CANARY

Tomography workshop

Edinburgh, 25-26 march 2014

CANARY

- CANARY is a technical demonstrator for MOAO
- Installed on the William Herschel Telescope (La Palma, Canaries)
- Born in 2007 as a « fast track project » for the need of the phase-A of EAGLE, a MOS proposal on the EELT
- Works on quadruplets (= 3+1) of stars
  - 3 off-axis stars for tomography
  - 1 central star for making an image and diagnostic purposes
  - 4 lasers guide stars
- First success in Sept. 2010 : MOAO demonstrated on-sky
- Recent sucessful attempts for astrophysics (merging galaxy cores)

CANARY phases

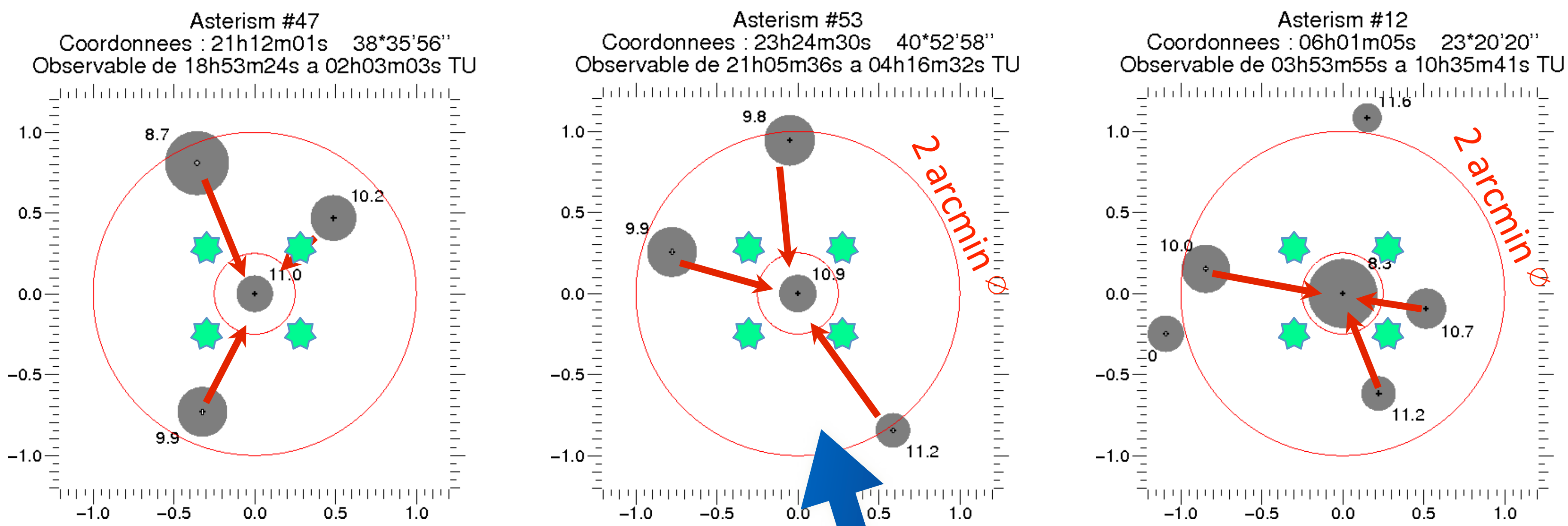
- 2010 – **PHASE A**
  - 3 NGS in 2.5 arcmin diameter
  - tomography + open loop

- 2012 – **PHASE B1**
  - PHASE A config +
  - 1 Rayleigh LGS on-axis in open-loop

- 2013 – **PHASE B2**
  - PHASE A +
  - 4 LGS Rayleigh on a square, 23’’ off-axis, at 21 km altitude

- 2014 – **PHASE C1** : LTAO
- 2015 – **PHASE C2** : 2-stage MOAO

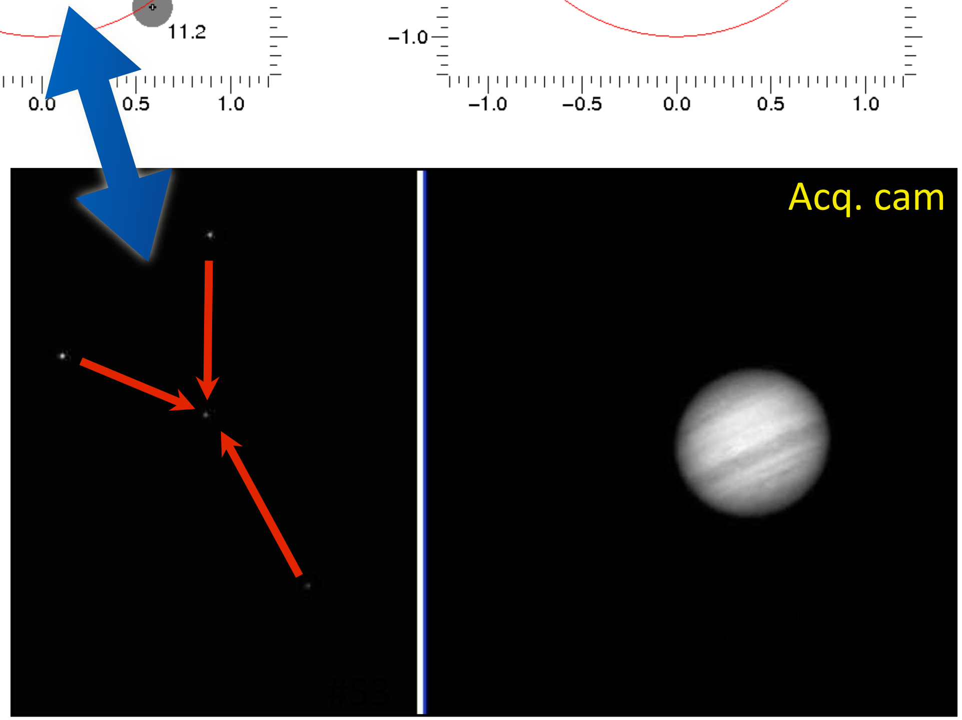
Observed asterisms



8.3 < magnitudes R < 11.2

25'' < Dist. from center < 65''

2.5' field of view



CANARY TOMOGRAPHY

CANARY MOAO control algorithm

- Learn and Apply : optimal static approach (MMSE)
  - get data from turbulence
  - learn, from the wavefront sensors data, what are the best parameters for the tomographic reconstructor
  - introduce turbulence knowledge + a priori (kolmo, deviations)
  - introduce calibrated system command matrix (truth → DM)
  - get the final static reconstructor
  - Vidal et al., « A tomography approach for MOAO », JOSA A, **27**, 253
- Temporal optimization : optimal temporal filtering
  - optimize the gain of an integrating filter versus
    - turbulence speed
    - noise propagated after tomographic reconstruction

MMSE tomographic reconstructor

- MMSE = minimum mean-square error
  - between $R \,.\, \overrightarrow{measur}$
  - and $\overrightarrow{phase}$
  - on average

- Minimizes $\langle\, |\overrightarrow{phase} - R \,.\, \overrightarrow{measur}|^2 \,\rangle$

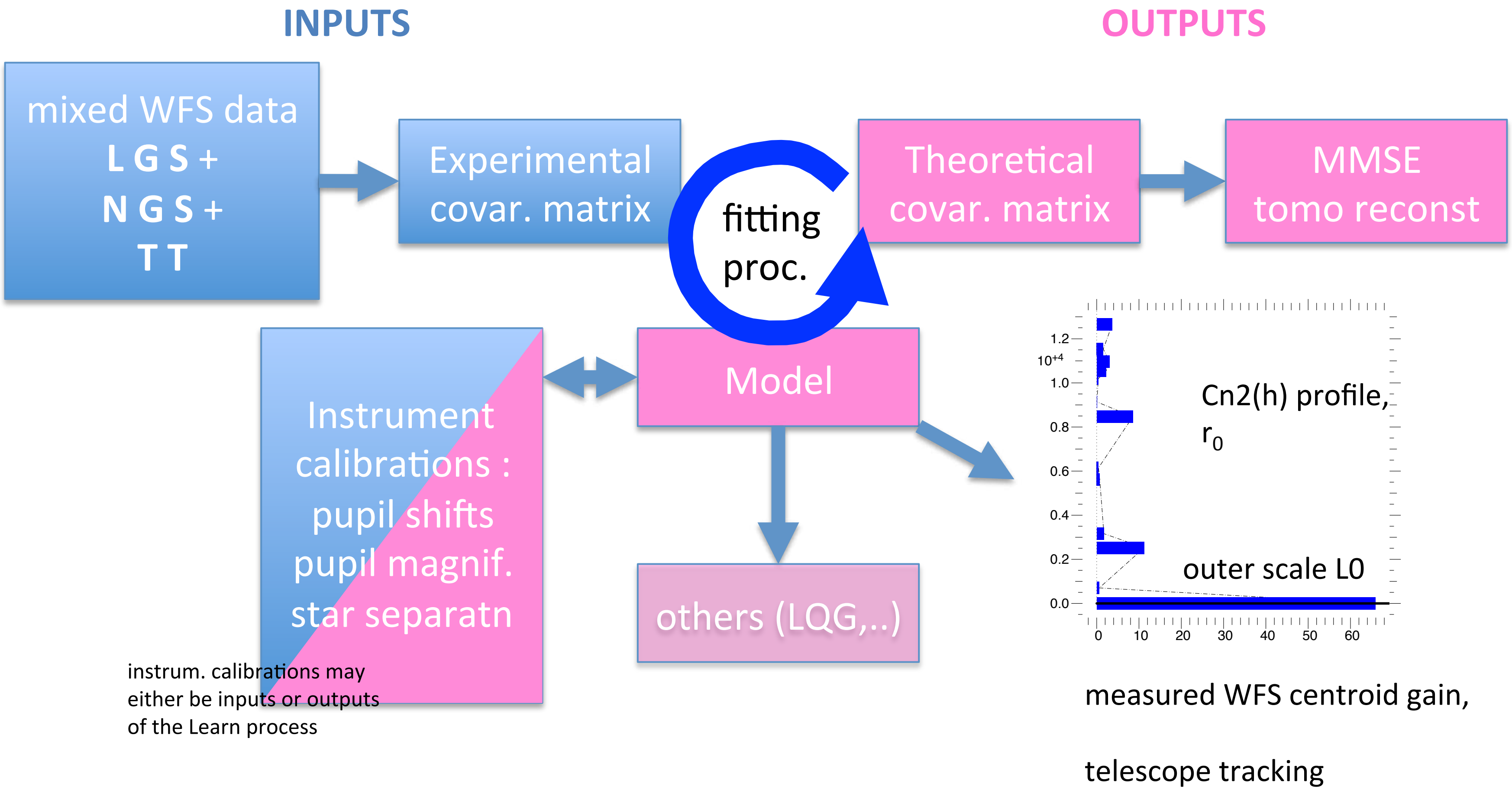
- Expression is $R = \langle\, \overrightarrow{phase} \,.\, \overrightarrow{measur}^t \,\rangle \,.\, \langle\, \overrightarrow{measur} \,.\, \overrightarrow{measur}^t \,\rangle^{-1}$

contains all information about how measurements are related to phase

contains all information about what measurements are made of
- noise
- geometry
- turbulence profile
- LGS, NGS ...

Today's method (Learn & Apply)

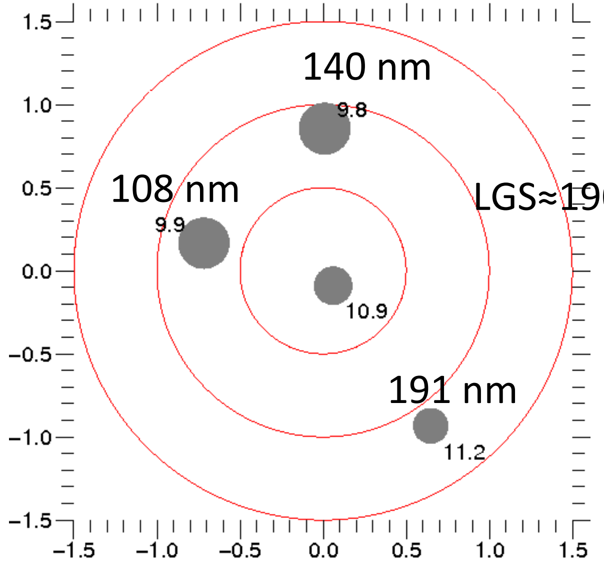
- Determination of covariance model
  - Based on the WFS data acquired by the instrument itself

