Detailed analysis of the first MOAO results obtained by CANARY at the WHT.

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SCOPE

CANARY is the multi-object adaptive optics (MOAO) pathfinder for the multi object IR spectrometer EAGLE currently proposed on the European Extremely Large Telescope (E-ELT). CANARY was installed in September 2010 on the William Herschel Telescope (WHT) Canary Islands, Spain. For the first time, MOAO correction has been demonstrated using 3 widely separated off-axis natural guide stars and one deformable mirror in open loop in a target direction. A fourth on-axis wavefront sensor (WFS), called truth sensor (TS) was used to characterise the residual error of the MOAO correction and compute a detailed error budget. As the TS is placed after the deformable mirror it also permits CANARY to operate as a classical on-axis closed-loop AO system for performance comparlson purposes. We present the detailed analysis of the fourth night of the September observation run (2010 Sep. 27th).

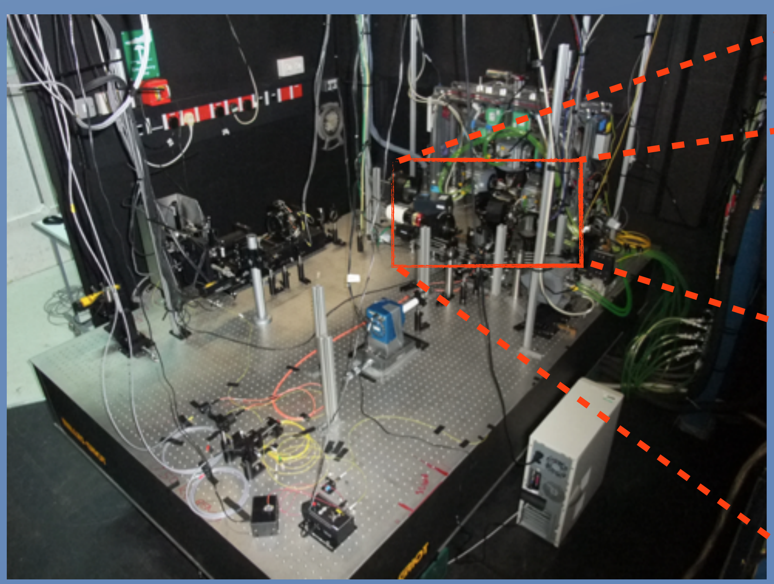
1- The bench

The bench is designed to perform a MOAO correction from 3 off-axis WFS in the central direction. A detailed description of the bench can be found in (1) and (2). It is composed of:

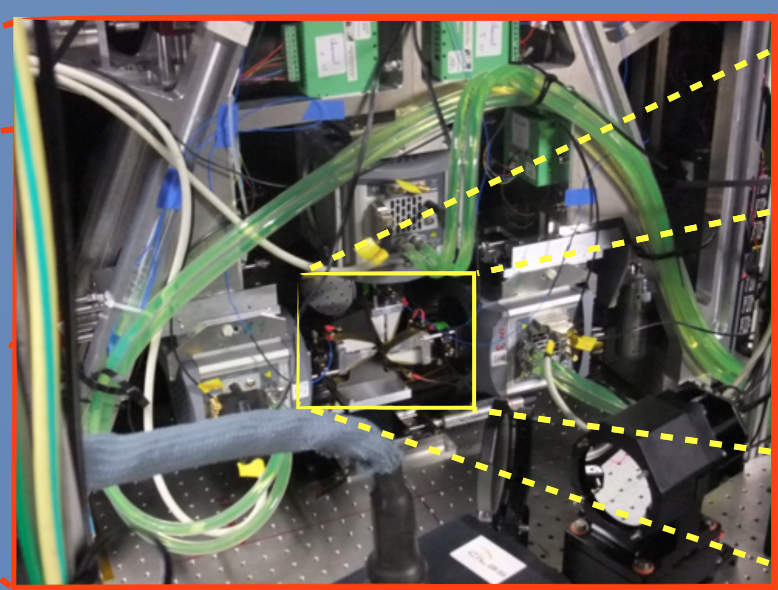
- 1 Deformable Mirror with 52 actuators driven in open loop
- A copy of the SPHERE Tip-Tilt
- 3 off-axis open loop WFS
  + 1 «Truth Sensor» (TS) on-axis:
    ANDOR iXonEM 860 EMCCD cameras 128x128
    7x7 subap with 16pix per subap (60cm on-sky)
    0.25''/pixel
    pick-off prism with field stop 6 arcsec

