Turbulence parameter estimation with Paranal Observatory wavefront sensors

P.J.V. Garcia, **P.P. Andrade**, J. Milli, J. Kolb, C. Correia, M.I. Carvalho & Gravity collaboration

pgarcia@fe.up.pt

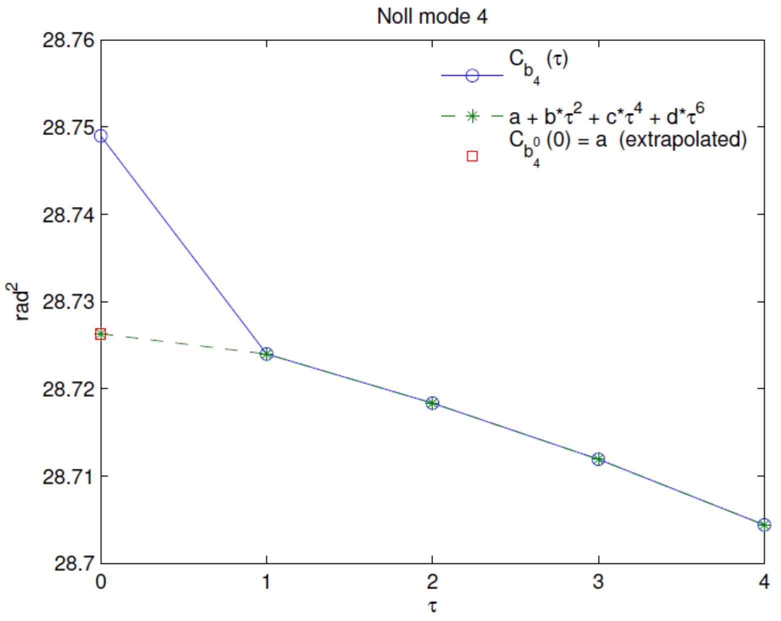
Wavefront sensing in the VLT/ELT era, 4th edition, 28-30 October 2019, Firenze, Palazzo dei Congressi

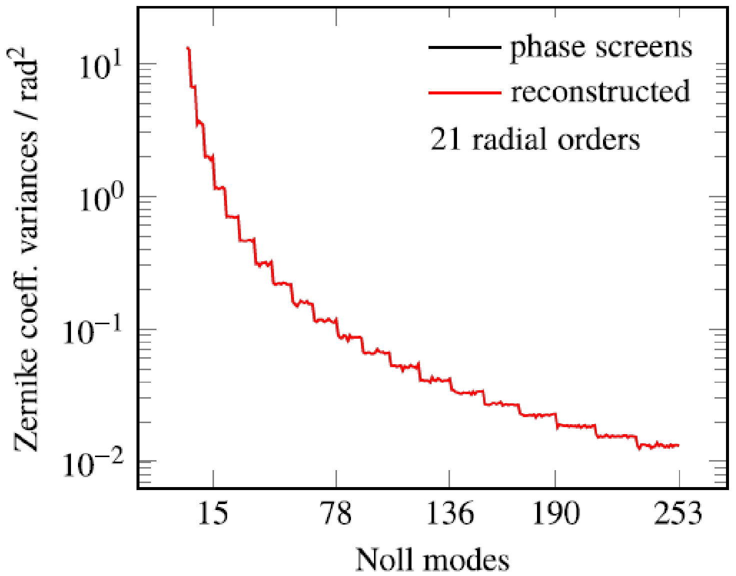
Estimation of r0 and L0

- Site evaluation and characterization
- Optimization of AO systems, including temporal updates
- Predictions of point spread functions (with or without AO)
- Optimization of fringe-trackers for optical interferometry
- Addressed by many dedicated experiments
  - Balloons, DIMM, MASS, SLODAR, SCIDAR, …
- Advantages of estimation using Shack-Hartman WFS
  - Ubiquity in large telescopes ➔ make use of existing infrastructure
  - Spatio-temporal synchronism
  - Identical turbulence path (including dome seeing) of the observations
- Previous work
  - Single sensor: Schöck+2003, Fusco+2004, Jolissaint+2018
  - Multiple sensor: Wilson+2002, Guesalaga+2017, Ono+2017