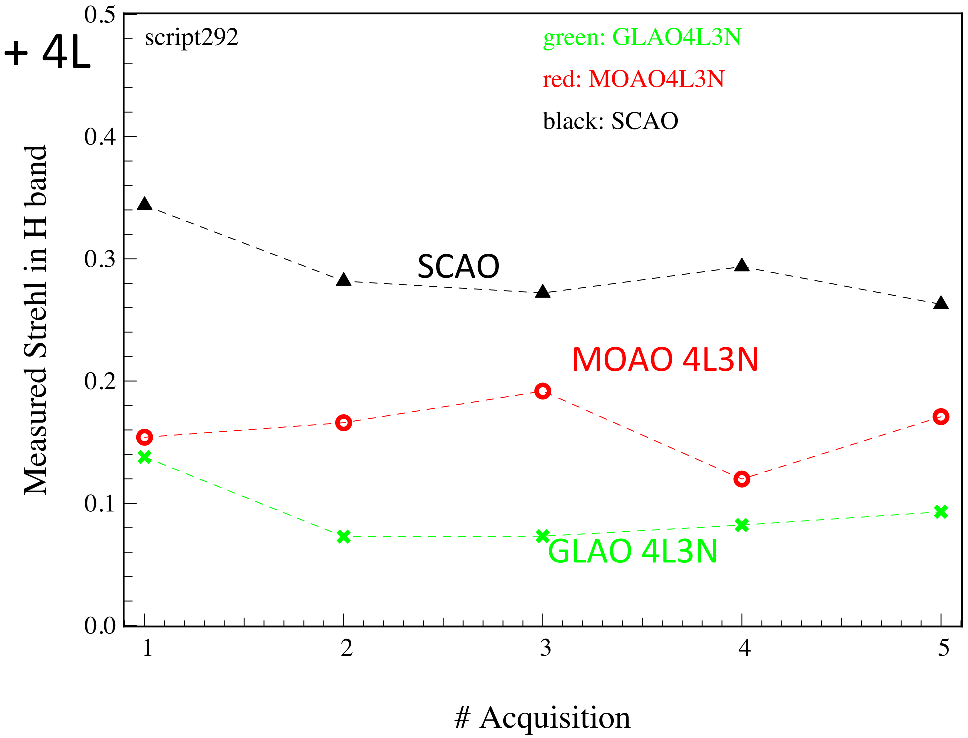


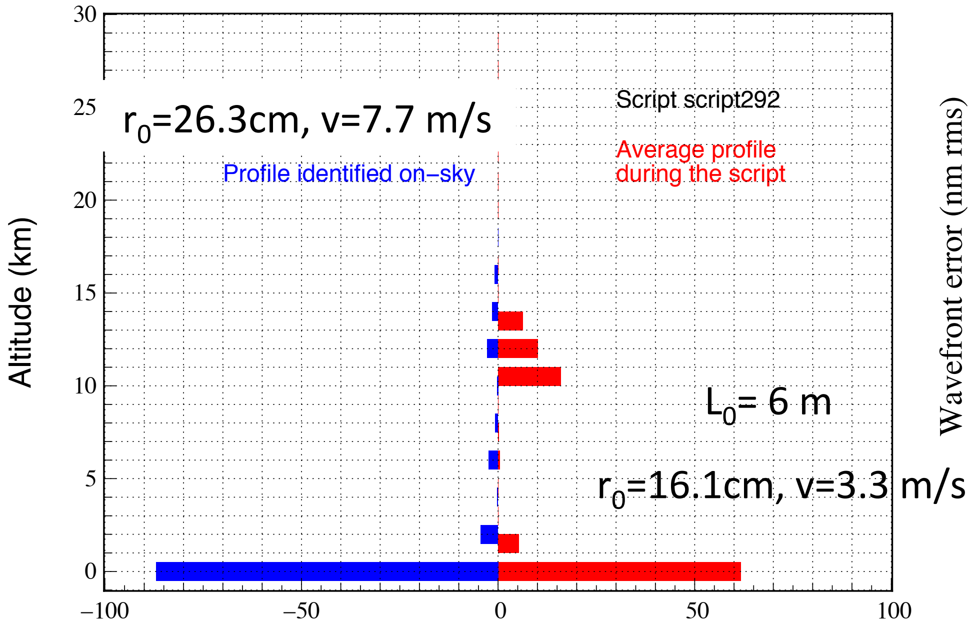
CANARY ON-SKY RESULTS

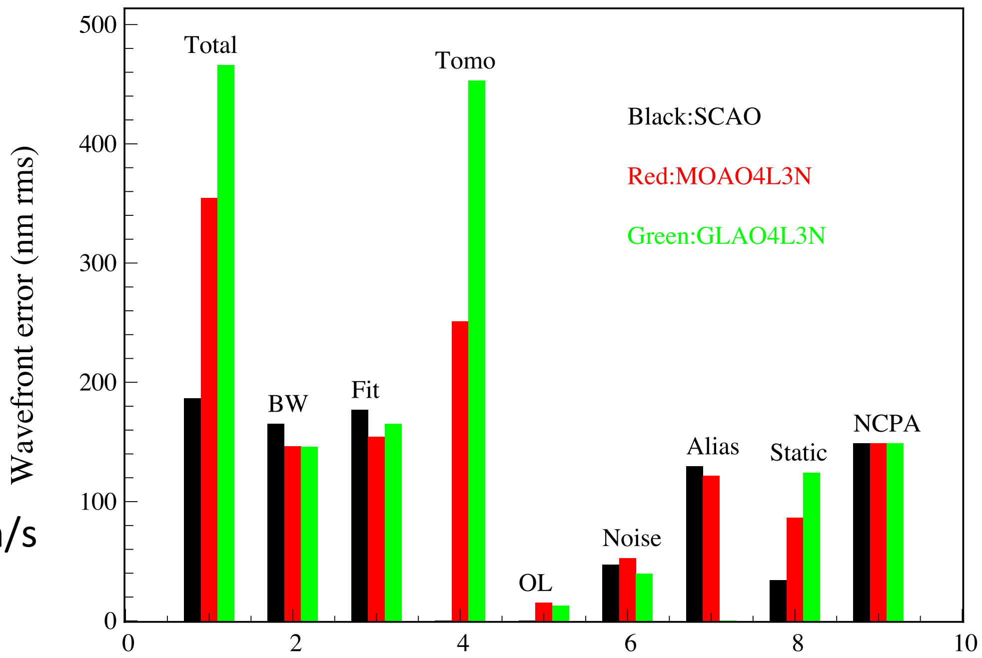
MOAO vs GLAO

- Using full info 3N + 4L
- ast. A53, 17/9/13 2h30, script 292



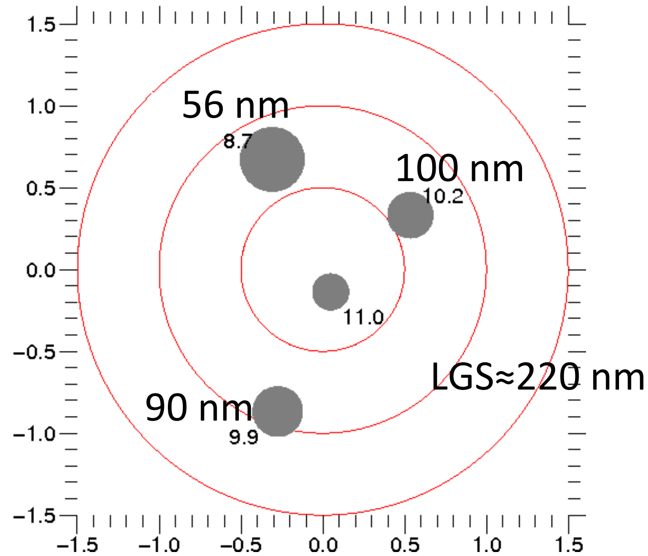


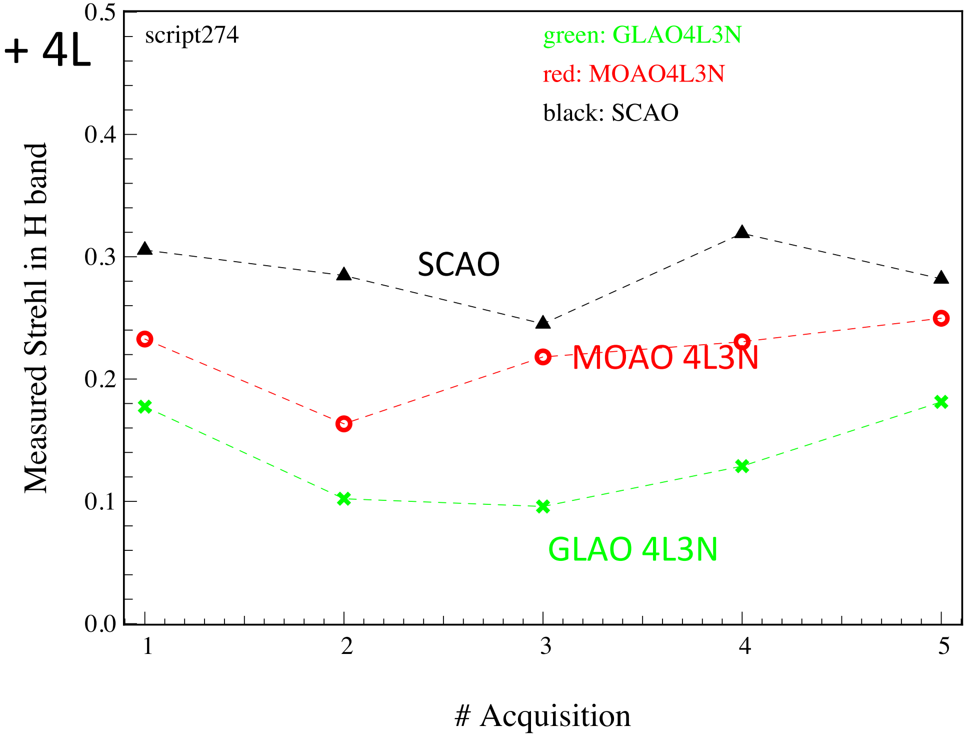


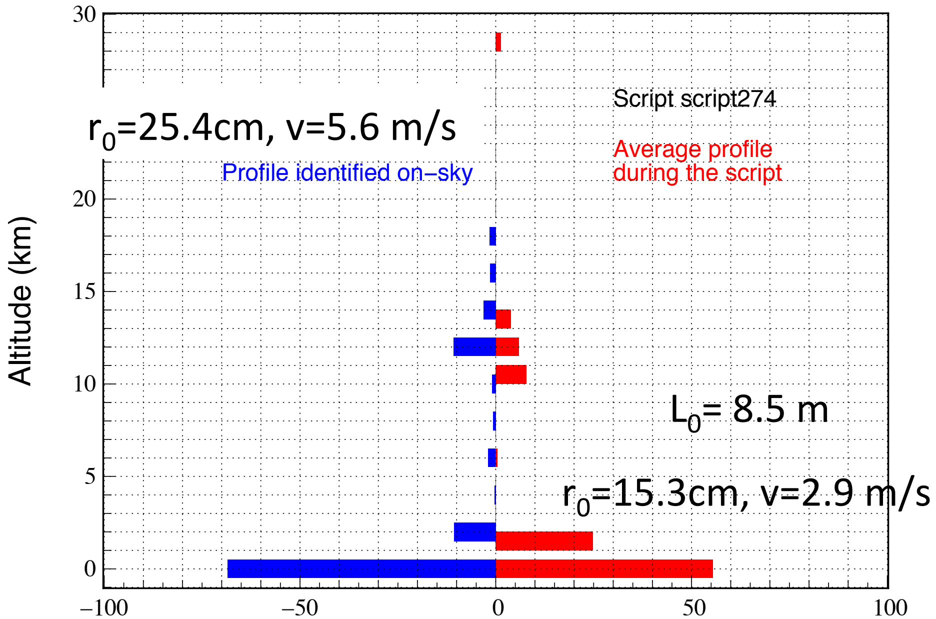


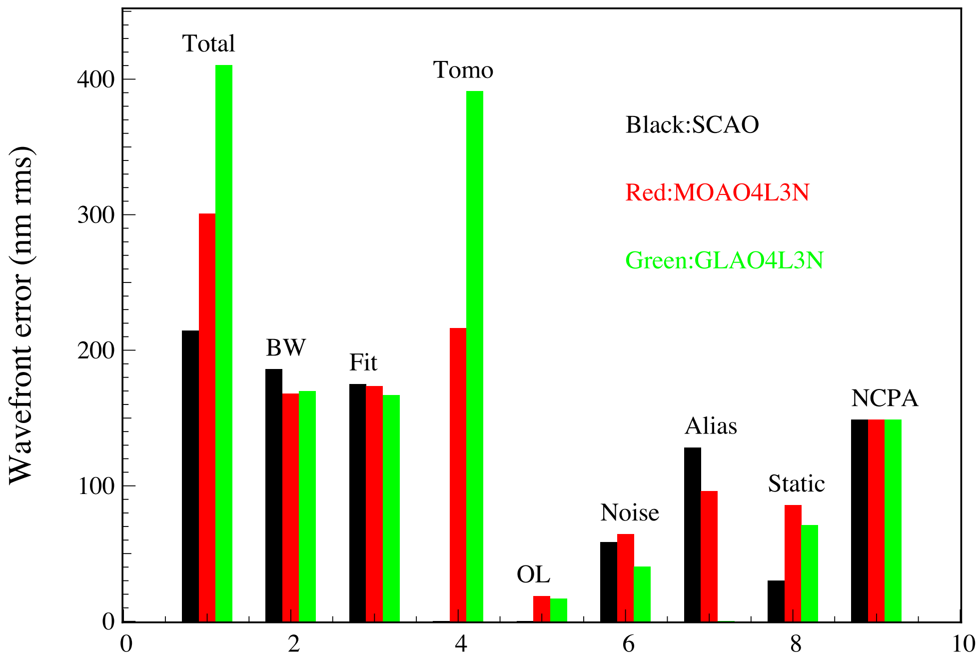
MOAO vs GLAO

- Using full info 3N + 4L
- ast. A47, 17/9/13 21h56, script 274



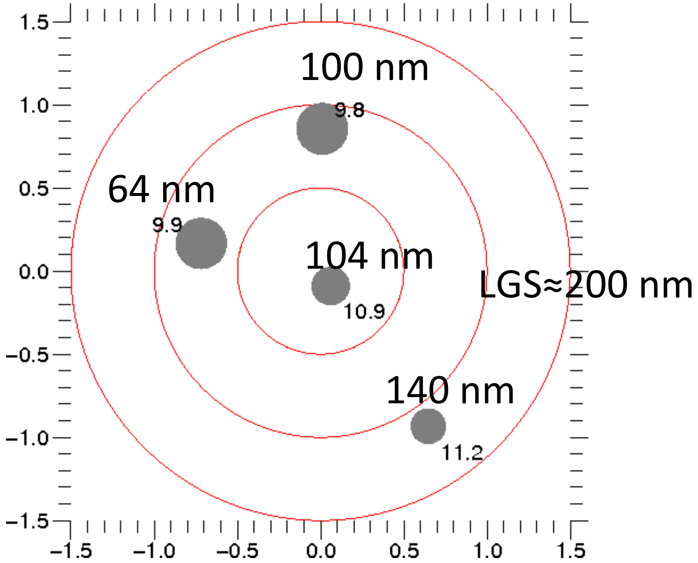


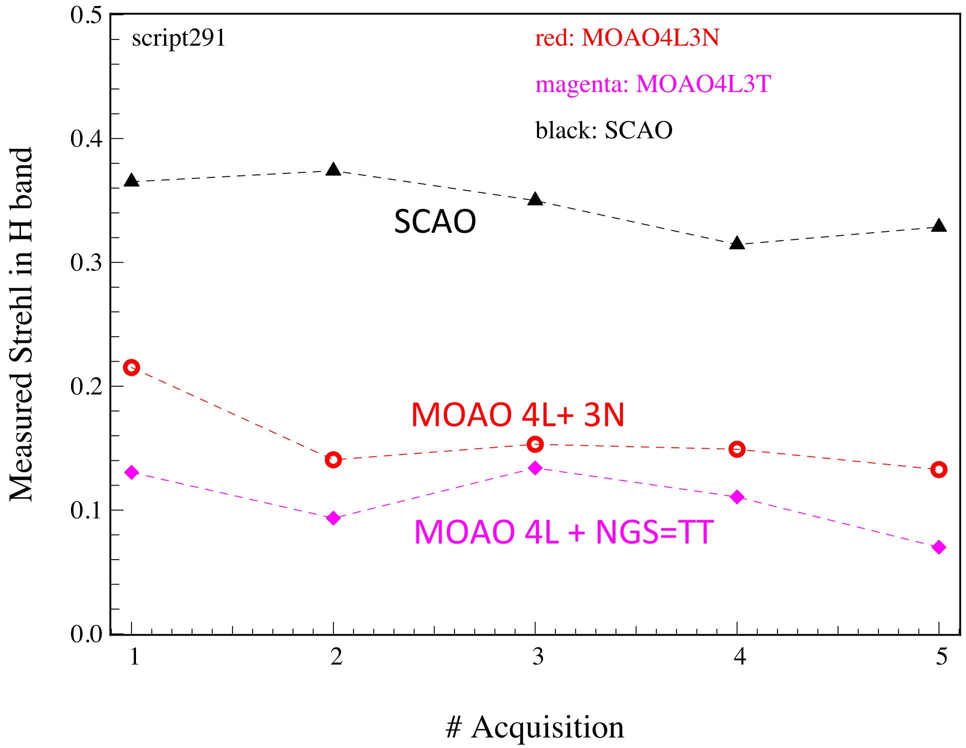


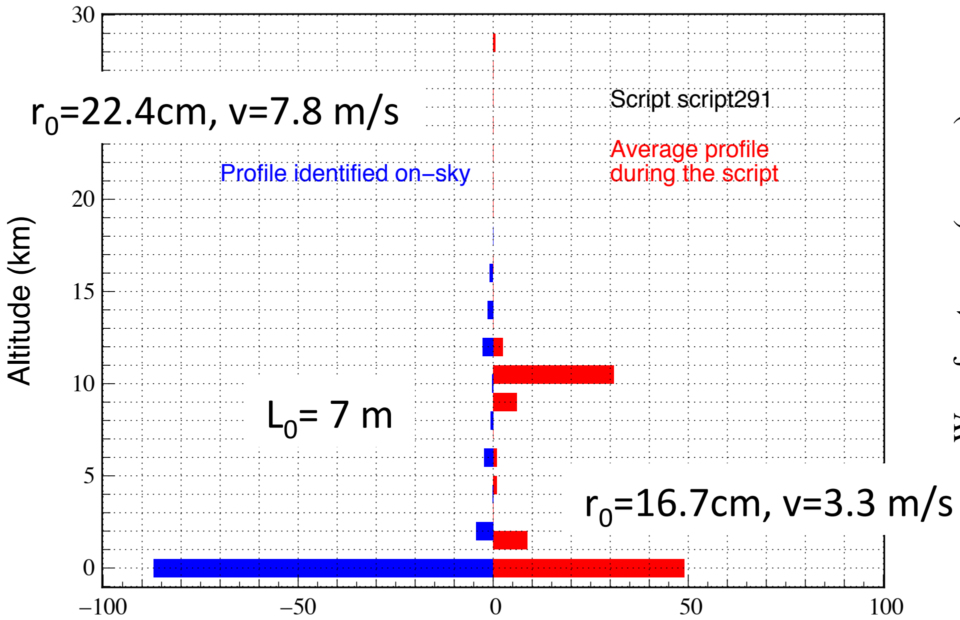