- Target Acquisition System (TAS)
  - Moves the 3 ANDOR cameras (4Kg each) across the 2.5' field
  - 50kg and 6 DC motors with 6 LVDT (position sensors)
  - Absolute accuracy ≈ 0.1mm (0.5'' on -sky)
  - Fidelity better than 10µm
  - Anti-collision system (Hardware and Software)

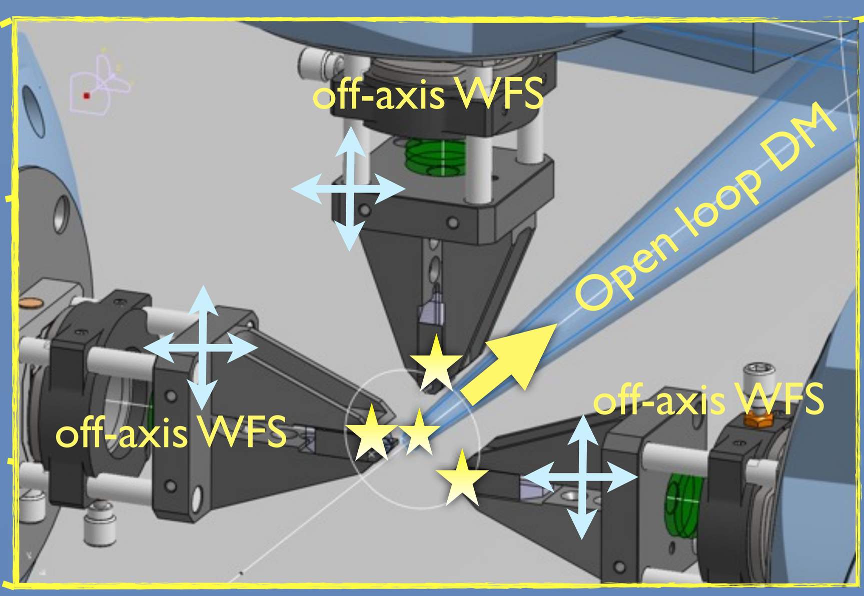
- 1 IR camera Xeva-1.7-320 Xenics
  - IR image @ 1.49µm
  - RON 200e- rms per pixel
  - beam at f/42
  - pix sampling 0.037arc on sky
- Telescope simulator
  - Movable sources visible and IR all across the field (3 off-axis + on-axis)
  - 2 Phase screens (Ground and movable Alt layer)



CANARY @ Nasmyth platform (WHT)



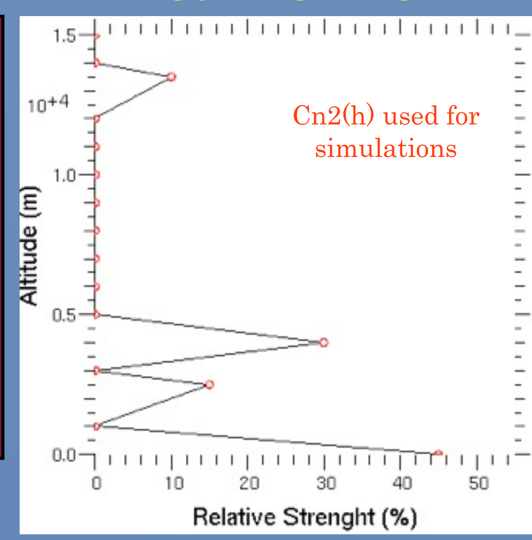
Target Acquisition System (TAS)



2.5' de-rotated field of view

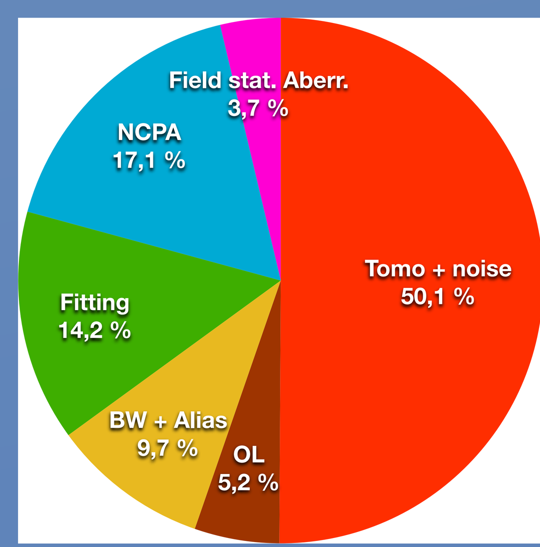
2- CANARY simulations

We present here a result of a Monte-Carlo simulation of CANARY. We simulated 3 off-axis stars placed at 1' from the central (target) direction. A 4 layers turbulence profile was simulated (maximum altitude at 13500m). An optimized MOAO reconstruction was computed in the target direction. We present the predicted error budget computed from the simulation. The seeing condition simulated was 0.94" (r0 = 12cm). We expected a Strehl Ratio (SR) in H band around 22% without any static error. Taking into account the static aberrations measured on CANARY expected SR reduces to 15%.

