Seeing estimation from Adaptive Optics Telemetry

Nuno Morujão (MEng Physics Student)

Collaborators: Paulo Garcia, Carlos Correia, Paulo Andrade, Johann Kolb, Julien Woillez

Motivation

R. Wesson/ESO

- Site evaluation and characterization;

- Non-consensual values for the turbulence parameters;

- Optimization of the adaptive optics systems and fringe trackers;

- Understand if and how climate change is affecting turbulence parameters (r0 and L0);

- Use AO telemetry data for the estimation of turbulence parameters;
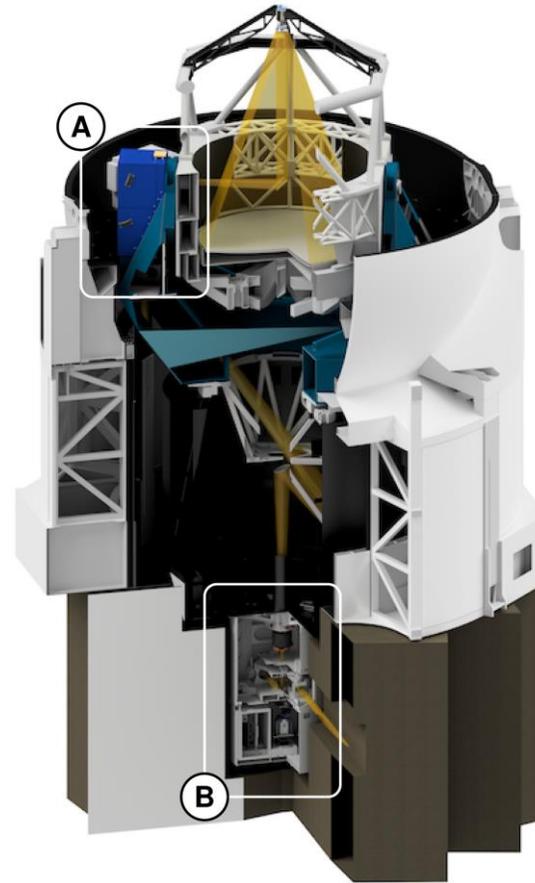
- Operational adoption of the algorithm;

NAOMI - the new AO system of the VLTI

ESO/G.Hüdepohl

Woillez + 2019

Advantages

- Spatial resolution – 4 AT's at Paranal;

- Temporal coverage – near-continuous estimation of the seeing;

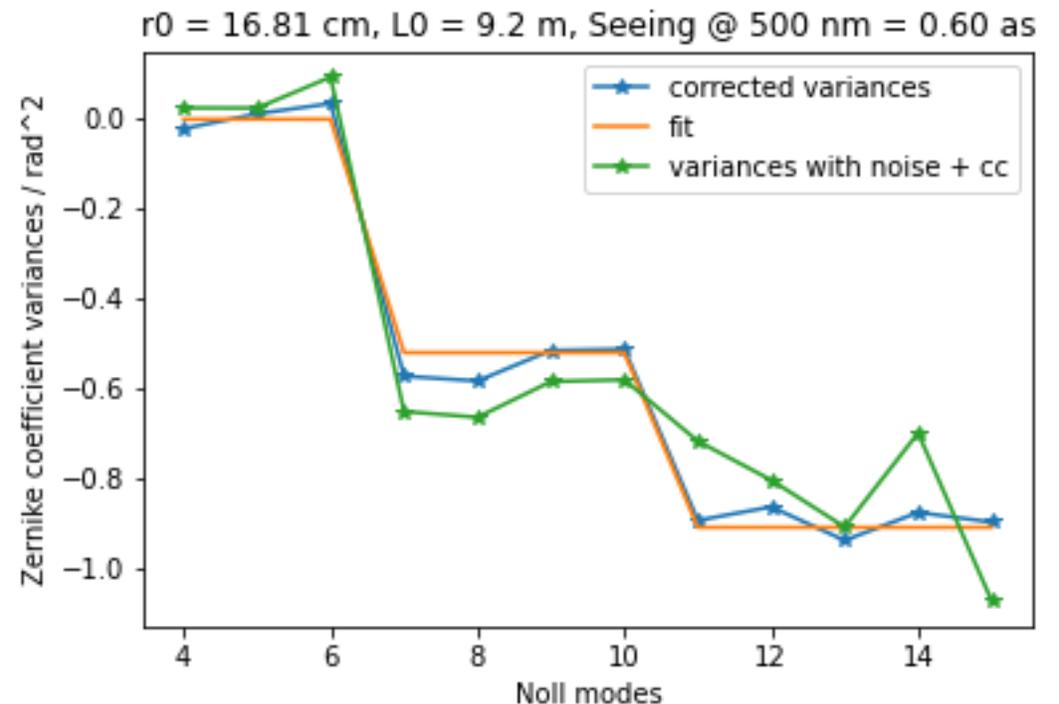- Source matching – Direct correspondence to the observing telescope;

Challenging scenario:
- VLTI/ATs – 4 NAOMIs;
- SH-WFS (**4x4**, visible);
- Diameter: 1.8 m