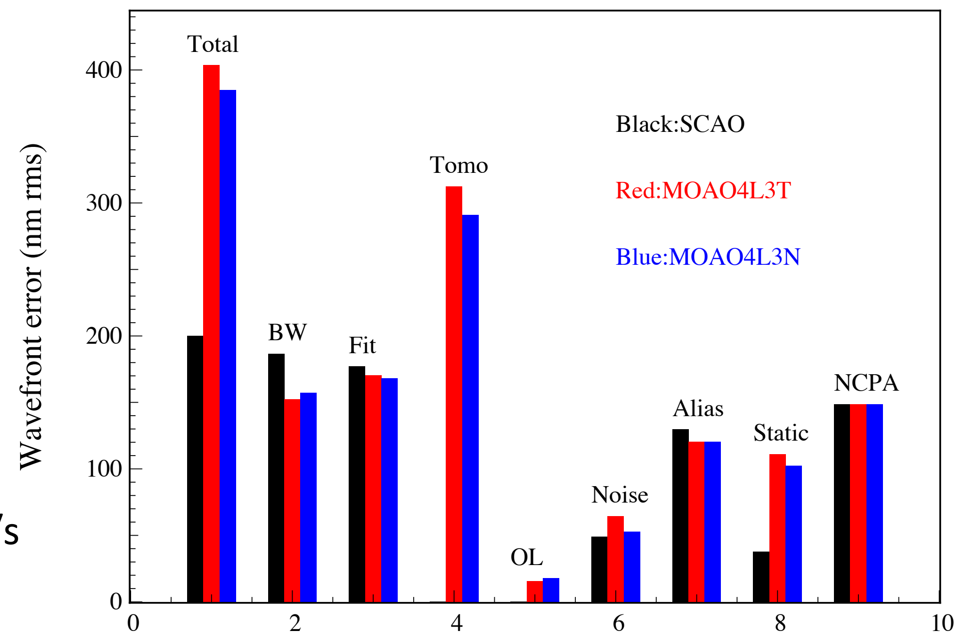
4L3T vs 4L3N

- Using full info 3N + 4L
- ast. A53, 17/9/13 2h15, script 291



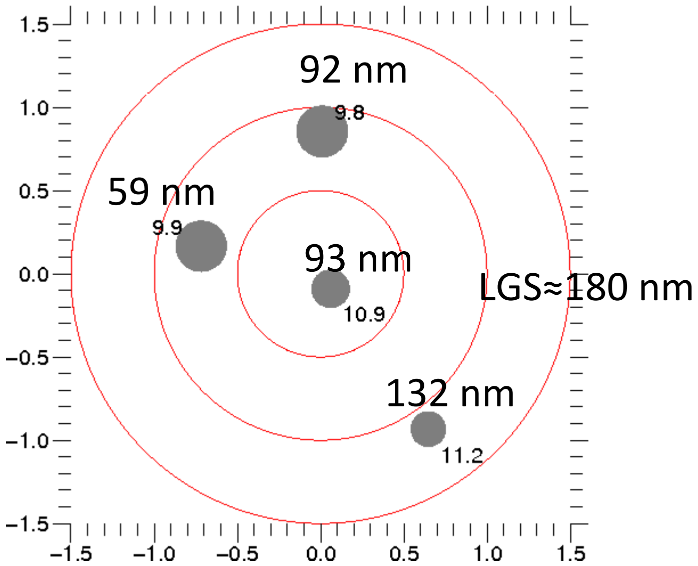


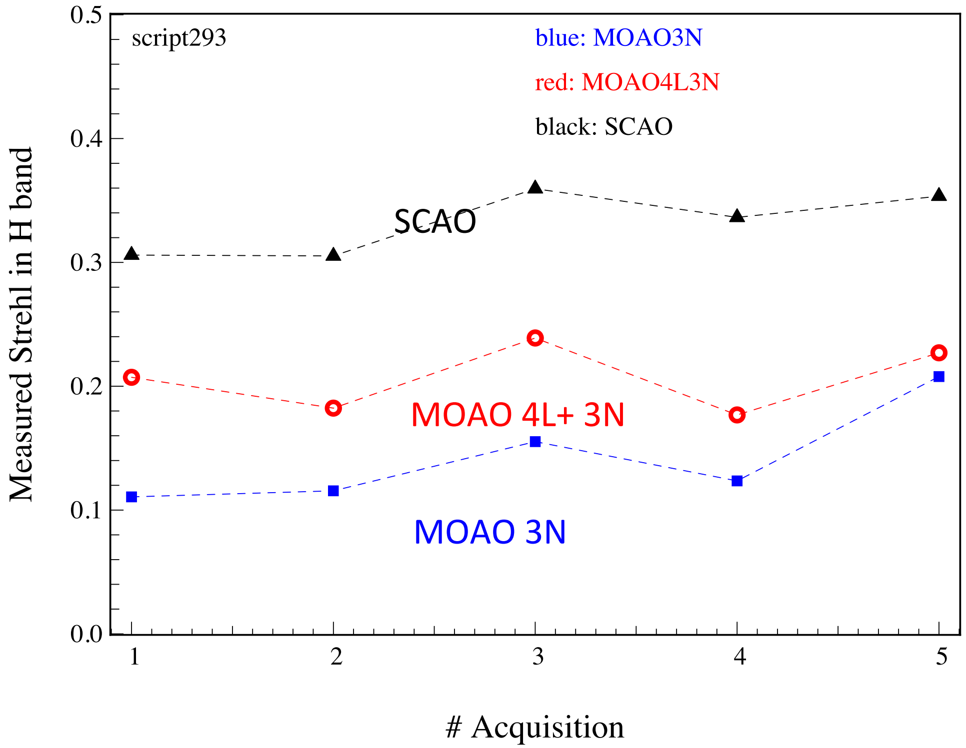


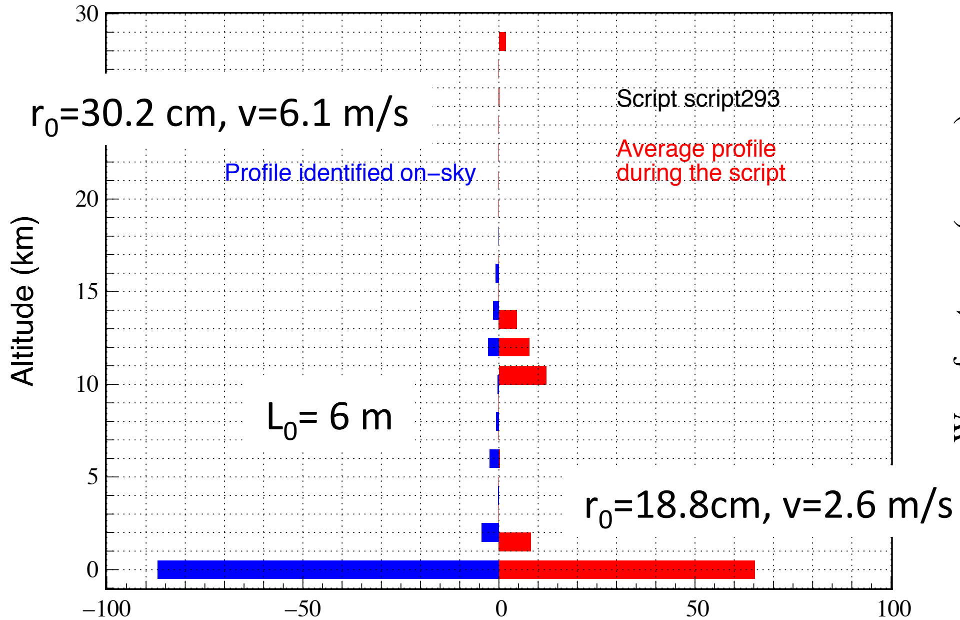


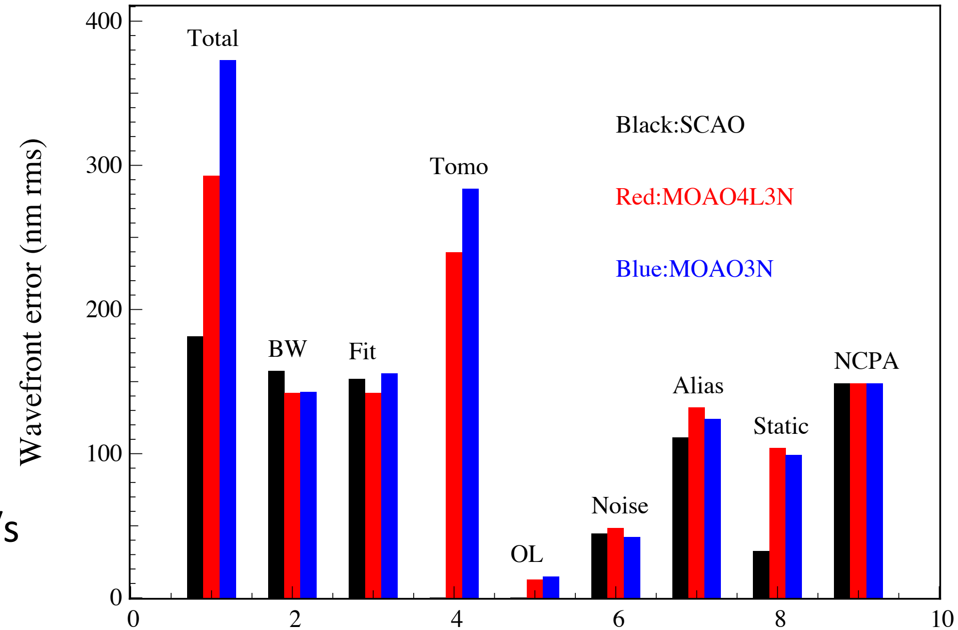
3N vs 4L3N

- Using full info 3N + 4L
- ast. A53, 17/9/13 2h39, script 293



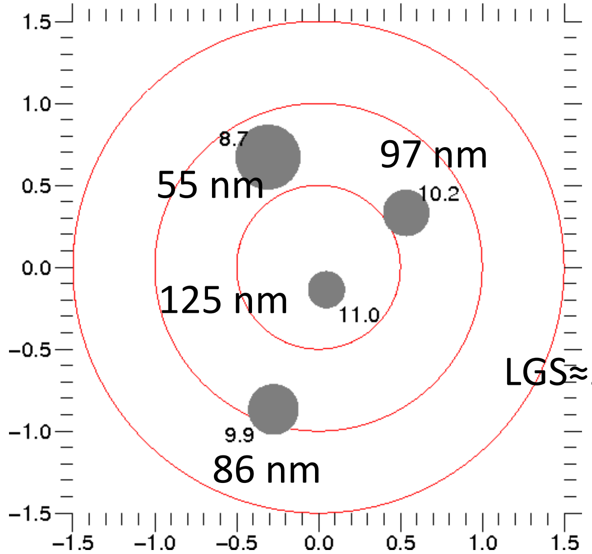


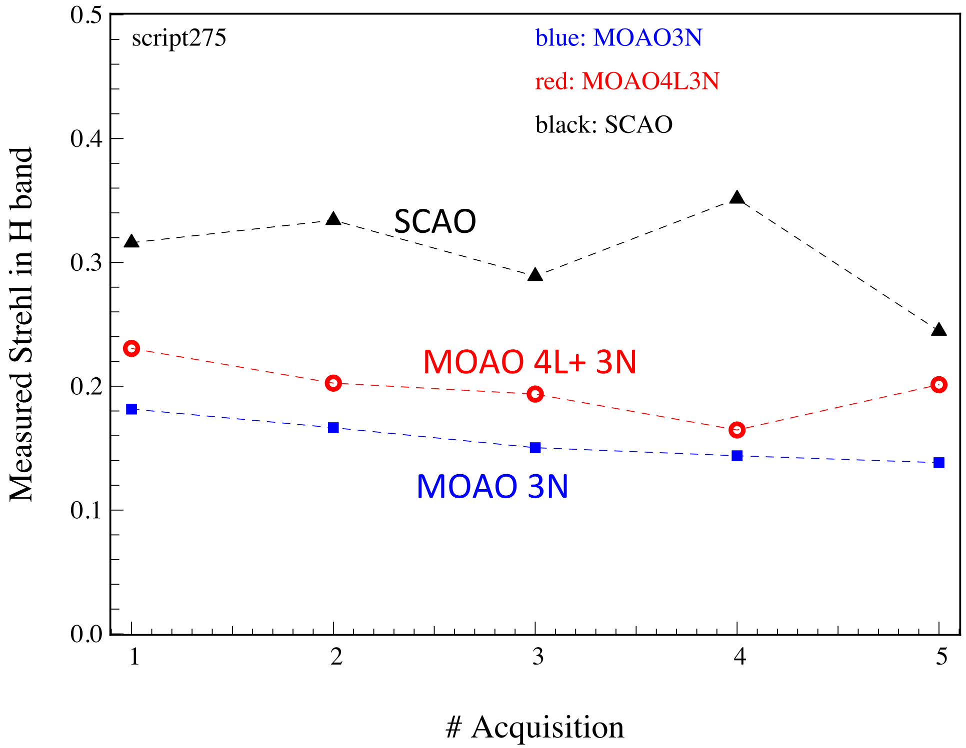


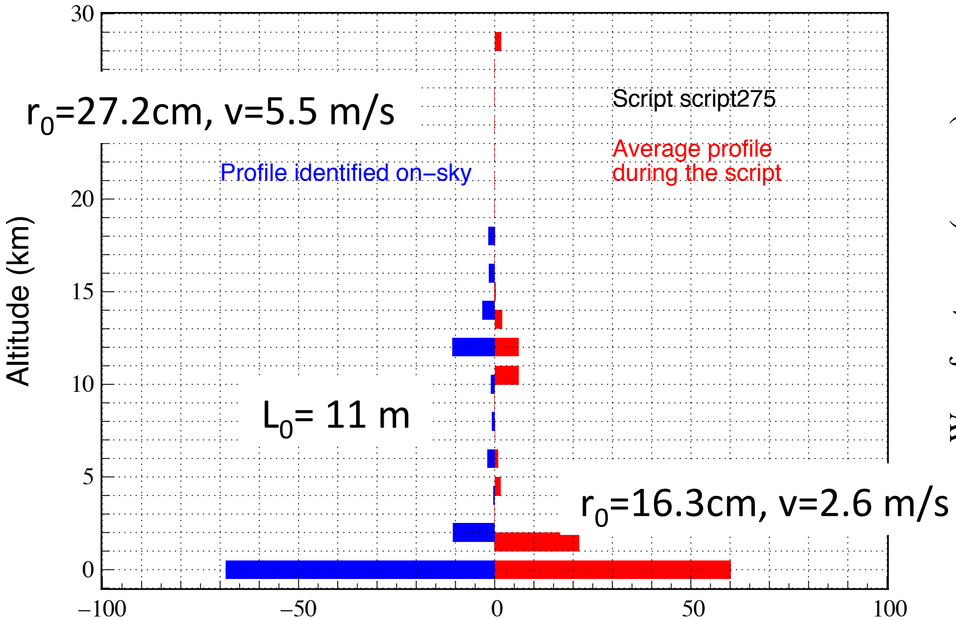


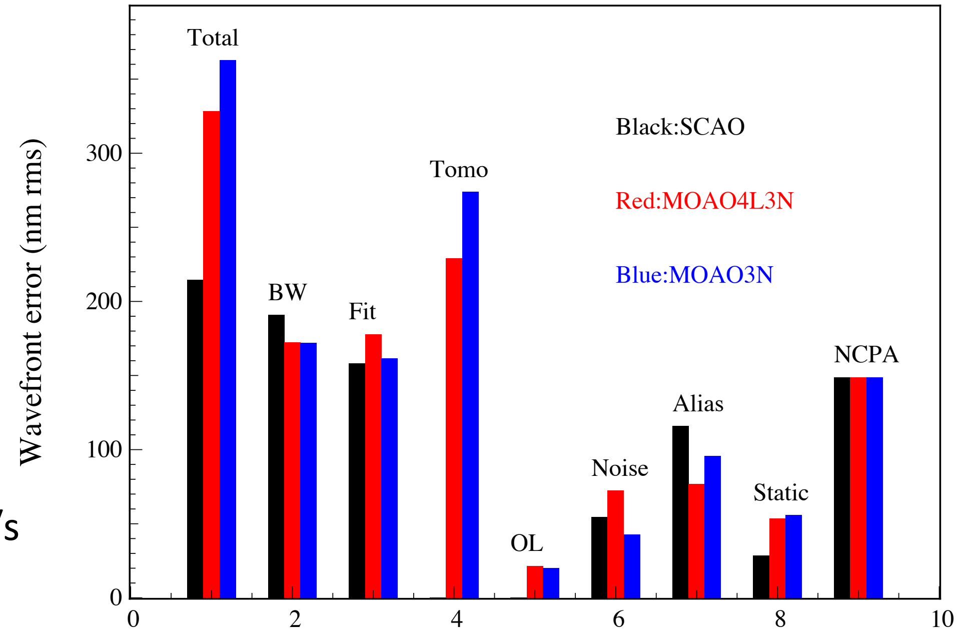
3N vs 4L3N

- Using full info 3N + 4L
