An on-line turbulence profiler for the VLT's adaptive optics facility (AOF)

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Centro de Astro-Ingeniería

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Staff

- 8 professors (permanent positions)
- 7 postdocs
- 14 graduate students

Some research activities

- **High resolution spectroscopy (Vanzi et al.)**
  Echelle spectrographs, Fibre optics characterization
- **Planet finding (Jordán, Suc, et al.)**
  Hat-South member
- **Cosmic microwave background (Dunner & Cactus group)**
  ACT (145, 220 and 280 GHz)
- **Cosmological Simulations (Padilla et al.)**
- **Wide-field adaptive optics (Bechet, Guesalaga et al)**
  Atmospheric Characterization, Vibrations Mitigation, Laser shaping

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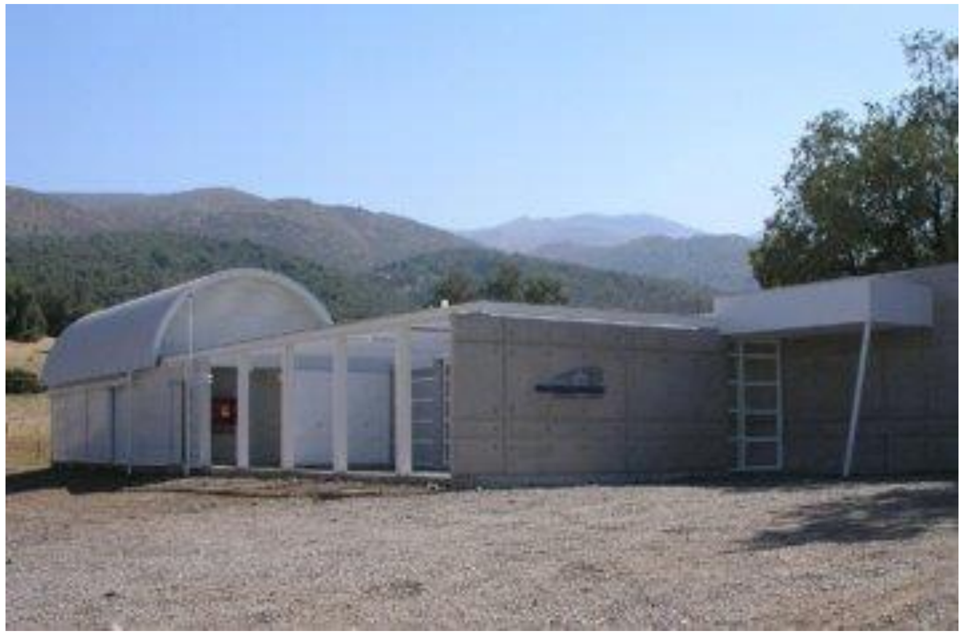
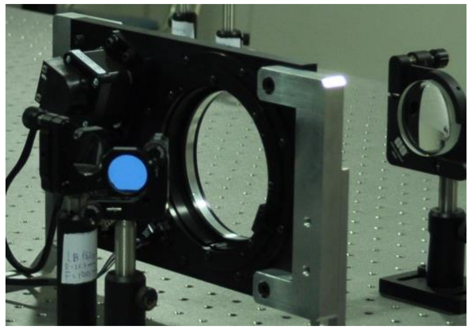


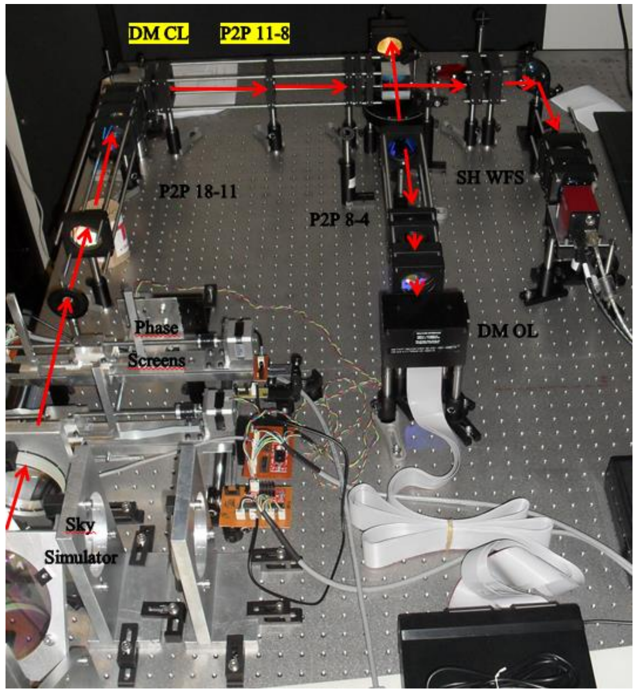
Teaching Observatory @ Sta. Martina (outskirts of Santiago)

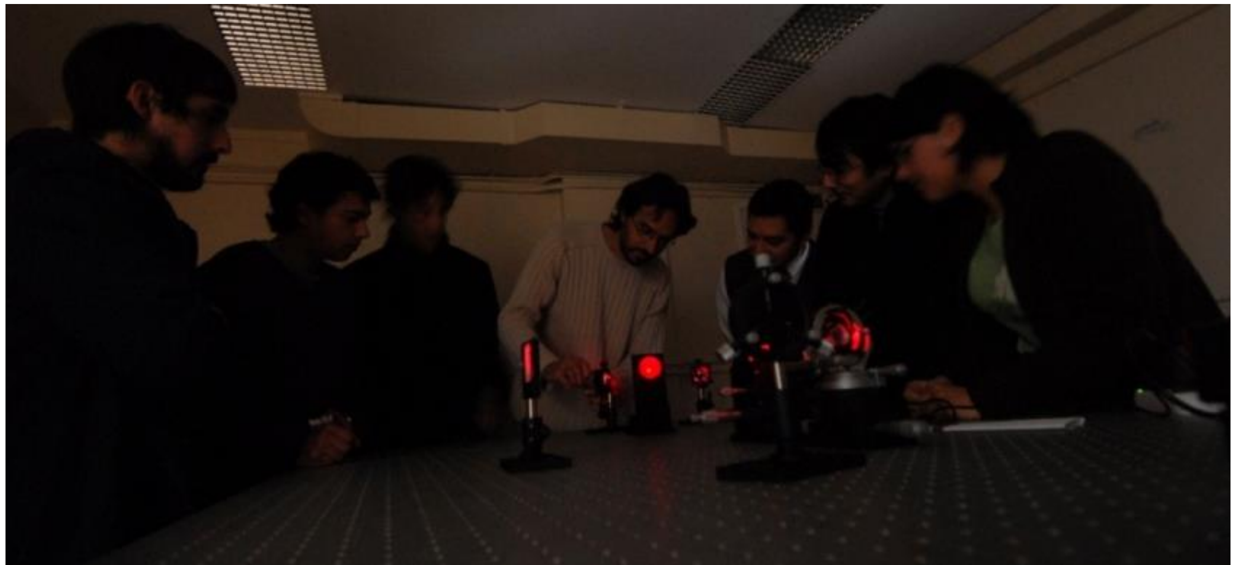
- Undergraduate teaching
- Testing of instruments
- ESO 50 cm, CTIO 40 cm

Laboratory equipment (Adaptive optics)

- 5 optical tables (1 MOAO experimental setup)
- 3 Boston MEMS DM, 140 actuators
- 1 Xinetics DM, 37 actuators
- 3 bimorph DMs, 48 actuators
- 5 Shack-Hartman WFS (24 x24 subapertures)
- Phase-screens for turbulence simulation

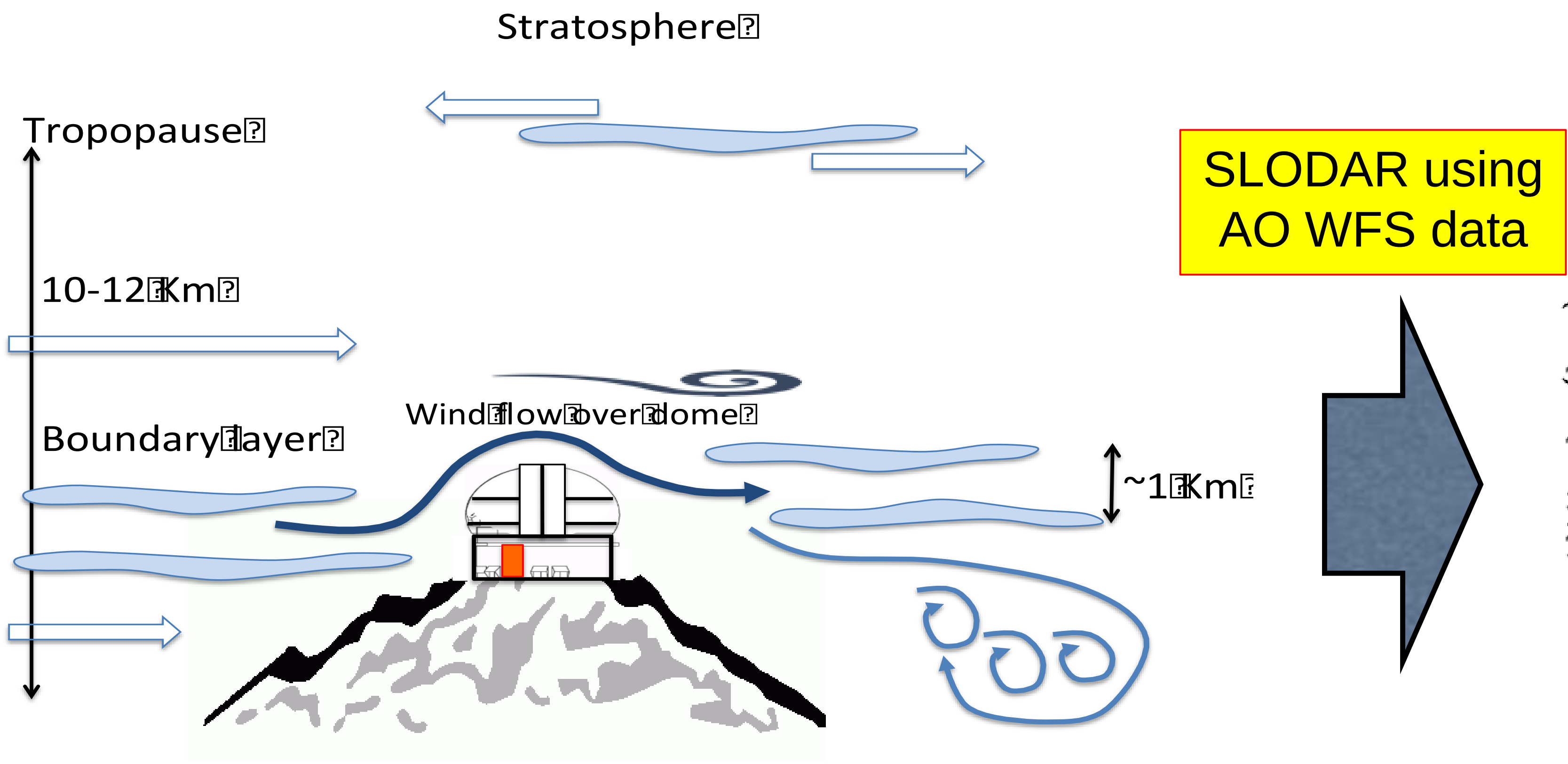


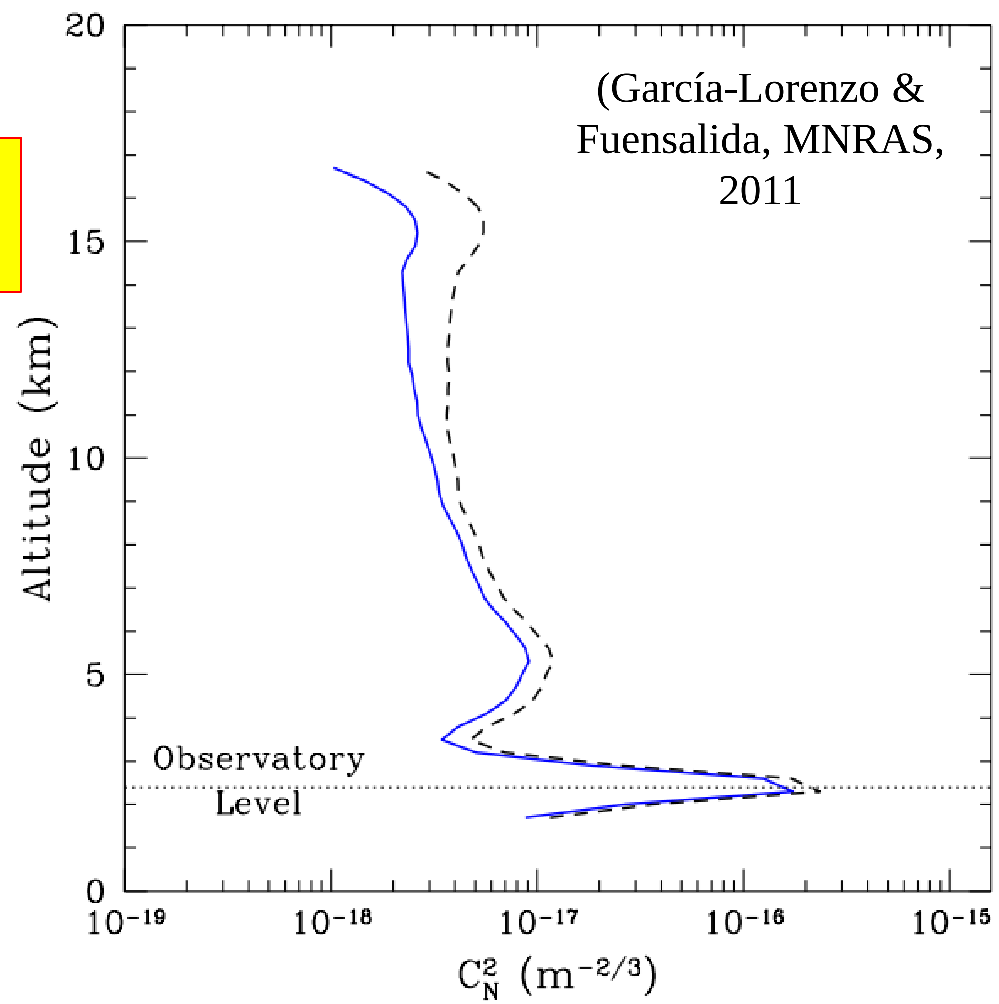




"Embedded" (on-line) turbulence profilers

(profilers using WFS of telescopes' facility instruments)