3

Methods: background

Andrade+ 2019 ("Estimation of atmospheric turbulence parameters from Shack–Hartmann wavefront sensor measurements", MNRAS, 483, 1192):
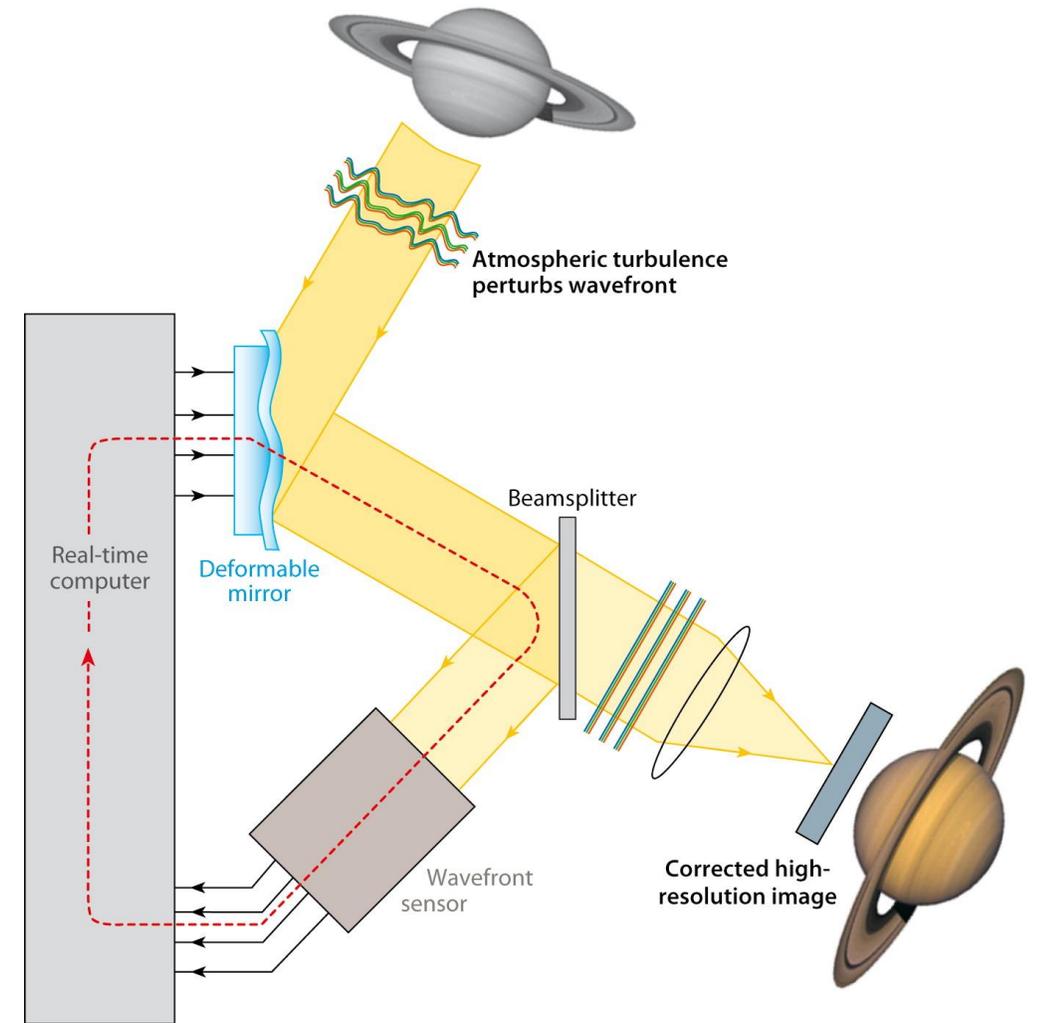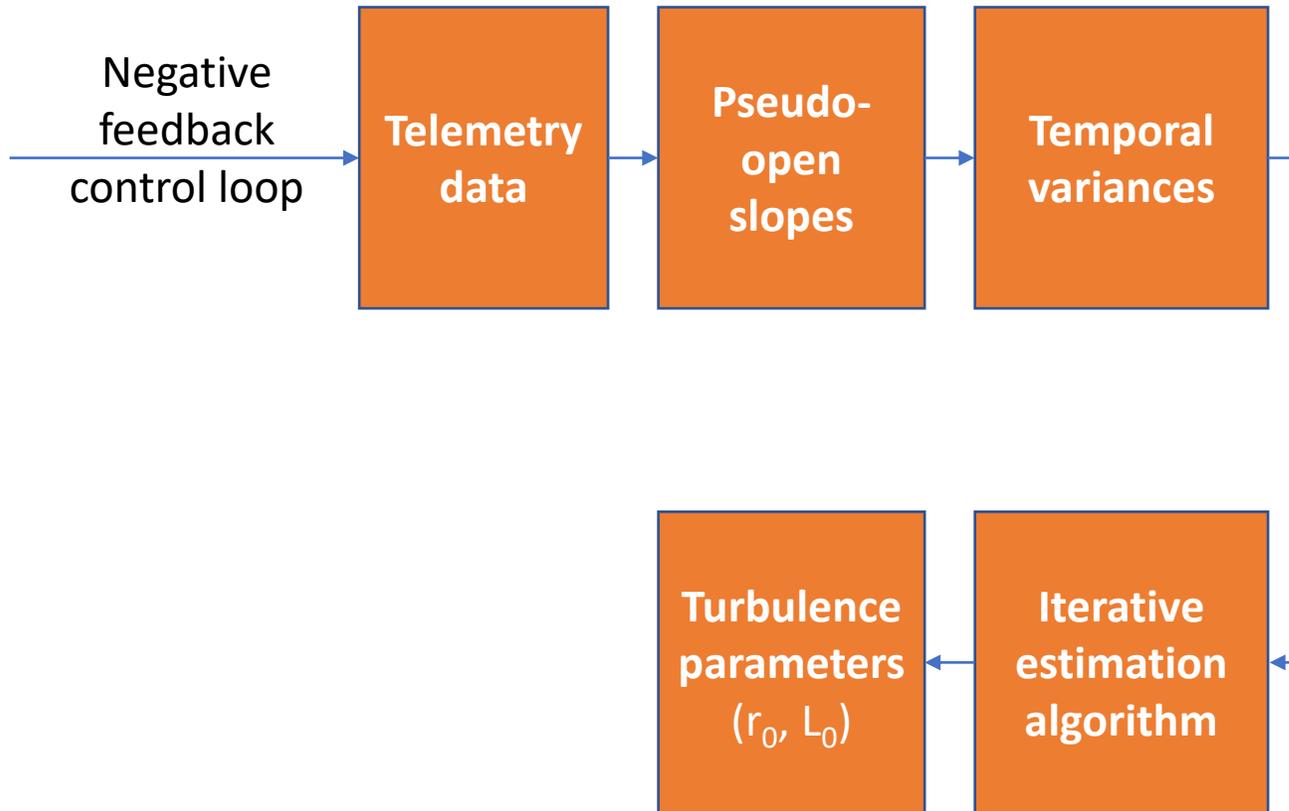
- Fit theoretical variances;