- ast. A47, 17/9/13 22h03, script 275



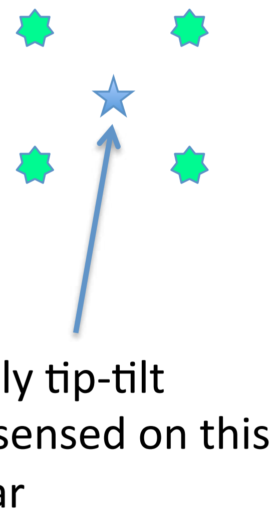


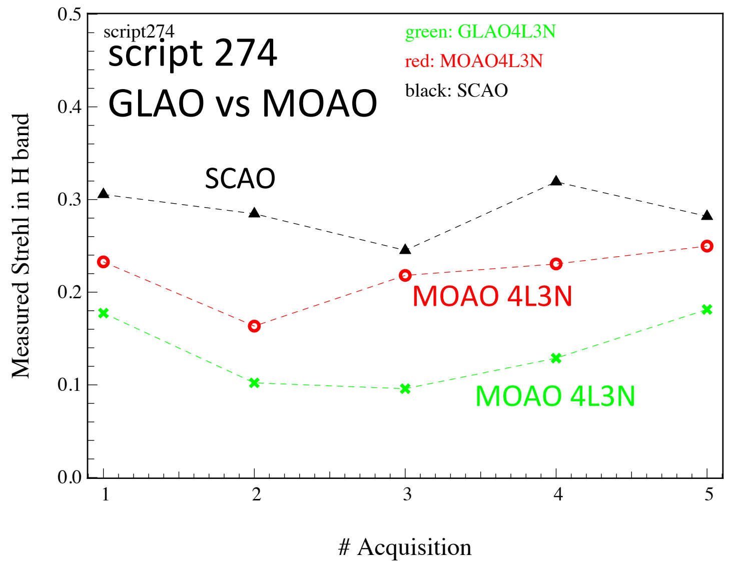


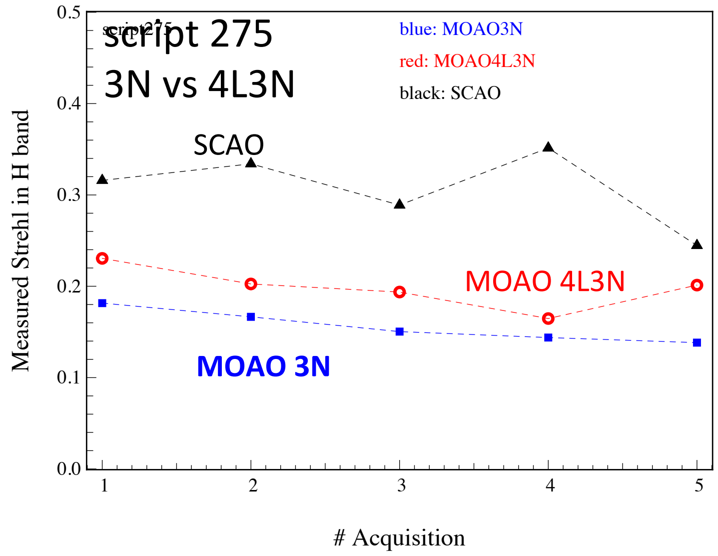


The « Pluto mode »

- Originally intended to observe Pluto (that has, actually, never been observed)
- 4 LGS in open loop + 1 TT star (=pluto) in closed loop on truth sensor
- Allows to test tomography purely on LGS
- Comparison between MOAO and GLAO



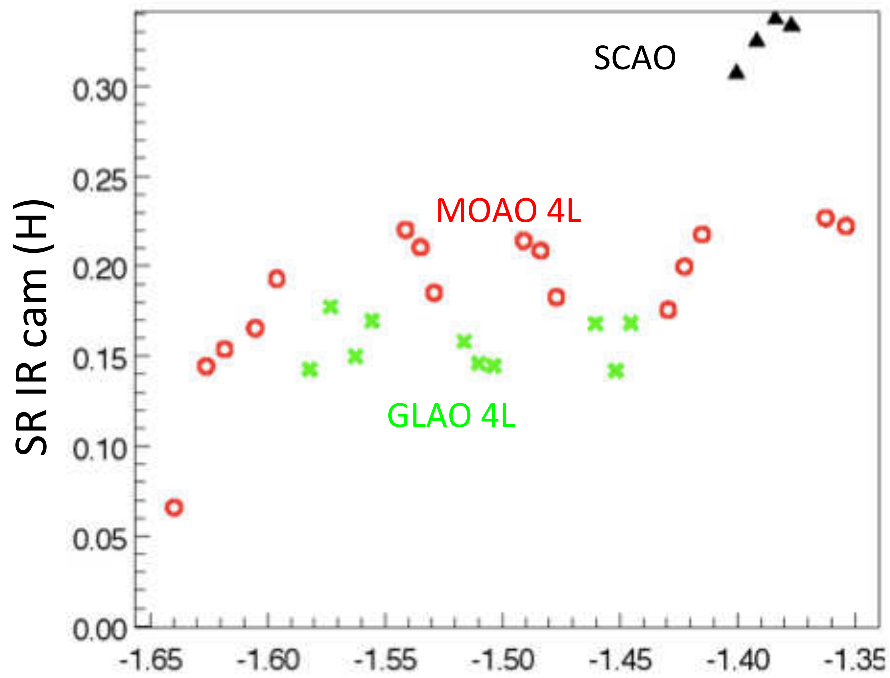




Tomography with 4L

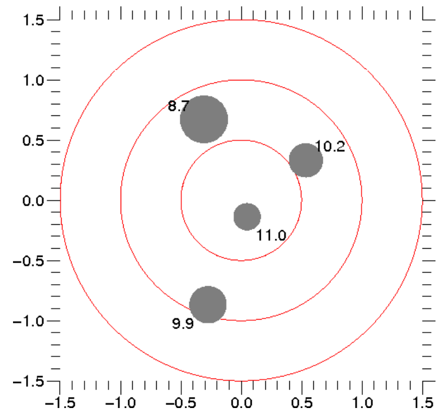
- With, and without lasers
- ast. A47, 17/9/13 22h03,
- script 274, 275 + pluto mode

