Direct piston reconstruction approaches to control segmented ELT-mirrors

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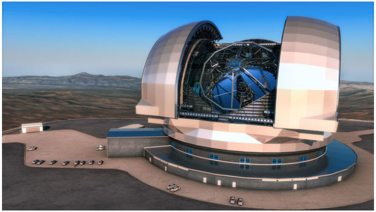
Outline

- Wavefront Reconstruction
  - ↳ talk by Iu. Shatokhina
- Telescope Spiders
- Split Approaches



Wavefront Reconstruction

We are able to perform accurate and robust wavefront reconstruction...

News on WF reconstruction from Austria

Algorithm	Strehl ratio	Complexity
Matrix-Vector Multiplication (MVM)	$\approx$ 0.62 [1]	$O(n^2)$
Preprocessed CuReD (P-CuReD) [2]		$O(n)$
Conv. with Linearized Inverse Filter (CLIF) [3]		$O(n^{3/2})$
Pyramid FTR (PFTR) [3]		$O(n \log n)$
Finite Hilbert Transform Rec. (FHTR)		$O(n^{3/2})$
Singular Value Type Reconstructor (SVTR) [4]	0.77	$O(n^{3/2})$
Conjugate Gradient for Normal Eq. (CGNE) [5, 6]		$O(n^{3/2})$
Steepest Descent [5, 6]	$\geq$ 0.79	$O(n^{3/2})$
Pyramid Kaczmarz Iteration (PKI) [5, 6]	0.81	$O(n^{3/2})$
Nonlinear Landweber Iteration	$\geq$ 0.83	$O(n^{3/2})$

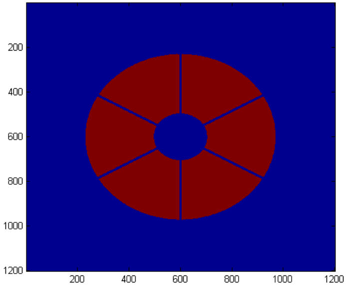
(METIS, modulation 0, frame rate 1kHz, high flux, 500it)

[1] M. Le Louarn et. al., *Latest AO simulation results for the E-ELT*, poster AO4ELT5.
[2] Iu. Shatokhina, A. Obereder, R. Rosensteiner, R. Ramlau,*Preprocessed cumulative reconstructor with domain decomposition: a fast wavefront reconstruction method for pyramid wavefront sensor*, Applied Optics 52(12), 2640-2652 (2013).
[3] Iu, Shatokhina, R. Ramlau, *Convolution- and Fourier-transform-based reconstructors for pyramid wavefront sensor*, Applied Optics 56.22 (2017),pp. 6381-6390.
[4] V. Hutterer, R. Ramlau, *Wavefront Reconstruction from Non-modulated Pyramid Wavefront Sensor Data using a Singular Value Type Expansion*, Inverse Problems, accepted.
[5] V. Hutterer, R. Ramlau, Iu. Shatokhina, *Real-time AO with pyramid wavefront sensors: Theoretical analysis of pyramid forward model*, in preparation.
[6] V. Hutterer, R. Ramlau, Iu. Shatokhina, *Real-time AO with pyramid wavefront sensors: Accurate wavefront reconstruction with iterative methods*, in preparation.

Wavefront Reconstruction

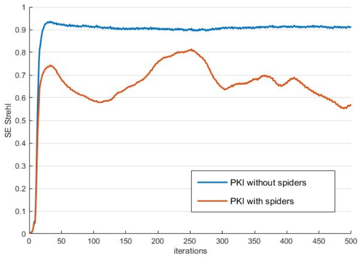
We are able to perform accurate and robust wavefront reconstruction...

... unless we are taking wide telescope spiders into account.



Telescope spiders

- pupil segmentation & break in spatial connectivity of the data
- differential piston effects between the segments
- extremely poor wavefront reconstruction



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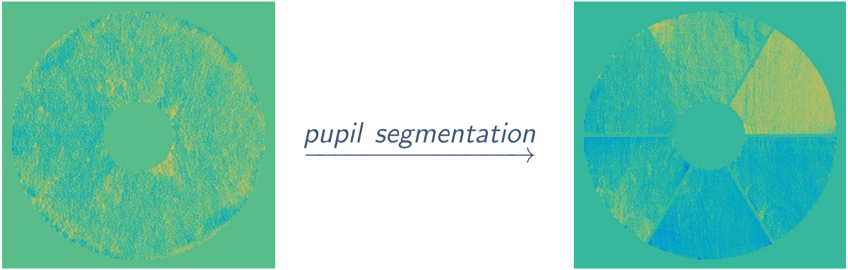


How can we handle missing data under spider legs?

