FEWHA for the MORFEO instrument

Balancing between reconstruction quality and run-time

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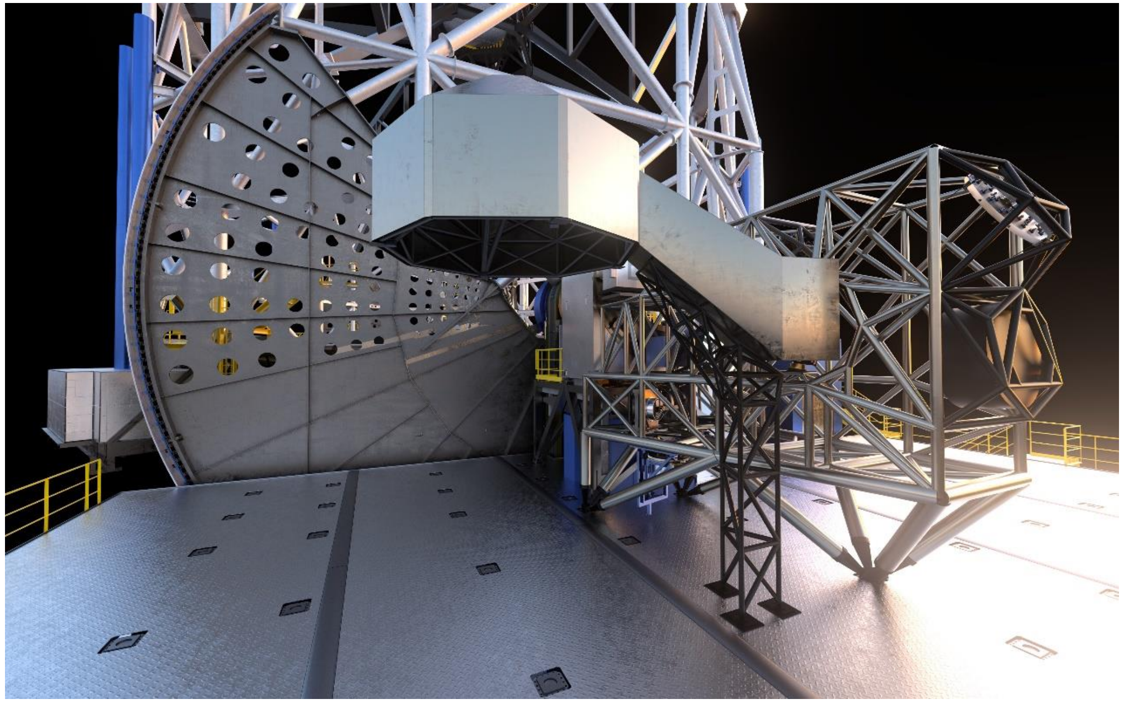
Wavefront Sensing in the VLT/ELT Era VII Porto, Portugal October 21st, 2022

Multi Conjugate Adaptive Optics Relay (MORFEO)

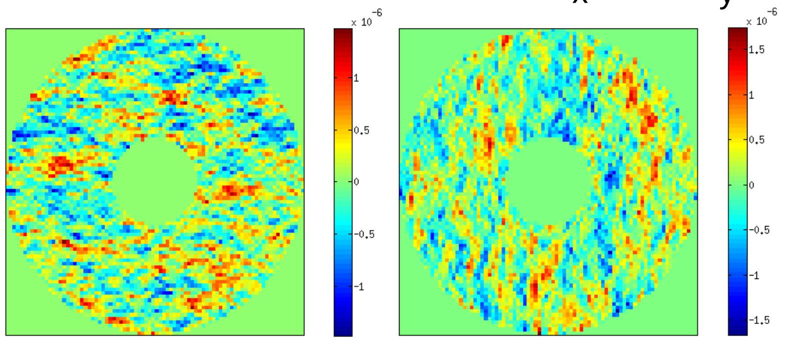


Credit: ESO

- **Adaptive Optics module** for ESO‘s Extremely Large Telescope (ELT)
- **Aim**: Providing good wavefront correction over a large field of view
- Requires tomographic estimation of 3D atmospheric wavefront disturbance

