Turbulence parameter estimation with Paranal Observatory wavefront sensors

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1

1

Estimation of r0 and L0

- Site evaluation and characterization
- Observation scheduling
- 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-telescope seeing) of the observations
- Previous work
  - Single sensor: Schöck+2003, Fusco+2004, Jolissaint+2018
  - Multiple sensor: Wilson+2002, Guesalaga+2017, Ono+2017

2

2

Cross-coupling is unavoidable in model fitting

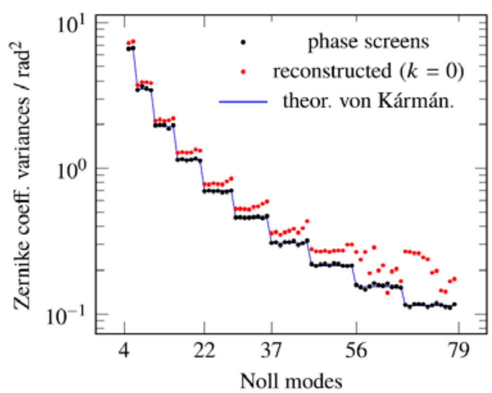
- A Shack-Hartmann is a “gradient” sensor
- The Zernike gradients matrix is non-orthogonal ➔ cross-coupling
- r0 and L0 are estimated using Zernike variances
- Diagonalizing the Zernike co-variance matrix (using Karhunen-Loève basis) would not solve the problem
- ➔No fitting functions for the r0 and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

3

3

Overcoming cross-coupling

Andrade+2019



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

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

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

$$\Gamma_{cc,i} = \sum_{j=J+1}^{M} \sum_{j'=J+1}^{M} c_{ij}\langle a_{\perp j} a_{\perp j'}\rangle c^t_{j'i} + 2\sum_{j=J+1}^{M} c_{ij}\langle a_{//i} a_{\perp j}\rangle\,,$$

- but a function of r0 and L0 ➔ iterative method

4

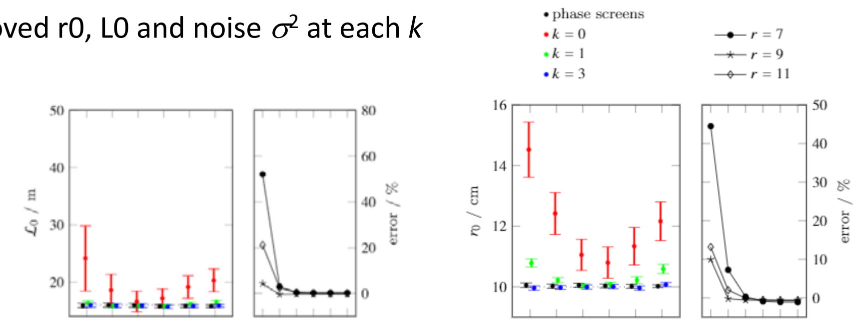
4

Iterative method (Andrade+2019)

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

$$\hat{\mathbf{p}}^k = \arg\min_{\mathbf{p}} \sum_{i=4}^{J(r)} \left\{ \log\left[(\langle a_{/\!/ i}^2\rangle_{\mathrm{vK}})(\mathbf{p})\right] - \log\left[\langle b_i^2\rangle - \sigma_{\mathrm{n},i}^2 - \Gamma_{\mathrm{cc},i}(\hat{\mathbf{p}}^{k-1})\right]\right\}^2, \quad k = 1, \ldots$$

- estimating improved r0, L0 and noise σ^2 at each k



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What about real data?

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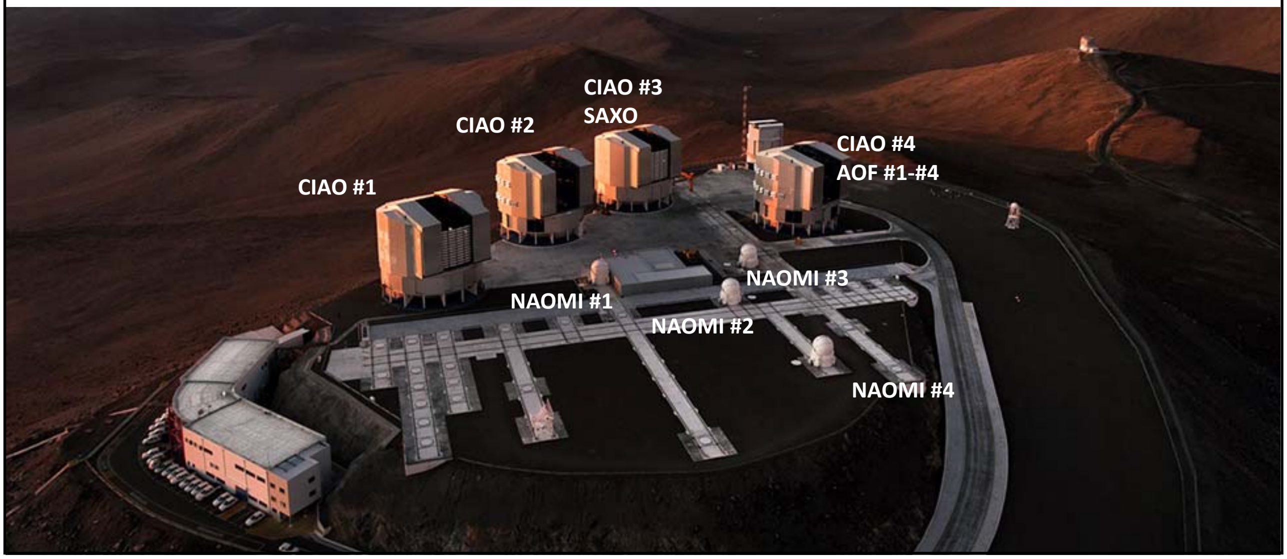
6