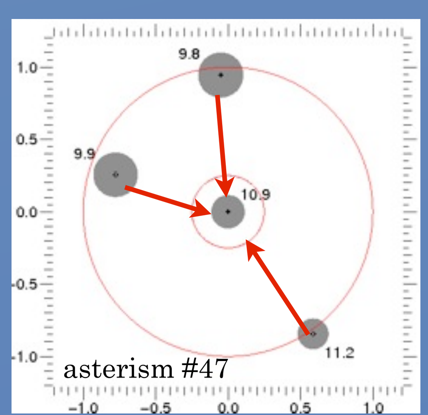


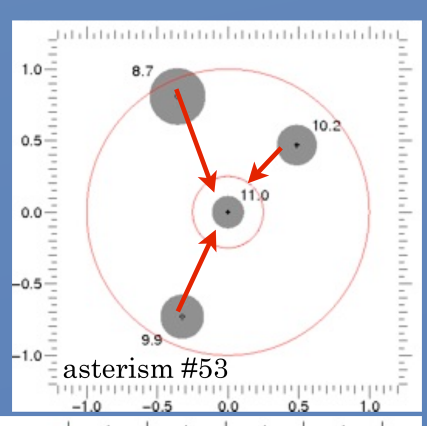
CANARY error budget simulation (4 layers profile)	
Error	Estimated value
Tomo + noise	257
Open Loop	83
Alias + BW	113
Fitting	137
NCPA	0 (150)
Field stat. Aberr.	0 (70)
Total (nm rms)	323 (363)
SR@1.65µm	21.8% (14.7%)