AO control - 2 step approach

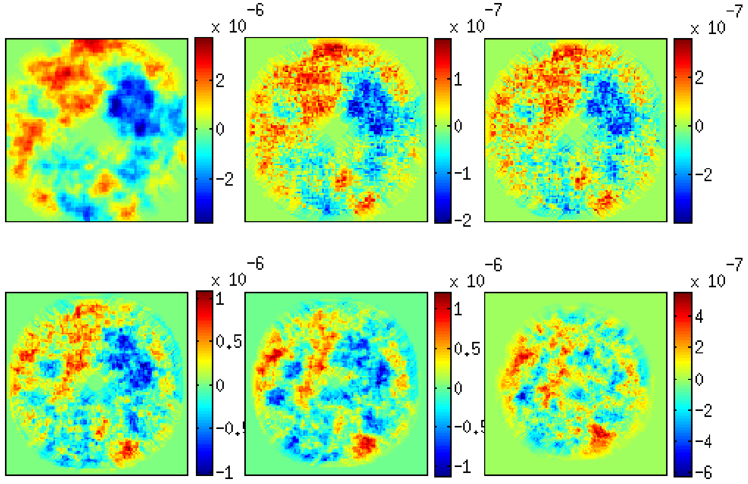
WFS measurements s_x and s_y



Atmospheric tomography

$$s = A\,\phi$$

6 turbulent layers ϕ

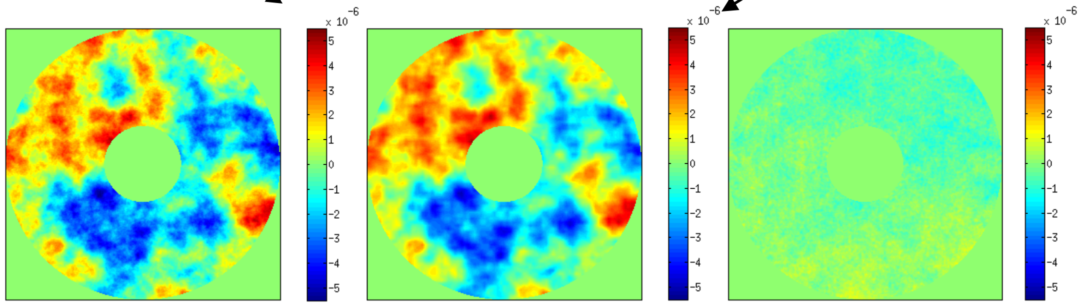


MVM method: $a = Rs$

R precomputed in soft-real time

Fitting / Projection step

$$a = F\,\phi$$



Incoming screen DM shape Residual

Finite Element Wavelet Hybrid Algorithm (FEWHA)

