INAF - Arcetri

Numerically Closing the Loop of the Adaptive Optics Sensor: the Validation of the Comsol Simulation

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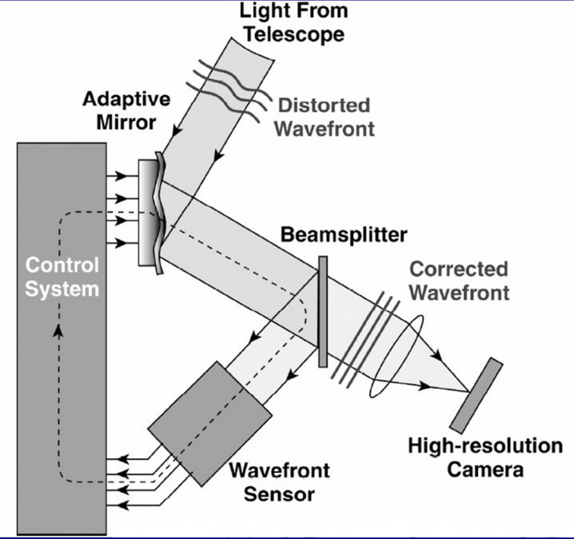
Outline



Light From Telescope
Adaptive Mirror
Distorted Wavefront
Beamsplitter
Control System
Corrected Wavefront
High-resolution Camera
Wavefront Sensor

The Control System

Improving the Closed-Loop Response

- A *feed-forward*, open-loop correction dramatically increases the closed-loop response of the servo system
- This correction is based on the DM stiffness matrix . . .
- . . . operatively defined by arbitrarily displacing one actuator, while all the others are constrained at 0, and calculating the reaction forces
- The *influence function* (IF) is the shape of the DM when poking a single actuator

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The Case Study
The VLT Zerodur DM

R_o/R_i	physical outer/inner radii
K_f/K_b	front/back surface conic constants
R_f/R_b	front/back surface optical radii
t_m	mean thickness
N	total number of actuators

	VLT
R_o	558 mm
R_i	48 mm
t_m	2.0 mm
R_b	4575.30 mm
K_b	0
R_f	4575.3 mm
K_f	−1.66926
N	1170

Convex Very Large Telescope DM [Biasi et al., 2012]

The Previous Results

A Necessary condition

Many advantages and a basic requirement

OPTICAL DATA ⇐ MATCHING ⇒ FEA

Already demonstrated for LBT and VLT mirror local stiffness

[Del Vecchio et al., 2013]

- Expanding the method to the whole DM allows
  - get rid of obscurations
  - avoid complex data processing @ edges
  - easier calibration

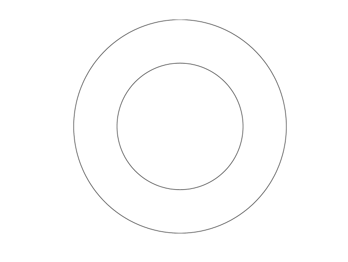
provided that the FEA matches the experimental data

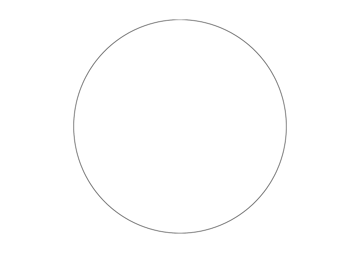
Images vs Simulations

- optical calibration $\looparrowleft$ 1170 Influence Functions
  - IF_i = image of $w_k = \begin{cases} 0 & \text{if } k \neq i \\ w^\star & \text{if } k = i \end{cases}$
- the actuator is moved until the set point via the *capsens* reading (close loop)
- the *capsens* signal is converted from an average capacitance signal, lower than the actual magnet position
- the real IF deformation field differs from the actuation command in the FEM
- a suitable operator makes the transformation

The Simulation I

The actual capsens implies too large models





Can we *squeeze* an annulus into a circumference?