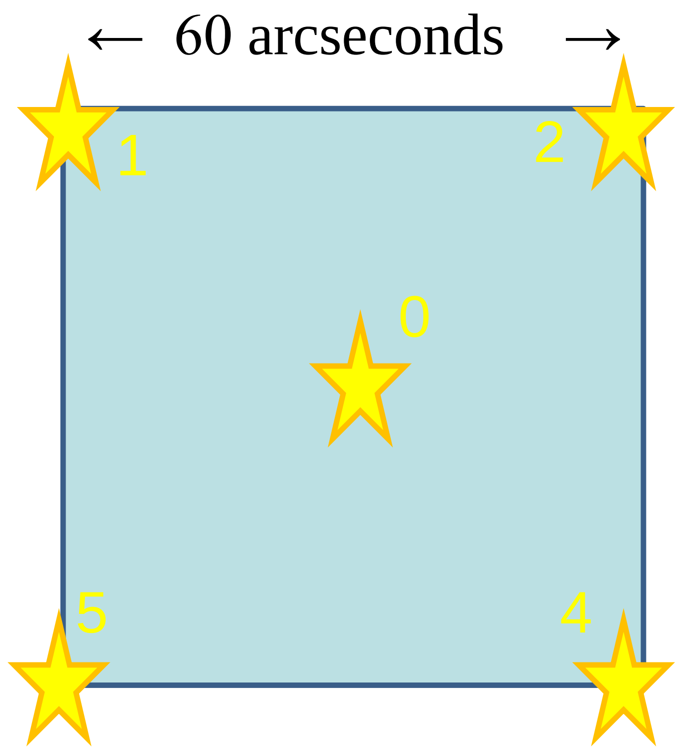


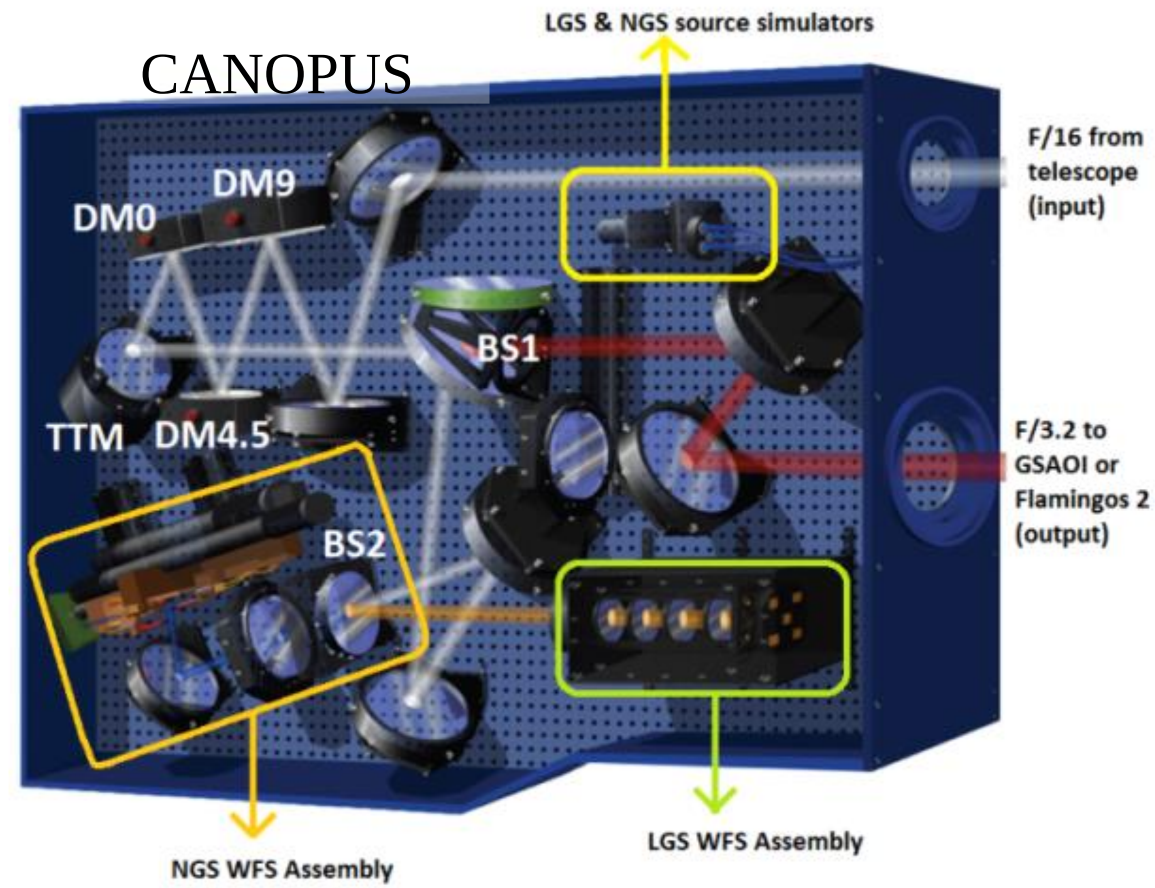
Motivation for embedded profilers:

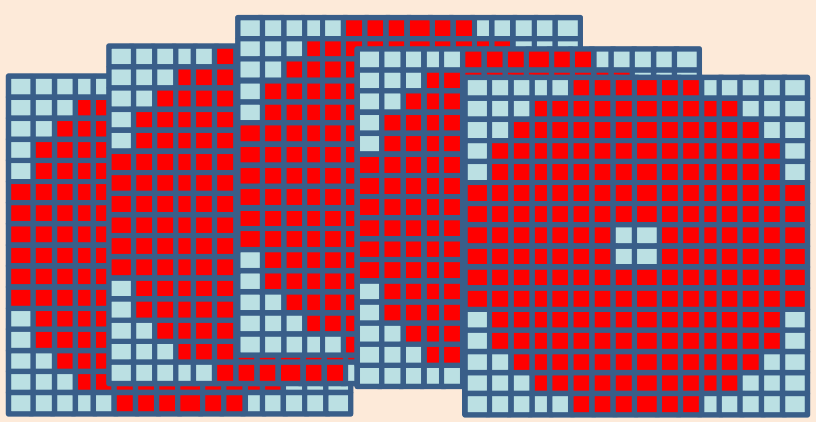
- An on-line profiler can help to characterize the performance of the AO system
- Predictive control via estimation of wind speed and wind direction
- Gather turbulence statistics of the site
- Characterization of the telescope environment (dome seeing, vibrations, mis-reg.)
- Optimize tomographic reconstructors and conjugation altitudes for DMs according to Cn^2 (h), L_0(h), wind, dome seeing, etc.

A Profiler for GeMS (Gemini-South MCAO System)

(The beginning)







5 WFSs

- 16x16 grid Shack-Hartmann
- 204 active subapertures (total: 1020)
- sampling rate <= 800 Hz

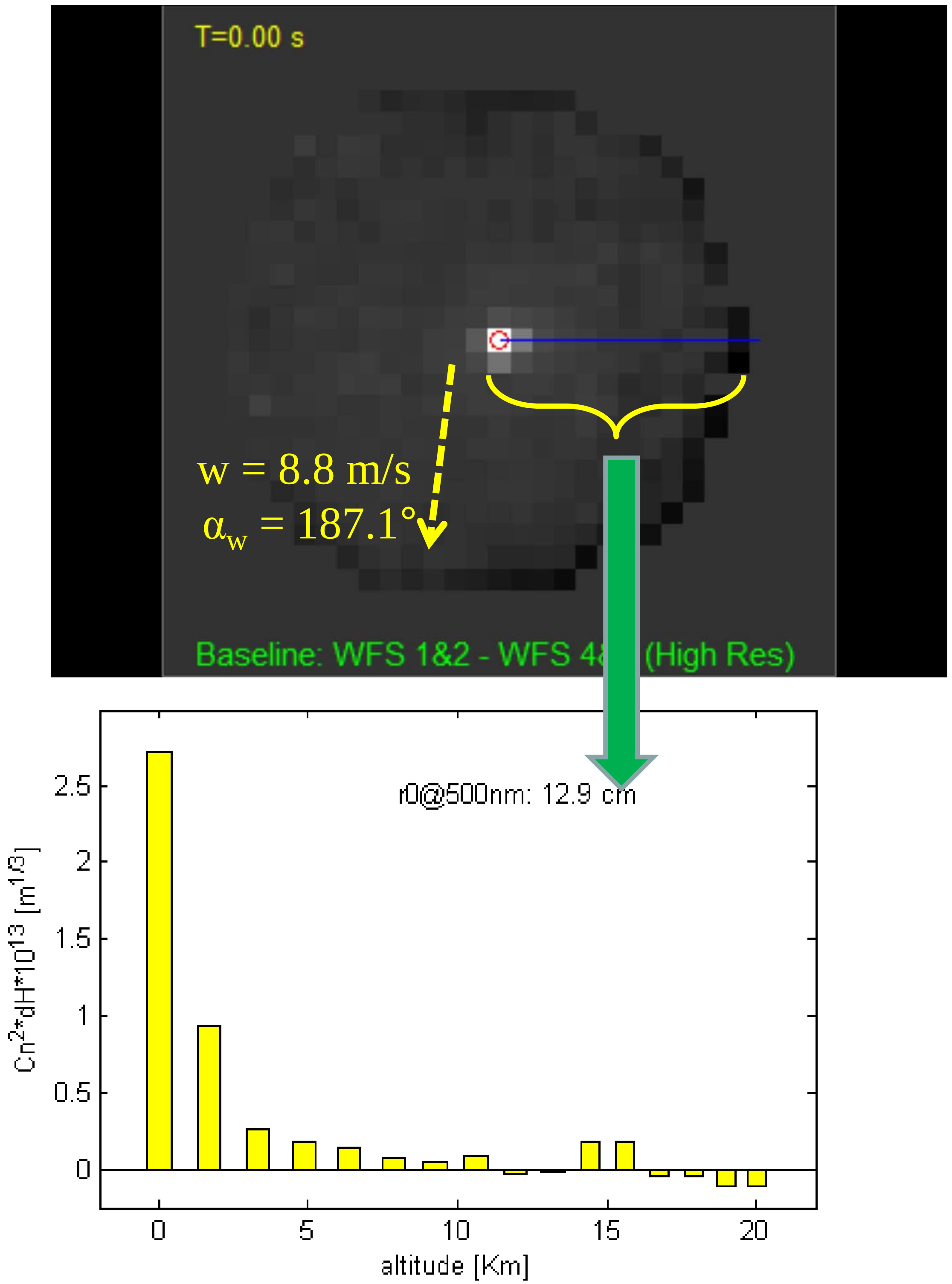
3 DMs

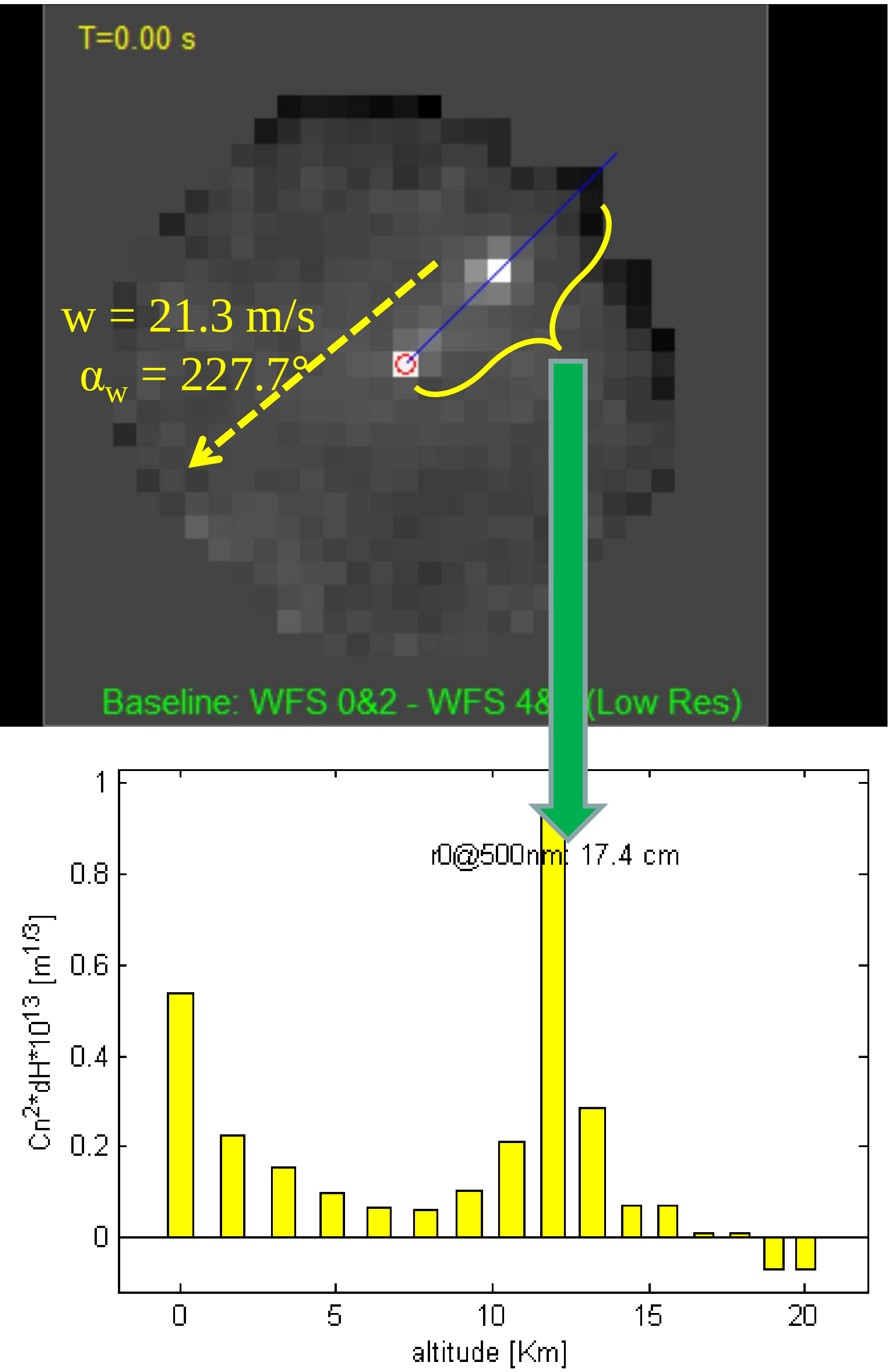
- 917 actuators in total
- 684 valid actuators (seen by the WFSs)
- 233 extrapolated actuators

GeMS: The $Cn^2(h)$ and "wind profiler"

