s = \sqrt{\left(k\sigma_{seeing}\right)^2 + \left(\frac{c_{ast} - c_{def}}{r_m}\right)^2}$$

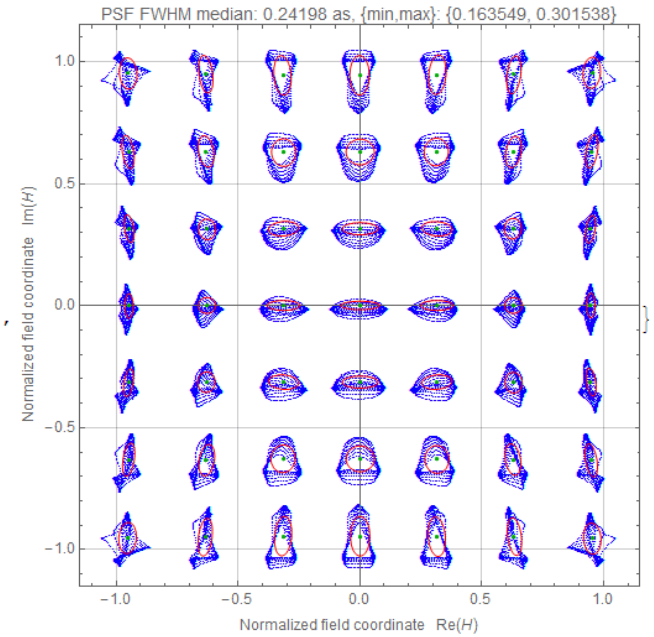


BUT this definition is seeing dependent

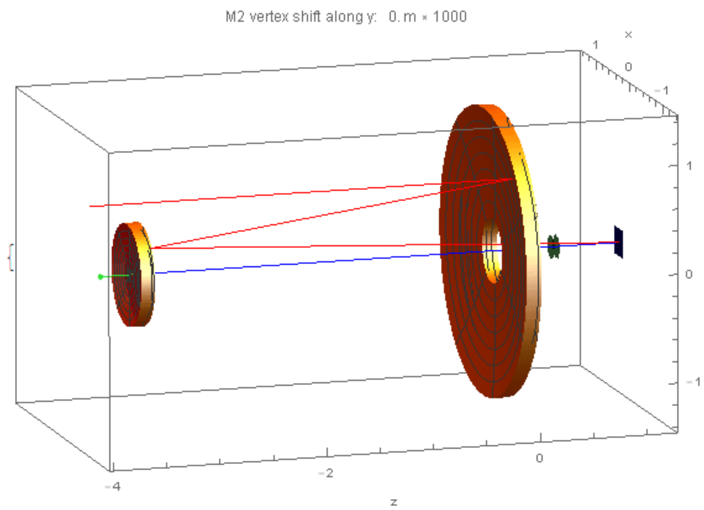
Signature of typical defects

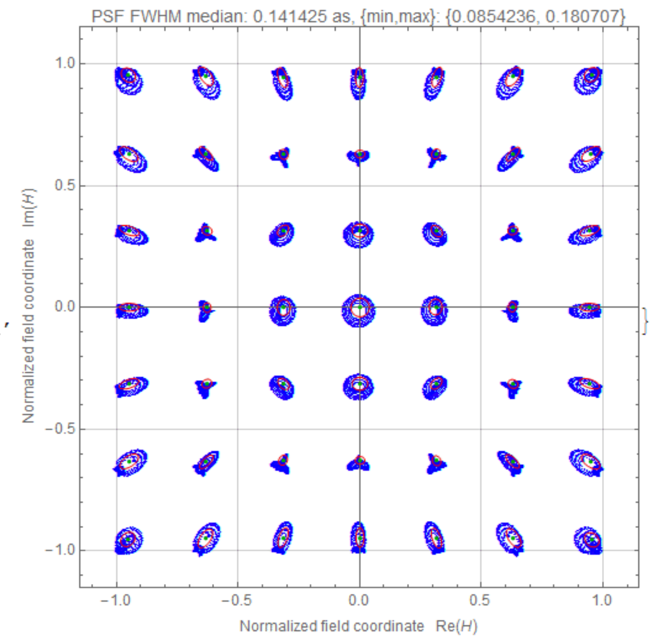
- ❑ M1 Astigmatism





- ❑ M2 shift





Seeing independent definitions

- The moduli of the measured root mean squares σ_l of the long axis and σ_s of the short axis depend on the seeing conditions.
- An alternative definition of the ellipticity is useful, unambiguous and seeing independent, in order to compare the optical theory with the measured parameters.
- One can assume that σ_l^2 and σ_s^2 are the quadratic sums of contributions from the seeing on the one hand and coma and the products of pairs of aberrations on the other hand. If the difference

$$\varepsilon = \sigma_l^2 - \sigma_s^2$$

is defined as the ellipticity modulus, the dependence on the seeing vanishes.

Algorithm