First approaches:

- measurement/phase interpolation
- sophisticated measurement extensions, e.g. generate data using the sensor forward model
- data smoothing
- temporal control of piston on segments

Should we use data provided under the spider legs?

How much quality do we loose in case of segmented mirrors?

How can we make existing reconstruction methods feasible under the presence of spiders?

Could we reach the same Strehl ratios as we would obtain without spider legs?

Split Approaches

Requests:

- compoundable with all existing reconstruction methods
- providing high reconstruction quality
- low computational complexity

Split Approach =
piston-free WF reconstruction + direct piston reconstruction

Split Approaches

$\rightarrow$ divide aperture Ω into segments Ω_i

Preconditions:

- reconstruction method can be implemented on segments Ω_i
- reconstructions Φ_i on every segment Ω_i need to be global piston free
- piston p_i on every segment is calculated independently by **direct piston reconstructors**

General idea:

$$\Phi = \sum_{i=1}^{n_{seg}} \Phi_i + p_i$$

Simulation settings

	METIS
telescope diameter	$37m$
central obstruction	28%
AO system	SCAO
science band	K
sensing band	K
pyramid WFS	$\surd$
modulation	4
subapertures	74×74
Van Karman atmospheric model	$\surd$
simulated layers	35
outer scale L_0 (m)	25
Fried radius r_0 (m)	0.157
photon flux	high
frame rate	500 Hz

simulation environment: Octopus

reconstruction method: P-CuReD algorithm (implemented on segments)

Which reconstruction quality is attainable?

Benchmark - Houdini Method:

- we calculate the piston information on segments directly from the incoming phase $\Phi_{incoming}$ (which is not known in practice)
- the extraction is represented by a matrix Q
- we obtain the piston values on segments by

$$p = Q\Phi_{incoming}$$

LE Strehl ratios:

0.892	without spiders
0.869	with spiders and Houdini method

Direct Piston Reconstructor I (talk by A. Obereder)

Actuator-Poke Approach:

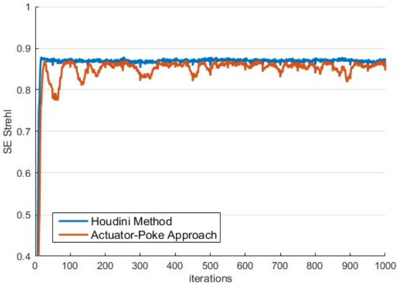
- use full poke matrix M of the system
- solve equation in a least-squares sense (regularization) $\rightarrow M^\dagger$
- extract piston information on every segement by matrix Q

$$p = Q\Phi = QM^\dagger s =: \mathcal{C}s$$

Direct Piston Reconstructor I

We cut down the computational expensive MVM approach to a direct piston reconstruction method.

matrix dimension $2n_a \times 2n_a \longrightarrow n_{seg} \times 2n_a$



more details → talk by A. Obereder

Direct Piston Reconstructor II (S. Raffetseder)

Zernike Piston Approach:

- describe incoming wavefront Φ using Zernike polynomials

$$\Phi(x, y) = \sum_{i=1}^{N} c_i z^{(i)}(r, \theta) =: Zc$$

- generating matrix M such that

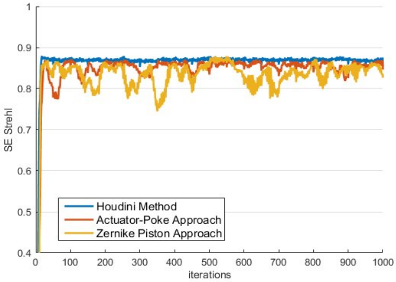
$$\mathbf{P}\Phi = s = Mc$$

- solve equation in a least-squares sense $\rightarrow M^\dagger$
- extract piston information on every segement by matrix Q