For T = 0 s, the turbulence profile in altitude is extracted from the baseline

For T > 0, the layers present can be detected and their velocity estimated

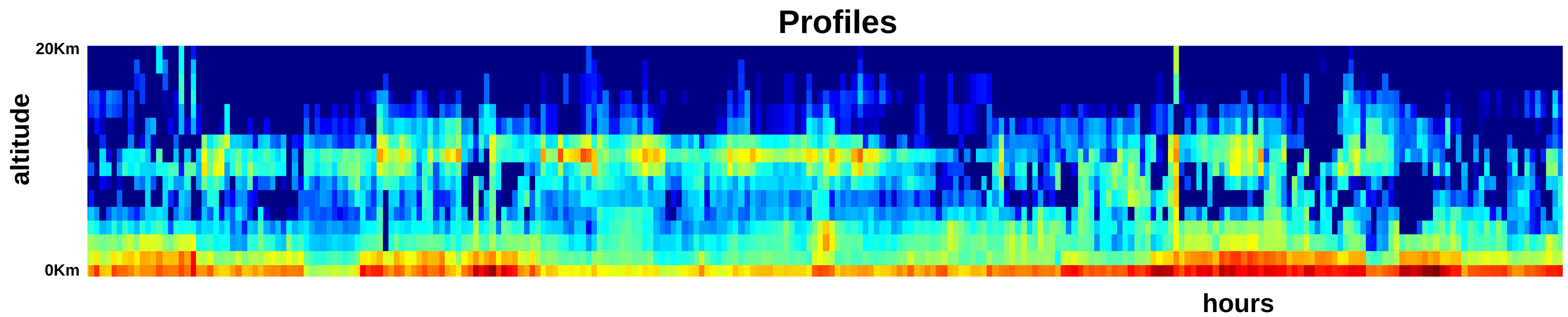


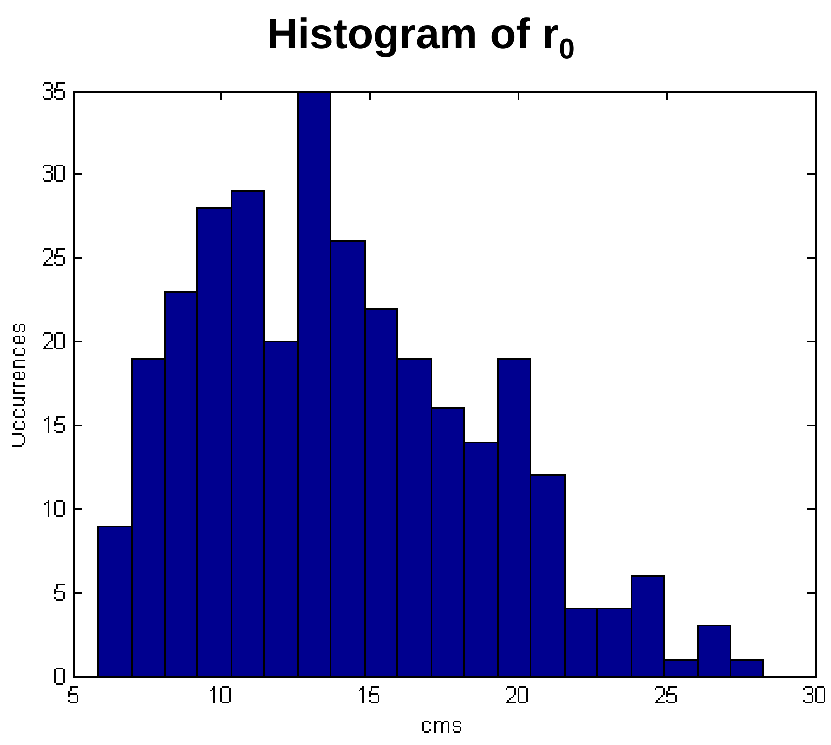


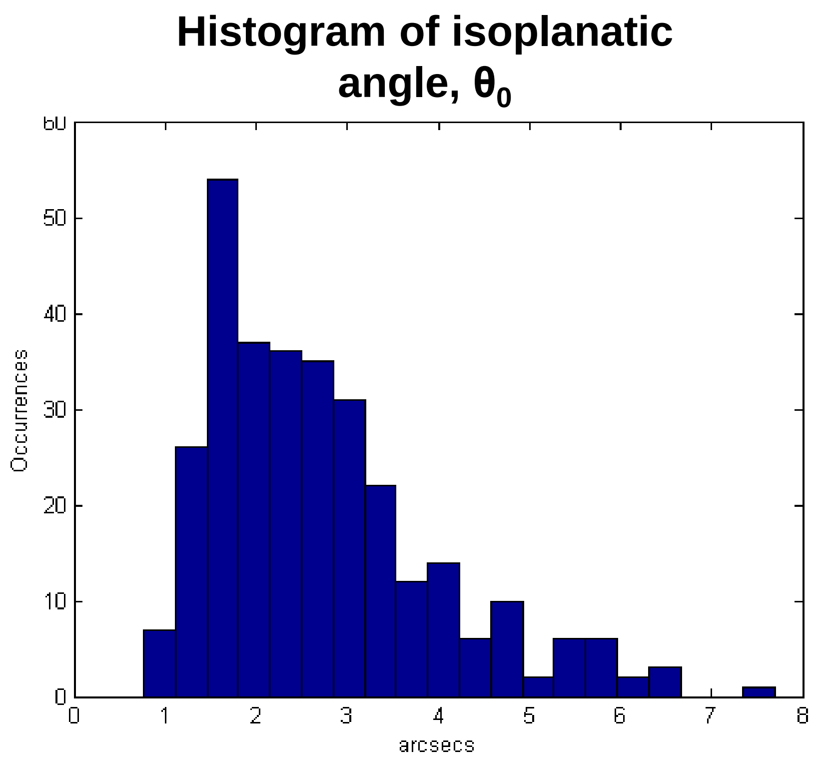
Cortés et al, MNRAS, 2018

GeMS: statistics for 1000+ profiles

(Several campaigns in 2012, 2013 and 2014)

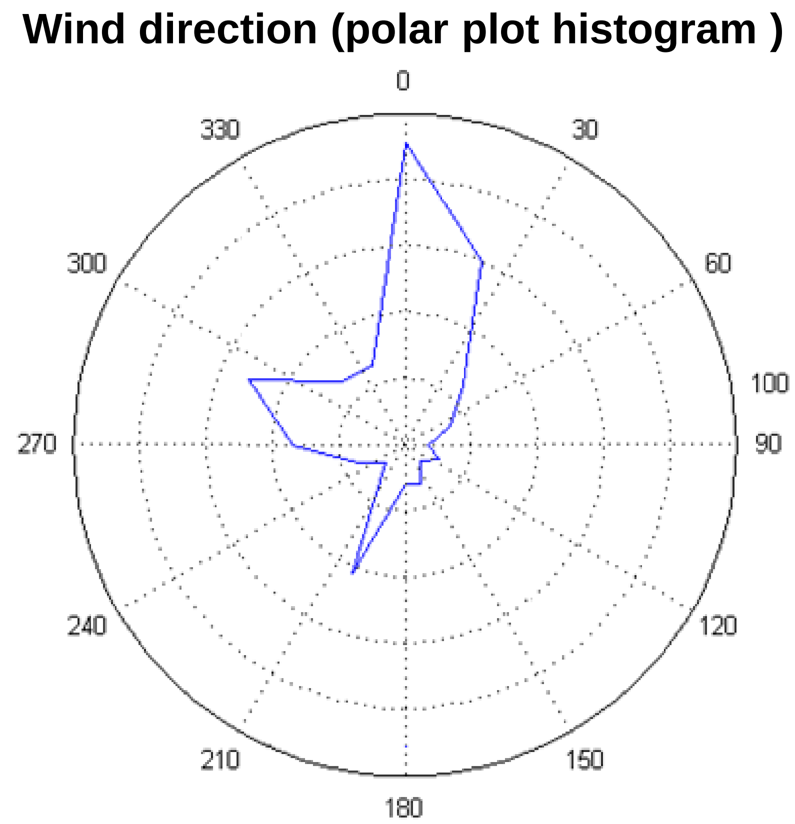


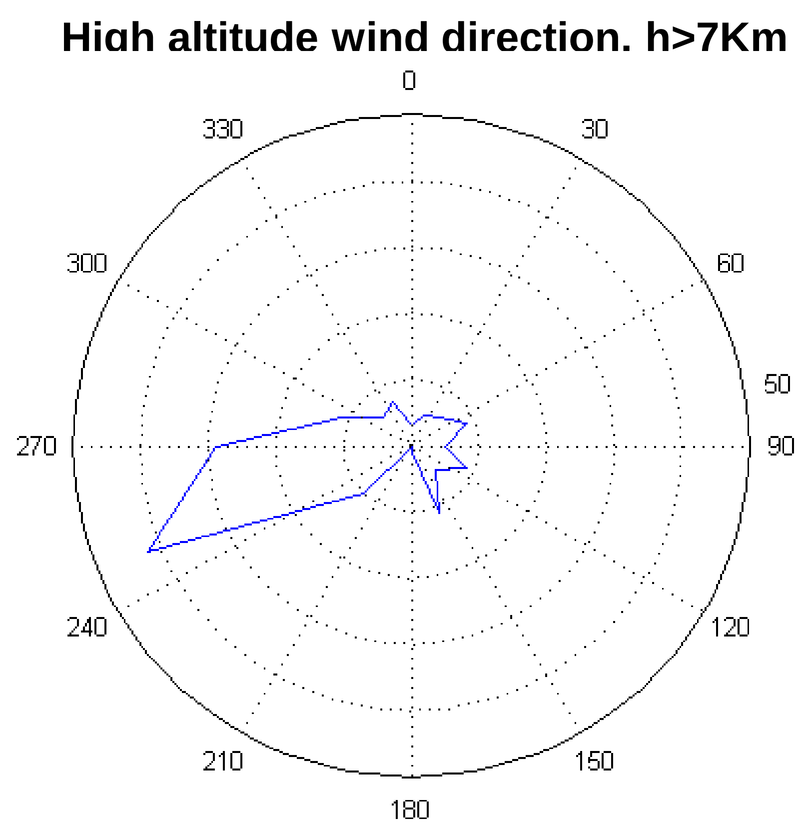


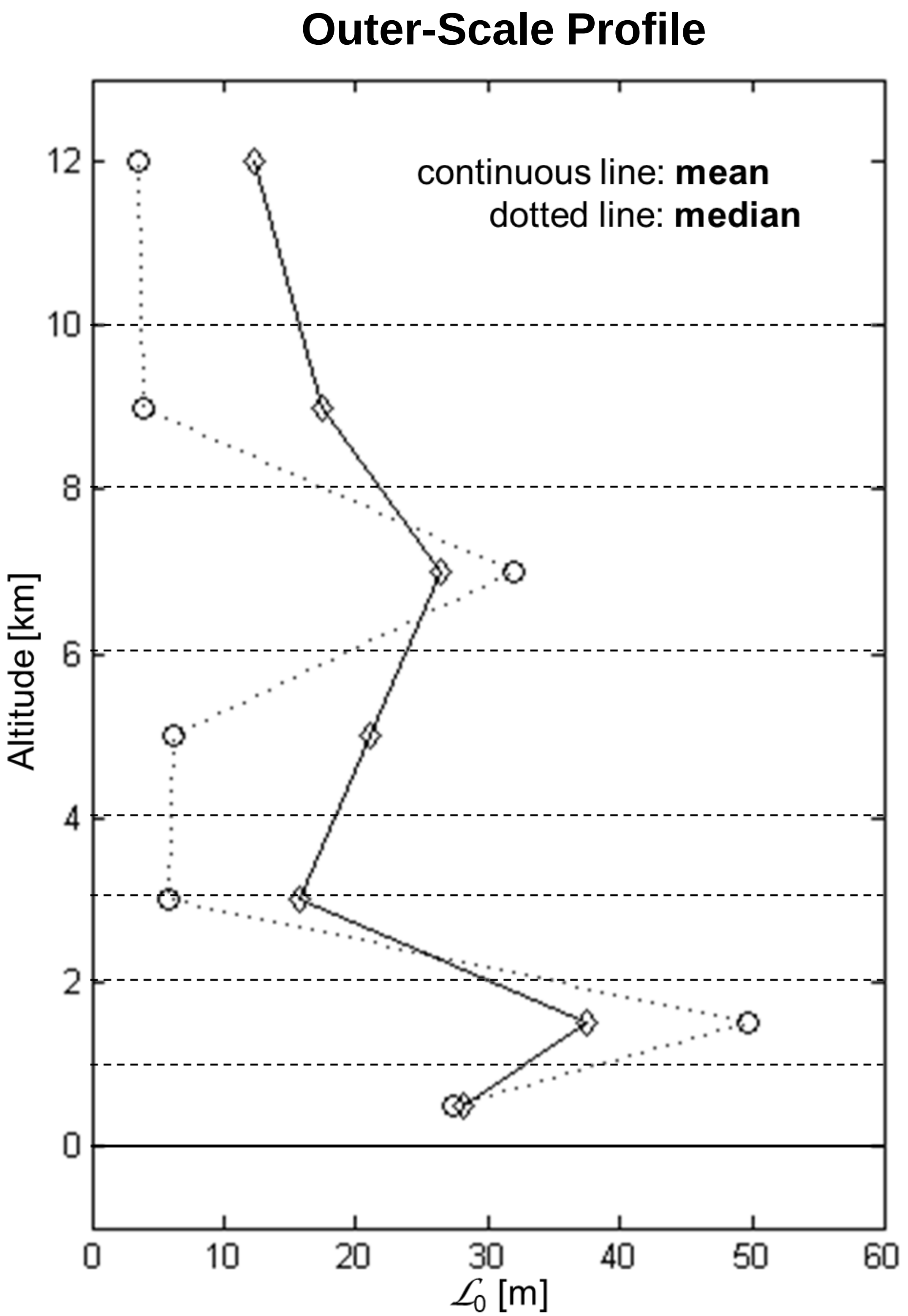


GeMS: statistics for 300+ $\mathcal{L}_0$(h) profiles

(Several campaigns in 2012, 2013 and 2014)



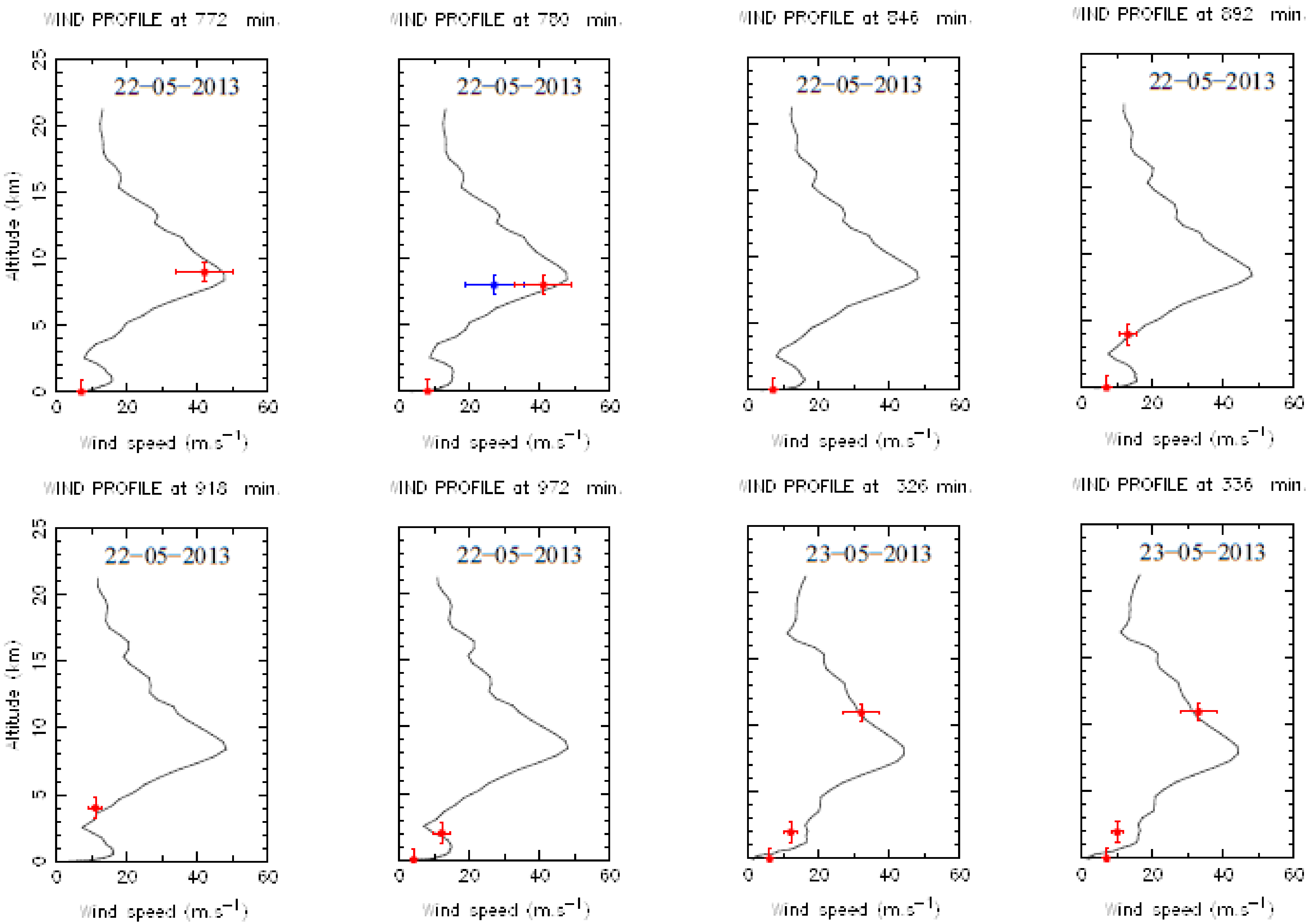




Guesalaga et al, MNRAS, 2017

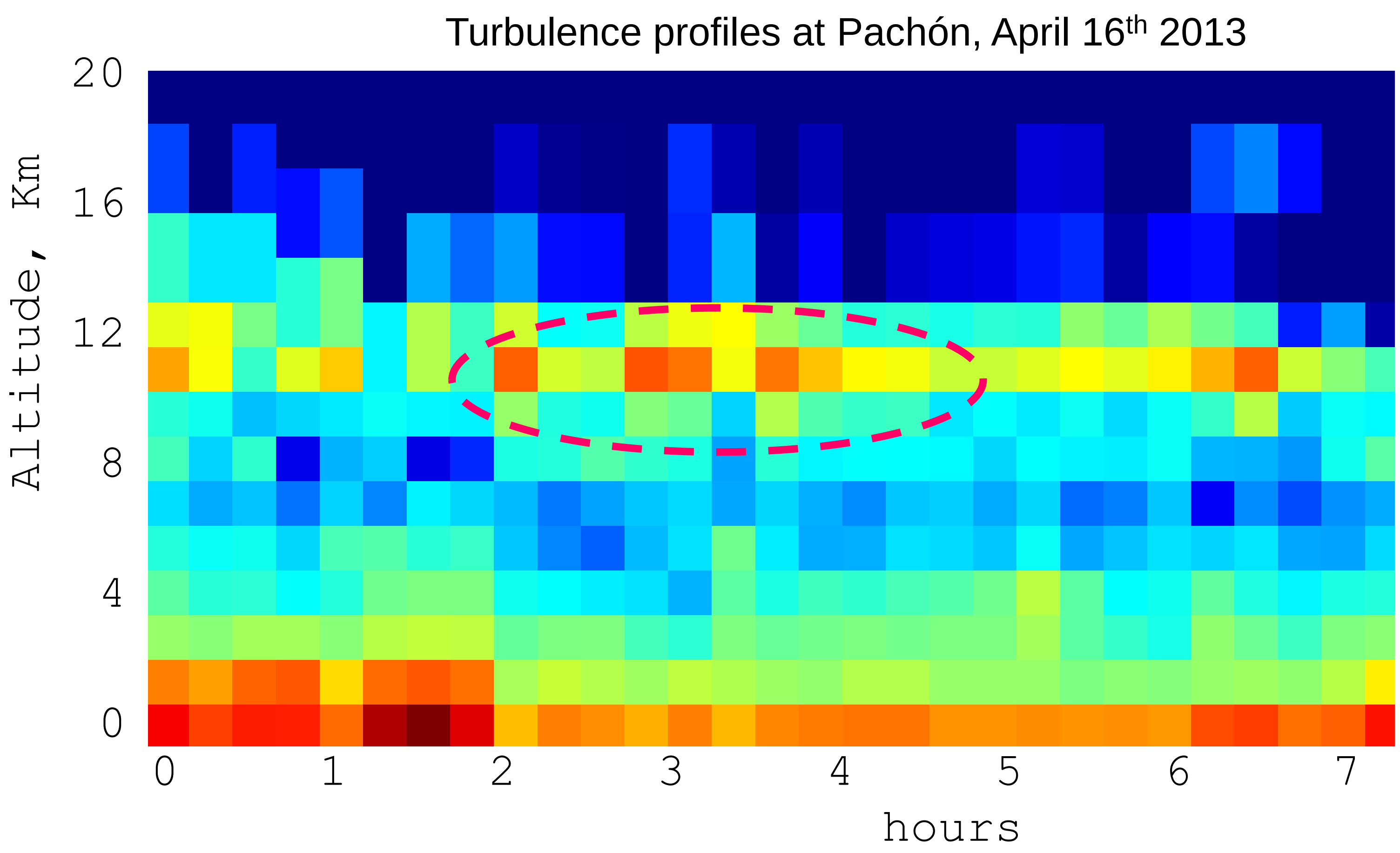
Comparing GeMS wind profiles to Meso-NH model