- Include **cross coupling effects** (function of r0 + L0) in model;

- **Iteratively** fit r0, L0 and noise;

Novel adaptations:

- Conversion of the algorithm into a χ^2 ;

- Estimation of the uncertainty of the fit through a Monte Carlo approach;

r0 = 16.81 cm, L0 = 9.2 m, Seeing @ 500 nm = 0.60 as

Methods: pipeline flow

Negative feedback control loop → **Telemetry data** → **Pseudo-open slopes** → **Temporal variances** → **Iterative estimation algorithm** → **Turbulence parameters (r_0, L_0)**

Atmospheric turbulence perturbs wavefront

Real-time computer

Deformable mirror

Beamsplitter

Wavefront sensor

Corrected high-resolution image

Davies R, Kasper M. 2012.
Annu. Rev. Astron. Astrophys. 50:305–51

Methods: iterative algorithm

- Initial measured variances are introduced in the model fit;

- Result in an initial set of turbulence parameters (r0, L0, noise);

- The estimated turbulence parameters are used to calculate the
  cross-talk = f(r0,L0);

- Cross-talk and noise are removed from the variances;

- Fit of corrected variances (r0, L0, noise);
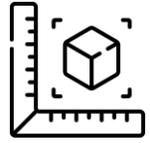
Shack Hartmann sensor

Measurement is done from derivatives of the used modal basis (Zernike polynomials)

$$\mathbf{s} = \mathbf{Gb}$$

- **s** – measured slopes vector
- **G** – derivative matrix
- **b** – reconstructed Zernike coefficients

$$\mathbf{G} = \begin{bmatrix} \dfrac{\partial Z_1|_1}{\partial x} & \dfrac{\partial Z_2|_1}{\partial x} & \cdots & \dfrac{\partial Z_N|_1}{\partial x} \\ \dfrac{\partial Z_1|_1}{\partial y} & \dfrac{\partial Z_2|_1}{\partial y} & \cdots & \dfrac{\partial Z_N|_1}{\partial y} \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{\partial Z_1|_M}{\partial x} & \dfrac{\partial Z_2|_M}{\partial x} & \cdots & \dfrac{\partial Z_N|_M}{\partial x} \\ \dfrac{\partial Z_1|_M}{\partial y} & \dfrac{\partial Z_2|_M}{\partial y} & \cdots & \dfrac{\partial Z_N|_M}{\partial y} \end{bmatrix}$$
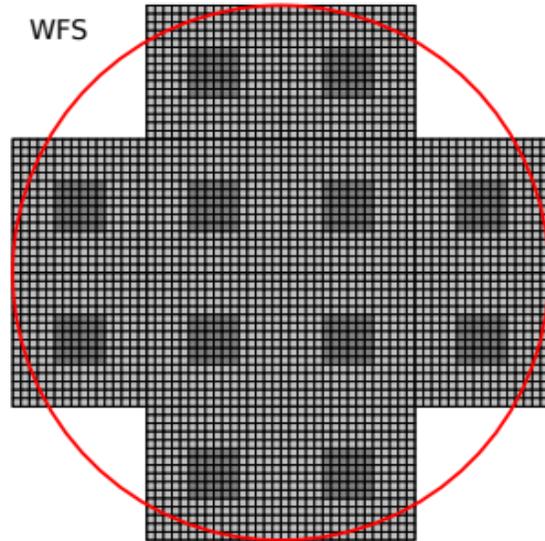
M – # of lenslets in the sensor
N – # of contemplated modes