Atmospheric tomography

- Reconstruct turbulent layers from sensor measurements

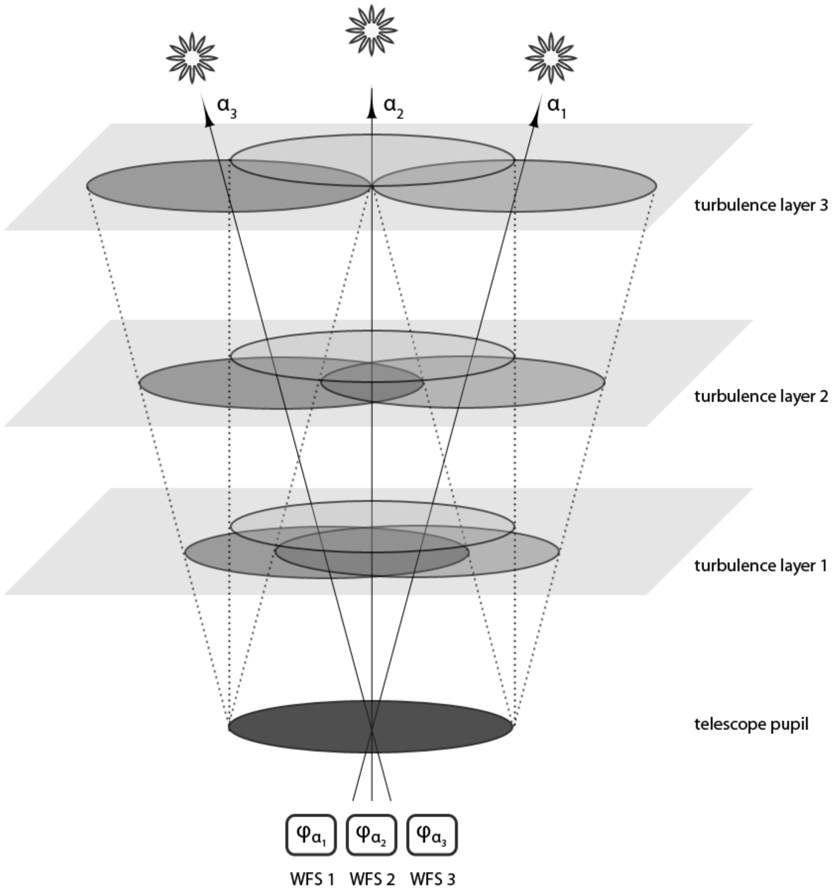
$$s = A\,\phi$$

- **Regularization:**
  Bayesian framework + maximum a-posteriori estimate

$$(A^{*}C_{\eta}^{-1}A + C_{\phi}^{-1})\phi = A^{*}C_{\eta}^{-1}s$$

- **Challenges**:
  demanding operations to be solved in real-time (500 Hz)

Sparse discretization + iterative solver



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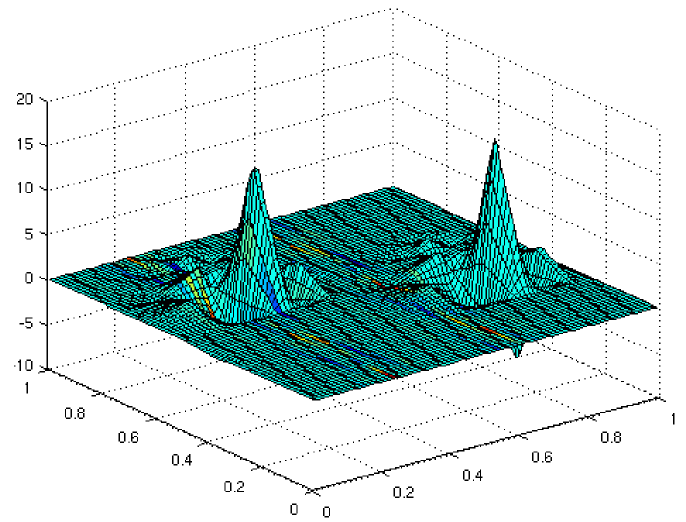
Finite Element Wavelet Hybrid Algorithm (FEWHA)

Wavelets for atmospheric tomography

- **Idea:** Using a wavelet basis for representing the turbulence layers
- **Why wavelets?**
  - Approximative properties (less coefficients)
  - Fast decay in the frequency domain
    → efficient turbulence statistics representation
  - diagonal C_{ϕ}^{-1} in wavelet basis
  - Discrete Wavelet Transfrom is O(n)
- **Wavelets of choice:** Daubechies 3



M. Yudytskiy and T. Helin and R. Ramlau. Finite element-wavelet hybrid algorithm for atmospheric tomography. J. Opt. Soc. Am. 2014.

Finite Element Wavelet Hybrid Algorithm (FEWHA)
Atmospheric tomography

- **Dual domain discretization**: wavelet basis + bilinear basis
- **Iterative approach**: Preconditioned Conjugate Gradient Method (PCG