Classic approach

- Simulate the WFS by generating a Zernike to slopes matrix ($\mathbf{H}_{//}$) and invert it obtaining the slopes to Zernike matrix ($\mathbf{H}^{+}$).
- For each WFS measurement recover the estimated Zernike coefficients (**b**) and then compute the variances $<b^2_i>$
- Denoise the variances via temporal correlation (Fusco method)
- Select a "good range" of radial orders to fit (start after focus, but where to end?)
- Fit the von Kármán model (i.e., definition of r0 and L0) to denoised variances and recover r0 and L0.
- Operating solution in NAOS (Fusco+2004)





Our approach

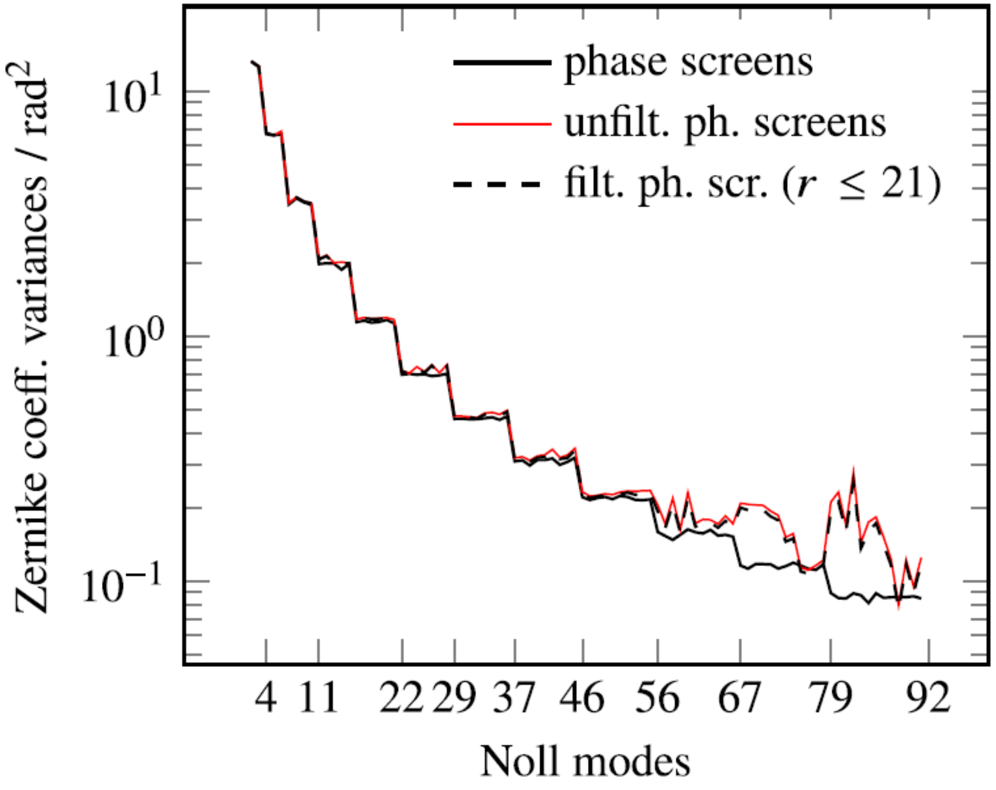
- Validate estimates from simulation (OOMAO, DASP, AOTools)
- Assume von Kármán turbulence
- Assume geometric Shack-Hartmann wavefront sensor
  - NACO like (14x14 sub-apertures, 8 m) + noise
- We have information on
  - Phase screen (assumed independent)
  - Estimated Zernike coefficients
  - True Zernike coefficients
  - True undetected (very high order) Zernike coefficients

