Update on pyramid topics: spiders, LWE, NCPAs, M4, sensitivtiy, K vs R band, . . .

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joint work with Victoria Hutterer & Ronny Ramlau

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WaveFront Sensing and Control in the VLT/ELT era III,
Paris, October 22-24, 2018

Topics

- Overview on novel reconstructors
- Reconstruction in the presence of spiders: three methods
- Handling M4 geometry
- Misregistration analysis
- LWE tests
- First approaches to handling NCPAs
- Pyramid sensitivtiy: K vs R band

Developed algorithms

- Iterative algorithms
  - Conjugate Gradient for the Normal Equation (CGNE)
  - Steepest Descent (SD)
  - Landweber-Kaczmarz Iteration (LKI)

V. H., R. Ramlau, I.S. *Real-time AO with pyramid wavefront sensors: Theoretical analysis of pyramid forward model*. Submitted. Available as preprint https://arxiv.org/abs/1810.00682

V. H., R. Ramlau, I.S. *Real-time AO with pyramid wavefront sensors: Accurate wavefront reconstruction with iterative methods*. Submitted. Available as preprint https://arxiv.org/abs/1809.10888

- Non-linear Landweber

V. H., R. Ramlau. *Non-linear wavefront reconstruction methods for pyramid sensors using Landweber and Landweber-Kaczmarz iteration*. Appl. Opt. 57(30), (2018).

See talk on Tuesday at 15:10

V. Hutterer & I.S., (Semi-)analytical and non-linear approaches towards optical gain compensation for pyramid sensors.

Fragmented pupil (spiders)

Three methods developed:

- Zonal minimum variance estimator with regularized sparse approximation of C_Φ (Ellerbroek02, Bardsley08)
- Split approach I: P-CuReD + DSPR I
- Split approach II: P-CuReD + DSPR II

V. Hutterer, I. S., A.O., R. Ramlau. *Advanced wavefront reconstruction methods for segmented ELT pupils using pyramid sensors*. Submitted.

Effect of misregistration

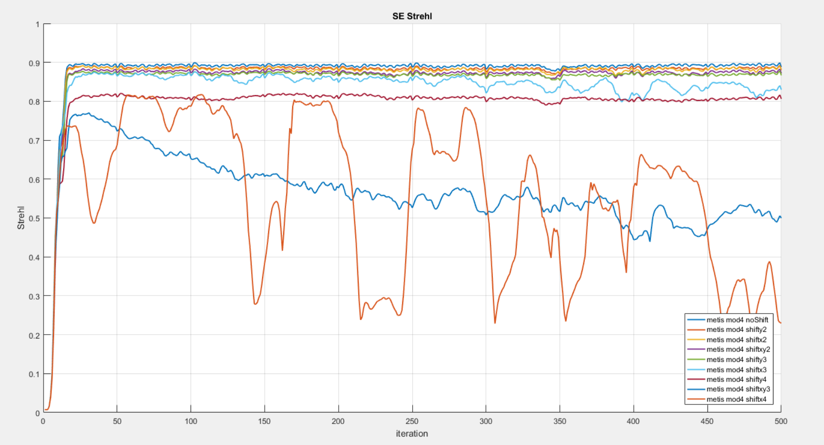
- subaperture size (WFS pixel size): 0.5m
- DM: M4
- unit of shifts: 1 discretisation pixel $\equiv$ 5cm
- unit of rotation: degree
- Results

misregistration	LE Strehl Ratio
x(0) y(0) rot(0)	89.2
x(1) y(1) rot(0)	88.9
x(2) y(0) rot(0)	88.2
x(0) y(2) rot(0)	88.5
x(2) y(2) rot(0)	87.4
x(0) y(0) rot(0.35)	88.5