$$\mathbf{G} = [\mathbf{G}_f, \mathbf{G}_r]$$
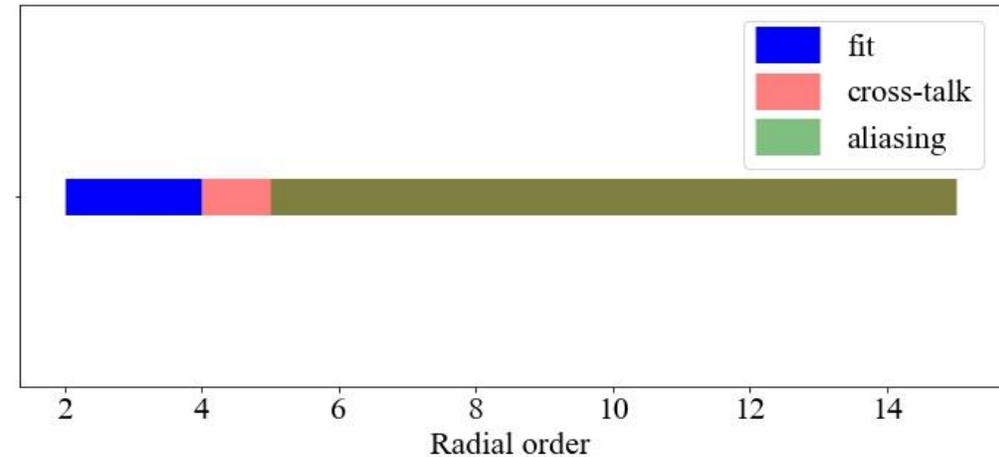
$\mathbf{G}_f$ – fitted modes
$\mathbf{G}_r$ – remaining modes

Error Sources

WFS

Woillez + 2019

Features	Value
SH-WFS lenslet configuration	4x4
# of active lenslets	12
Diameter of telescope	1.8 m
Central obstruction	7.7 %
Fitted Zernike modes	12

Present problems in NAOMI:

- **Aliasing –** Finite frequency of the sensor;

- **Measurement noise** – Read-out noise, photon noise, …

- **Cross-talk -** Non-orthogonality of **G** columns;

Cross-talk

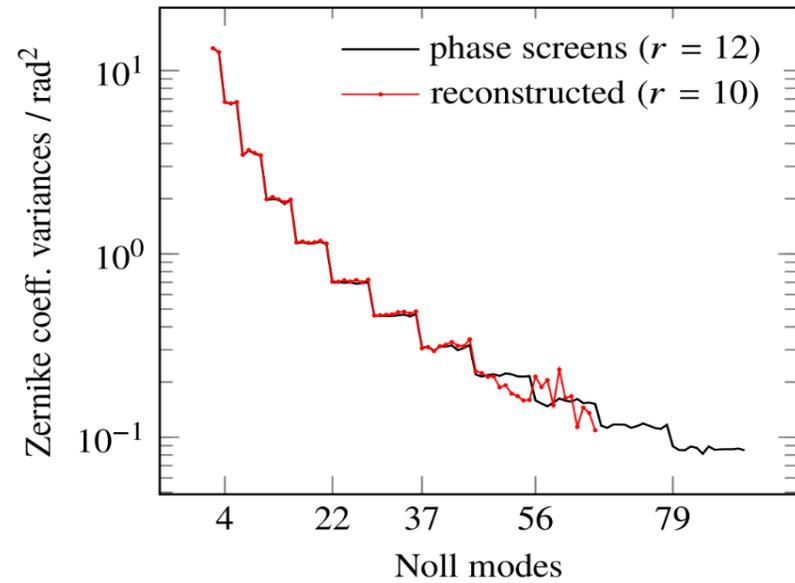Zernike polynomials don't possess orthogonal derivatives

↓

Columns of **G** are non-orthogonal

$$\mathbf{C} = \mathbf{H}^{+}\mathbf{G}_{r}$$

$\mathbf{H}^{+}$ - Inverse $\mathbf{G}_{f}$ matrix;
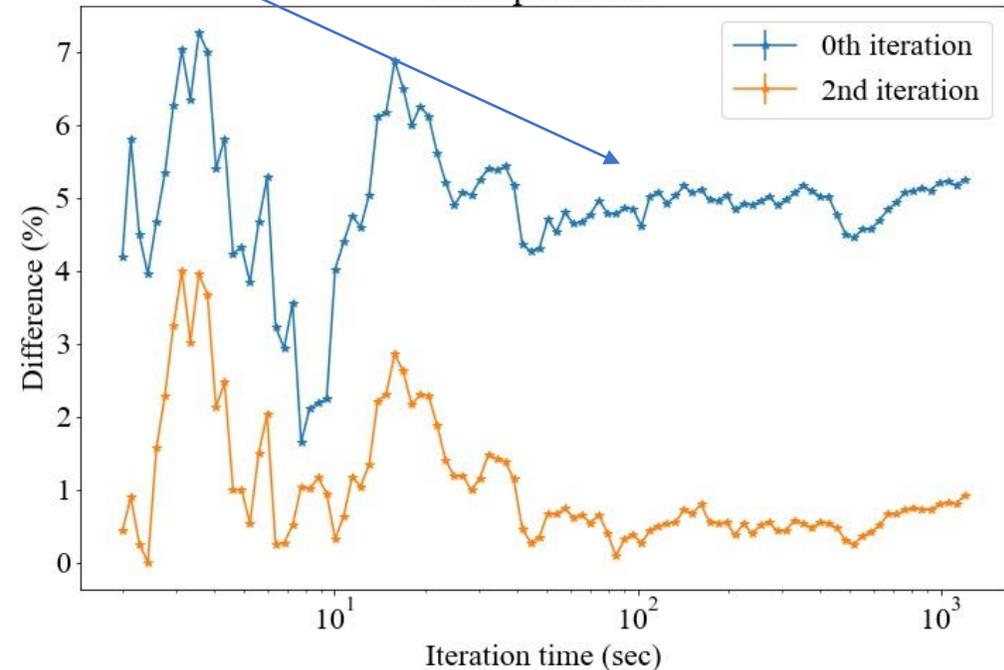
$\mathbf{C}$ - Cross-talk matrix;