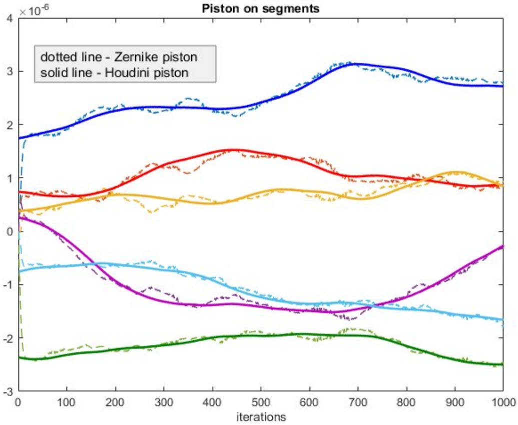
$$p = Q\Phi = QZc = QZM^\dagger s =: \mathcal{Z}s$$

Direct Piston Reconstructor II

- we transform PWFS data into SH-like data (pre-processing as for P-CuReD)
- SH sensor can be modeled in a linear way
- matrix M generated very fast (SH sensor)
- pseudo open loop control
- matrix $\mathcal{Z}$ is dense but has dimension $n_{seg} \times 2n_a$



Direct Piston Reconstructor II



Direct Piston Reconstructor III

Segment-Poke Approach:

- describe piston p as

$$p(x,y) = \sum_{i=1}^{n_{seg}} c_i \mathcal{X}_{\Omega_i}(x,y)$$

- generate segment-poke matrix M such that

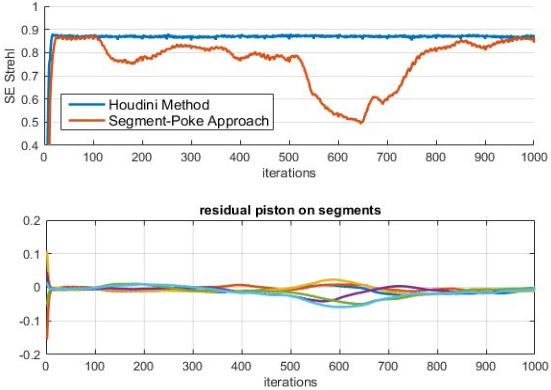
$$\mathbf{P}\mathcal{X}_{\Omega_i} = s_i = M\tilde{e}_i \qquad \forall i = 1, 2, \ldots n_{seg}$$

- solve equation in a least-squares sense $\rightarrow M^\dagger$
- calculate piston on every segment by

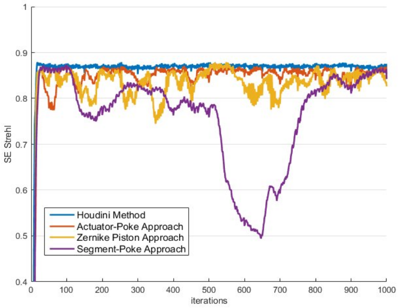
$$p = M^\dagger s$$

Direct Piston Reconstructor III

- stable until about iteration 100
- afterwards, the reconstruction suffers from differential piston effects



Direct Piston Reconstructors - Summary



	LE Strehl
without spiders	0.892
Houdini method	0.869
Actuator-Poke Approach	0.853
Zernike Piston Approach	0.832
Segment-Poke Approach	0.699

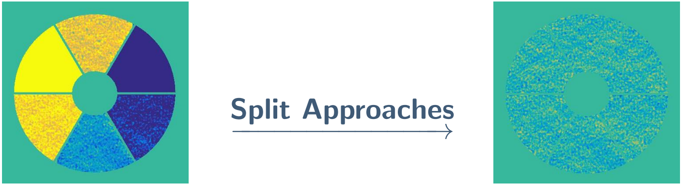
(LE Strehl ratio in K-band)

Direct Piston Reconstructors - Summary

- all methods are based on the **non-linear pyramid model including interference effects**
- the used matrices are dense but only of dimension $n_{seg} \times 2n_a$
- optimized with respect to **computational complexity (linear)**
- computational expensive steps can be precomputed off-line
  ↳ test stability with respect to varying parameters (atmosphere, photon flux, ...)

Conclusion

How could we make existing reconstruction methods feasible under the presence of spiders?



How much quality do we loose in case of segmented mirrors?
[$\sim$ 0.04 in terms of LE Strehl ratio]

Could we reach the same Strehl ratios as we would obtain without spider legs? [no/not yet]

Thank you for your attention!