Fast Active Optics Control of Wide-Field Telescopes based on Science Image Analysis

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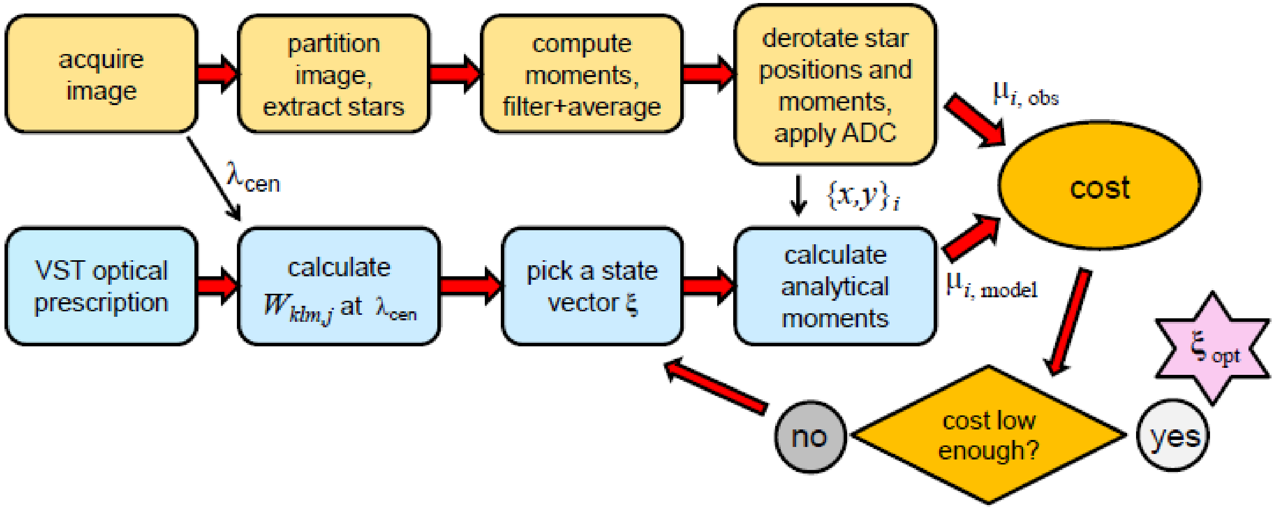
Goal:

- Compare observation with analytical model
- Quantify differences between PSFs in a seeing-independent way
- Based on 2nd central PSF moments, which can be both extracted and computed analytically

Processing:

- Science Image: Computation of ellipticities
- Model: Simulation of optical system behaviour injecting perturbations
- Iterative convergence to the perturbations which best fit the science image



Star extraction and moment computation

Goal: compute the ellipse parameters across the whole image

- ❑Partitioning the total frame of 16kx16k pixels into NxN equal tiles (N≤20) and identifying the brightest objects in each tile. Objects too close to another object or are too close to the image boundary, or those with saturated pixels, are rejected
- ❑Selecting only the brightest objects maximizes the signal-to-noise ratio and tends to filter out galaxies