- rule of thumb applicable (misaglinement stable up to 10

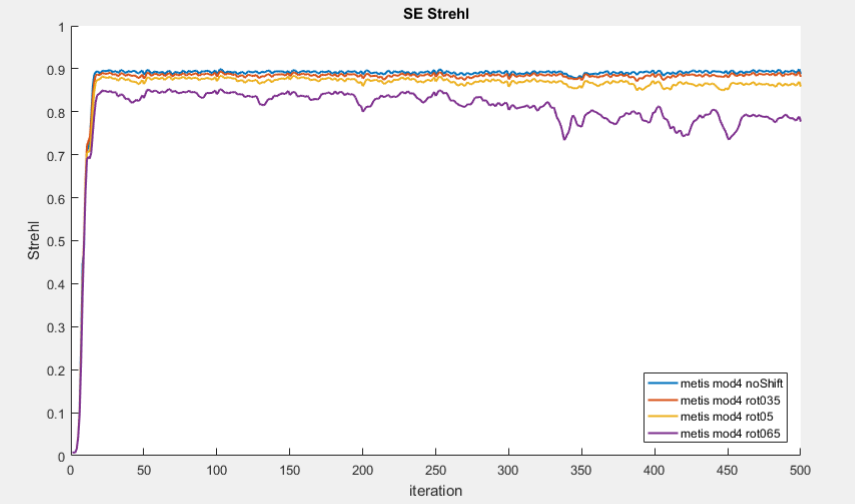
SE Strehl for different shifts

- 1 (discretisation) Pixel $\equiv$ 5cm $\equiv$ 10% of the subaperture size (WFS pixel)



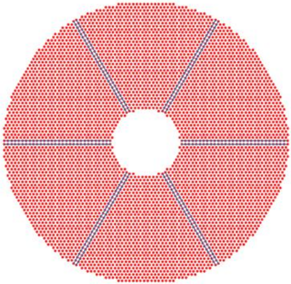
SE Strehl for different rotations

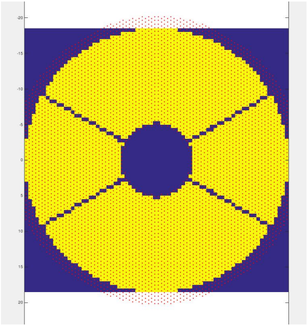
- 0.35 degree roation $\equiv$ 11cm shift for the "outer" subapertures



The M4 geometry

- Actuators arranged circular, spiders "included"
- Active subapertures shown for *frac_illum* $= 0.45$



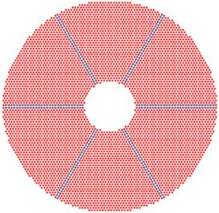


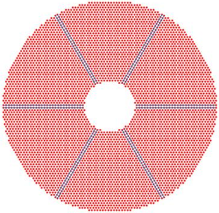
The M4 control pseudocode

```
actPos(2, nAct) ← x- and y− coordinates of the M4 actuator positions
I_sub ← mask holding the active subapertures/pixels
define and initialize DM_shape                  ▷ holds DM values on Fried Geometry
define and initialize DM_update                 ▷ holds DM updates on Fried Geometry
procedure LOOP                                  ▷ AO Loop
    (Sx, Sy) ← from Pyramid WFS
    DM_update = AAORec(Sx, Sy, I_sub)           ▷ update on Fried geometry
    DM_shape = IntegratorControl(DM_shape, gain, DM_update)
    DM_shape = TemporalFrequencyControl(DM_shape)
    M4_actuatorCommands = Interpolate(Extend(DM_shape), actPos)
    send M4_actuatorCommands to M4
end procedure
```

effects of temporal frequency control on the DM

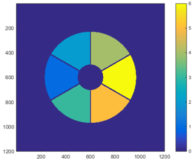
- the first 50 iterations without temporal frequency control
- iteration 10000-10050 and 20000-20050 with DM control