Cross-coupling is unavoidable in model fitting

- A Shack-Hartmann is a “gradient” sensor
- The Zernike gradients matrix is non-orthogonal ➔ cross-coupling
- r0 and L0 are estimated using Zernike variances
- Diagonalizing the Zernike co-variance matrix (using Karhunen-Loève basis) would not solve the problem
- ➔No fitting functions for the r0 and L0 exist in this basis
- ➔Statistical independence versus geometric coupling?...
- Cross-coupling is unavoidable in r0 and L0 joint estimation with model fitting
    - Other (far less simpler, untested) options might exist…

Onset of cross-coupling [phase screens]

- r0/L0 estimation is done in the low Zernike radial order range (r~2 to r~12)
- Aliasing strongly affects large radial orders (r~21 for our simulation)
- Cross-coupling has localized effects across "all" radial orders
- Cross-coupling is the dominant effect in r0/L0 estimation.



Overcoming cross-coupling

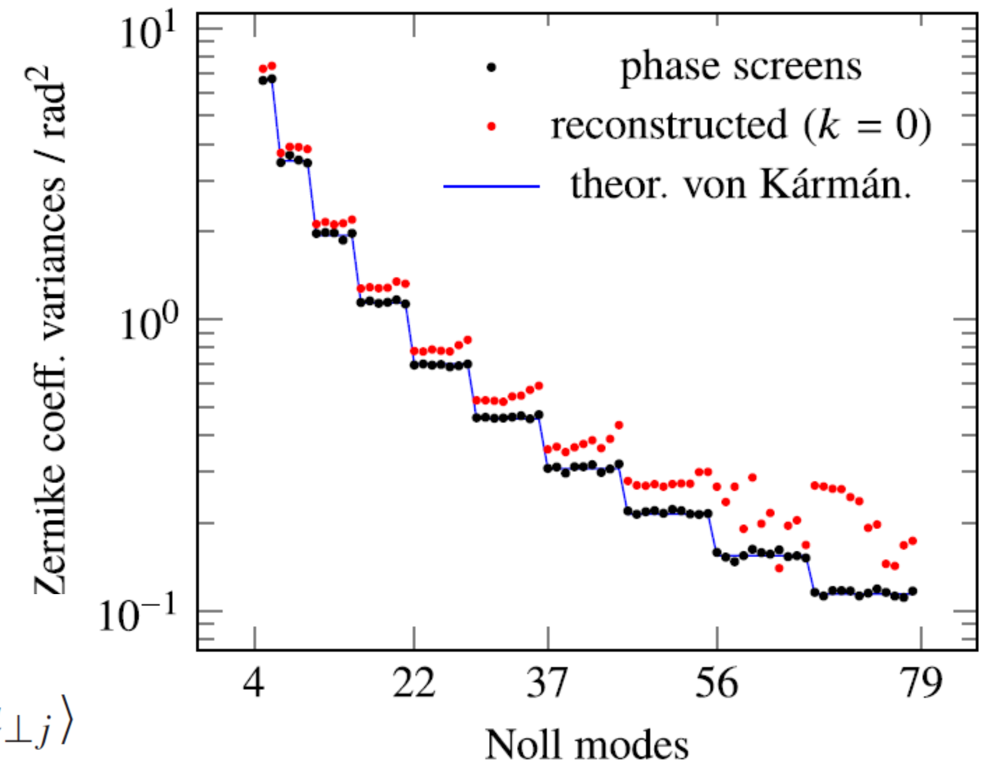
- Include cross-coupling and noise in the model for measured variances

$$\langle b_i^2 \rangle = \langle a_{\parallel i}^2 \rangle + \sigma_{\mathrm{cc},i}^2 + \sigma_{\mathrm{n},i}^2$$