Shack-Hartman WFSs at Paranal: +13!



7

Shack-Hartman WFSs at Paranal

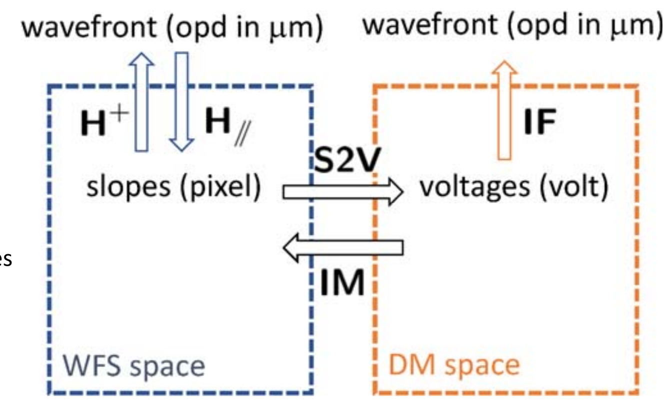
- SAXO
  - 40x40 WFS, visible, control in Karhunen-Loève modes
- CIAO #1-#4
  - 9x9 WFS, K-band, control in Karhunen-Loève modes, Coudé focus (rotation)
- NAOMI #1-#4
  - 4x4 WFS, visible, control in Zernike modes, Coudé focus (rotation)
- AOF #1-#4
  - 40x40 WFS, visible, Karhunen-Loève modes

8

8

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



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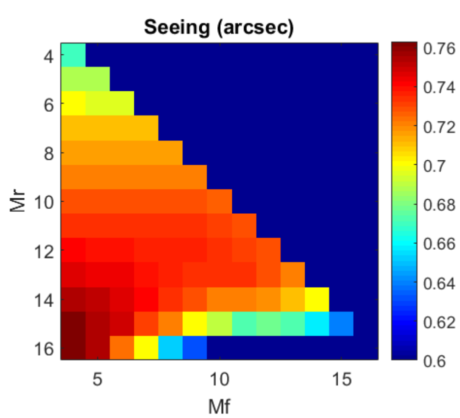
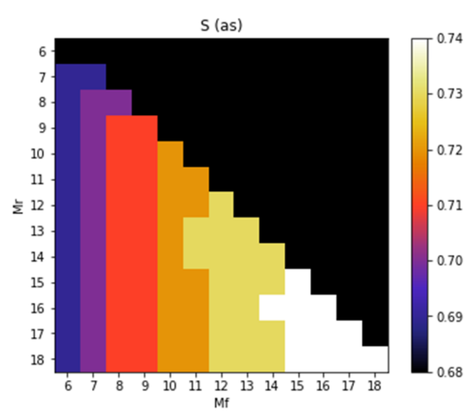
AOF data |

non-iterative (current method, left) versus iterative approach (right)



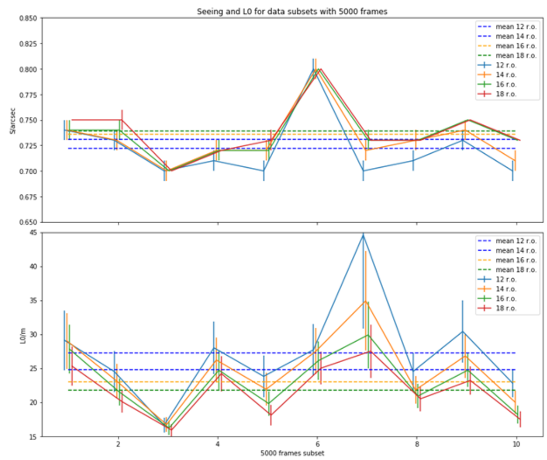


Results don't depend on the number of radial orders in the reconstructor and slightly depend on the number of orders in the fit.

10

10

AOF data | snapshots of temporal evolution



11

11

The curse of high precision

- We are extremely precise in the estimation of r0 and L0
- This does not make sense physically
  - Von Kármán is an approximation of turbulence in one layer
    - Cf. literature on deviations from von Kármán (e.g. Goodwin+2016, Gueselaga+2014, Lombardi+2010)
  - What we measure is an average of several layers across the atmosphere
    - Cf. next other talks in the present session!
  - Non-stationarity and correlation of the phase during measurements
- However temporal evolution opens up several possibilities.

12

12

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
- Telemetry data curation
  - Stay tuned …

13

13