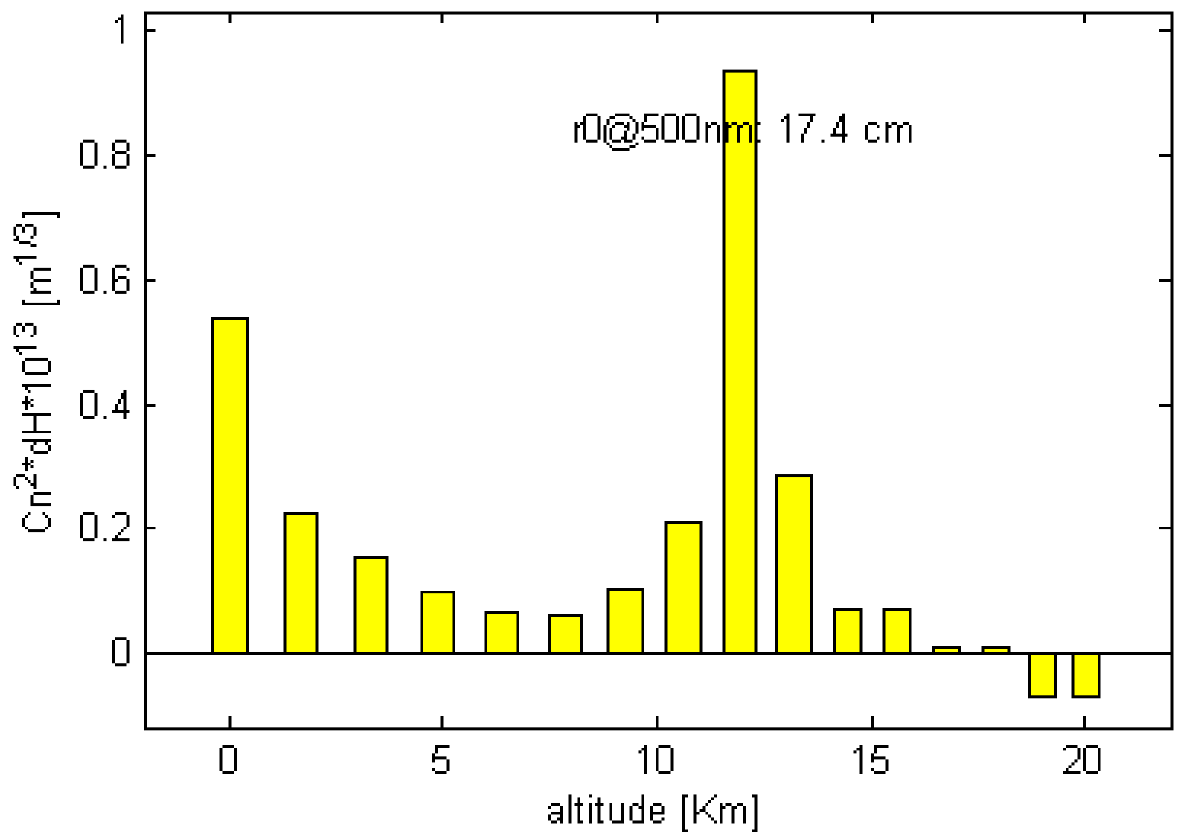
Red crosses are from GeMS profiler, continuous line is the meso-NH model