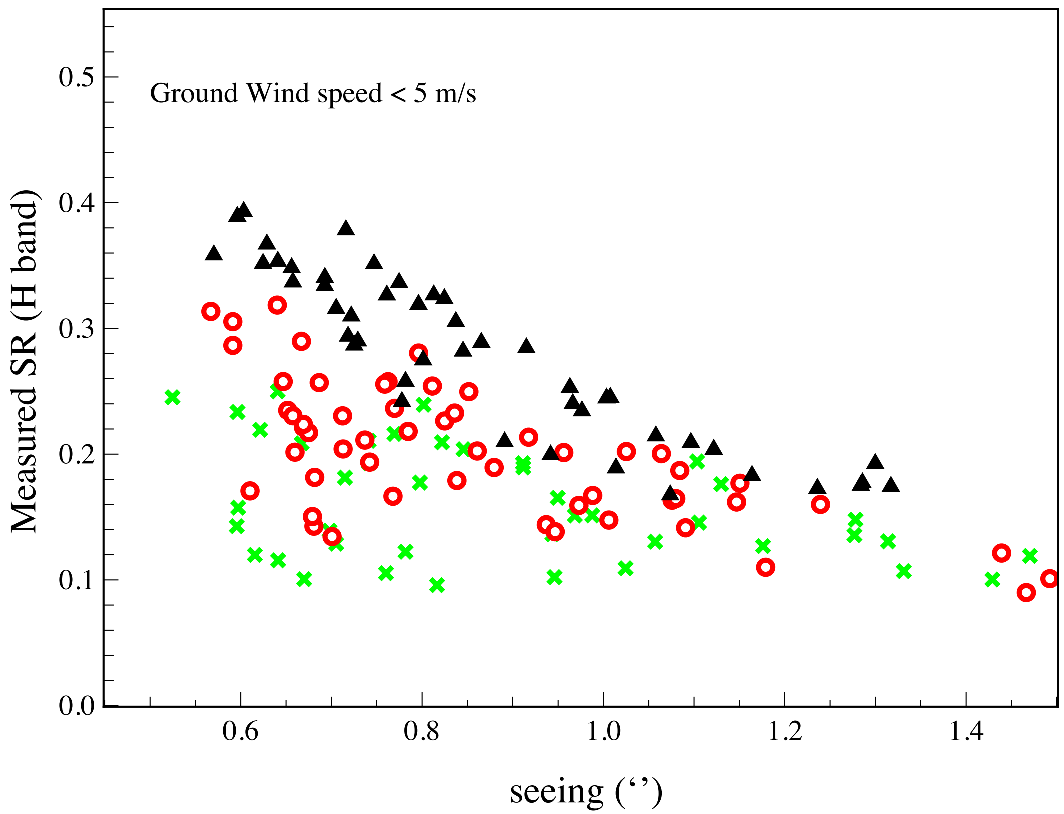
- Lasers are actually doing tomography



Overview of results on A47, Sept 2013

- MOAO performs well
- most of the time between GLAO and SCAO
- Bad seeings : ground layer dominates
  - GLAO ≈ MOAO
- Performance fluctuates quite a lot

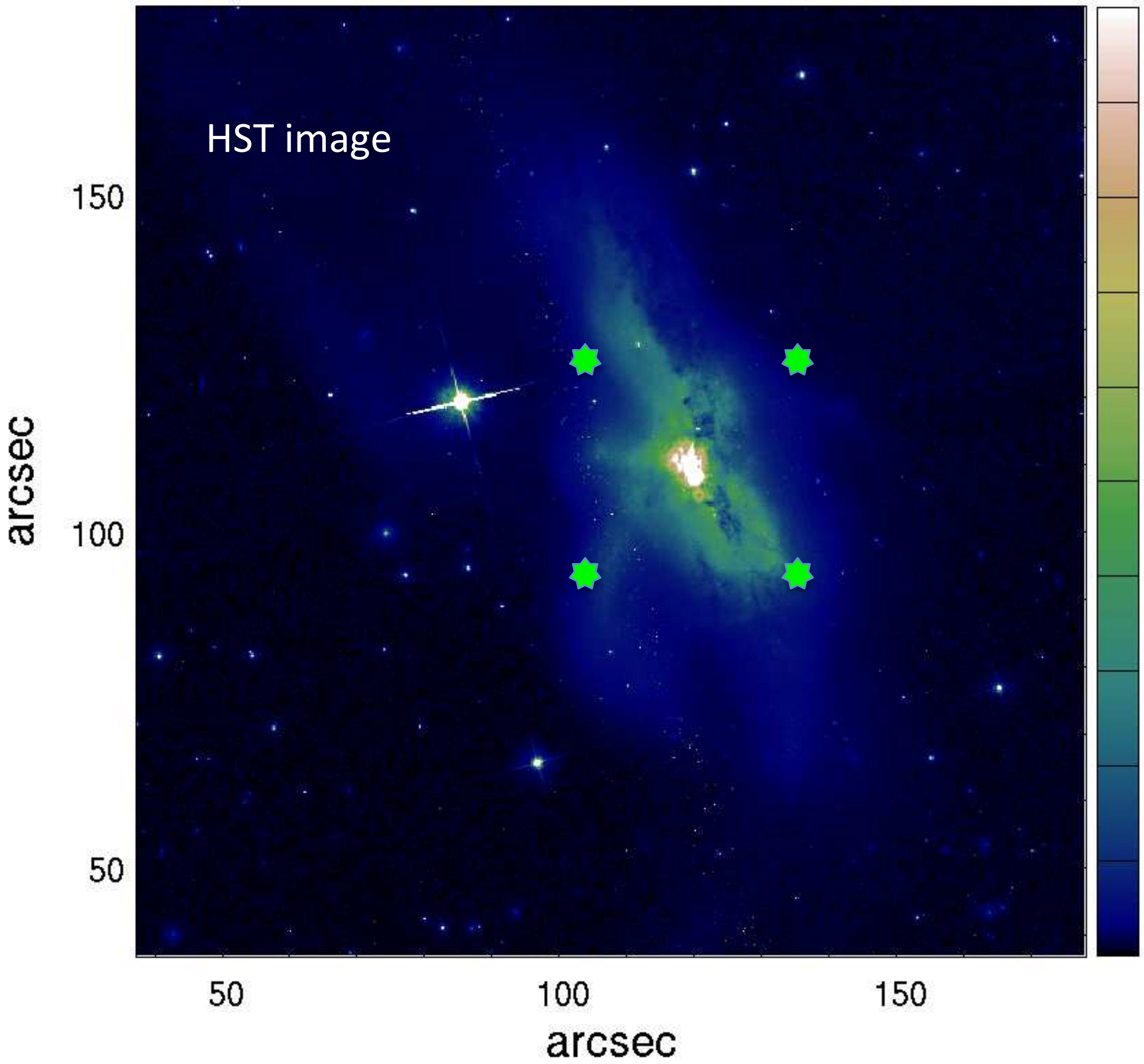


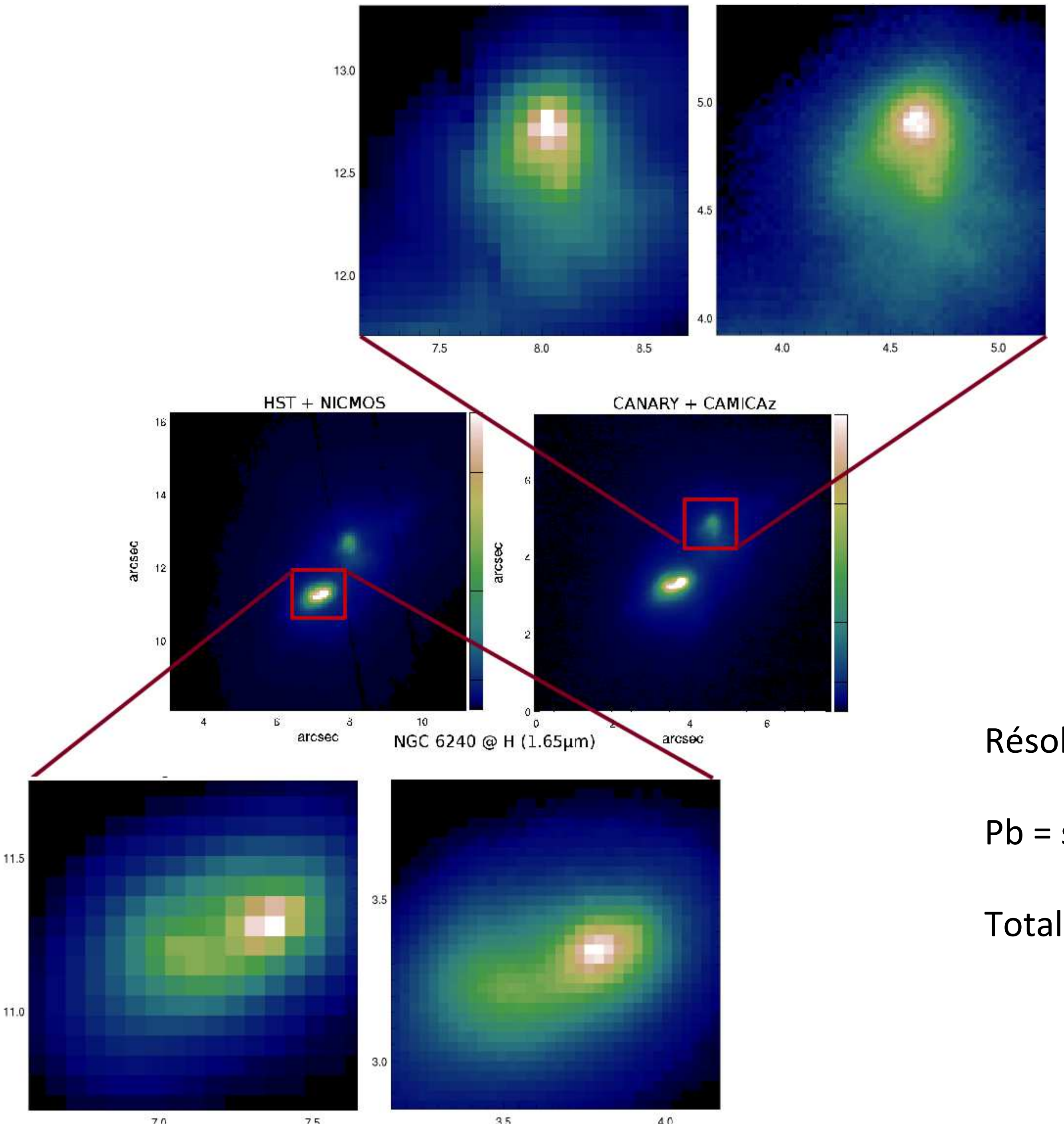


CANARY : astrophysical result

NGC 6240
Galaxies in interaction

1 guide star
38’’ off-axis
mR ≈ 13





NGC6240

Détails

Résolution ≈ 2x0.090’’

Pb = static aberrations

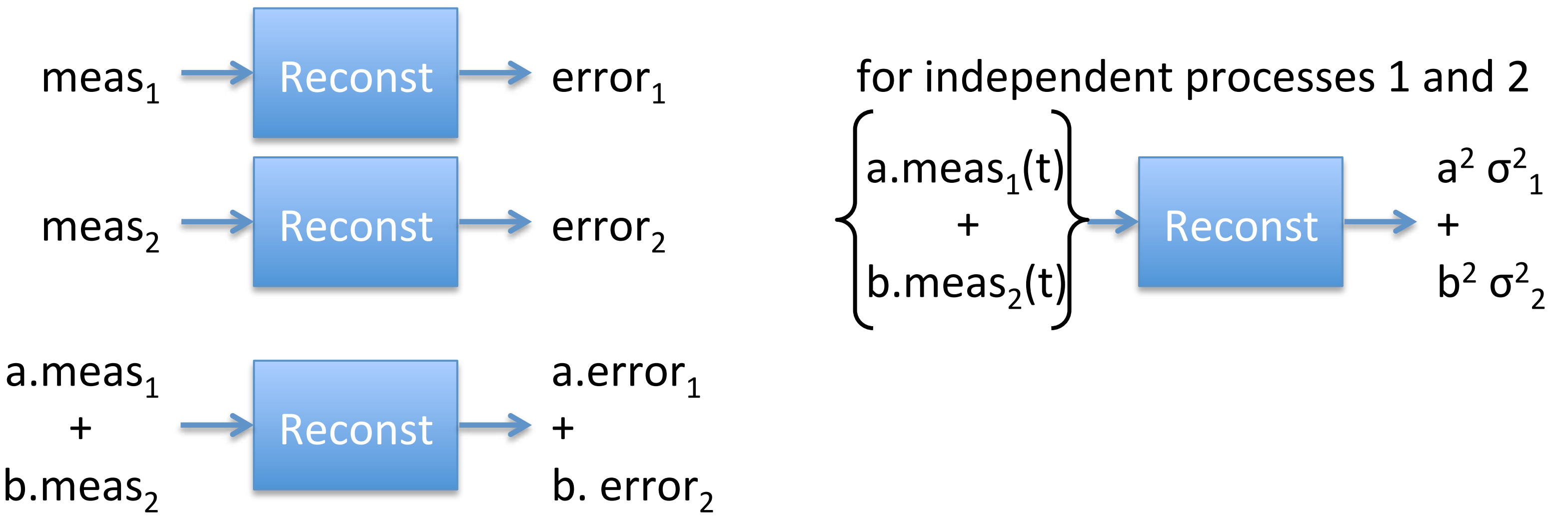
Total observation time ≈ 2.5 h

TOMOGRAPHIC ERROR

Vertical error distribution

- Common wrong ideas :
  - MMSE tomographic reconstructor designed for 2 layers compensation will perfectly compensate the 2 layers
  - MMSE tomographic reconstructor will perfectly compensate the ground layer anyway (because it's easy ?)
  - If all WFS see the same pattern → ground layer only → perfect compensation