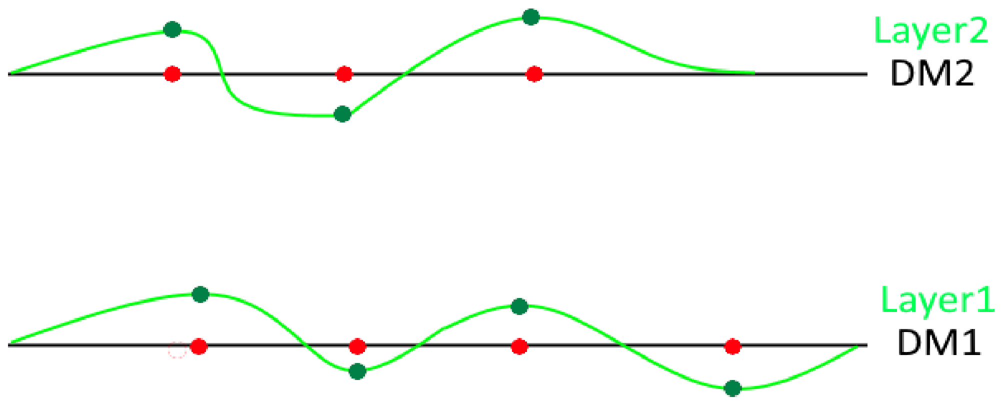
+ Fast, because of sparse matrices

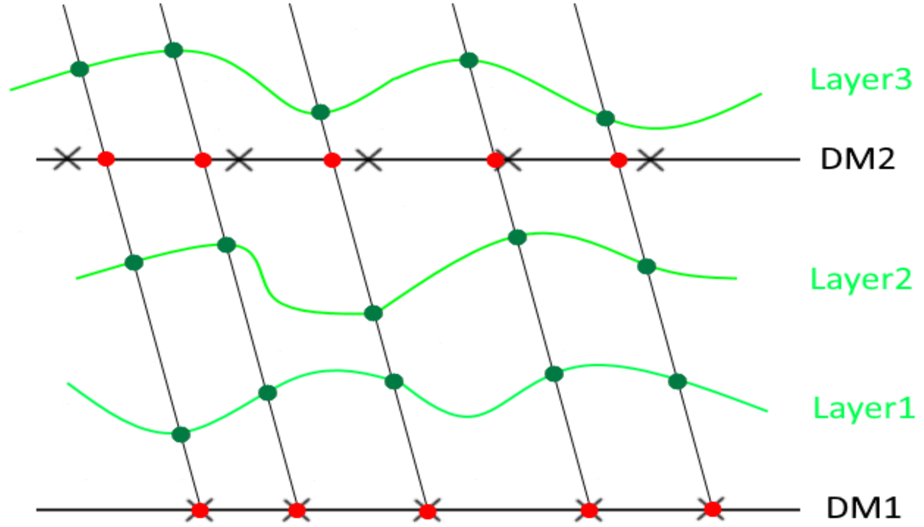
+ On the fly parameter updates (no soft real-time precomputation)

- More complex structure of the algorithm → harder to parallelize and pipeline

Finite Element Wavelet Hybrid Algorithm (FEWHA)

Mirror fitting for MCAO systems





Layers at altitudes of DMs: No mirror fitting necessary

$$a = W^{-1}c$$

More layers than DMs: Additional problem to be solved

$$\bar{P}^T \bar{P} a = \bar{P}^T P W^{-1} c$$

P … projection through layer ℓ into direction θ
$\bar{P}$ … projection through DM into direction θ

Real-time performance

Reducing the PCG iterations for tomography and mirror fitting

1. **Warm restart**: Reusing the solution from previous time step as intial guess for the PCG method of the next time step

2. **Preconditioning: (**Modified) Jacobi preconditioner

   M. Yudytskiy and T. Helin and R. Ramlau. A frequency dependent preconditioned wavelet method for atmospheric tomography. AO4ELT3 Conference. 2013.

3. **Augmented Krylov Subspace Method:** Reusing search directions of PCG from previous time step to speed up the PCG of the next time step

   B. Stadler and R. Ramlau. An augmented wavelet reconstructor for atmospheric tomography. ETNA. 2021.

Numerical simulations

in OCTOPUS

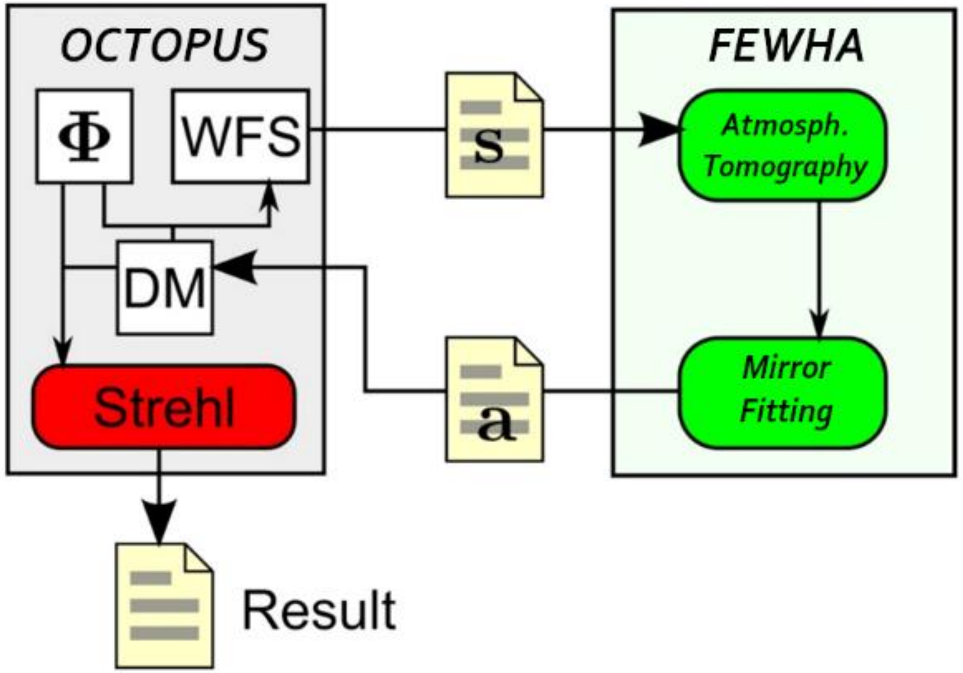
DMs (equidistant actuator spacing)			
	DM1	**DM2**	**DM3**
Actuators	75 x 75	47 x 47	37 x 37
Altitude	0 km	4 km	12.7 km
Spacing	0.5 m	1 m	1 m