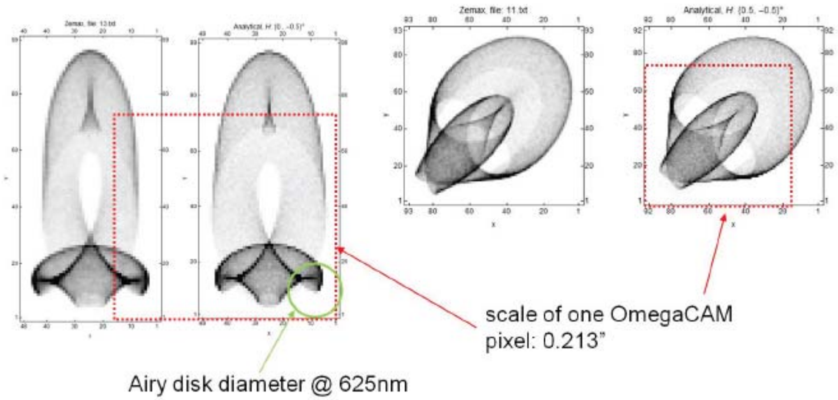
First approach: **SExtractor** (Bertin) => catalogues

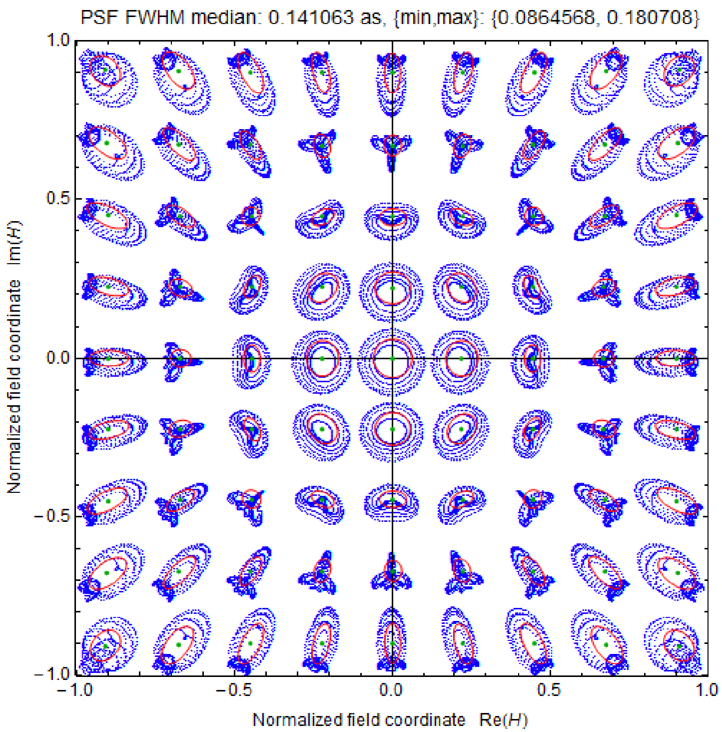
Alternative approach proposed by Holzlöhner: **OVALS**