- true variances, noise and cross coupling
- It turns out that the cross-coupling contribution is analytic (cf. Conan 2000, Takato+1995)

$$\sigma_{\mathrm{cc},i}^2 = \sum_{j=J+1}^{M} \sum_{j'=J+1}^{M} c_{ij} \langle a_{\perp j} a_{\perp j'} \rangle c_{j'i}^{t} + 2 \sum_{j=J+1}^{M} c_{ij} \langle a_{\parallel i} a_{\perp j} \rangle$$

- but a function of r0 and L0 ➔ iterative method

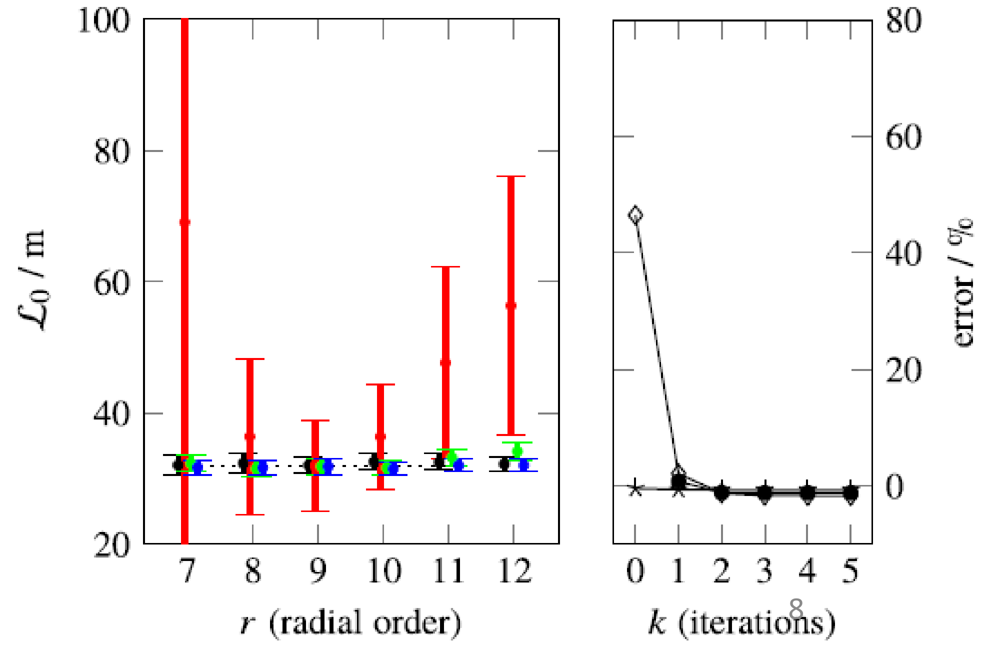


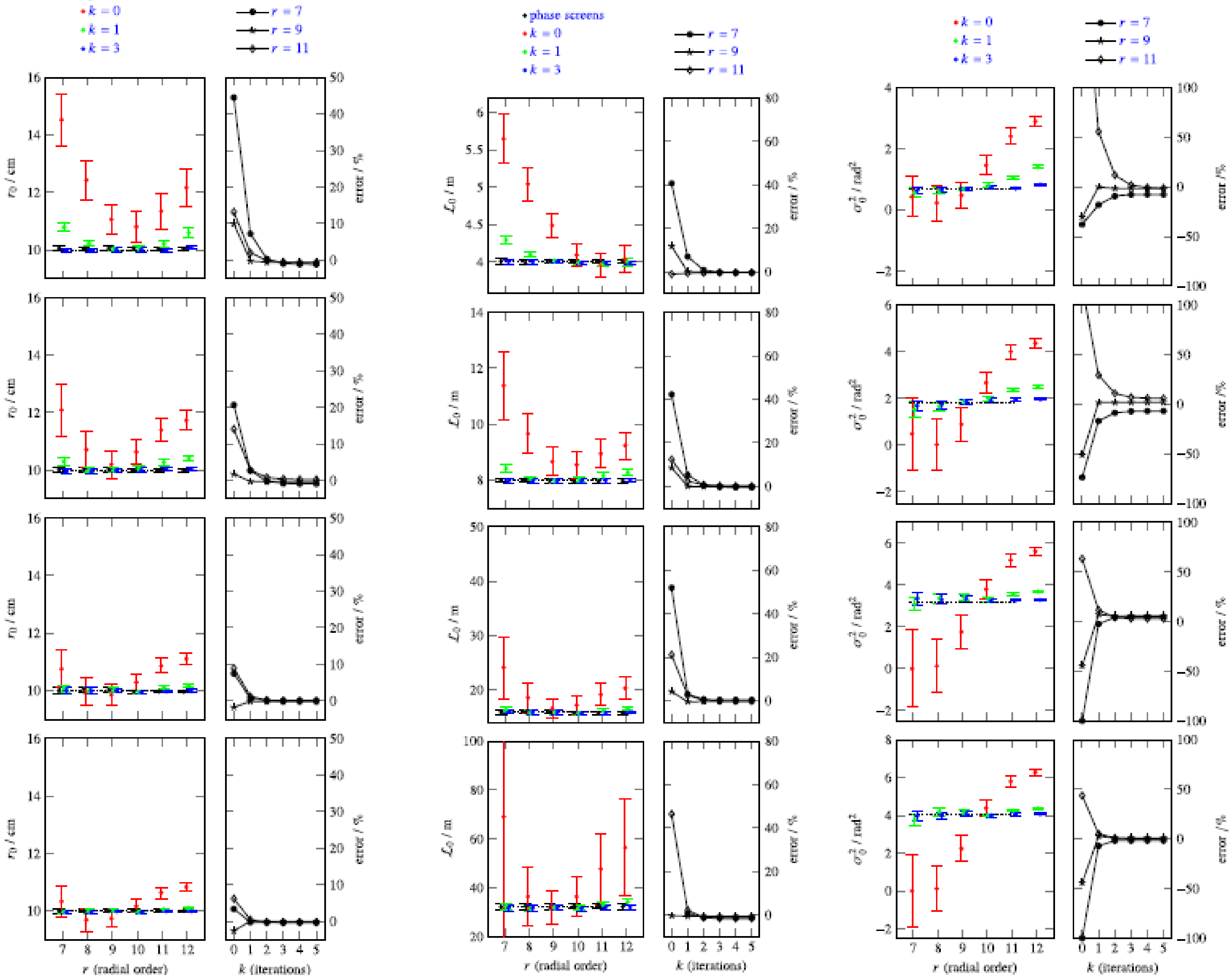
Iterative method

- Iteration zero is classic approach, obtain biased estimates of r0 and L0
- Remaining iterations include cross-coupling correction

$$\hat{\mathbf{p}}^k = \arg\min_{\mathbf{p}} \sum_{i=5}^{J(r)} \left\{ \log\left[(\langle a_{/\!/}^2\rangle_{\mathrm{vK}} + \sigma_{\mathrm{n},i}^2)(\mathbf{p})\right] - \log\left[\langle b_i^2\rangle - \sigma_{\mathrm{cc},i}^2(\hat{\mathbf{p}}^{k-1})\right] \right\}^2, \quad k = 1, \ldots$$

- estimating improved r0, L0 and noise σ^2 at each k
- [Alternative of joint estimation not obvious.]