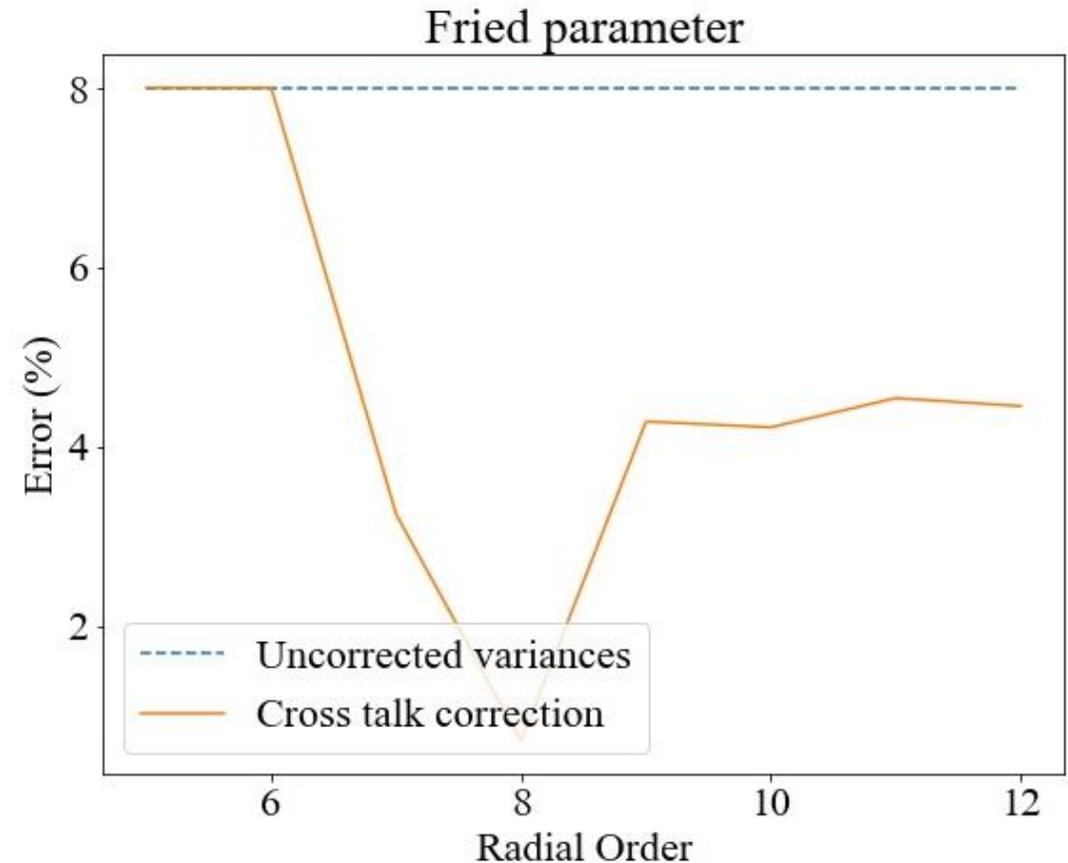Result in: $\mathbf{b} = \mathbf{a}_{f} + \mathbf{C}\mathbf{a}_{r}$

No **C** correction

Andrade + 2019

Cross-talk & aliasing mixing

- Modes above the fifth radial order display aliasing.

- Only one non aliased radial order.

- We still see improvements to our correction if we include aliased modes.

Fried parameter

Results

Total data sample:

Date window - (11/2018 - 03/2020)
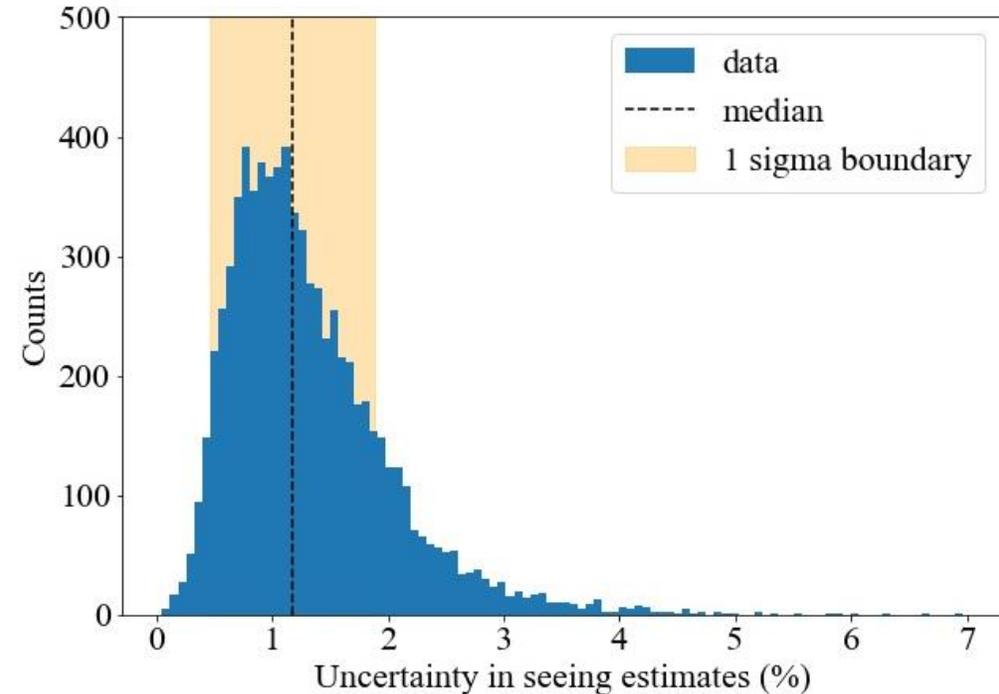
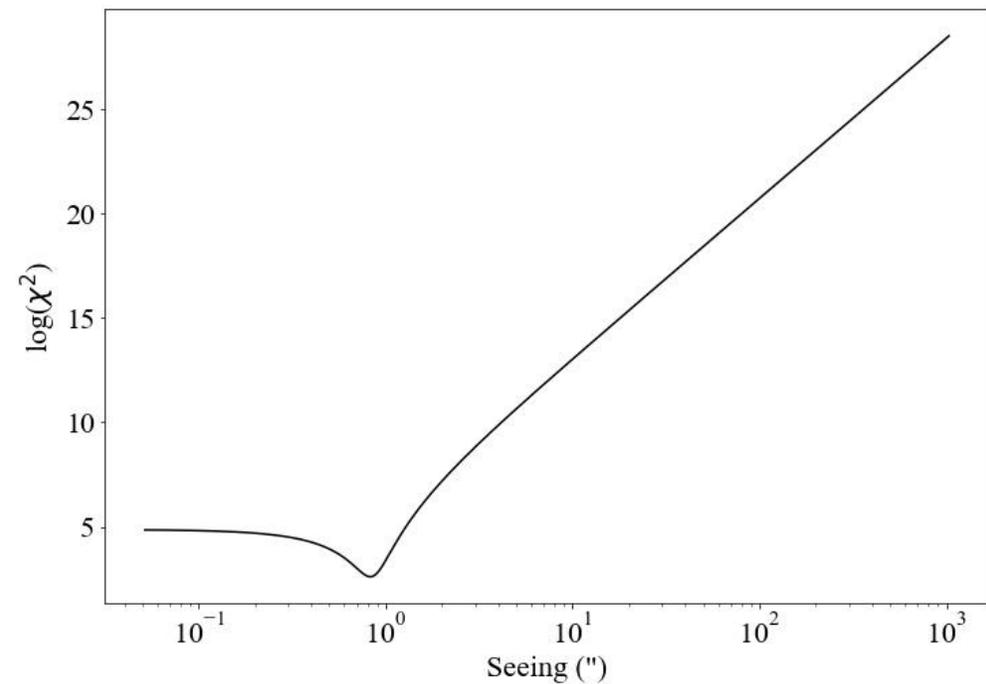**Total data size - 8170 data measurements**

Loop frequency - 500 Hz

Minimum time horizon - 20 seconds

Internal consistency in the estimation algorithm was found.

Median uncertainty of 1.2%.

A single well-behaved minima was found in the χ^2 map for the seeing.
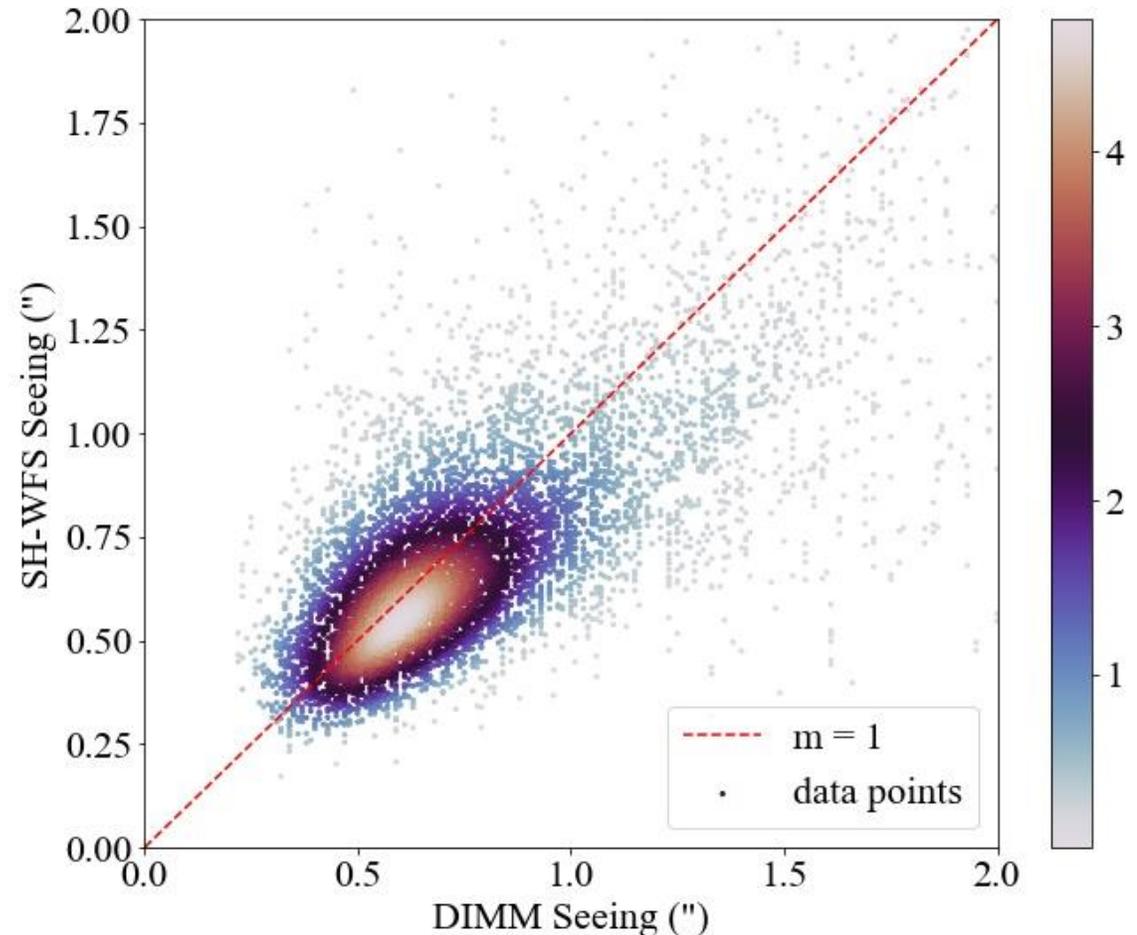
Seeing comparison: telemetry vs DIMM