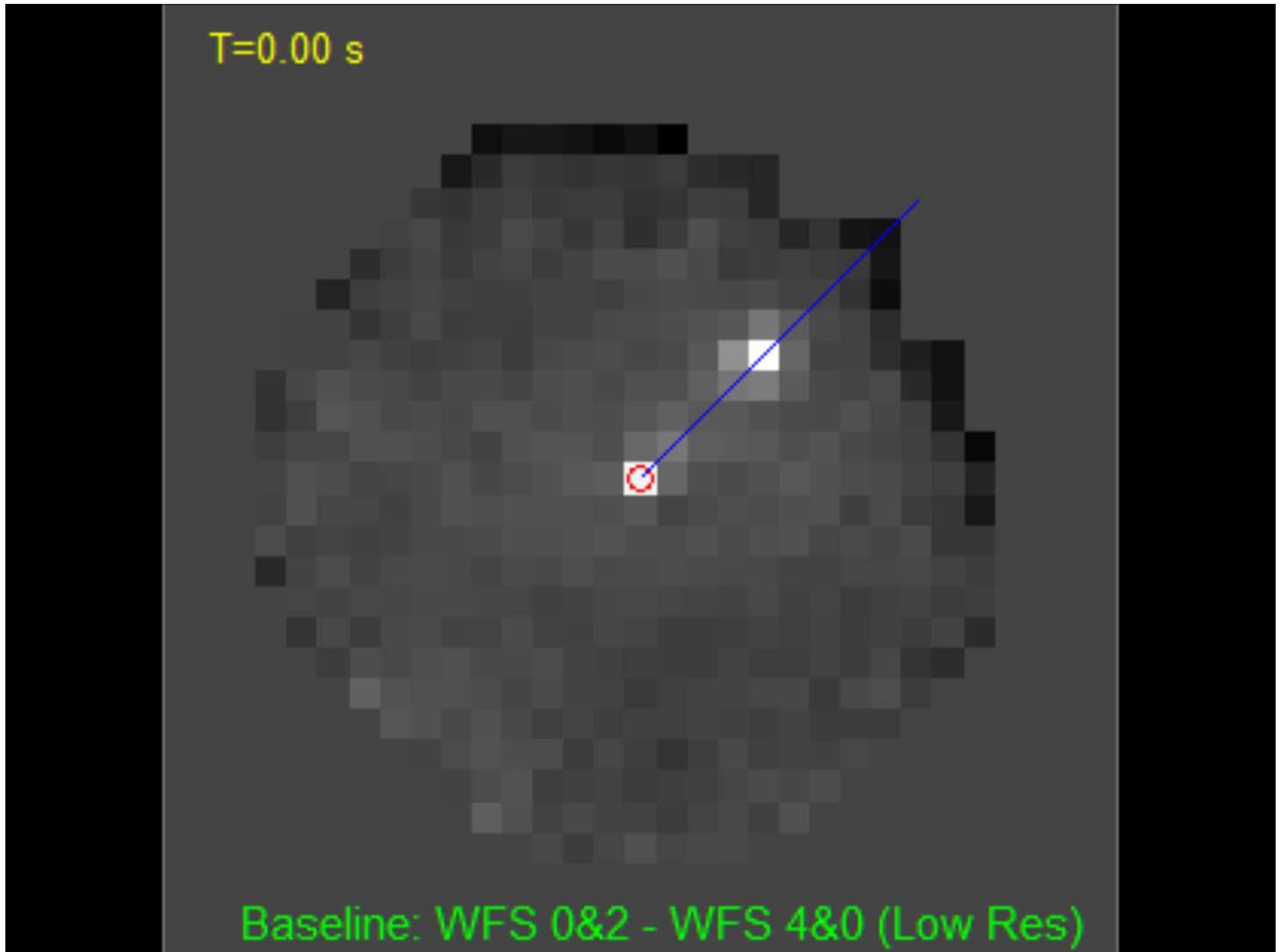


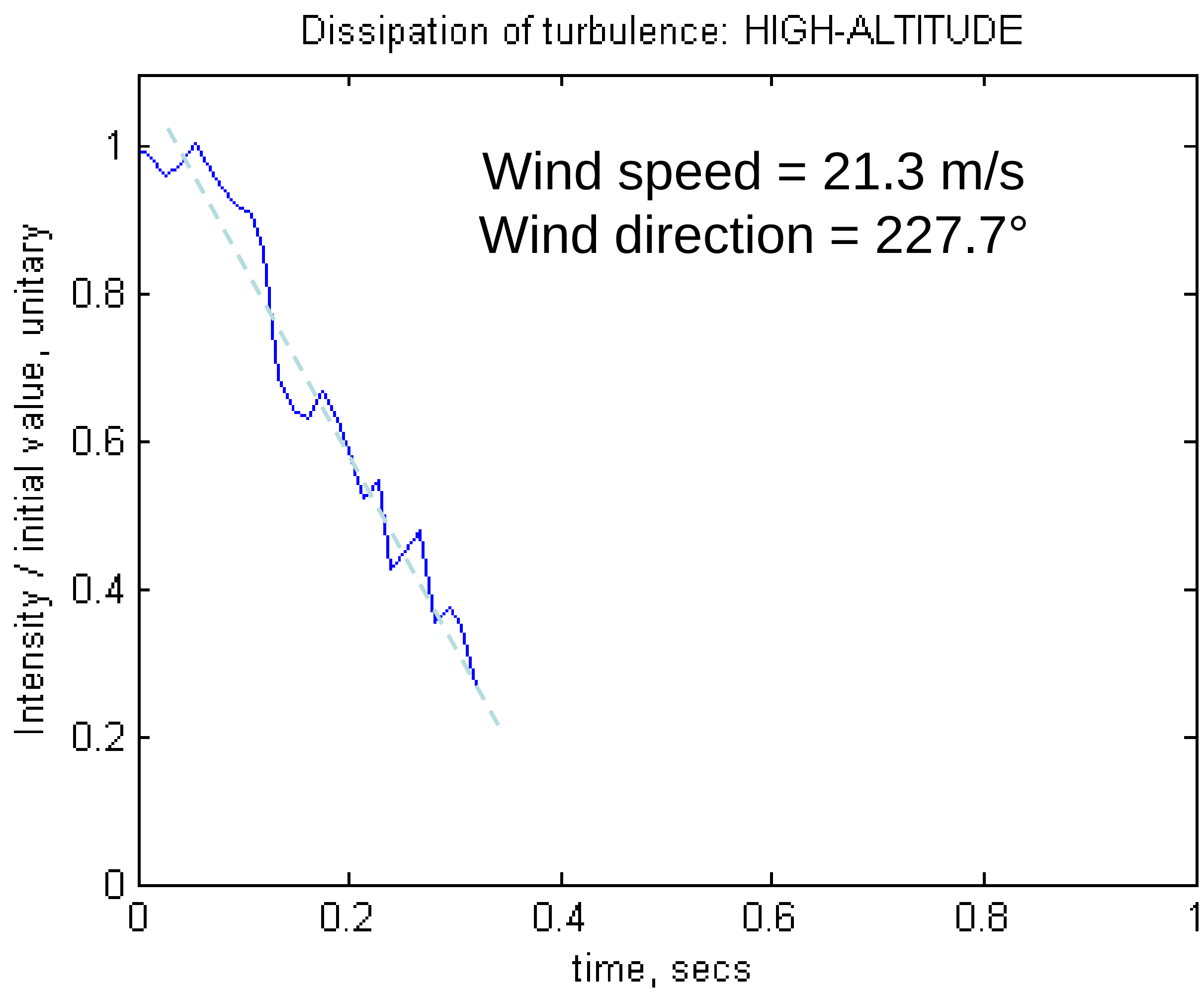
Sivo et al, MNRAS, 2018

GeMS: frozen flow study



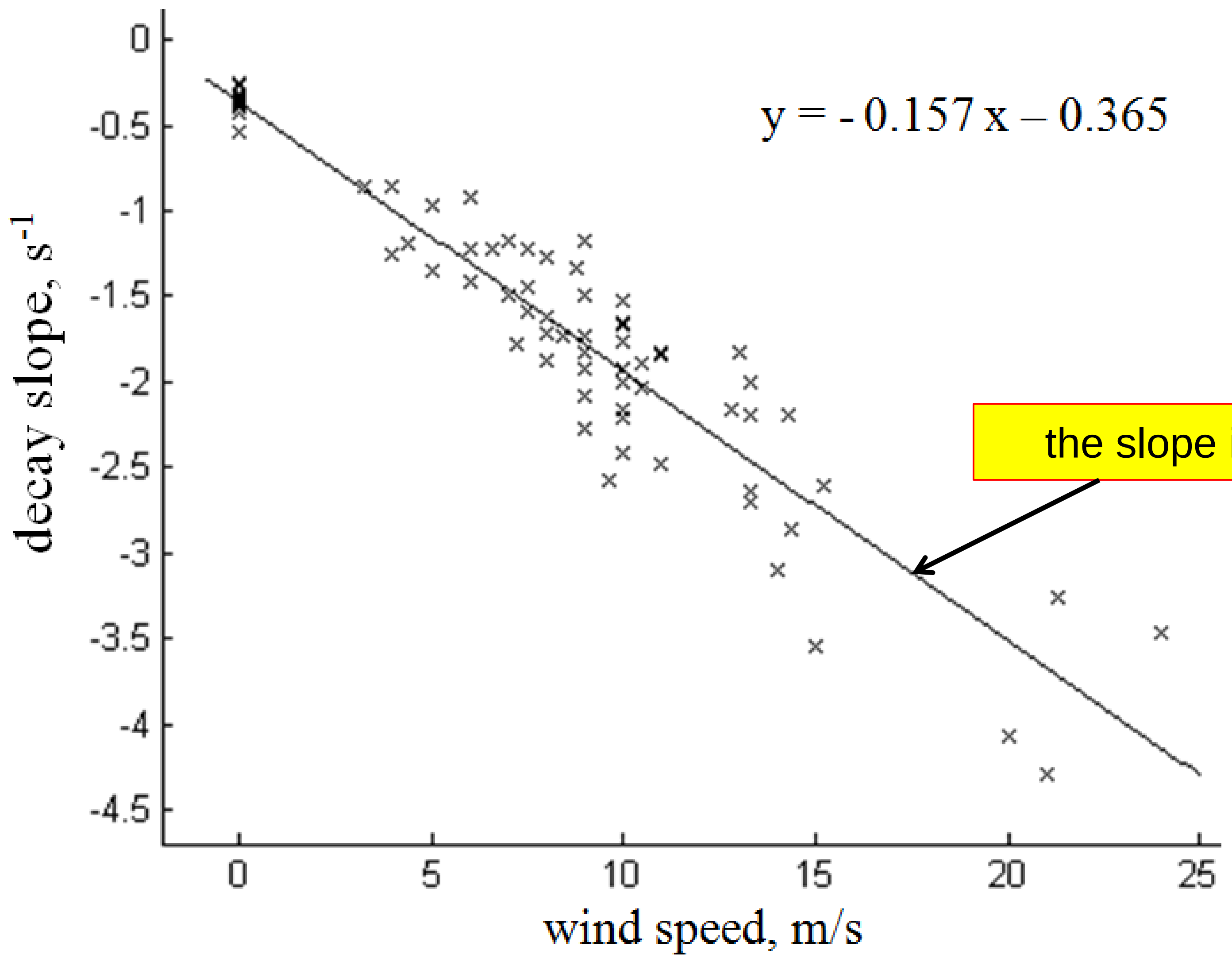






GeMS: Frozen flow study

Dependence of frozen flow to wind speed



the slope is in m^{-1}

Guesalaga et al, MNRAS, 2014

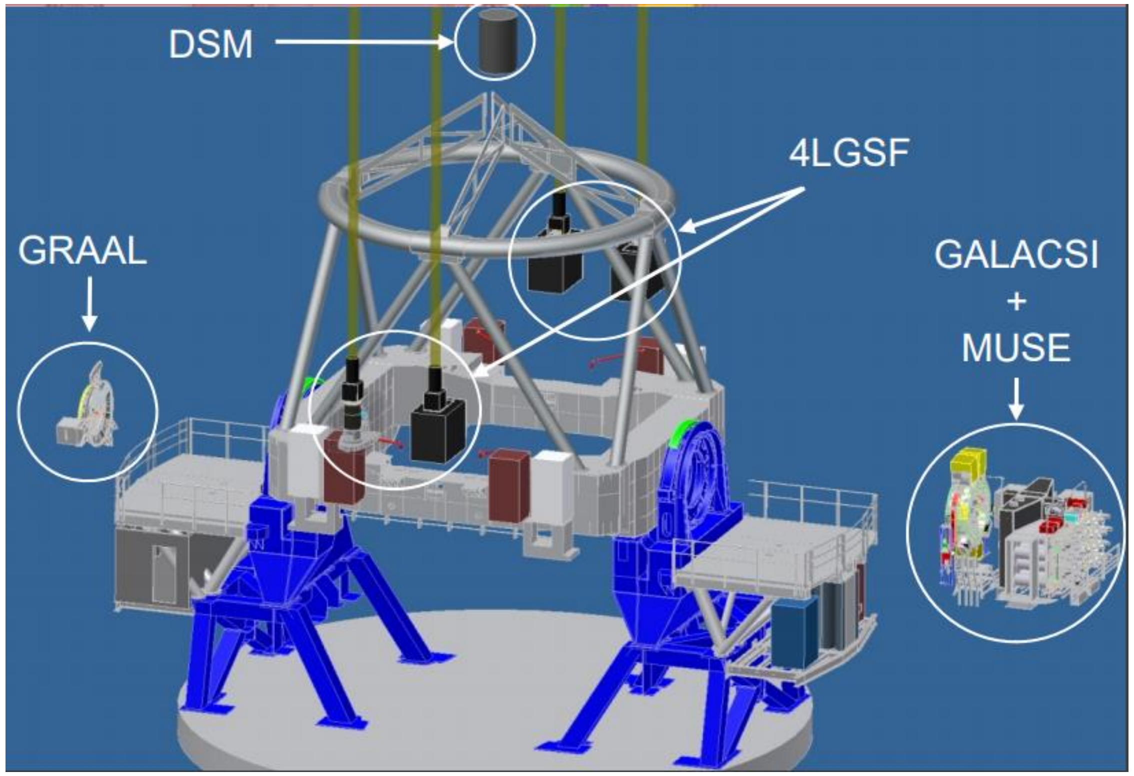
Problems with GeMS profiler

- Resolution in altitude limited by subaperture diameter.
- Strong effect of $L_0(h)$ on accuracy, specially for layers near the ground or system operating under strong dome turbulence conditions.
- When trying to isolate individual layers, there are multiple functions to deconvolve the cross-correlation image (depending on height and outer-scale), so it is not a practical approach.
- Long processing time (*t* > 7 mins).

Main conclusion: including $L_0(h)$ in every step of the profiling process **is a must**.

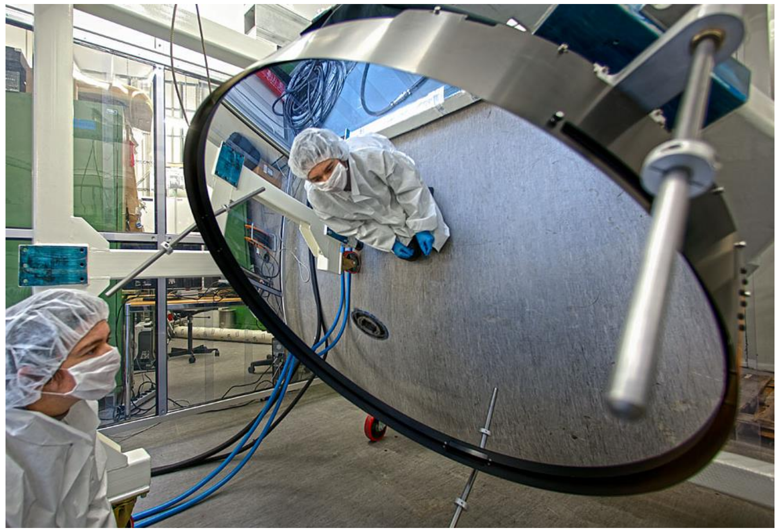
An On-line Profiler for ESO's Adaptive Optics Facility (AOF)

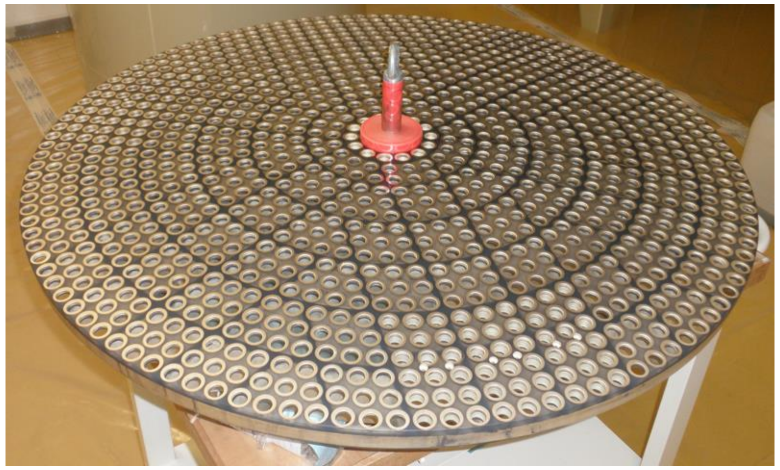
Colaborators from ESO: J.Kolb, S.Oberti, J.Valenzuela

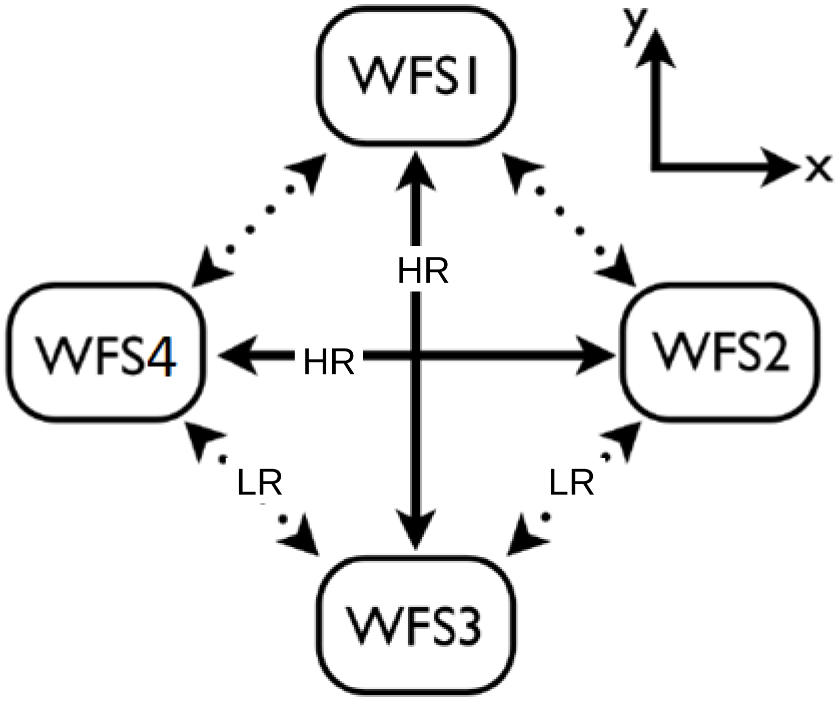


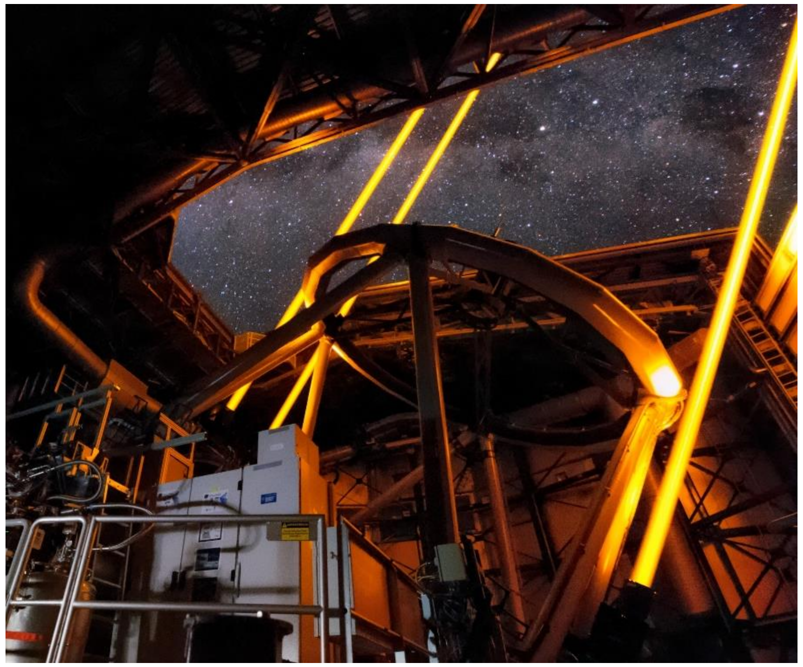
AOF main characteristics:

- 3 operational modes: GALACSI x 2 and GRAAL
- 4 sodium laser asterism
- WFSs: 40 x 40 subapertures (20cm diameter)
- Deformable secondary mirror (1170 actuators)









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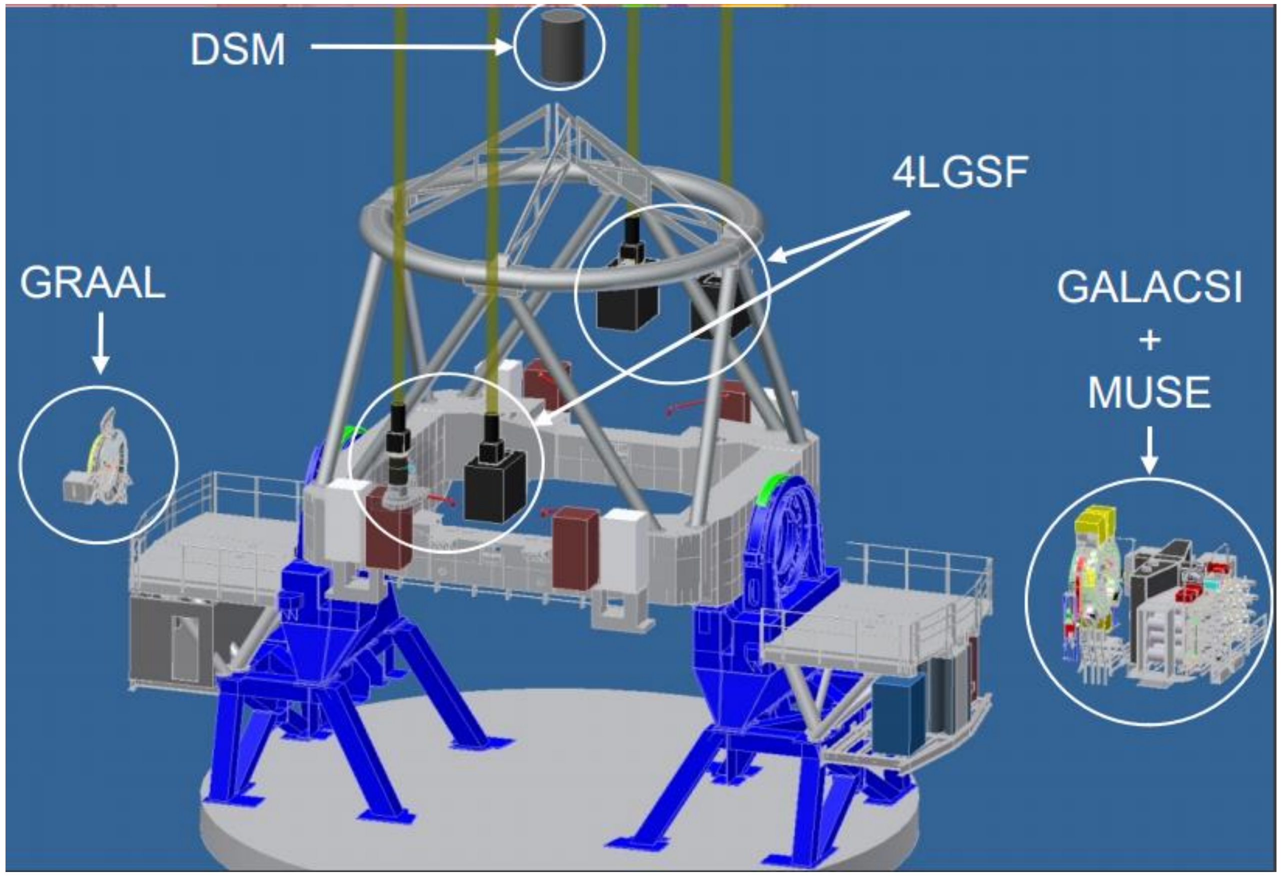
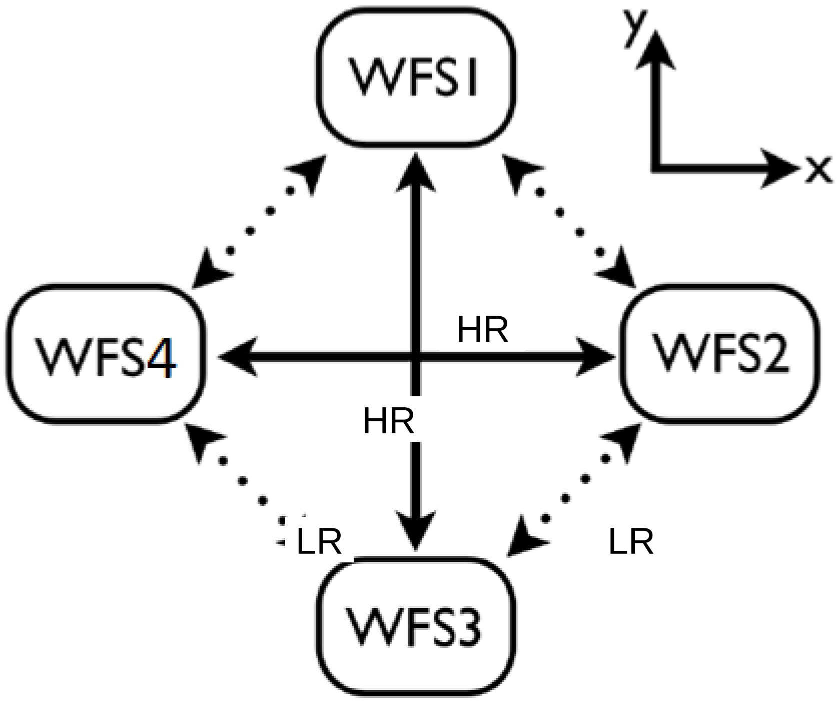


GALACSI is the AO system developed to increase the performance of the MUSE instrument, a panoramic integral-field spectrograph working at visible wavelength.

GRAAL feeds HAWK-I, a NIR imager (0.85 - 2.5 µm). The science field of view is 7.5 arcmin square. GRAAL compensates for the lowest layers of the atmospheric turbulence (up to ~ 2 km.