L0 = 4 m, 8 m, 16 m, 32 m

r0 = 10 cm

SNR (@ r=9) = 10

Increasing SNR will not help [it is a bias]

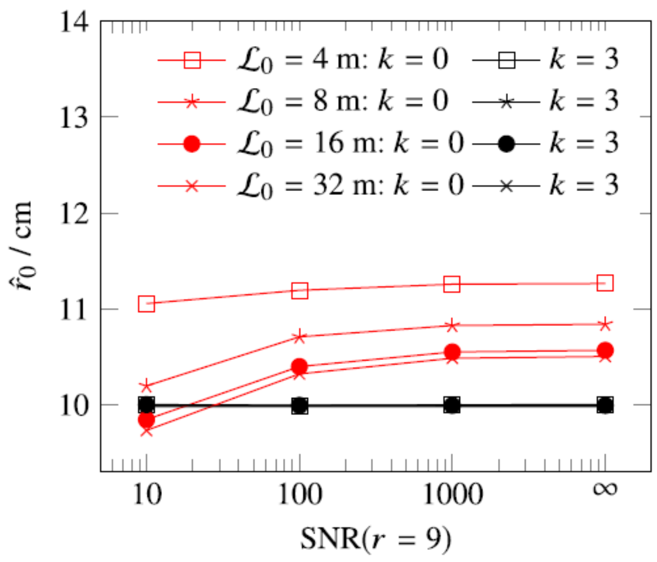


Figure 8. Fried parameter estimations as a function