PSF reconstruction and deconvolution for extremely large telescopes

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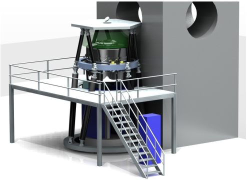
Outline

- Image improvement via deconvolution
- PSF reconstruction
- Simulation results

MICADO

Multi-AO Imaging Camera for Deep Observations



Source: MICADO Consortium

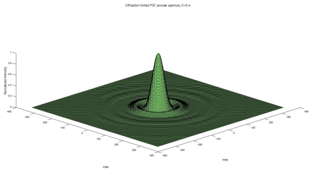
- First light instrument of the ELT
- Single-Conjugate Adaptive Optics in MICADO
- Multi-Conjugate Adaptive Optics in MAORY (coupled to MICADO)
- High contrast & resolution imaging

Image formation on a telescope

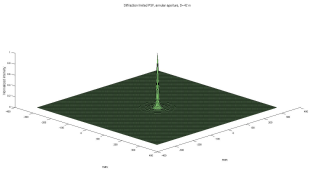
- Observed image I_T is degraded by the point spread function (psf):

$$I_o(x) = \int I(y) \cdot PSF_T(x-y)\,dy$$

- PSF without atmosphere: $PSF_T = |\mathcal{F}(\chi_T)|^2$



PSF of the VLT (8m)



PSF of the ELT (40m)

Reasons for the need of PSF reconstruction

- image improvement in post processing
- quality evaluation for the AO system
- to account for image degradation through
  time delay
  higher order aberrations
  non common path aberrations
- direction dependent PSF in different AO modes
- wavelength dependent

PSF – Optical Transfer Function (OTF)

Fourier transformed relation:

$$\mathcal{F}(I) = \mathcal{F}(I_g) \cdot \mathcal{F}(\mathcal{PSF})$$

Relation PSF - OTF:

$\mathcal{F}(\mathcal{PSF}) = \mathcal{OTF}$

OTF with atmospheric aberration: with $\mathbf{f} = \rho/\lambda$

$$\mathcal{OTF}(\mathbf{f}) = \int_{\mathbb{R}} P(\mathbf{x})P(\mathbf{x}+\rho)e^{i(\phi(\mathbf{x})-\phi(\mathbf{x}+\rho))}d\mathbf{x}.$$

Optical Transfer Function (OTF)

- $\phi(\mathbf{x})$: normally distributed random variable with zero mean.
- Long enough exposure time $\rightarrow$ substitute time average $\langle \cdot \rangle$ for expected value $\mathbf{E}\cdot$.
- Normalized long exposure optical transfer function

$$\langle \mathcal{OTF}(\mathbf{f}) \rangle = \frac{1}{S} \int_{\mathbb{R}} P(\mathbf{x}) P(\mathbf{x} + \boldsymbol{\rho}) e^{-\frac{1}{2} D_\phi(\mathbf{x}, \boldsymbol{\rho})} d\mathbf{x},$$

with $D_\phi(\mathbf{x}, \boldsymbol{\rho}) := \langle (\phi(\mathbf{x}) - \phi(\mathbf{x} + \boldsymbol{\rho}))^2 \rangle$.

Véran's algorithm (J.-P. Véran et al., 1997)

- Decompose $\phi = \phi_{\|} + \phi_{\perp}$
- Use Zernike polynomials as basis functions
- calculate and average $D_{\phi_{\|}}$ from measured data on the fly
- estimate and average $D_{\phi_{\perp}}$ from simulations before with the help of statistical models of the atmosphere
- neglect parts corresponding to correlations between $\phi_{\|}$ and $\phi_{\perp}$
- Calculate $\mathcal{OTF}_t$
- Combine the three parts to the $\mathcal{OTF}$
- Apply the inverse Fourier transform to get the $\mathcal{PSF}$

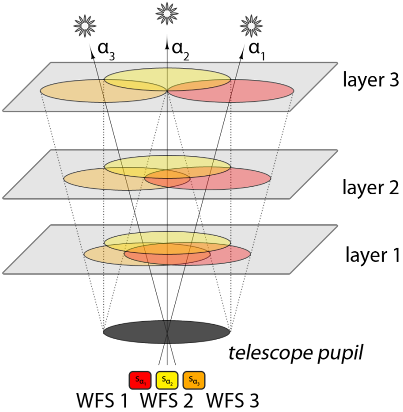
PSF reconstruction improvements (W., Hofer, Ramlau)

- change basis functions: bilinear splines
  - sparse structure of the functions $\rightarrow$ speed up
  - drawback: higher order terms can not be simulated well on this grid
    $\rightarrow$ simulation only for $D_{\phi_\perp}$ on a finer grid
    $\rightarrow$ computationally more demanding
- use 4D structure function instead of an averaged 2D version for $D_{\phi_\|}$
  - gives a better estimate
  - drawback: demands more computational power and memory

PSF reconstruction for MCAO (W., Saxenhuber, Ramlau)

- Use tomographic reconstruction of the atmosphere from measured data (intermediate result of gradient-based method)
- Project through the atmosphere to get PSFs for each desired direction using A_{dir} (as in gradient-based method)
  $\rightarrow$ pseudo-wavefronts used for calculations
- Simulate higher order terms not seen by WFS
- Combine the parts

The tomography problem



Input:

- reconstructed incoming wavefronts φ_{α_g} on Ω_D (aperture) from LGS $g = 1, \ldots, G$ and NGS $g = G+1, \ldots, G+N$

Goal:

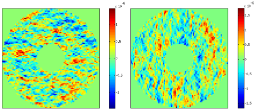
- **fast** reconstruction of turbulence layers $\Phi^{(l)}$ on Ω_l , $l = 1, \ldots, L$

inverse problem

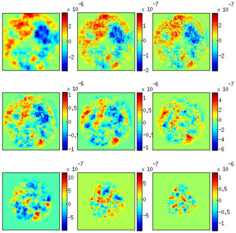
$\Longrightarrow$ requires **regularization**.