The Simulation II

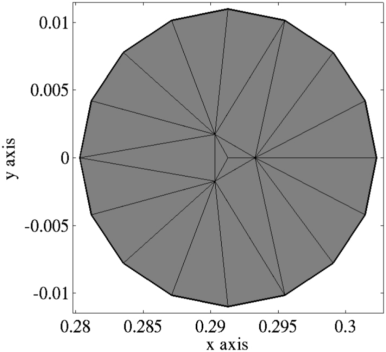
Approximating the capsens signal

- $C = \int_0^{2\pi}\int_{r_i}^{r_o} \frac{\varepsilon}{z(r,\theta)} r dr d\theta = \frac{\varepsilon A}{z^\star}$
- $\frac{1}{z^\star} = \frac{1}{A}\int_0^{2\pi}\int_{r_i}^{r_o} \frac{1}{z(r,\theta)} r dr d\theta$
- Taylor expansion of $\frac{1}{z}$ around $r^\star$ $\forall\theta$
- $r^\star = \frac{2}{3}\frac{r_o^2 + r_i^2 + r_o r_i}{r_o + r_i}$ minimizes the error

The Simulation III

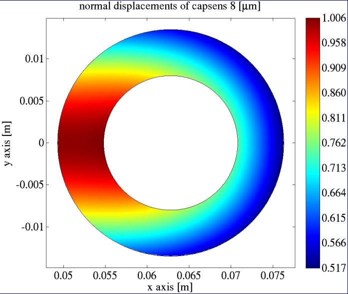
Modelling tricks

- insert 1170 circumferences of radius $r^{\star}$
- mesh them with only 22 triangles (*Delaunay method*)

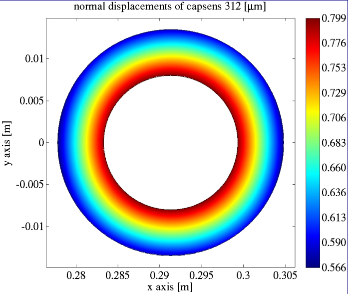


Verifying the $r^\star$ approximation on two VLT actuators

8 @ (0.063,0) (*edge*) error $< 3.5\%$



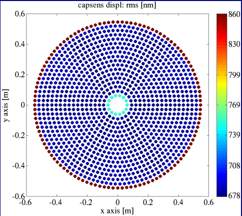
312 @ (0.291,0) (*central*) error $< 1\%$



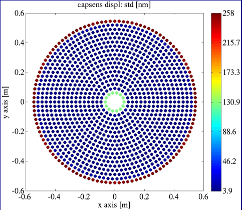
Simulation Results II

The VLT *capsens* displacements

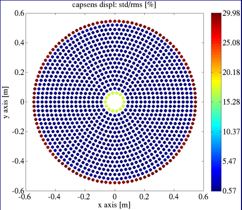
RMS



STD



STD/RMS



Typical std/rms ratio $\approx$ 1%

Processing the Interferometric Data I

Interferometric Data

Experimental IFs

Interferometric data sets $\rightsquigarrow$ mirror deformation map

How the IF data are collected

- displacement $+c$ applied to the ith actuator (an image w_1 is captured)
- displacement $-c$ applied to the ith actuator (an image w_2 is captured)
- repeating these steps N times, $2N$ frames are obtained
- resulting image: $w_m = \frac{1}{N} \sum_{i=1}^{N} \frac{(w_{i1} - w_{i2})}{2c}$

Processing the Interferometric Data II

Interferometric Data

FRAME RATE = 25 Hz

EACH w_m FRAME IS CORRECTED FOR TIP-TILT AND DEFOCUS

PISTON ADJUSTED SO THAT $|w_m| = 0$ AFTER MASKING THE IF PEAK

w_m IS FINALLY NORMALIZED TO UNITARY MAXIMUM VALUE

Image noise = .014

Given by the convection residuals, it's computed as the RMS of the images after masking out the actuated region to be compared with the unitary IF peak value

Data Matching I

FEM $\overset{\text{consistency}}{\Longleftrightarrow}$ Image

- $\mathbf{F_m} \overset{\mathbf{M}}{\Longrightarrow} \mathbf{F_c}$
  - $\mathbf{F_m}$ = model IF data (actuator displaced at the magnet locations)
  - $\mathbf{F_c}$ = image (actuator displaced at the capacitive sensor ones)
  - $\mathbf{M}$ = $n_{act} \times n_{act}$ transformation matrix: $\mathbf{M}(i, j)$ = value of $\mathbf{F_m}(i, j)$ (ith IF, jth actuator) averaged over the capacitive sensor ring as mapped on $\mathbf{F_m}$
- $\mathbf{F_c} = \mathbf{M}^{-1}\mathbf{F_m}$
- each $\mathbf{F_c}$ image is finally
  - re-aligned to match the interferometer images geometry
  - normalized to unitary maximum value
- As a result, $\mathbf{F_c}$ and interferometer images are directly comparable*