of SNR($r = 9$), for reconstructions with $r = 9$ and $r_0 = 10$ cm. Note that the $k = 3$ curves overlap.

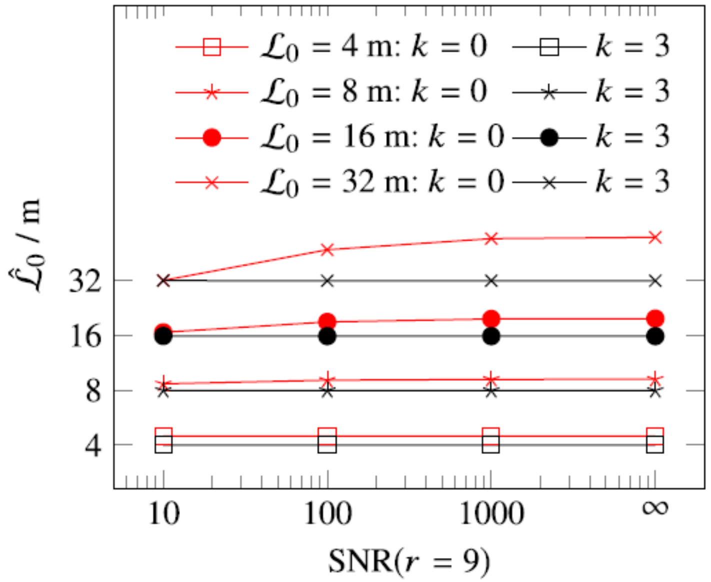
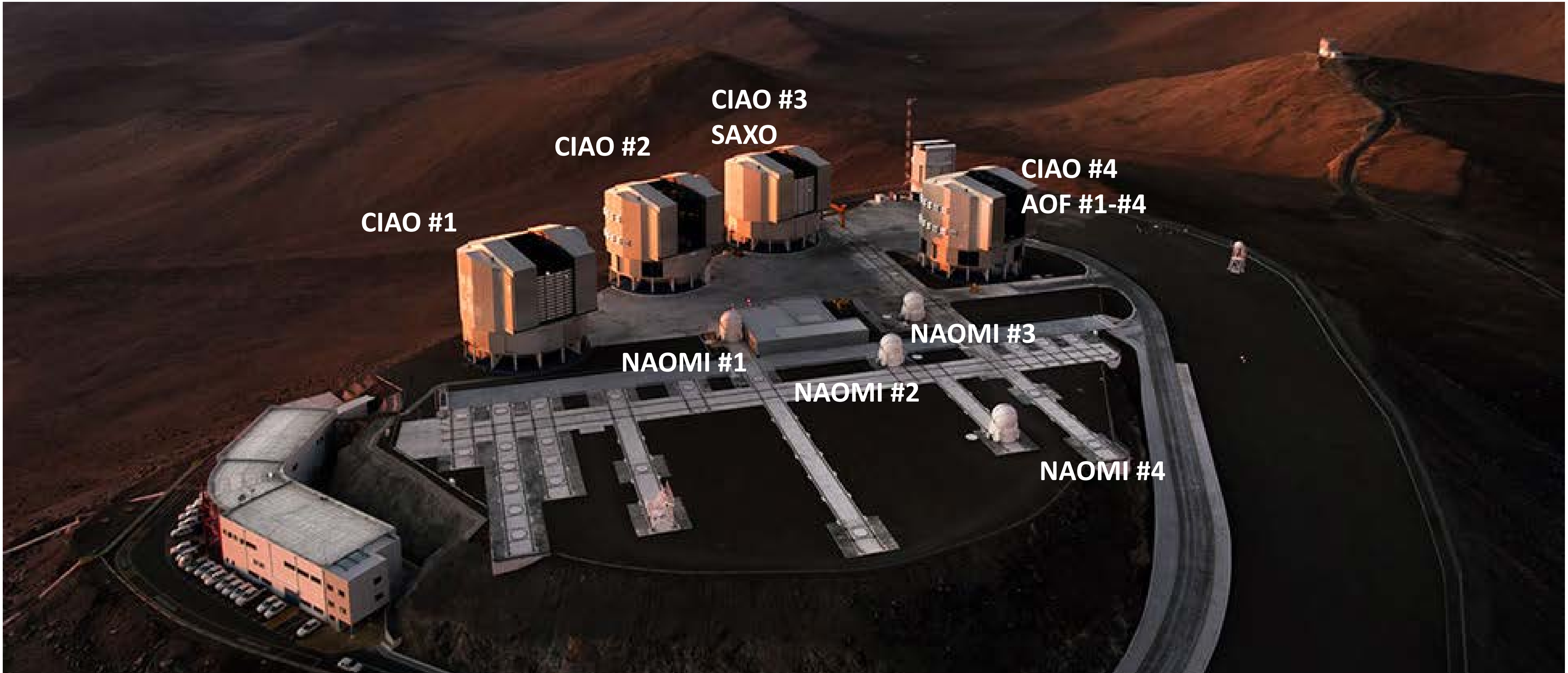