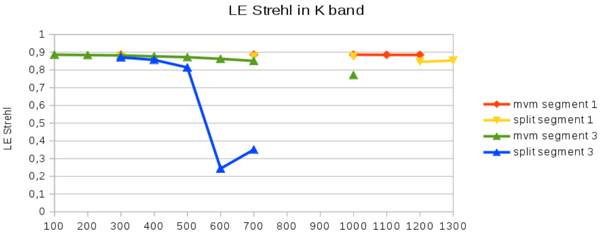




LWE simplified: fragmented pistons

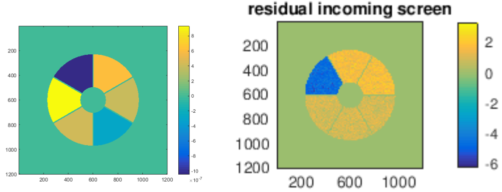
- Simulations in Octopus: add additional LWE screens to WFS and science path
- First approach: add fragmented pistons of different amplitude
- Reconstructors: split and zonal mvm
- Results: loss in quality in dependence from amplitude, location of piston and the reconstructor used



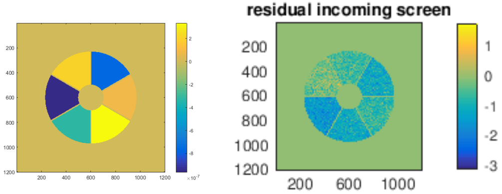


LWE simplified: fragmented pistons (cont.)

- Simulate LWE on 6 pupil fragments simultaneously
- Amplitudes up to around 1μm (as expected on ELTs)



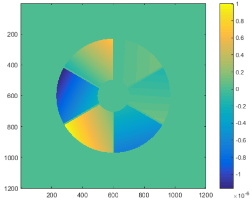
LE100@K=0.80

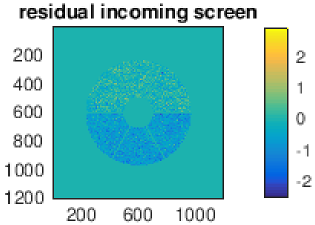


LE100@K=0.753

Realistic LWE

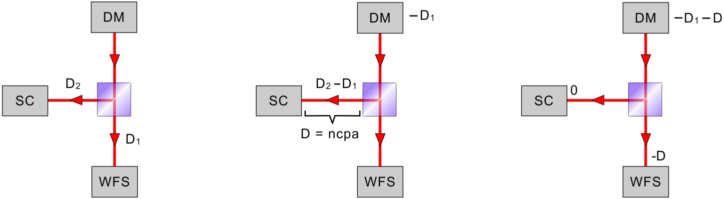
- A combination of tip/tilt and piston on each pupil fragment, with amplitudes up to around 1μm (as expected on ELTs)
- Reference case (no LWE) LE@K=0.89

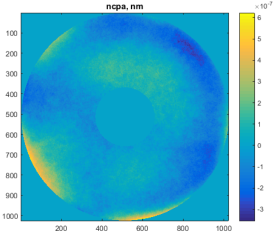




LE100@K=0.819

NCPAs





Credits: Tibor Agocs & Olivier Absil

- Simulations in Octopus: add additional NCPA screens ϕ_{ncpa} to WFS path only

NCPAs (cont.)

- Reference case (no NCPA) LE Strehl 0.89, rms=100nm
- How much correction quality do we lose? No correction:

$$\phi = PCuReD(Sx(\phi + \phi_{ncpa}), Sy(\phi + \phi_{ncpa}))$$

- Assuming linearity of sensor, two correction approaches
- Correction 1: compute data $Sx(\phi_{ncpa}), Sy(\phi_{ncpa})$; assuming linearity of sensor, subtract measurements

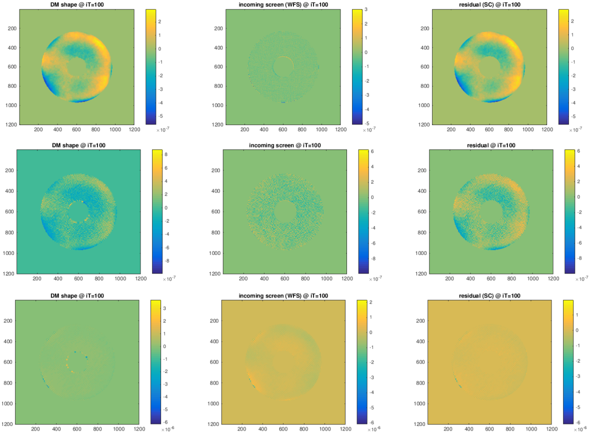
$$Sx' = Sx - Sx(\phi_{ncpa}), \qquad Sy' = Sy - Sy(\phi_{ncpa})$$