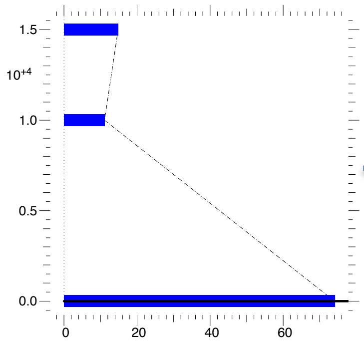
- Error superimposition principle



Vertical error distribution

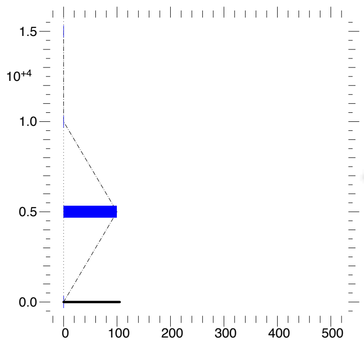
- Summing profiles is allowed (encouraged ?) :

profile 1



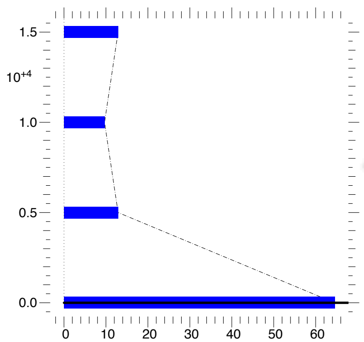
Reconst → $\sigma^2{}_1$

profile 2



Reconst → $\sigma^2{}_2$

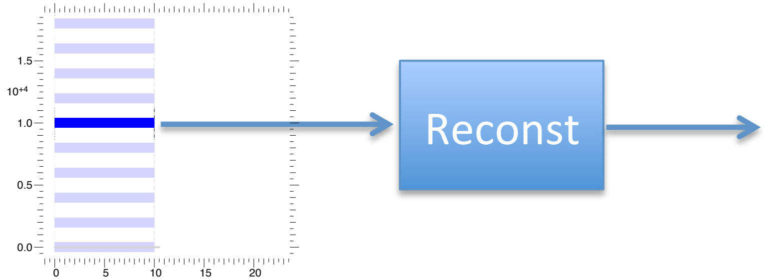
both



Reconst → $\sigma^2{}_1 + \sigma^2{}_2$

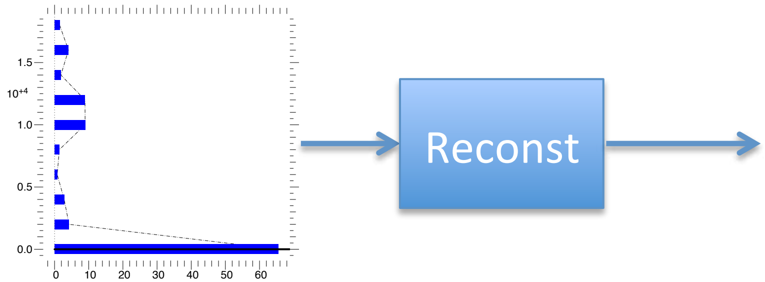
Vertical error distribution (VED)

- Summing layers of unitary strengh strengh (C_n^2=1, r_0=D, seeing=1''...)



$\varepsilon^2(h)$

Valid for any kind of tomo reconstructor, not only MMSE !



$$\sum_h C_n^2(h)\,\varepsilon^2(h)$$

vertical error distribution:
$\varepsilon^2(h)$ is associated to a <u>given reconstructor</u>

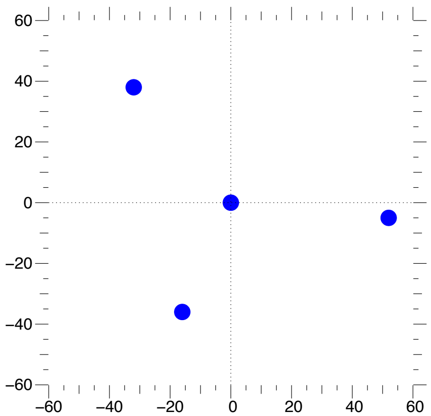
note : $\sum_h r_0^{-5/3}(h)\,\varepsilon^2(h)$ can be more convenient

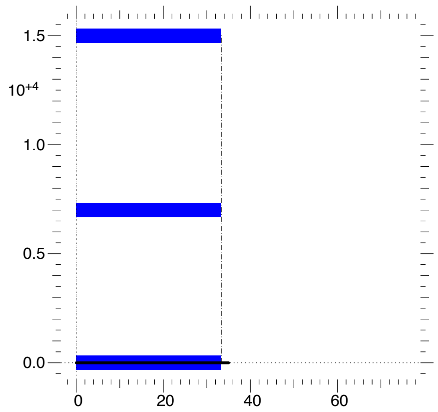
Building the VED

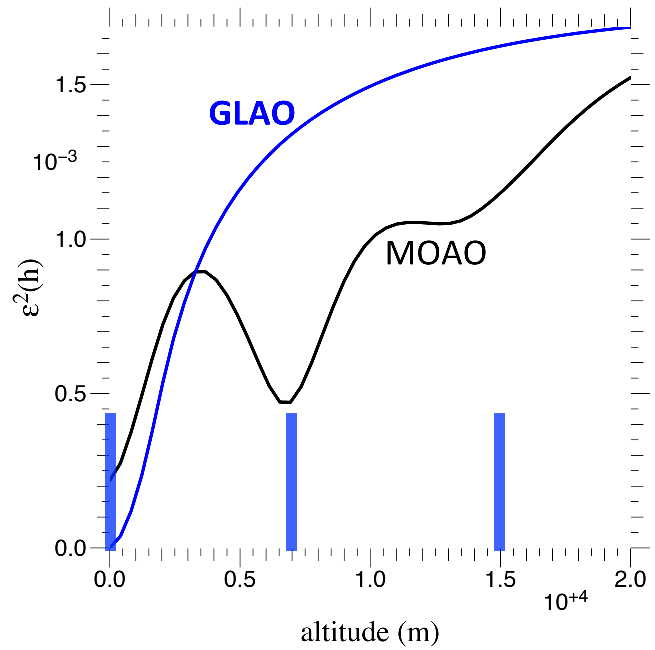
- Simulate covariance matrices of single layers, at each altitude
  - every ≈ 500 m ?
- with unitary $C_n^2(h)$
- derive the error on each

$$\langle \overrightarrow{err}.\overrightarrow{err}^t\rangle = \langle \overrightarrow{phase}.\ \overrightarrow{phase}^t\rangle - \langle \overrightarrow{phase}.\ \overrightarrow{meas}^t\rangle.R^t - R.\langle \overrightarrow{phase}.\ \overrightarrow{meas}^t\rangle^t + R.\langle \overrightarrow{meas}.\overrightarrow{meas}^t\rangle.R^t$$

- $\varepsilon^2(h)$ allows to
  - compute the tomographic error
  - anticipate the impact of unexpected layers
  - assess the impact of altitude change

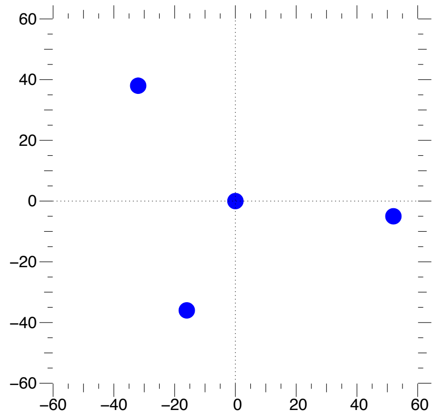


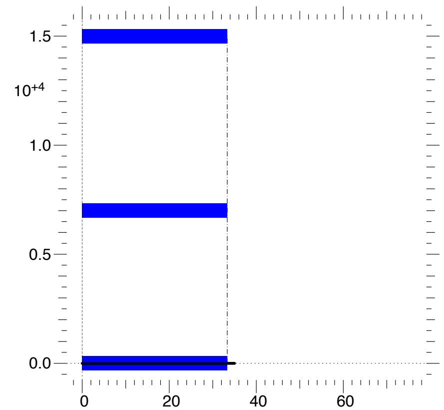


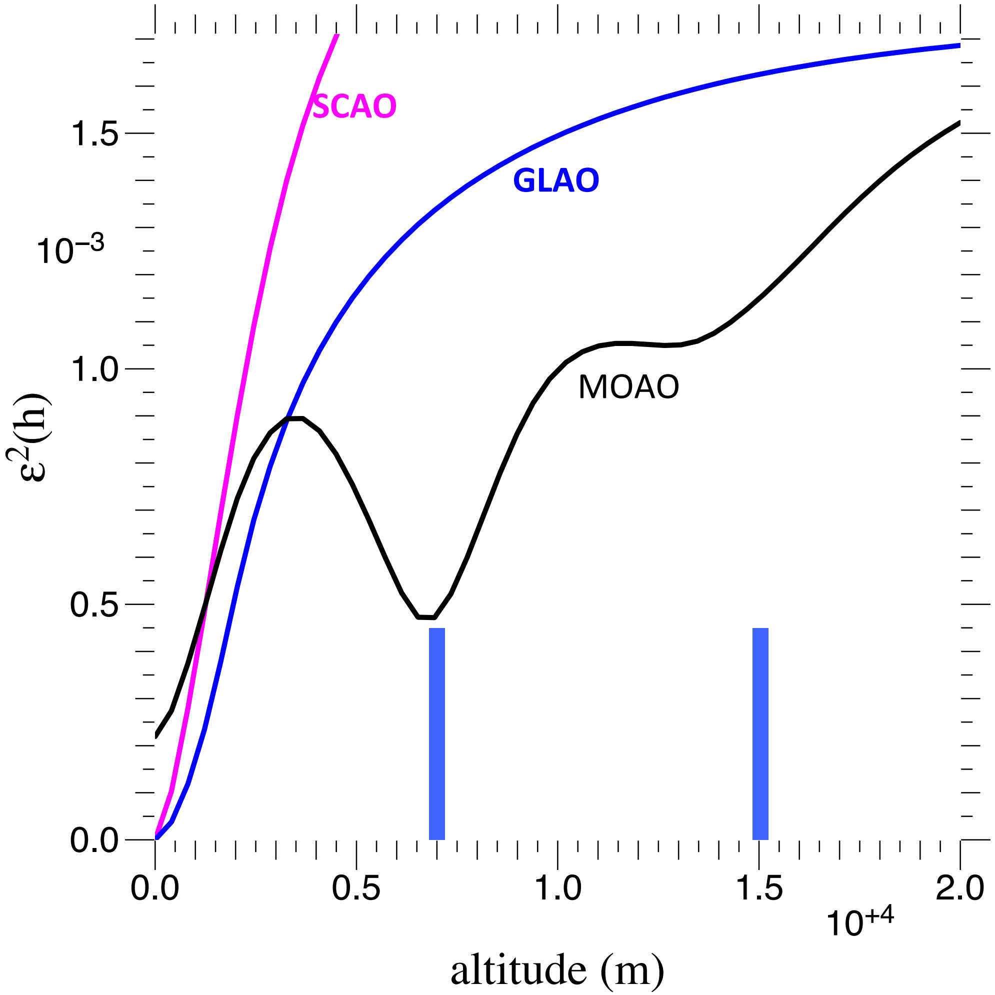


VED example

- Same example, cont'd :
  - SCAO case : R=1 Identity matrix (grows like $H^{5/3}$)
  - error on the 3 layers increase w altitude, although declared w same strengh
  - GLAO beats MOAO for 0<H<2500m
  - error at ground layer is not 0 for MOAO (beware of static aberrations..)
  - « notch » holes : width is in ($Ø_{subap}/\alpha$)=2500m here

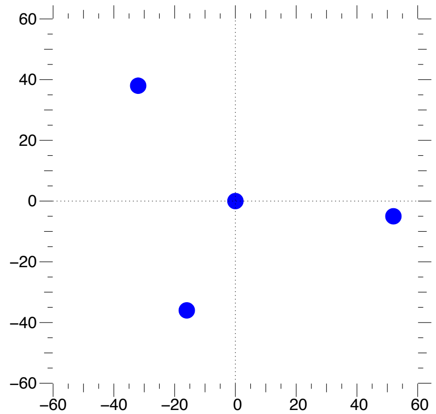


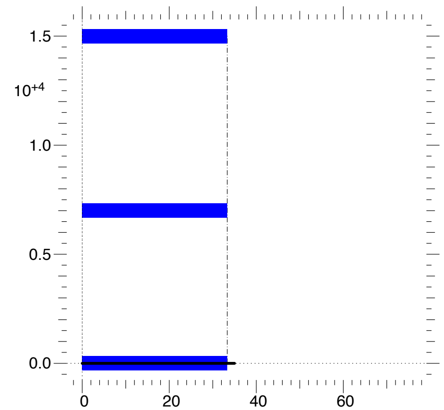


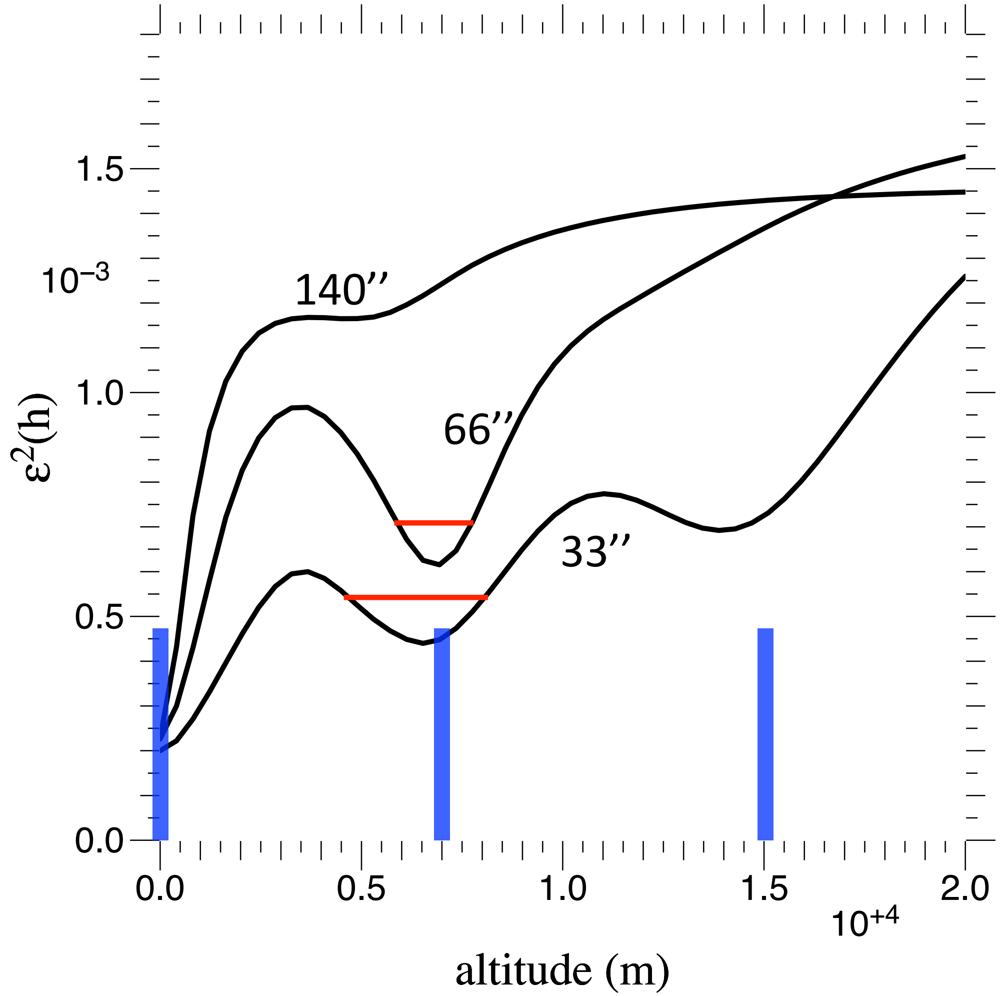


VED example

- Varying the star separation :
  - Zoom on an asterism
  - « notch » holes : width is in ($Ø_{subap}/\alpha$)
  - ($Ø_{subap}$/33'')=3500m here
  - « notch » holes are present until pupils do not overlap enough (or any more ..)