ESO's Adaptive Optics Facility (AOF)



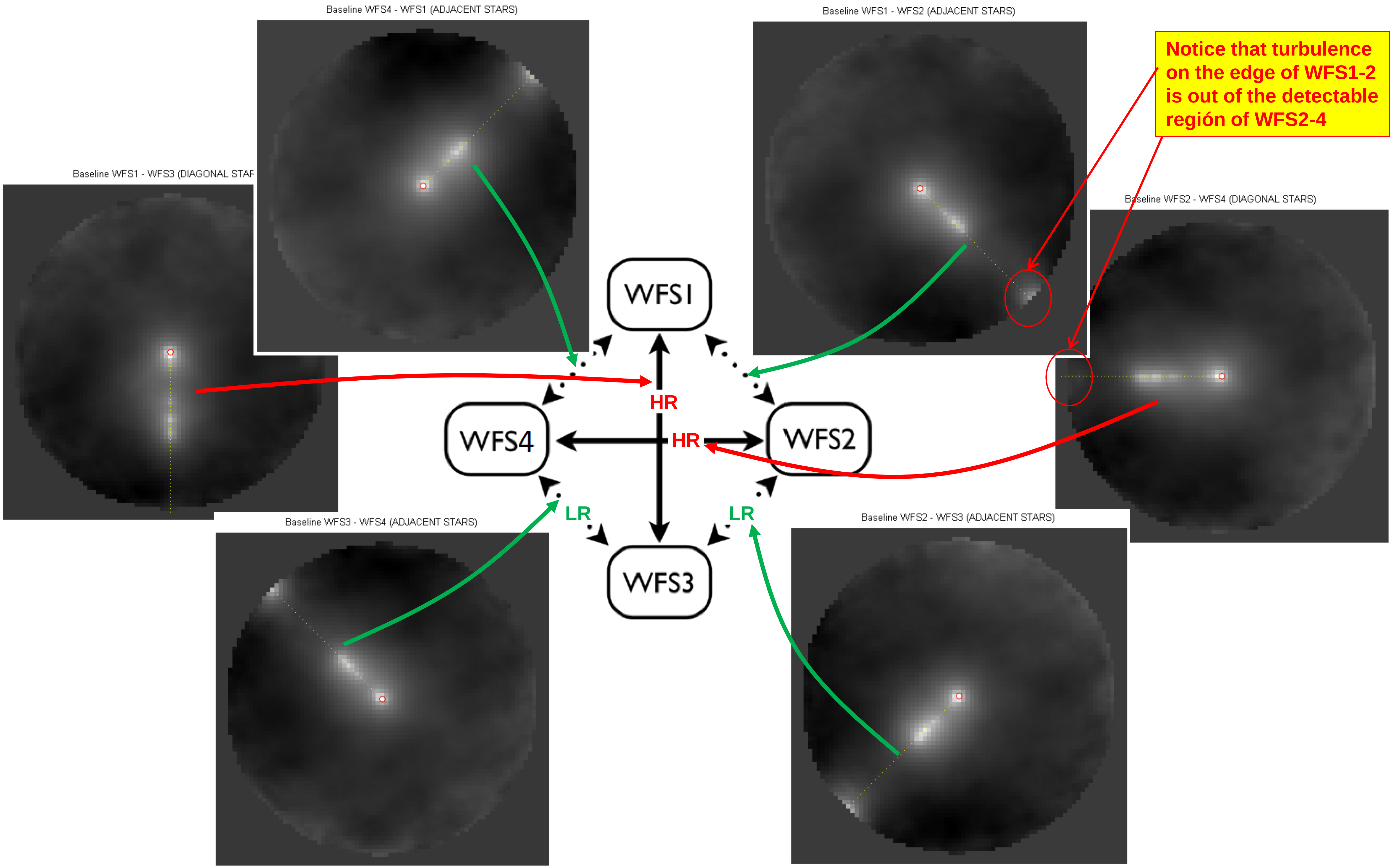
AOF main characteristics:

- 4 sodium laser asterism
- WFSs: 40 x 40 subapertures, 20cm diameter
- 2 altitude resolutions (star separations)
- Deformable mirror for GLAO and LTAO
- 3 operational modes: GALACSI x 2 and GRAAL

AOF Mode	Low Resolution (LR) Baseline			High Resolution (HR) Baseline		
	θ_{LR} ["]	$h_{max,LR}$ [km]	δh [km]	θ_{HR} ["]	$h_{max,HR}$ [km]	δh [km]
GAL NFM	14.1	-	-	20	24.5	1.7-0.9
GAL WFM	90.6	12.4	0.55-0.41	127.8	9.14	0.28-0.22
GRAAL	492	2.49	0.102-0.096	696	1.76	0.05-0.049

Range is due to the LGS cone effect

The method: Cross-Correlations of Pseudo Open Loop Slopes (POLS) for pairs of WFSs

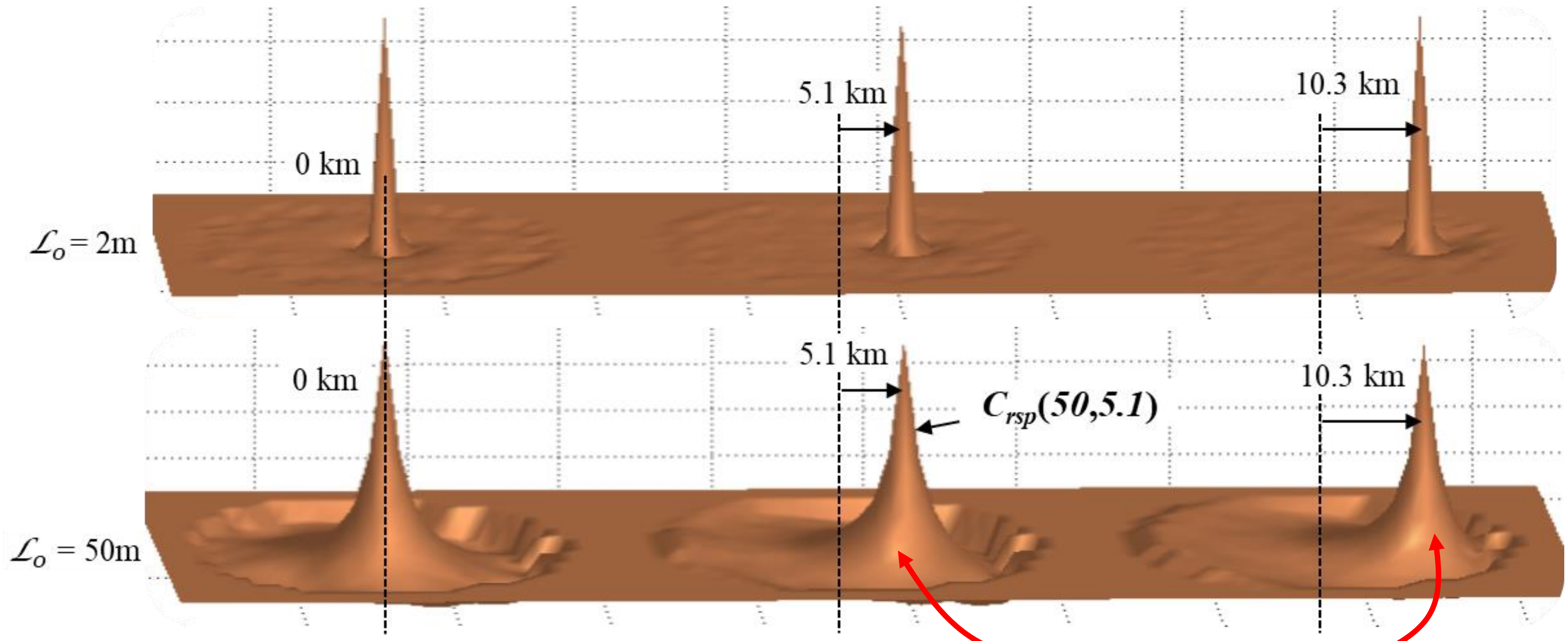


The method: Reference or response functions

The first step in the profiling technique is to generate (only once) the reference functions: cross-correlations between pairs of WFSs POLS for different values of layer height and outer scales.

A grid of 33 altitude divisions and 12 outer-scale values is constructed

- Discrete values for $\boldsymbol{h}$: $\{1{:}N\}\cdot\Delta h$, N is chosen ≈ 80% of maximum number of bins
- Discrete values for $\mathcal{L}_o$: {1, 2, 3, 4, 6, 8, 11, 16, 22, 32, 50, 100}



Guesalaga et al, MNRAS, 2017

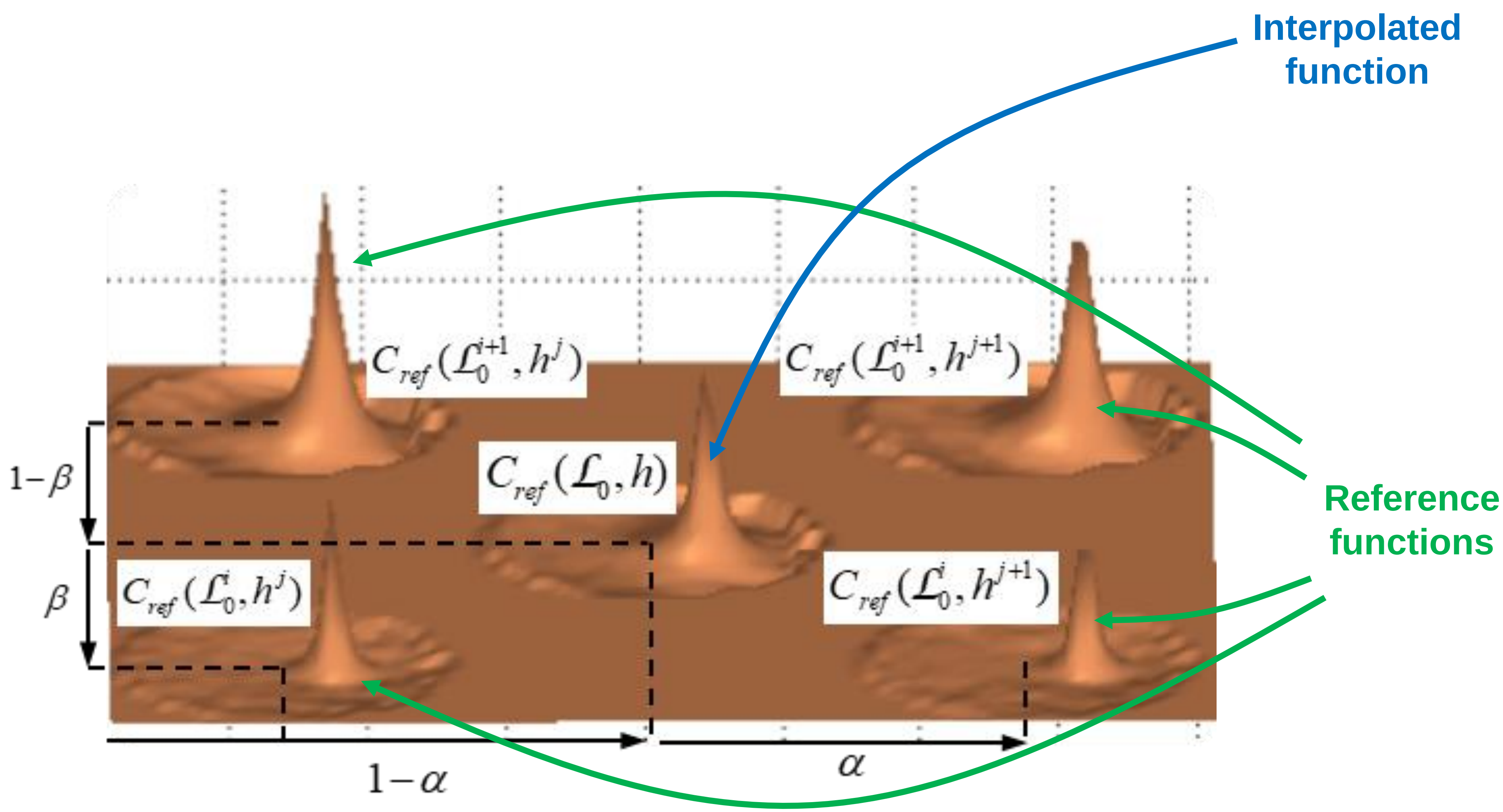
The method: Search for minimum using interpolated functions from reference grid

Search for mínimum:

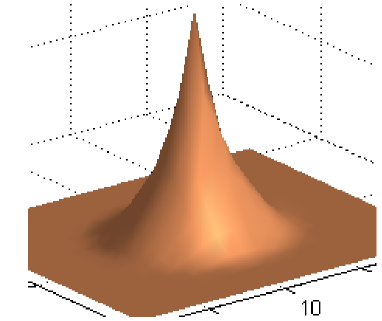
$$\underset{\omega, \mathcal{L}_0, h}{Min} \left\langle \left(C_{meas} - \sum_{i=1}^{N_Z} \omega_i \cdot C_{ref}^{i}(\mathcal{L}_0, h) \right)^2 \right\rangle$$

Interpolation:

$$C_{ref}(\mathcal{L}_0, h) = \left((1-\alpha) \cdot C_{ref}(\mathcal{L}_0^{i}, h^{j}) + \alpha \cdot C_{ref}(\mathcal{L}_0^{i+1}, h^{j}) \right) \cdot (1-\beta) + \left((1-\alpha) \cdot C_{ref}(\mathcal{L}_0^{i}, h^{j+1}) + \alpha \cdot C_{ref}(\mathcal{L}_0^{i+1}, h^{j+1}) \right) \cdot \beta$$

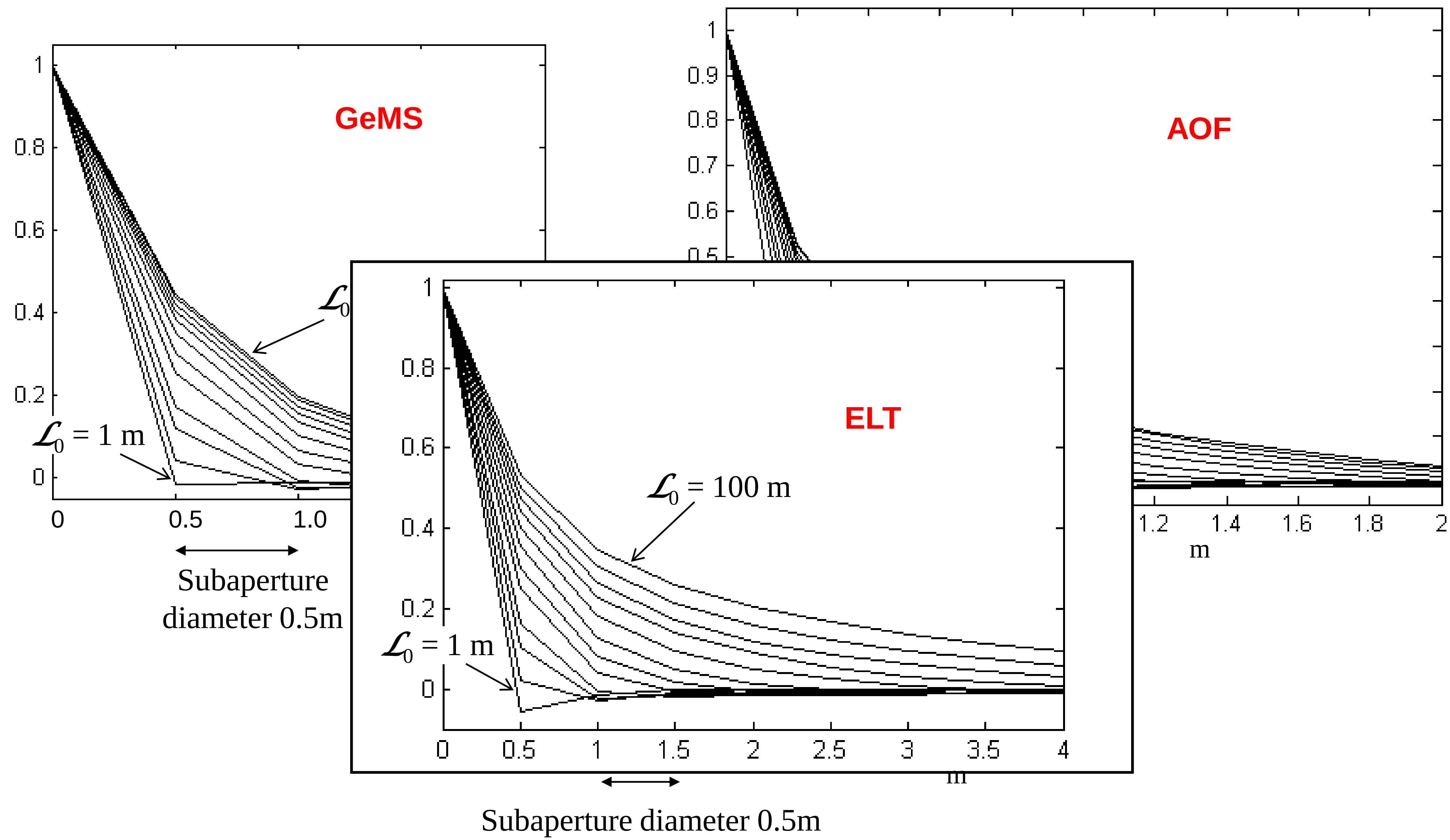


The method: Choice of $\mathcal{L}_o(h)$ for the response functions in the reference grid