Wavefront Senors		
	LGS - WFS	**NGS - WFS**
Type	SH - WFS	SH - WFS
Number	6	3
Geometry	74 x 74 subap.	2 x 2 subap.
Subap. size	10 x 10 pixel	6 x 6 pixel
GS asterism	45 arcsec	55 arcsec
Wavelength	589 nm	1650 nm
Flux	500 photons/subap./frame	500 photons/subap./frame
Detector RON	$3.0e^{-}$/pixel/frame	$3.0e^{-}$/pixel/frame

System parameters	
Telescope	37 m diameter
Obstruction	11 %
Fried parameter	12.9 cm
Turbulence layer	35 layer, von Kármán, L0=25 m
Na-layer height	90 km
Na-layer FWHM	11.4 km
Delay	2 frames
Evaluation wavelength	K band
Simulation duration	1 s

Parallel implementation on CPU

- **Global parallelization** over number of layers or WFSs
  → block diagonal structure of matrices
- **Local parallelization** inside the blocks



- Parallel, matrix-free implementation in C++
- FEWHA called as external library in OCTOPUS
- Run-time measurements only for FEWHA
  (no data movement)

Test settings

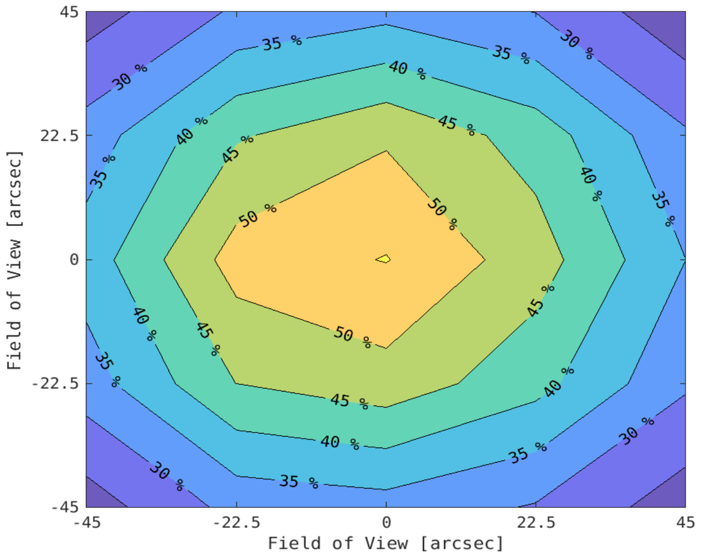
1. **MORFEO with 2 post focal DMs**
   a) Reconstructing 3 layers directly at the altitudes of the DMs (no mirror fitting)
   b) Reconstructing 9 layers with a mirror fitting step

2. **MORFEO with 1 post focal DM**
   a) Reconstructing 2 layers directly at the altitudes of the DMs (no mirror fitting)
   b) Reconstructing 9 layers with a mirror fitting step