Figure 9. Outer scale estimations as a function of SNR($r = 9$) for reconstructions with $r = 9$ and $r_0 = 10$ cm.

Cf. Andrade+ 2019 ("*Estimation of atmospheric turbulence parameters from Shack–Hartmann wavefront sensor measurements*", MNRAS, 483, 1192) for a detailed presentation.

What about real data?

Shack-Hartman WFSs at Paranal: +13!

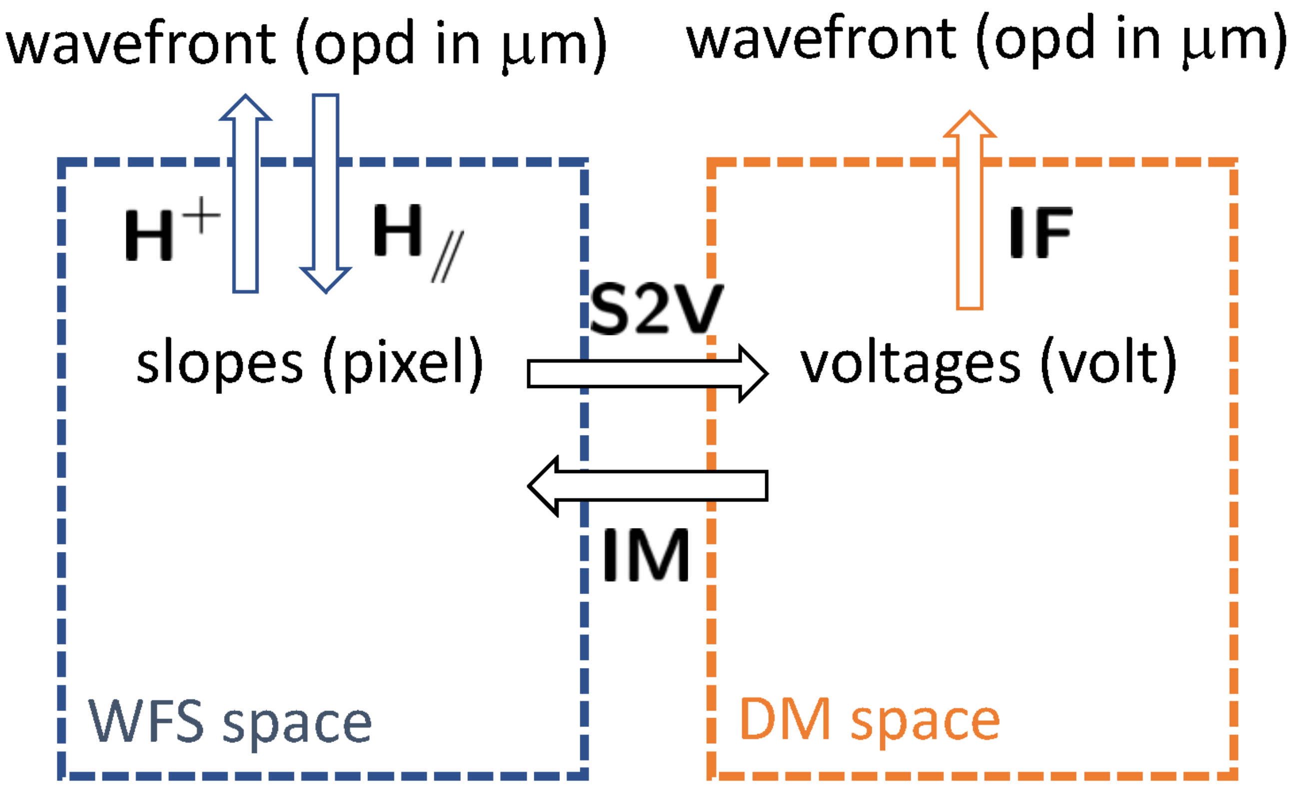


Shack-Hartman WFSs at Paranal

- SAXO
  - 40x40 WFS, visible, control in Karhunen-Loève modes
- CIAO #1-#4
  - 9x9 WFS, K-band, control in Karhunen-Loève modes, Coudé focus (rotation)
- NAOMI #1-#4
  - 4x4 WFS, visible, control in Zernike modes, Coudé focus (rotation)
- AOF #1-#4
  - 40x40 WFS, visible, Karhunen-Loève modes

Estimating r0 and L0 from real data

- Open loop
  - Pros: simple
  - Cons: uses science time
  - Method
    - Slopes to Zernike matrix is a geometric model
    - Convert to Zernike coefficients
    - Apply fitting to variances
- Closed loop
  - Pros: runs parallel to science
  - Cons: complex combines voltages + slopes
  - Method
    - Define where to work (DM or WFS)
    - Convert voltages or slopes
    - Convert to Zernike coefficients
    - Apply fitting to variances



Some results (open loop with NAOMI)

Work in progress….

Some results (open loop with CIAO)

Work in progress….

Some results (SAXO, closed loop archival dat

Work in progress….

Future prospects & challenges

- Short term
  - Work on closed loop data issues…
  - Run pipeline on archived data
- Paranal turbulence parameters
  - How does the estimation change with WFS characteristics?
  - How does r0 and L0 change from telescope to telescope?
  - Can we have a picture of these parameters on the mountain top (position/height)?
  - Non-stationarity effects, SPARTA implementation, etc

  ➔ more news in Adaptive Optics Week 2020
- Telemetry data curation
  - document, archive, distribute, standards ➔ DADS is the way forward

Adaptive Optics Workshop Week @ Porto 2020
Porto, Portugal -- 30th March to 3rd April