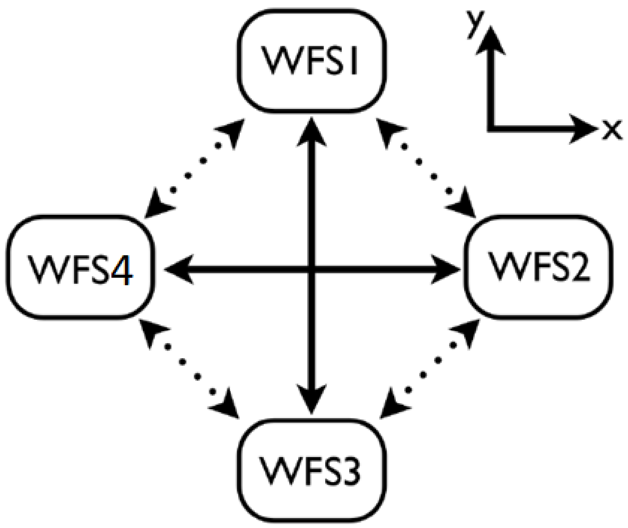


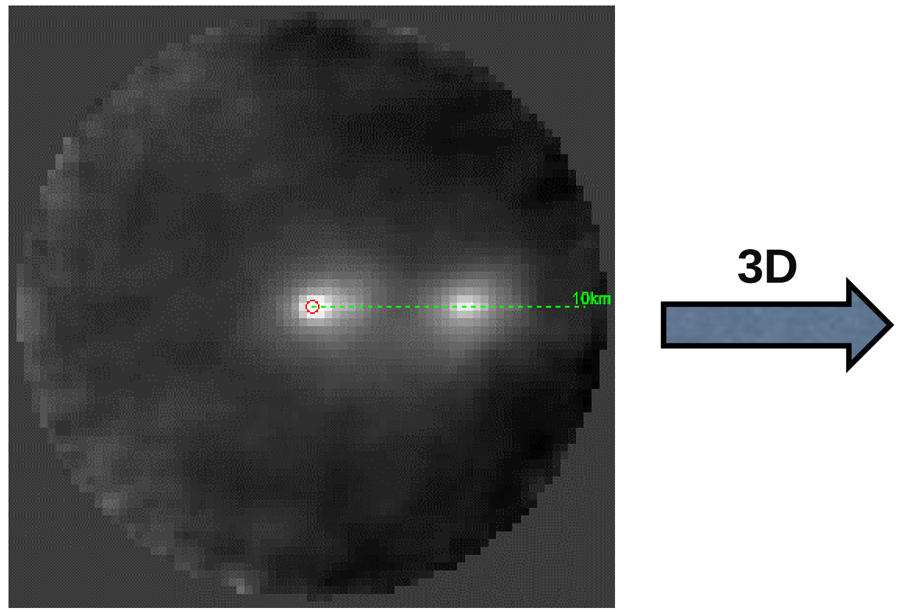
Discrete values for $\mathcal{L}_o$: {1, 2, 3, 4, 6, 8, 11, 16, 22, 32, 50, 100}

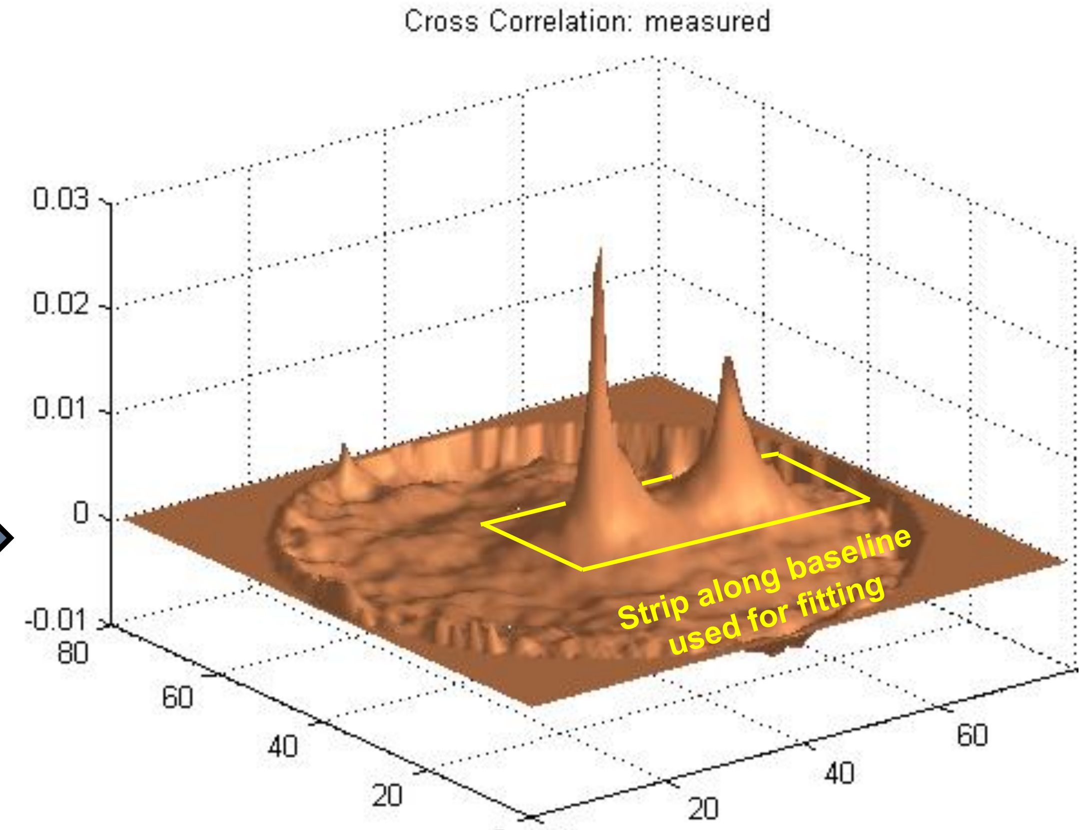
Discrete values for $\boldsymbol{h}$: $\{1{:}N\}\cdot\Delta h$, N is chosen ≈ 80% of maximum number of bins