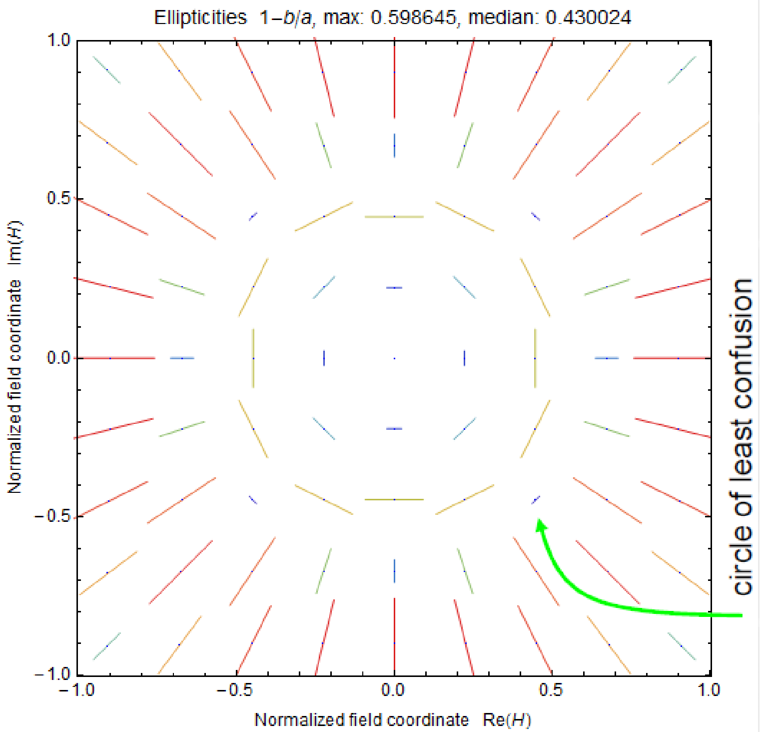
- ➢Works on VST FITS files (550 MB, 32 CCDs)
- ➢Tiles the image e.g. 20×20, reduces only few brightest stars in each
- ➢Rejects saturated stars, outliers, CCD errors etc.
- ➢Parallel processing
- ➢Reduces full image in a few seconds
- ➢Beats SExtractor by far

Analytical model

- ❑Wavefront aberration expansion (Hopkins)
- ❑Generalized to misalignments (Shack & Thompson)
- ❑Nodal theory
- ❑Coefficients of wavefront expansion computed from plate theory (Burch)