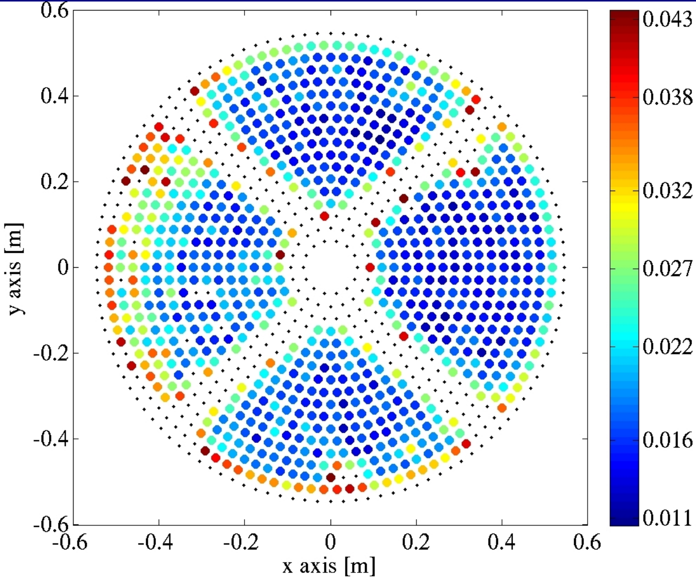
* The uncertainties in the identification of the *capsens* areas and in the images alignment are possibly responsible for systematic errors in the analysis of the subtraction residuals

Data Matching II

Comparison

- take a 80 by 80 pixels area centered at the actuator locations (a grid of 5×5 actuators — the IF is practically flat outside this area); (*figure will follow*)
- $\mathbf{F_c}$ *images* $\ominus$ *experimental data* $=$ *difference map*
- compute the RMS of the difference for each IF; (*figure will follow*)

Results I
The Overall Response



Results I

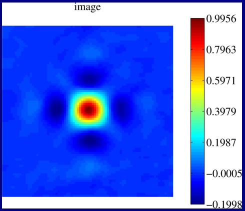
The Overall Response

- 849 of 1170 actuators (colored dots)
  - $.011 \leq \textit{RMS difference} \leq .043$
    - applied displacement = 1
  - $\approx$ 60% of values is $\leq .02$
    - typical experimental data noise = .014
  - maximum values close to the edges
- 321 of 1170 actuators (black dots)
  - inner and outer DM edges
  - areas obscured by the spiders
  - some bad pixels

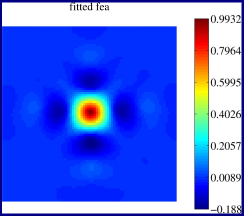
Results II

Detailing the Difference

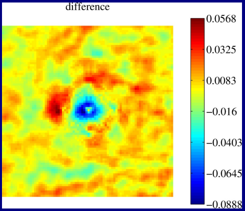
The VLT displacement around actuator # 312



normalized interferometric image



correspondent matrix **F_c**



difference

The difference spans from $-.089$ to $.057$

Although its shows some residue structures,
noticeable at the actuator locations,
the global matching is within the experimental noise

Lessons Learned & Future Work

The matching strategy

COMSOL IFS AND INTERFEROMETRIC MEASURES

numerical data vs measured data

difference ≈ experimental noise

Suitable Comsol tools replicate the measures

A completely numeric, highly accurate control system is achievable

Future developments

Funding request submitted last Monday

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For Further Reading I

Biasi, R., Andrighettoni, M., Angerer, G., Mair, C., Pescoller, D., Lazzarini, P., Anaclerio, E., Mantegazza, M., Gallieni, D., Vernet, E., Arsenault, R., Madec, P.-Y., Duhoux, P., Riccardi, A., Xompero, M., Briguglio, R., Manetti, M., and Morandini, M. (2012).
VLT deformable secondary mirror: integration and electromechanical tests results.
In Ellerbroek, B. L., Marchetti, E., and Véran, J.-P., editors, *Adaptive Optics Systems III*, volume 8447 of *Proc. SPIE*. SPIE.

For Further Reading II

Del Vecchio, C., Briguglio, R., Xompero, M., Riccardi, A., Gallieni, D., and Biasi, R. (2013).
Computing the influence functions of an adaptive optics large deformable mirror: the numerical method and the experimental data.
In *Comsol Conference*, Proc. Comsol. Comsol.