$$\phi = PCuReD(Sx', Sy')$$

- Correction 2: subtract ϕ_{ncpa} from reconstruction $PCuReD(Sx, Sy)$

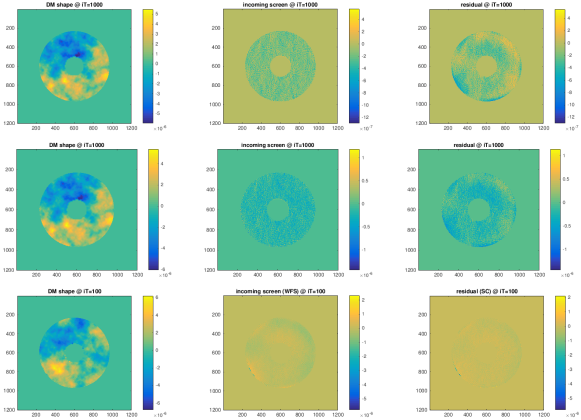
$$\phi = PCuReD(Sx(\phi + \phi_{ncpa}), Sy(\phi + \phi_{ncpa})) - \phi_{ncpa}$$

NCPAs (cont.) – no atmosphere

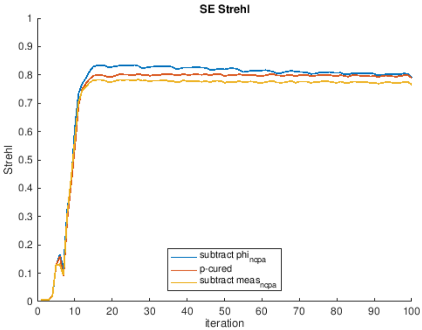


No ATM	LE100
P-cured	0,905
subtract meas_ncpa	0,881
subtract phi_ncpa	0,942

NCPAs (cont.) – with atmosphere



NCPAs (cont.) – with atmosphere

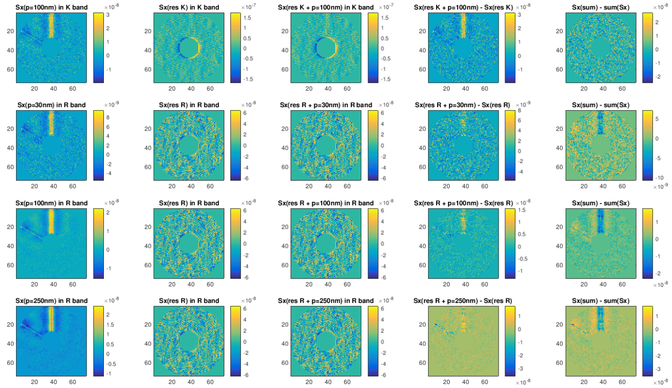


	LE100	LE1000	rms, nm
P-cured	0,798	0,798	166
subtract meas_ncpa	0,775	0,767	180
subtract phi_ncpa	0,813	0,697	210
no ncpa	0,890	0,890	120

- To do: improve interpolation
- Another correction approach: linearize around ϕ_{ncpa}

Pyramid senstivity: K vs R band

- Sensitivity to fragmented piston with and without residual in background
- $rms_{res} \approx$ 100nm corresponds to
  - $\approx$ 0.28 rad in K band $\longrightarrow$ in the linear range of pyramid
  - $\approx$ 0.89 rad in R band $\longrightarrow$ far from the linear range of pyramid



- Non-linearity is the problem!
- Analytical formulas (see talk of VH & IS tomorrow)

Summary

- Three algorithms that solve pupil fragmentation (aka island effect, spiders) problem in K band
- Iterative and non-linear algorithms
- Stable control of M4
- Misregistration analysis
- First simulations in presence of LWE
- First simulations in presence of NCPAs

Further steps:

- Consider more realistic LWE data
- Handling NCPAs: linearize around NCPAs
- Combine NCPAs and LWE

Thanks

Thank you for attention!