3-Step-Approach (Saxenhuber, Ramlau)

WFS measurements s^x and s^y

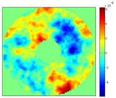


turbulent layers



↓ *Wavefront Reconst.*

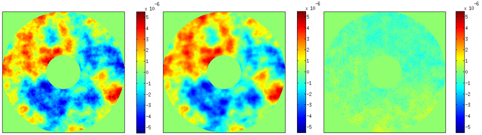
incoming wavefront



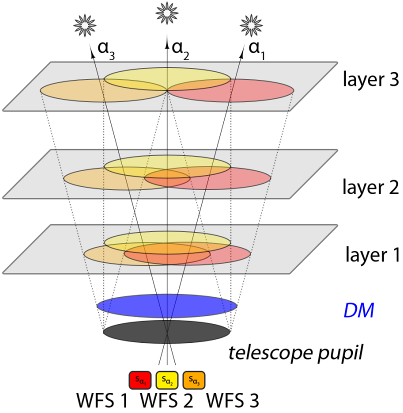
Atm. Tom. ⟶

↙ *Projection step*

incoming screen | DM shape | residual



Projection Step: Shape of deformable mirror

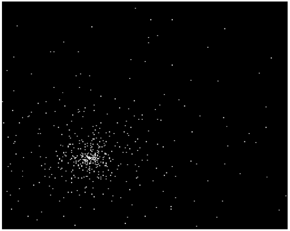


- projection of reconstructed layers into direction of interest *dir* (application of $\mathbf{A}_{dir}$)
- here: zenith (center direction)
- additional gain control possible: input (for LGS and NGS separately) and/or output gain

Deconvolution

$$I_o = I * PSF + n.$$

- observed image I_o, noise n
- Blind deconvolution: PSF and I are unknown
- PSF_{rec} good approximation, but still containing errors
- simple deconvolution might give no reasonable results



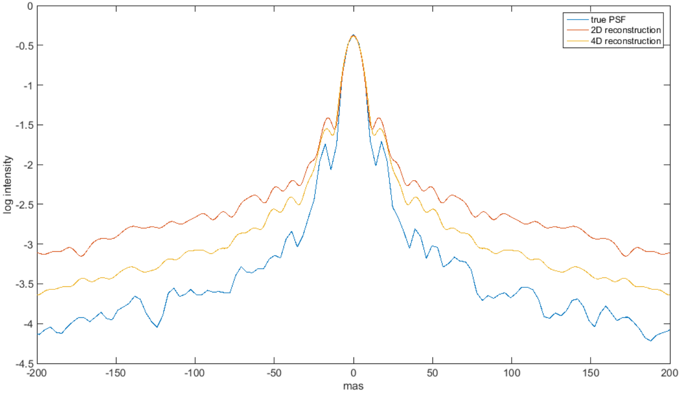
Blind Deconvolution (Dykes, Ramlau, Reichel, Soodhalter, W.)

- Idea: Simultaneously improve PSF_{rec} and reconstruct deconvolved image I
- The improved PSF should not be too far off from PSF_{rec}
- The deconvolved image I should keep the properties of I_o

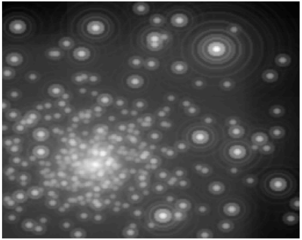
$$\|I * PSF - I_o\|_2 + \alpha_1 \|I - I_{prior}\| + \alpha_2 \|PSF - PSF_{rec}\| \to \min_{I,PSF}$$

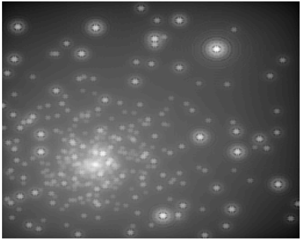
- Big matrix to represent I_o
- use Lanczos-process to get a small matrix with good eigenvalue approximation
- solve the small system
- Only for radially symmetric PSF possible
- Where to get PSF_{rec} from?

PSF reconstruction for MCAO



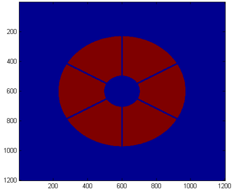
Deconvolution - observed vs. improved image





Future Work: Adaption to real life setting

- obstruction of aperture by "spiders" $\rightsquigarrow$ non-connected segments on WFS ($\rightarrow$ see Poster by Ramlau et al)
- Pyramid WFS ($\rightarrow$ Posters by Shatokhina and Hutterer)
- inexact atmospheric information ($\rightarrow$ Poster by Auzinger)
- Non-common path errors
- Use additional prior information on the objects in the image in the deconvolution process
- Extend deconvolution algorithm to non-symmetric PSFs



Literature

[1] *D. Saxenhuber, R. Ramlau, A Gradient–based method for atmospheric tomography*, Inverse Problems and Imaging, 10(3): 781–805, 2016 .

[2] *R. Wagner, Ch. Hofer, R. Ramlau, Point spread function reconstruction for Single-Conjugate Adaptive Optics* (in preparation), 2017.

[3] *R. Wagner, D. Saxenhuber, R. Ramlau, Point spread function reconstruction for Multi-Conjugate Adaptive Optics* (in preparation), 2017.

[4] *L. Dykes, R. Ramlau, L. Reichel, K. Soodhalter, R. Wagner, Lanczos-based fast blind deconvolution methods* (in preparation), 2017.