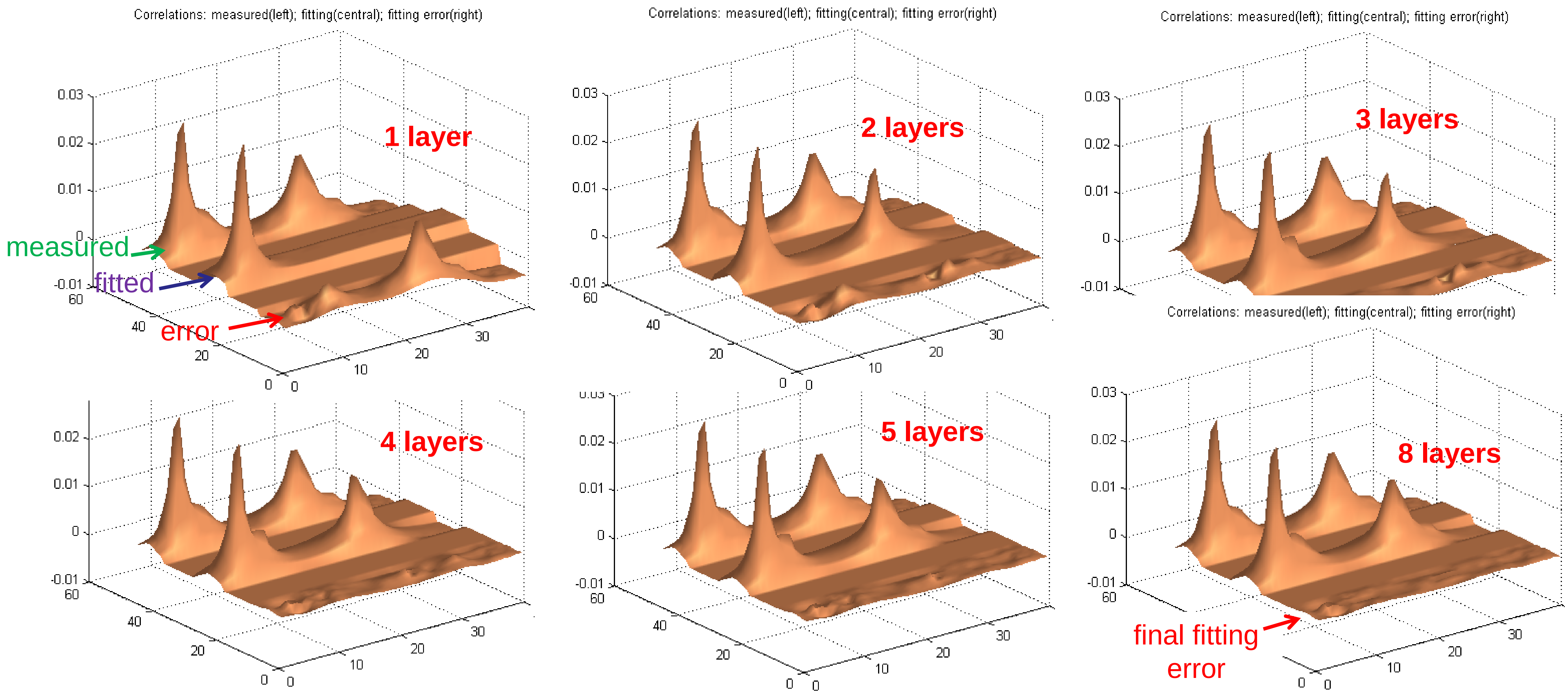


The method: Fitting sequence



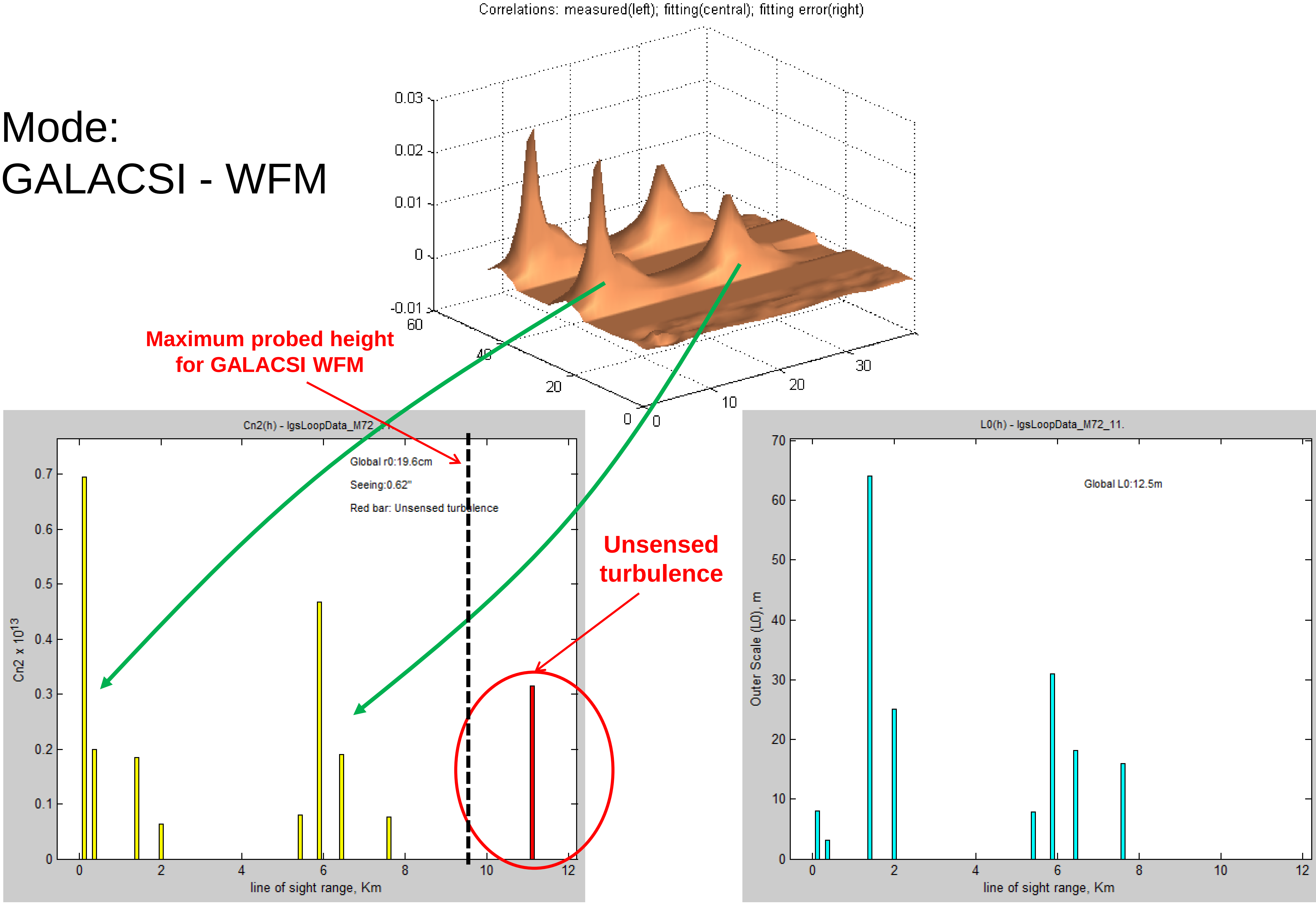




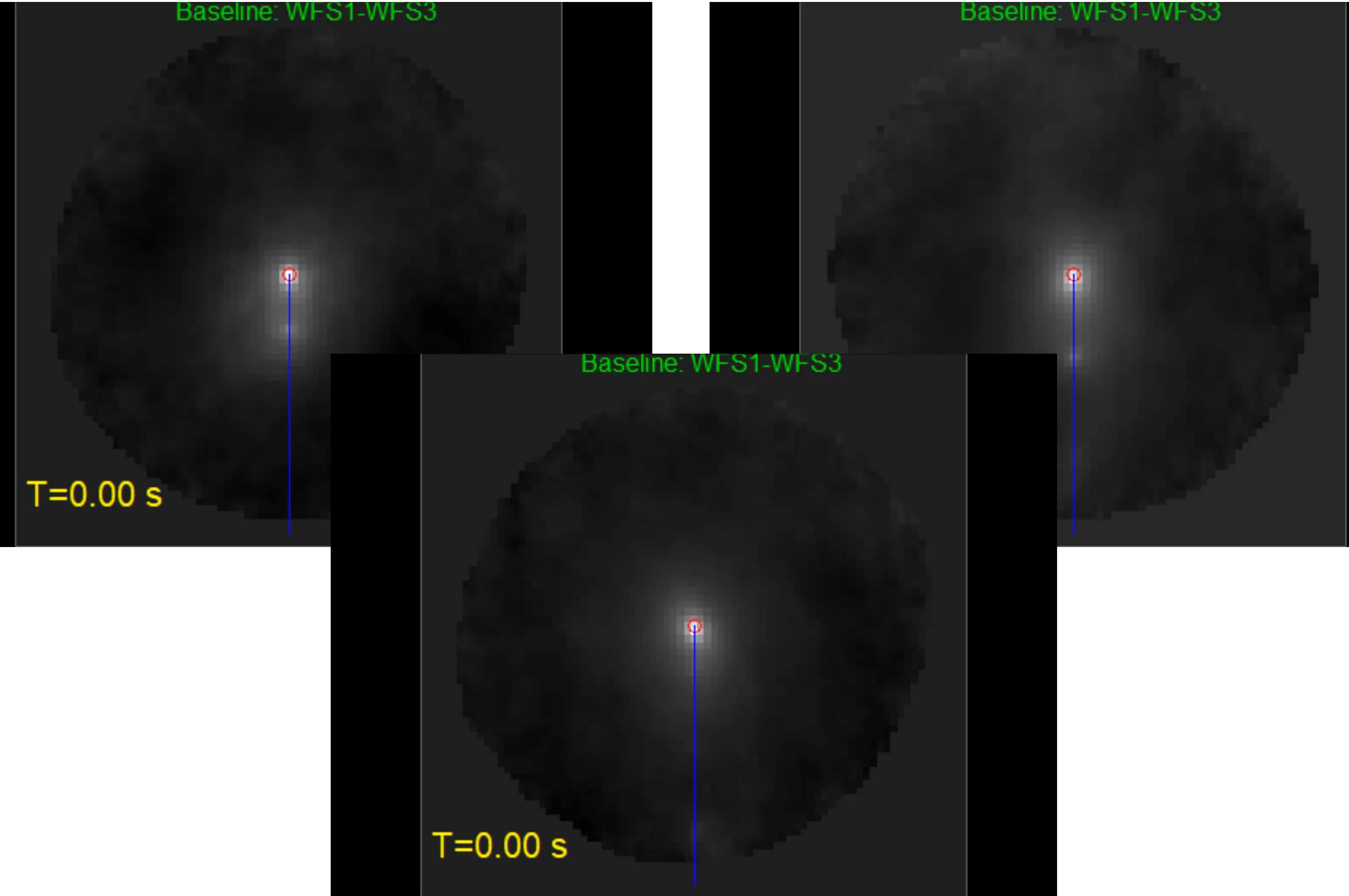


The method: Fitting sequence

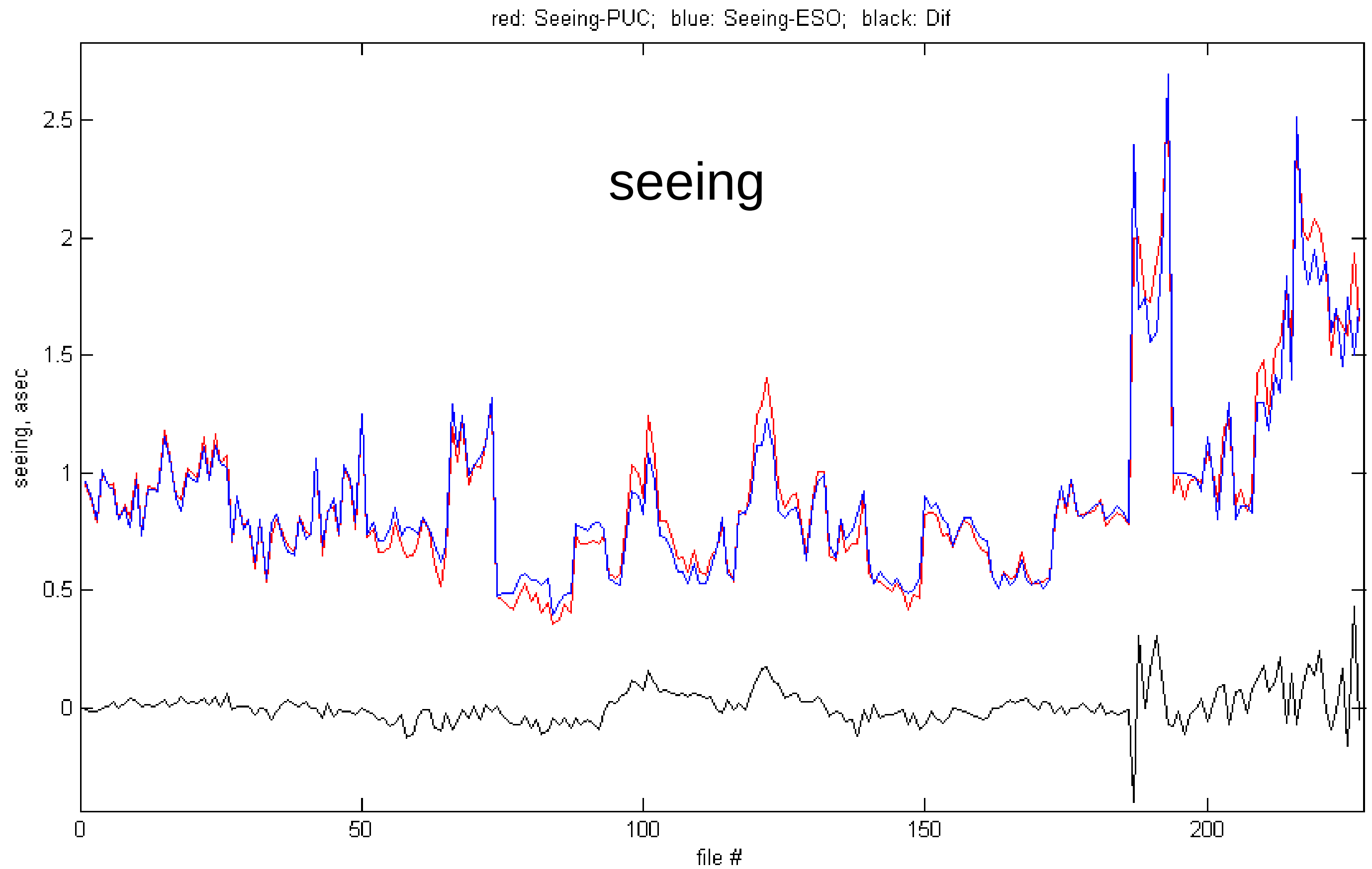
Mode:
GALACSI - WFM

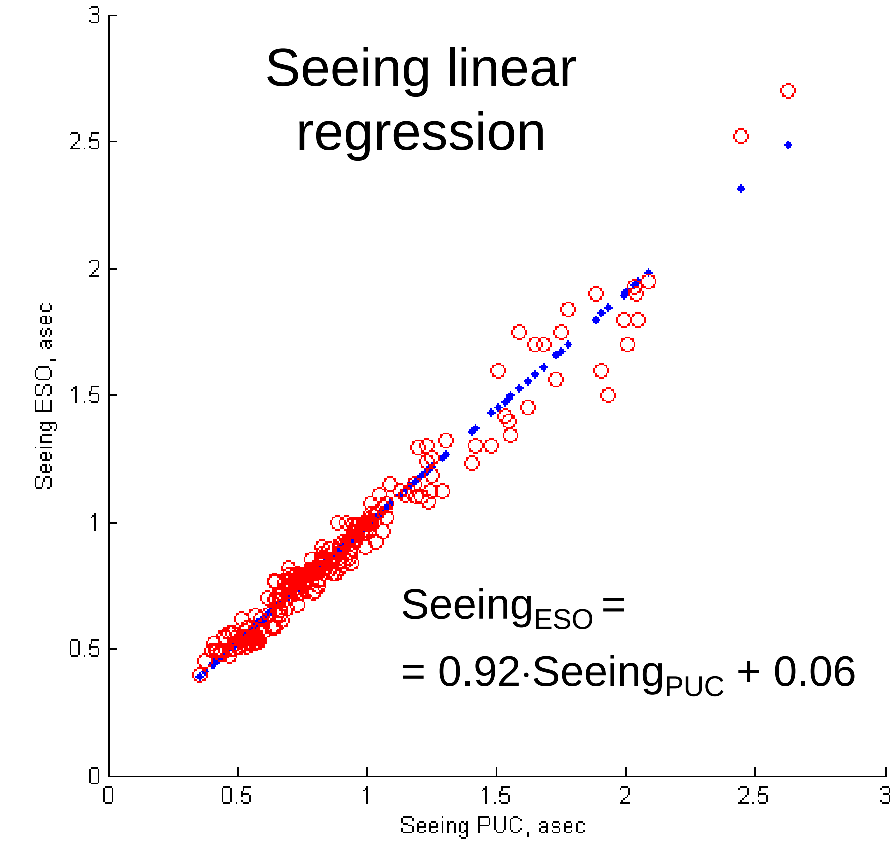


The method: Temporal Cross-Correlation (wind speed)

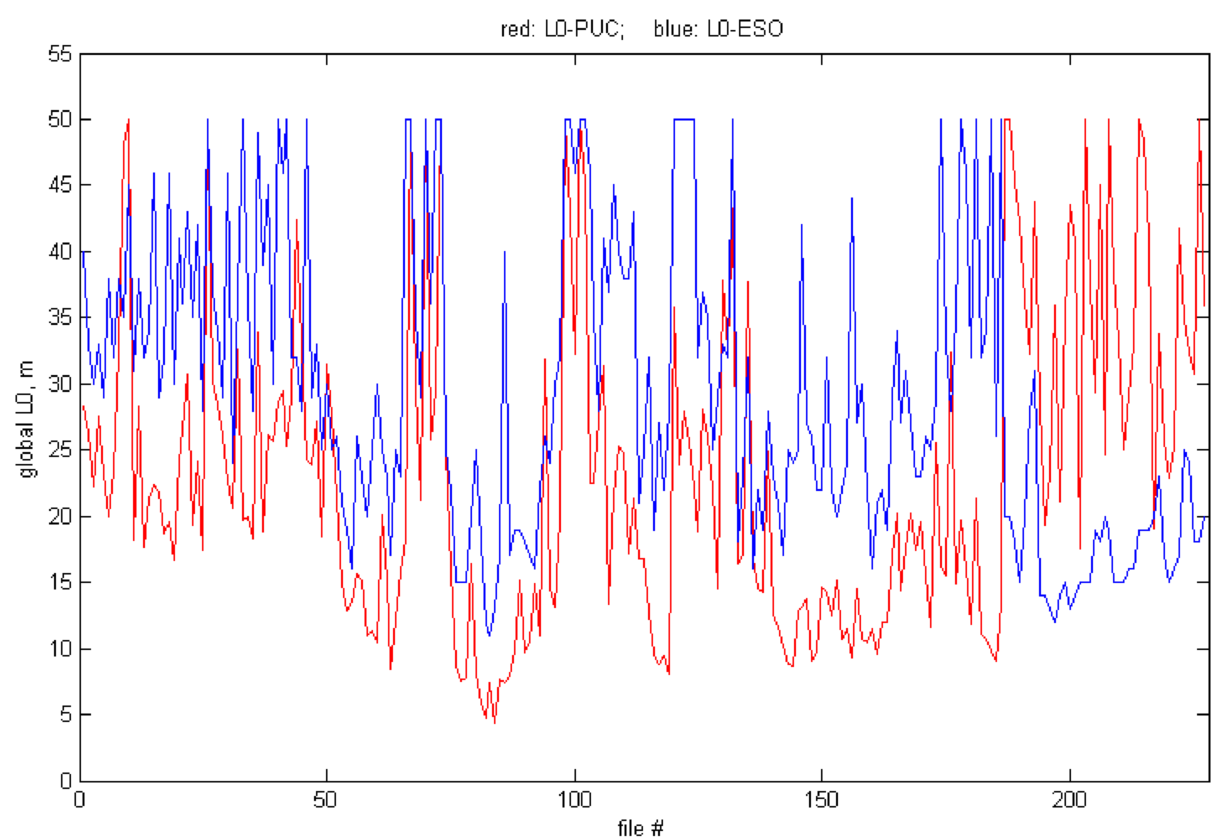


Comparison against an independent technique for seeing and global L_0

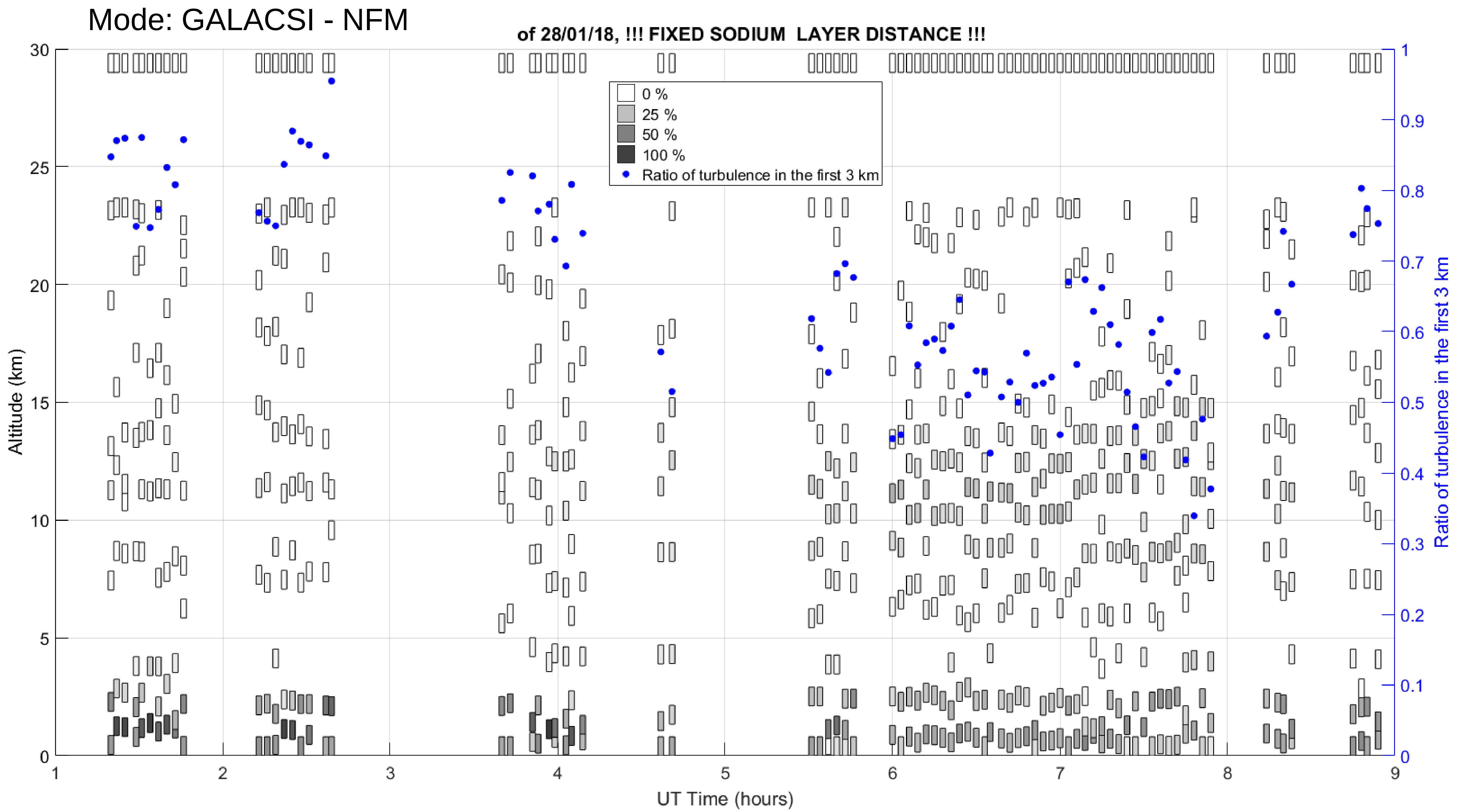




Global outer-scale



Implementation in SPARTA (AOF’s RTC)



Conclusions for turbulence profiling

- The information exists for accurate profiling (in quantity and quality)
- Profiles for C_n^2, L_0 and wind direction & magnitude are currently in use in the AOF (automatic wind profiles under development)
- Including the outer scale in the profiling methods is a must
- In the ELT, the outer scale estimation will be essential
- Reliable estimation of larger outer scales is limited to 3 or 4 times the diameter of the telescope (30m for the VLT; 150m for the ELT)
- Processing times compatible with system operation ($t < 2$ mins @ 8 layers)
- A comprehensive comparison with simultaneous with Durham's Stereo-SCIDAR data is coming soon