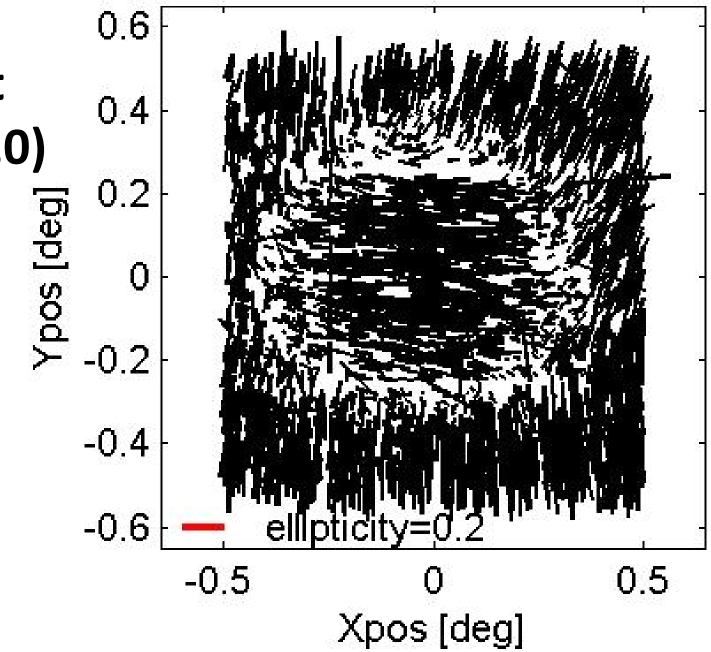




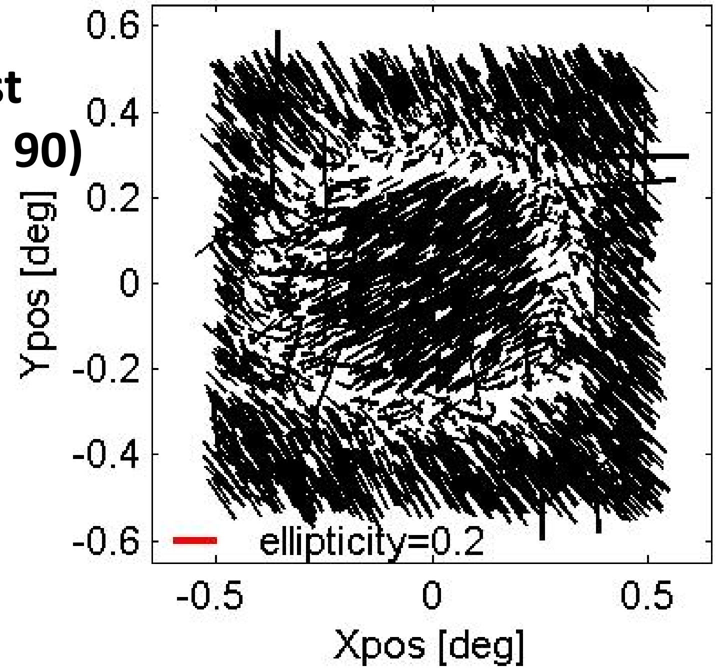
Real images used to tune the method

Test set: images taken during VST commissioning (with seeing good enough, applying known perturbations to the optical system)

Ast (500,0)