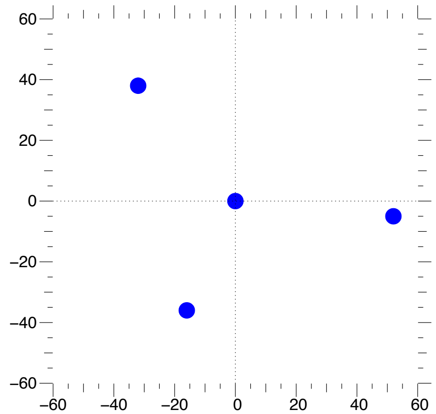


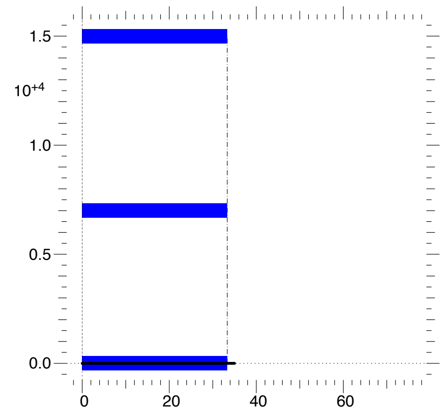


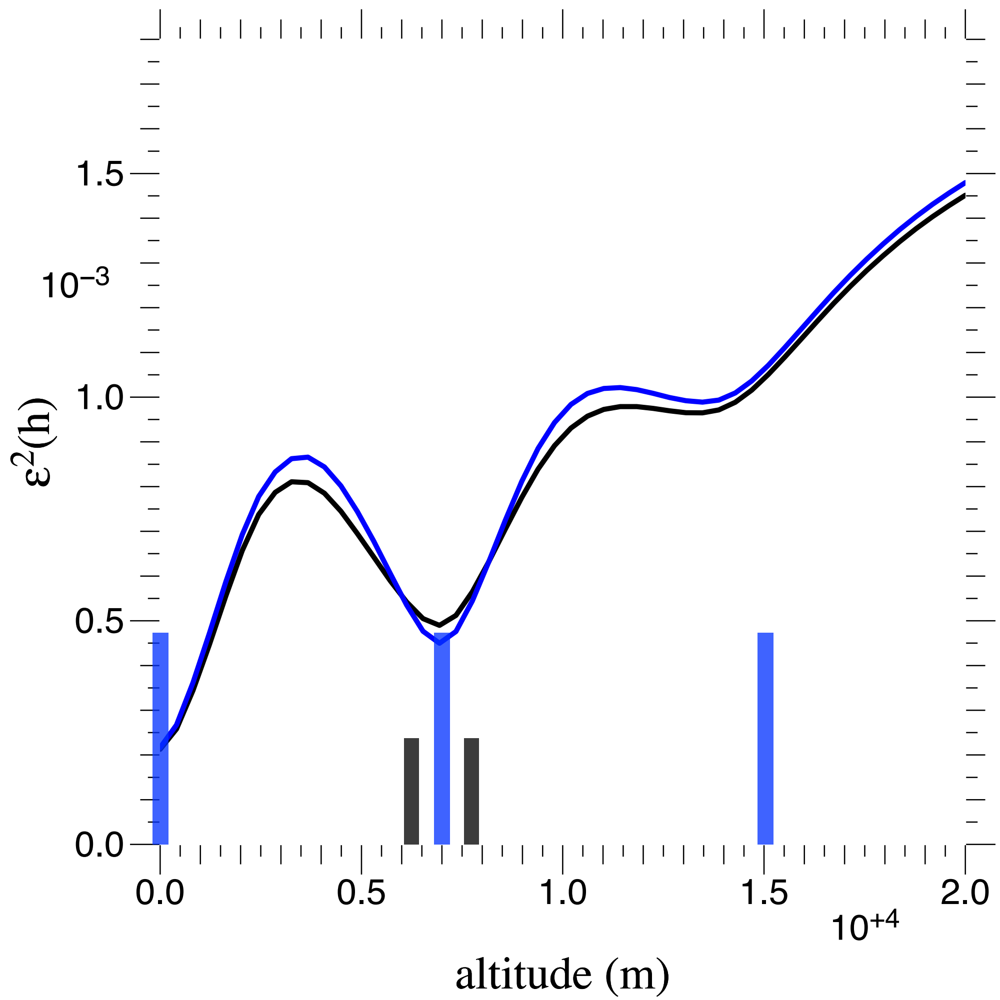


VED example

- Splitting 1 single layer in 2
  - Separated by 1500 m
  - makes ≈ no difference

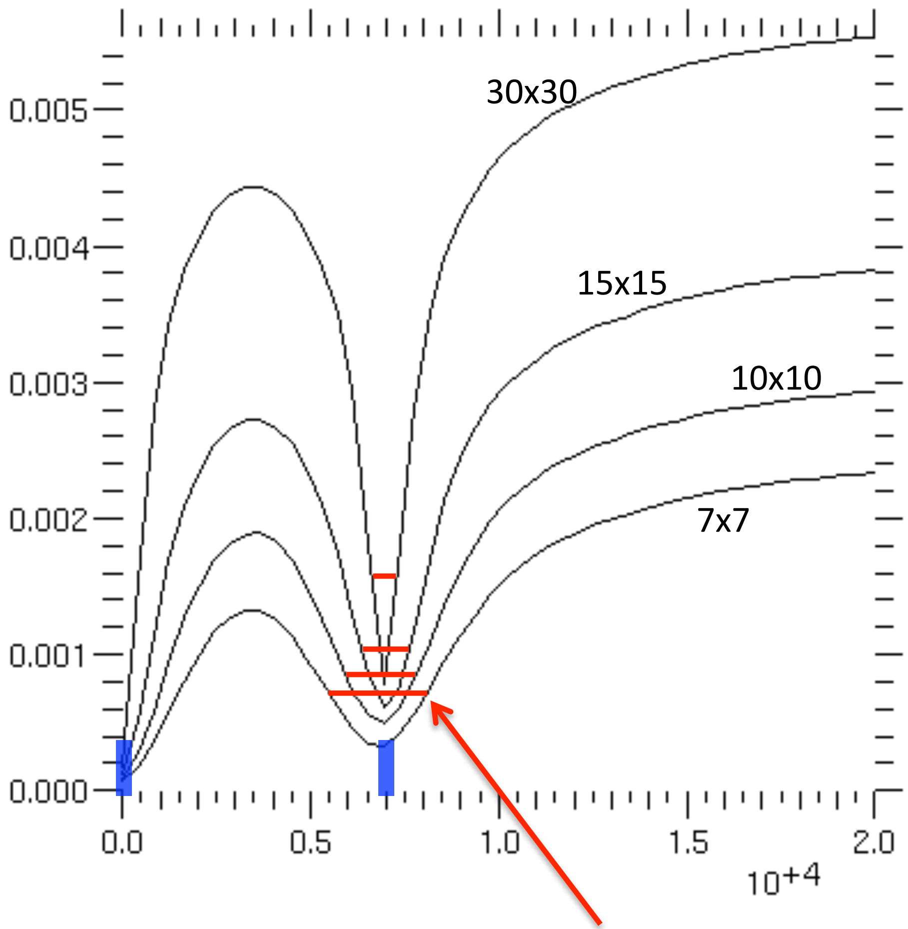






VED on an EELT ?

- Telescope diameter kept constant
- Increasing the number of subapertures creates sharper « notch holes » in the VED → sensitivity/resolution in altitude is higher
- An increased resolution of the profile is required

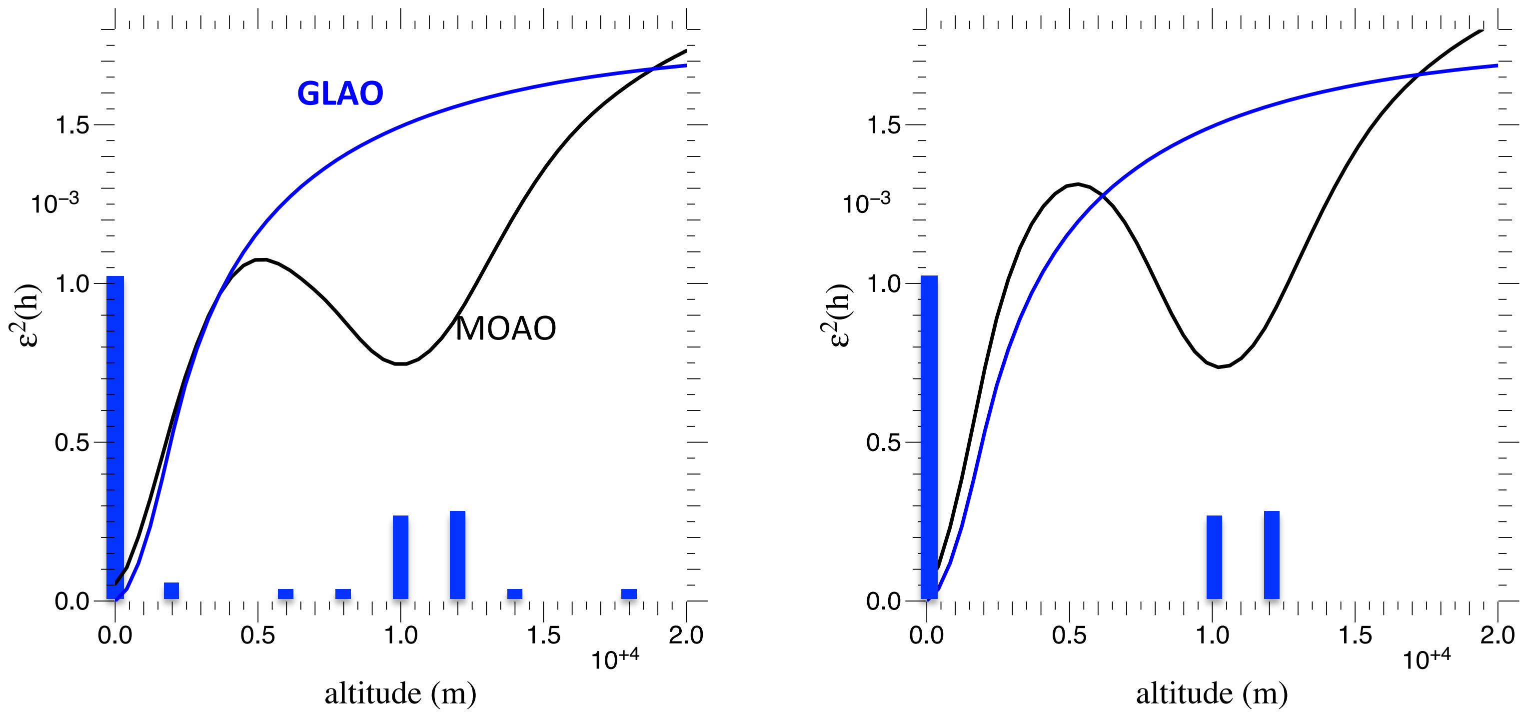


Lengh of red dash proprotionnal to $Ø_{ssp}$ / α

Impact of multiple thin layers

- Example on a CANARY profile
- Notice how introducing small layers allow to reduce the error