Strehl ratio in 5x5 directions over FoV

35 layer atmosphere, 3 DMs

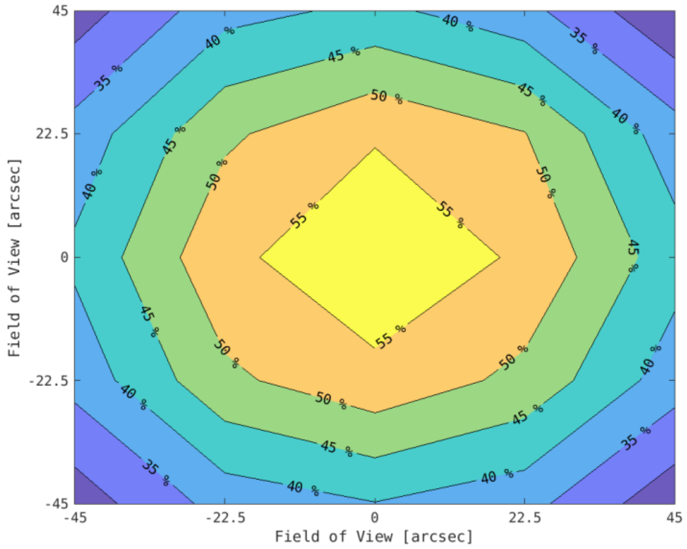
3 rec. layer



- Center Strehl Ratio: 55.22 %
- Average Strehl Ratio: 36.07 %

- Number of PCG iterations: [2, -]
- Run-time: 1.5 ms

9 rec. layer



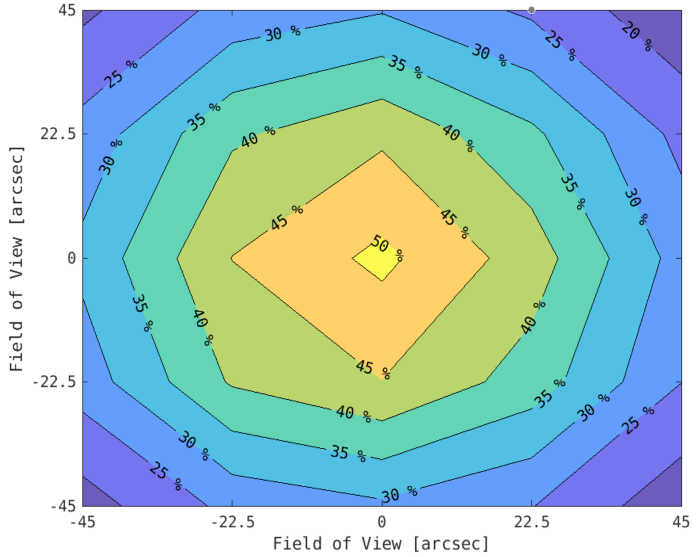
- Center Strehl Ratio: 58.89 %
- Average Strehl Ratio: 41.57 %

- Number of PCG iterations: [4, 2]
- Run-time: 8.1 ms

Strehl ratio in 5x5 directions over FoV

35 layer atmosphere, 2 DMs

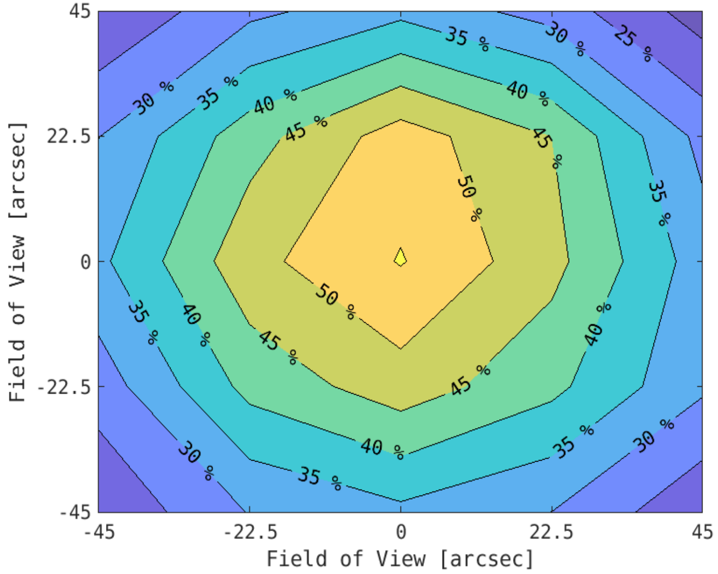
2 rec. layer



- Center Strehl Ratio: 51.21 %
- Average Strehl Ratio: 30.95 %

- Number of PCG iterations: [2, -]
- Run-time: 1.4 ms

9 rec. layer



- Center Strehl Ratio: 55.30 %
- Average Strehl Ratio: 34.52 %

- Number of PCG iterations: [4, 2]
- Run-time: 7.9 ms

Summary

- Wavelet based, iterative real-time reconstructor FEWHA
- Fast + good reconstruction quality
  - Sparse discretization with wavelet and bilinear basis
  - Reduced number of PCG iterations
  - Matrix-free, parallel implementation in C++
- No soft-real time precomputation of the inverse

  → on the fly parameter updates

Ongoing and future work

- Comparison with the Fractal Iterative Method (FrIM) in OCTOPUS
- Interface to PASSATA simulator

  → compare with well-tuned MVM

- Implementation on FPGAs (together with Microgate)
- Testing at bench and on-sky

Microgate's Real Time Reconstructor

Thank you!

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