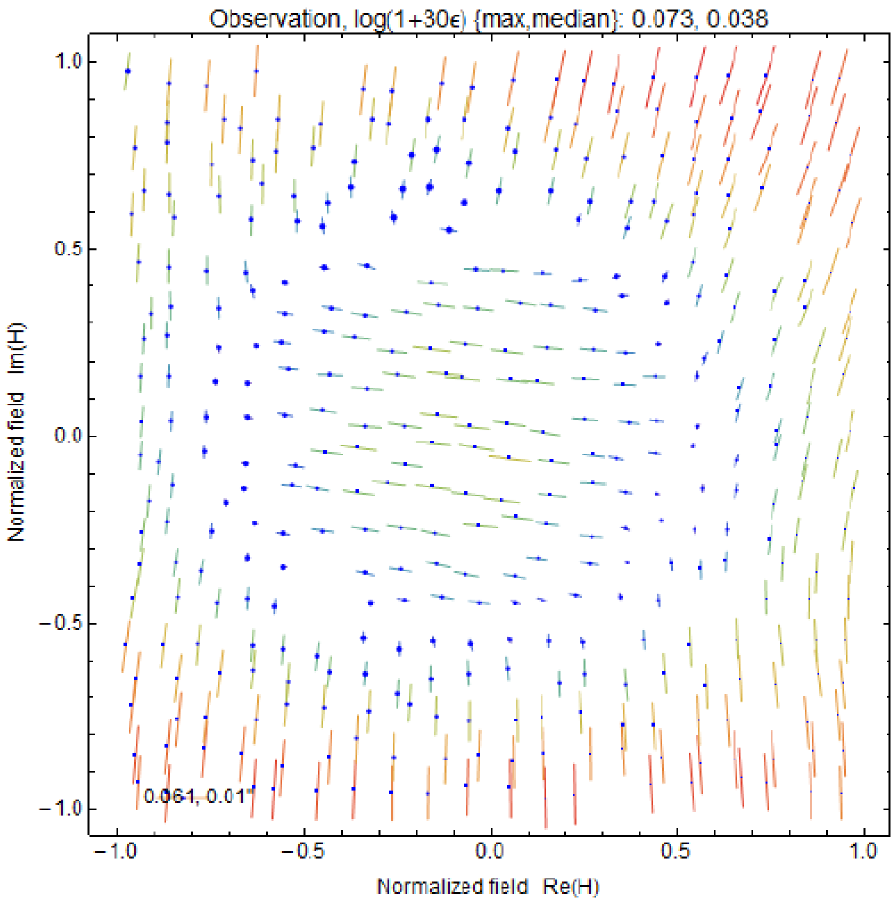


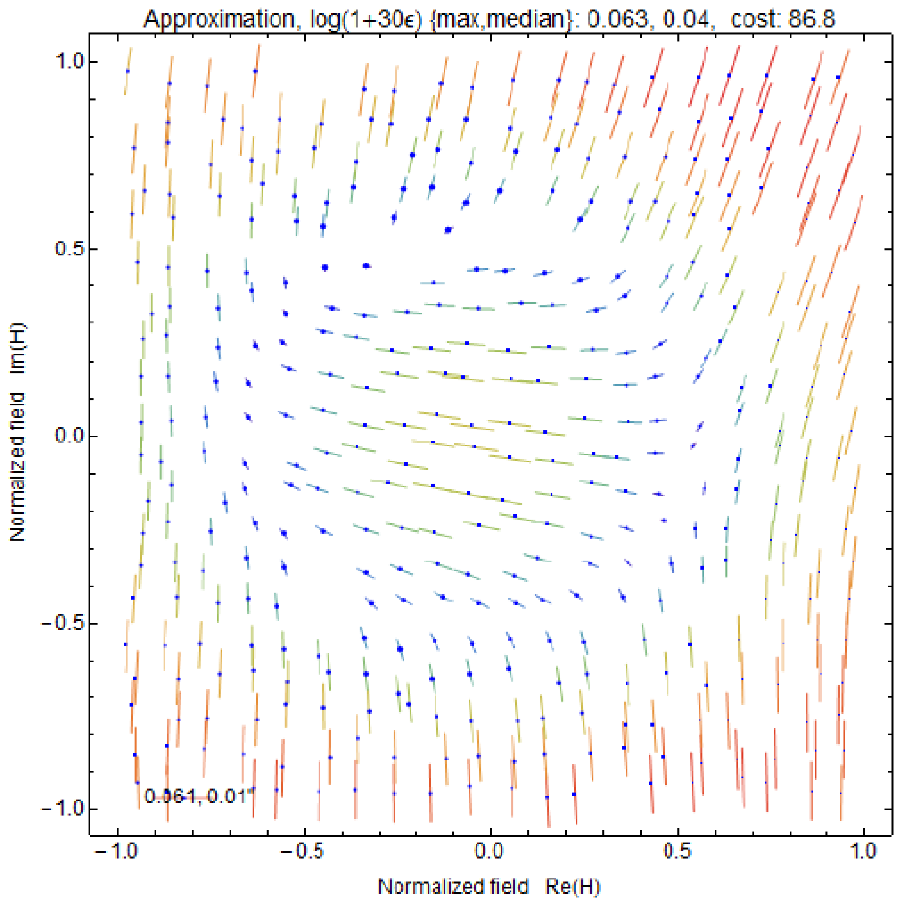
Ast (500, 90)



- Least-squares fit: Nelder-Mead algorithm (*Mathematica* ver.9)
- Simulation with 9 DOF
- 12 parallel threads with random initial values
- Can run on a laptop