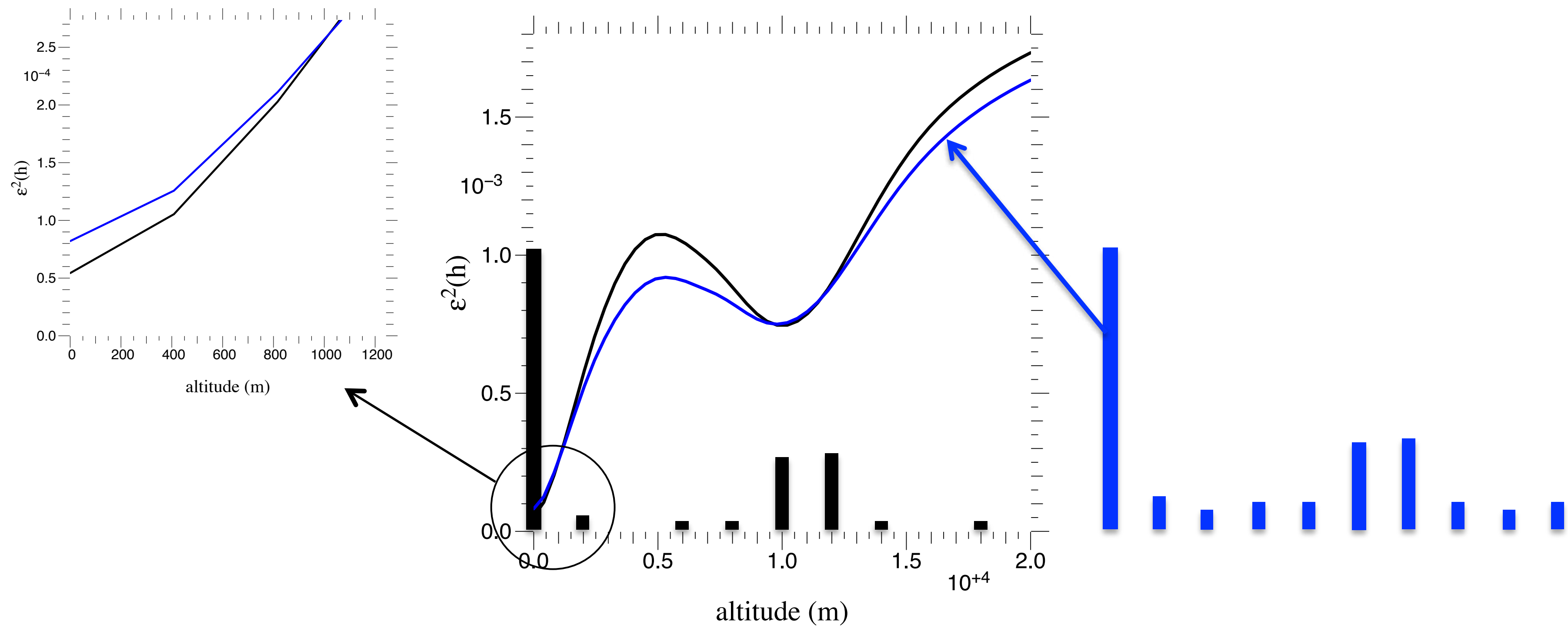
- Can extra « fake » layers be inserted « in case they pop-up » ?



Impact of multiple thin layers

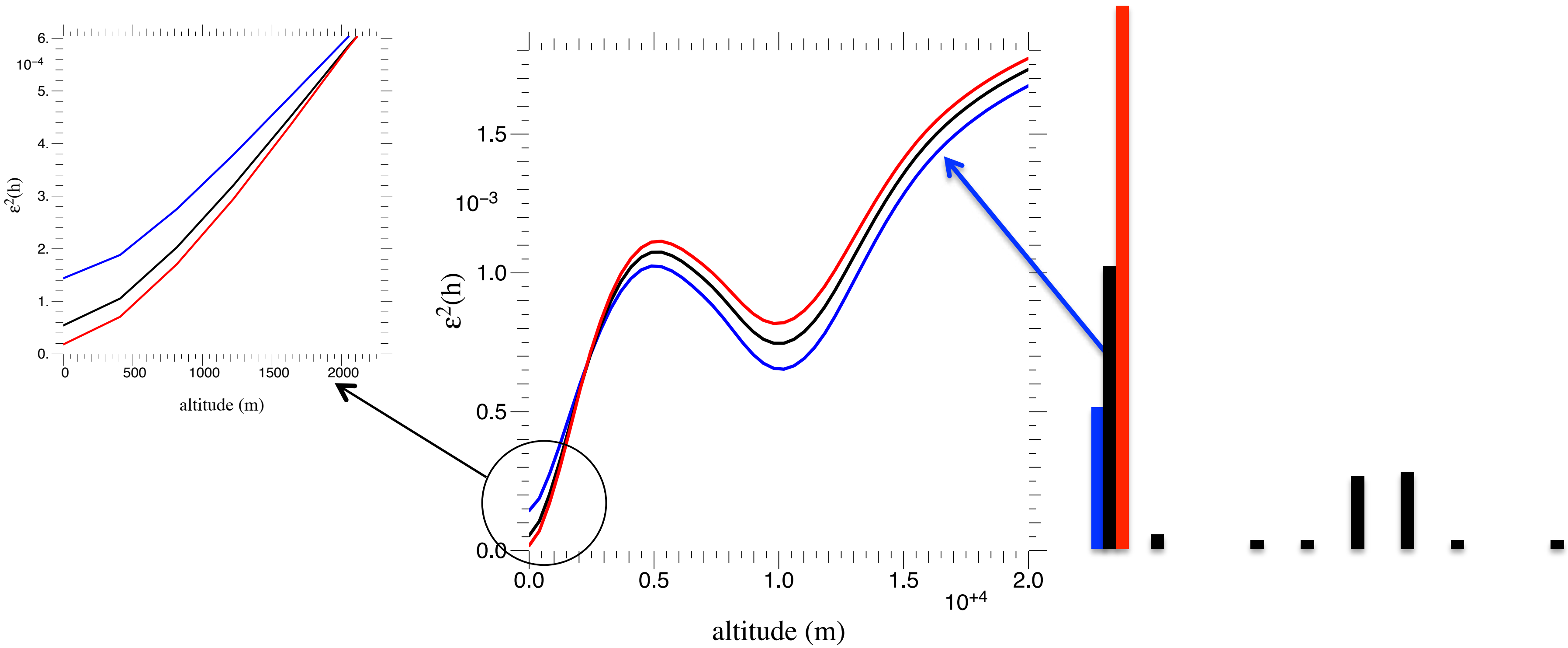
- Example on a CANARY profile
- Notice how introducing small layers allow to reduce the error

- Can extra « fake » layers be inserted « in case they pop-up » ?
  - yes, but ...
  - you then pay most of the price on the ground layer



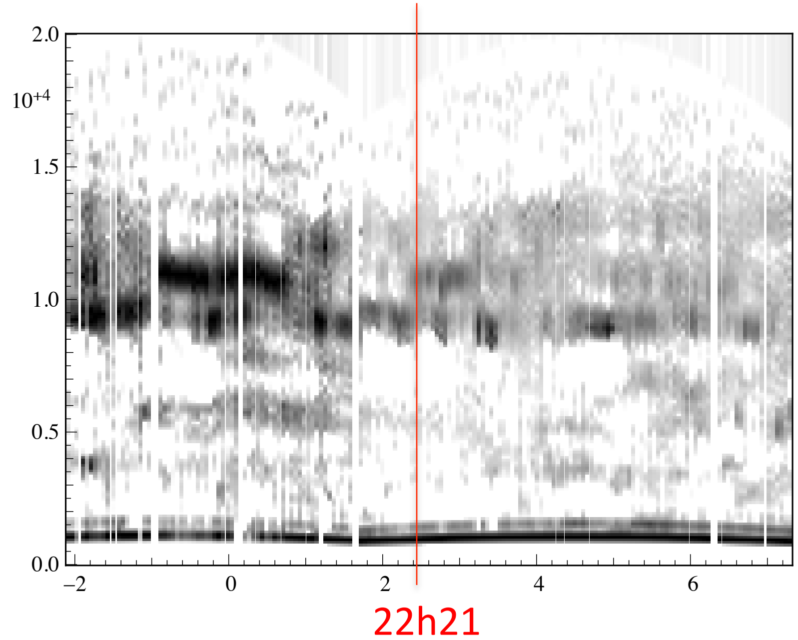
Impact of ground layer strengh

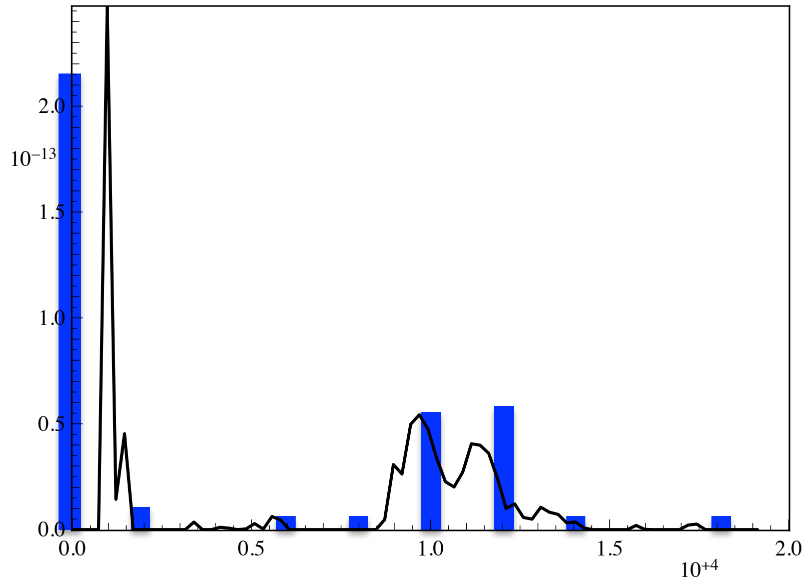
- Same example on the same CANARY profile
- 3 MMSE reconstructors
  - different Ground Layer strengh
- Safe tomography : protect yourself, consider doubling the layer.



Scidar data analysis

- Scidar
  - Operated by James Osborn on JKT 1 m telescope
  - many data, all night long
- Match pretty well with CANARY data
- Ground layer / low layers need adjustment
- Many « weak » layers appear/disappear all the time
- However they're not crucial to optimize the reconstructor



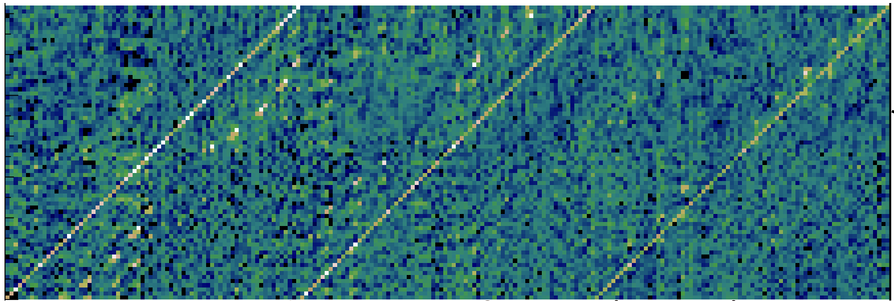


VED of a raw reconstructor

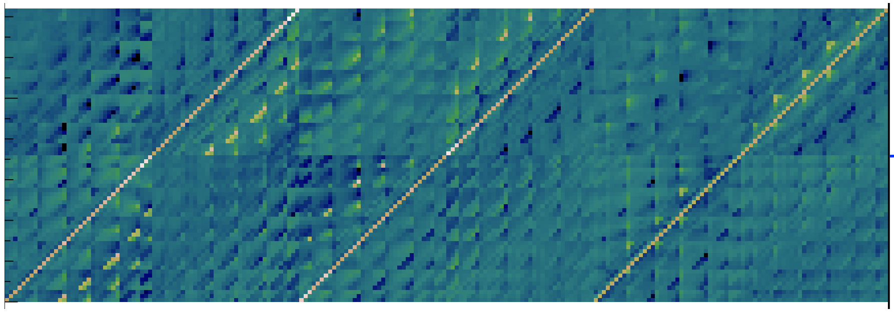
- Raw reconstructor is :

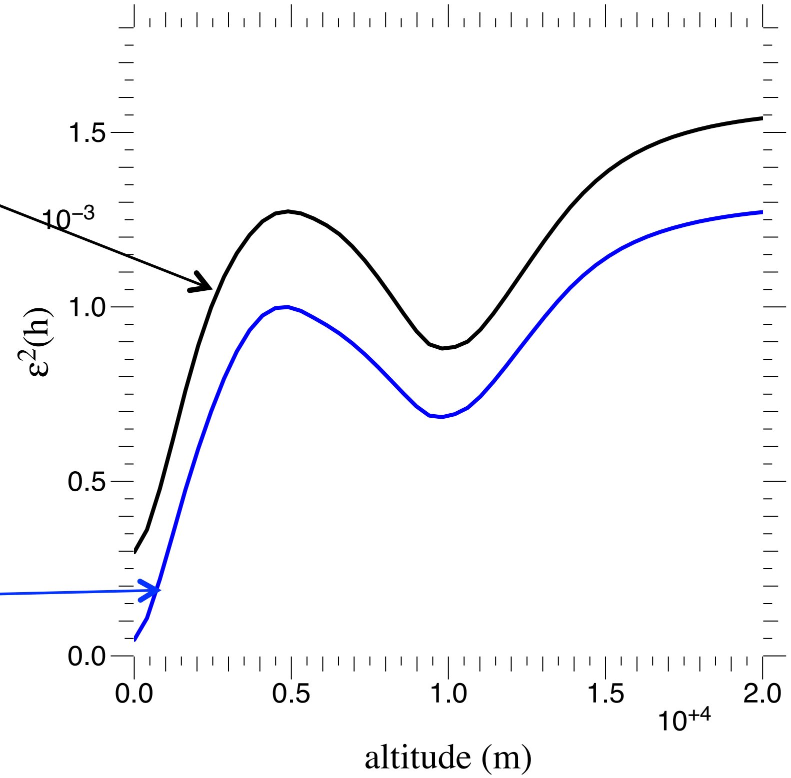
  $$R_{raw} = \langle \overrightarrow{measur}_{TS} . \overrightarrow{measur}^t \rangle . \langle \overrightarrow{measur} . \overrightarrow{measur}^t \rangle^{-1}$$

- Built with **NO** knowledge on the profile at all
- Offset wrt « learned MMSE »
  - temporal convergence ? (hyper-adapted to the learning sequence)
  - lack of robustness
- Naturally immunized against 10km layers



computed on 10000 frames (≈1 mn)





Conclusion

- Tomography demonstrated by CANARY
- More important : simulations validated
  - provided an average ≈100 nm model error is added
- Science demonstration also done
  - although CANARY is not suited for that
- VED : new tools can help understand tomography for EELT ...