Seeing estimates are available from the DIMM;

Excellent agreement between DIMM and AO telemetry based seeing;

% level differences;

Causes:
- Different instrument locations;
- Different dome turbulence in DIMM;
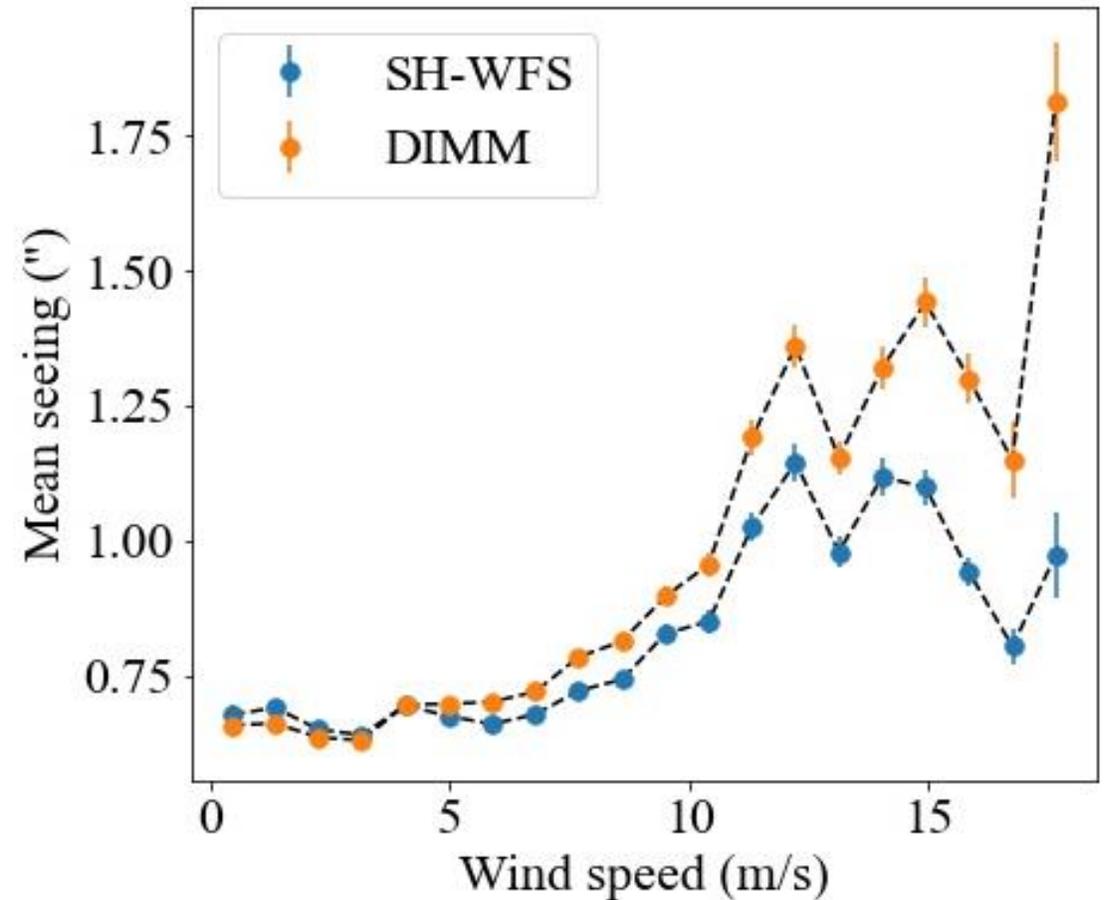- Noise estimation from fit;

Seeing comparison: wind-speed

As the wind-speed increases the differences between DIMM and AO telemetry based seeing data estimates also increases.