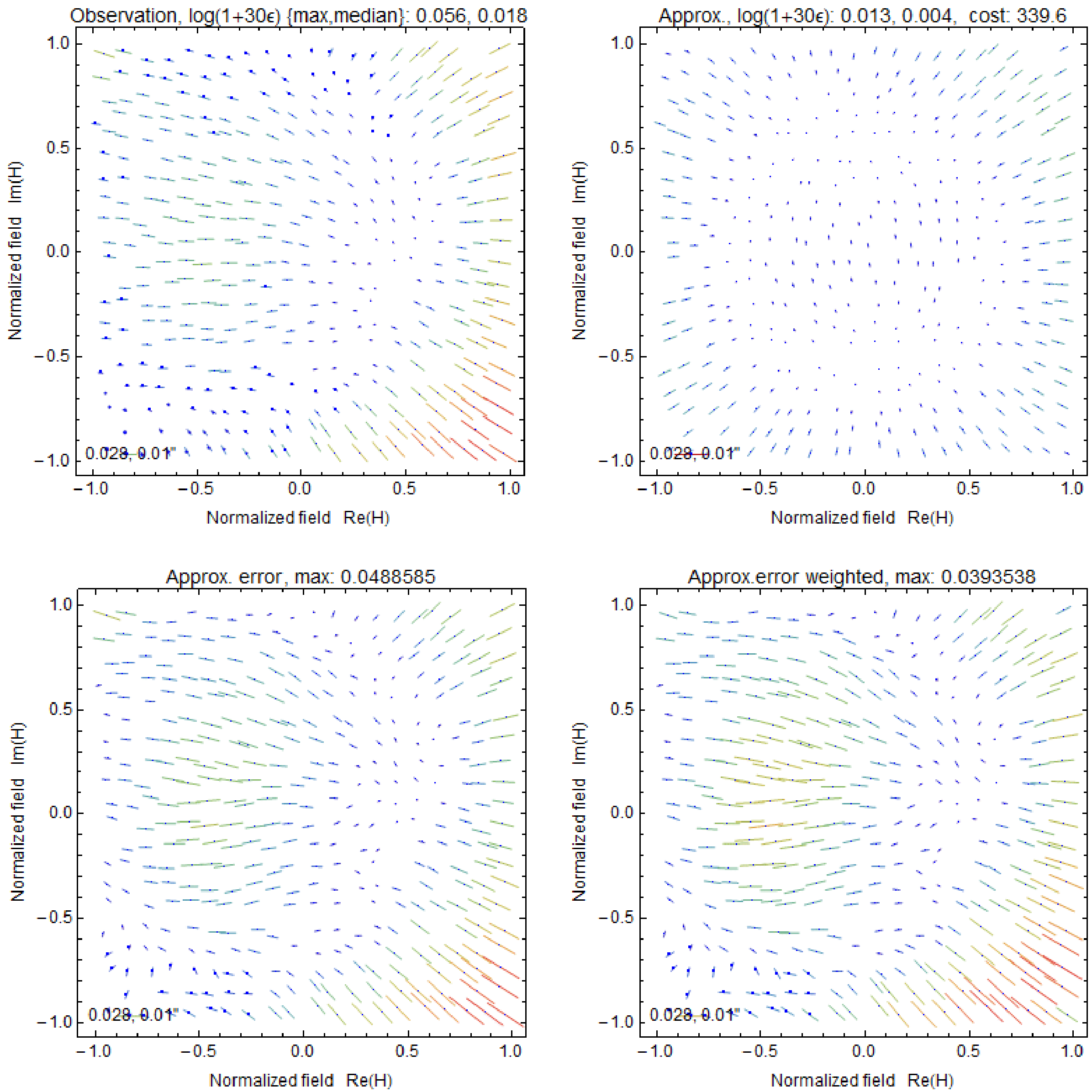
Real Image vs Model





Iterative convergence - animation

- Test image with 60” coma neutral rotation
- 9 degrees of freedom
- Rigid Body Motions on M2 (x,y,z,tip-tilt)
- M1 astigmatism and trefoil
- Runs in ~20s on desktop PC



Tested on the real system

- Few technical nights in 2015
- Donuts algorithm improvement + 1st tests of ellipticity method
- Semi-manual mode
- Corrections given by the ellipticity method based on OmegaCAM images.
- Automatically analysed each incoming image
- Computed correction commands
- Large amounts of misalignments artificially introduced
- The method recovered the alignment within a few iterations.
- The resulting images had residual aberrations often comparable to the "donut" IA method.

<u>Conceptually verified</u>

Conclusions

- Developed model for arbitrary perturbed (wide-field) telescopes that reproduces spot diagrams
- Analytical model
- Star extractor (Ovals) processes ~3000 stars in ~15 sec from 16k×16k OmegaCAM image (550MB)
- Cost function based on seeing-independent PSF ellipticity differences
- Can diagnose perturbed states of VST, fast enough for closed-loop active optics in survey cadence
- Applied approach to VST commissioning data (induced perturbations)
- Concept proved on sky @ Paranal
- A number of other systems could immediately benefit from this result (8m telescope alignment?)
- Option for active optics in wide-field telescopes VST, VISTA, PanSTARRS, DECam, LSST?