The difference is caused by:
- Vibrations in the defocus mode – Especially affected by wind-shake;

Outer scale estimation

- Can't be estimated with NAOMI telemetry data consistently;

- Small telescope diameter leads to a minimum detectable frequency larger than the frequency associated with the outer scale (20 meters);

- It's translated in the χ^2 map as a weak (absent) minima;
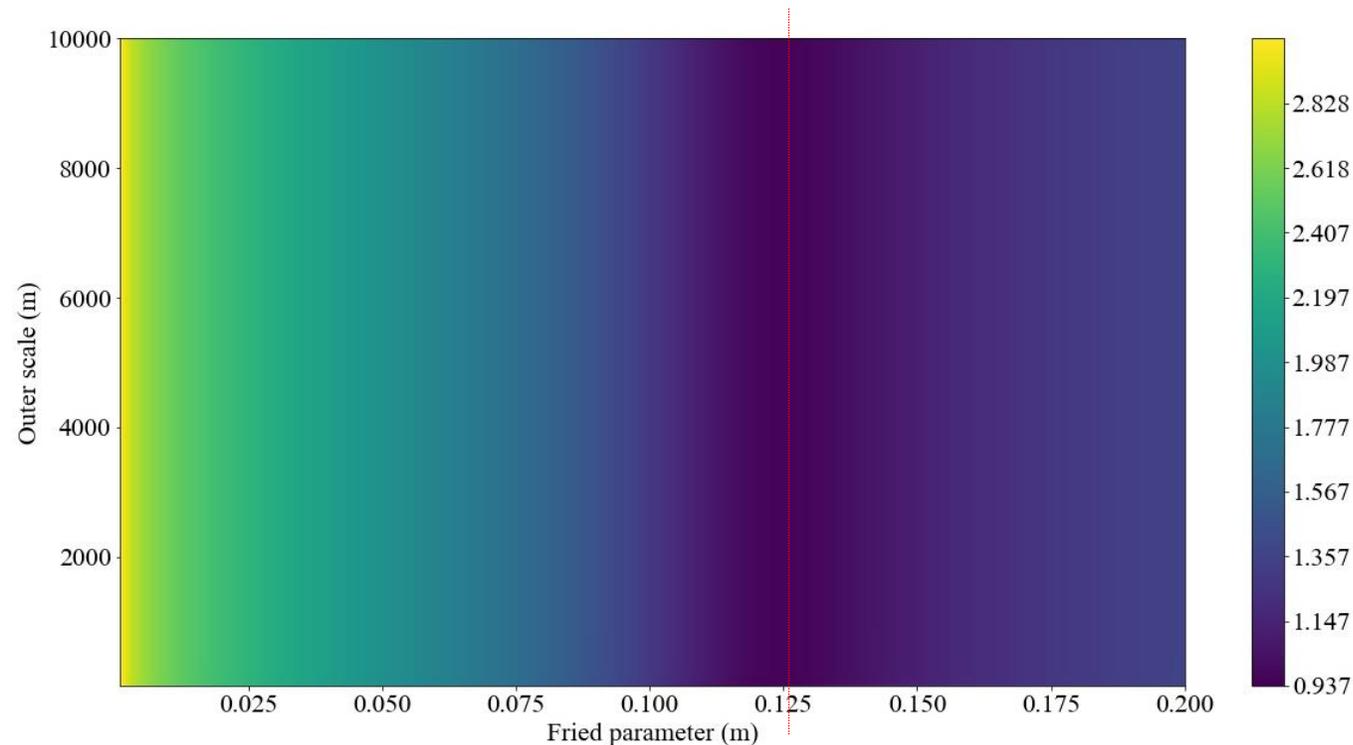
Consistency of estimates

The seeing is consistent across the ATs.
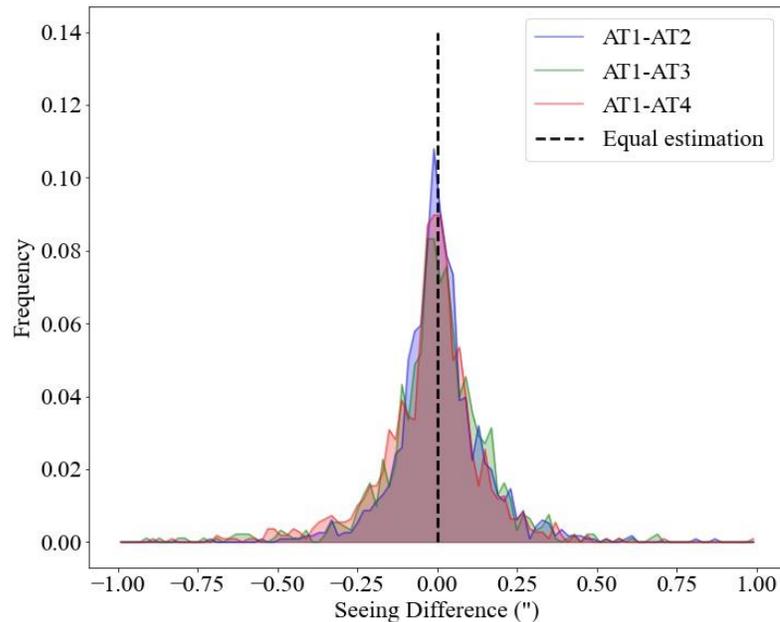
Data	Mean ('')	Standard Deviation ('')
$AT_1 - AT_2$	0.011 ± 0.004	0.1
$AT_1 - AT_3$	-0.000 ± 0.006	0.2
$AT_1 - AT_4$	-0.020 ± 0.005	0.2
$AT_2 - AT_3$	-0.013 ± 0.004	0.1
$AT_2 - AT_4$	0.010 ± 0.005	0.2
$AT_3 - AT_4$	-0.012 ± 0.004	0.1

Status and Future Goals

- Algorithm is operational;

- Improves estimation to sub % error wrt DIMM;

- Agreement across ATs;

- Deployable to track seeing on 20 sec time scales;

- Explain the remaining differences between NAOMI and DIMM;

- Automatic removal of abnormal modes;

- Improve noise estimation algorithm;

- Improve estimation with data fusion of the four telescopes and fringe-tracking data;

Thank You !