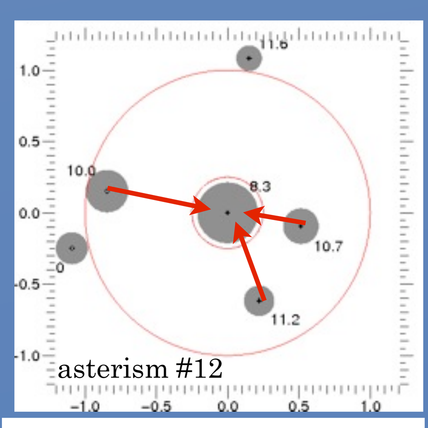
CANARY SIMULATIONS

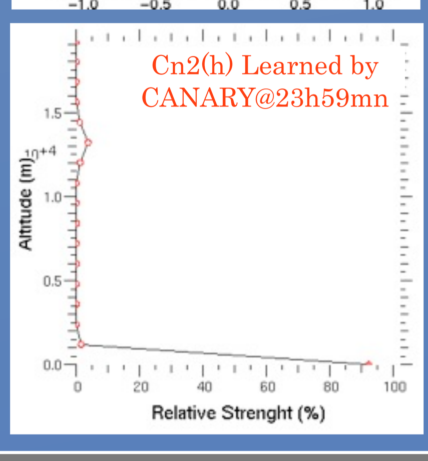


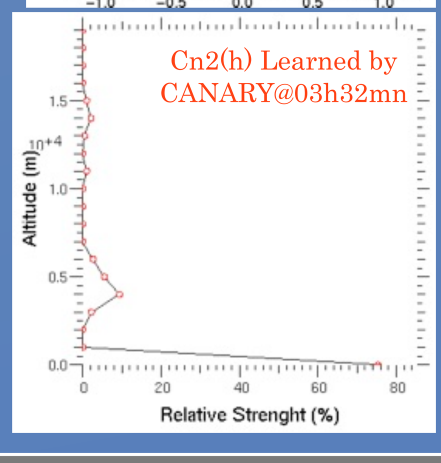
3- CANARY MOAO on-sky results

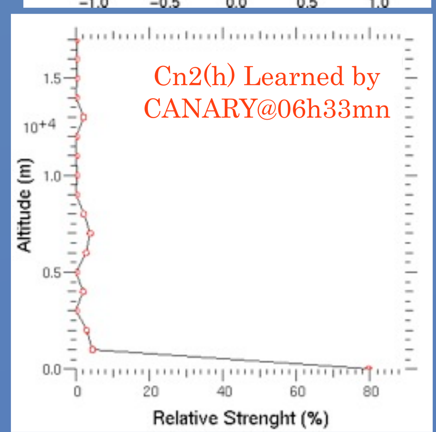


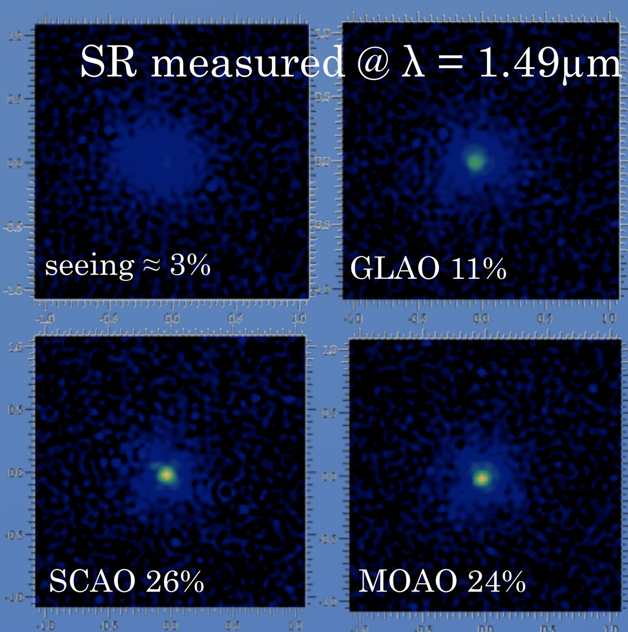










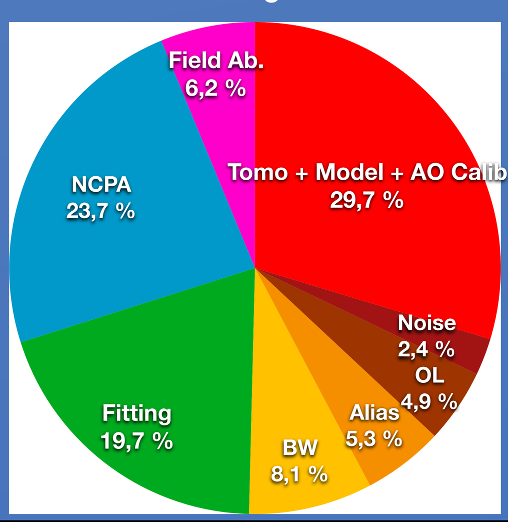


Error budget @00h10mn12s on ast #47 (r0= 16.3cm / 0.63")	
Tomo + Model	168
Noise	48
Open Loop	68
Aliasing	71
BW	88
Fitting	137
NCPA	150
Field stat. Aberr.	77
Total error (nm rms)	308
Estimated SR@1.49µm	18.5%
IR image SR@1.49µm	21 %

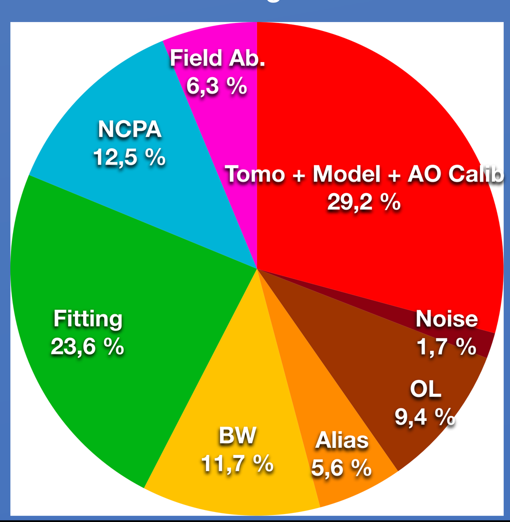
Error budget @03h24mn44s on ast #53 (r0= 10.0cm / 1.03")	
Tomo + Model	229
Noise	55
Open Loop	130
Aliasing	100
BW	145
Fitting	206
NCPA	150
Field stat. Aberr.	106
Total error (nm rms)	424
Estimated SR@1.49µm	4.1%
IR image SR@1.49µm	9.4%

Error budget @06h07mn07s on ast #12 (r0= 13.0cm / 0.79")	
Tomo + Model	194
Noise	96
Open Loop	125
Aliasing	84
BW	113
Fitting	165
NCPA	150
Field stat. Aberr.	72
Total error (nm rms)	371
Estimated SR@1.49µm	8.7%
IR image SR@1.49µm	14.9%

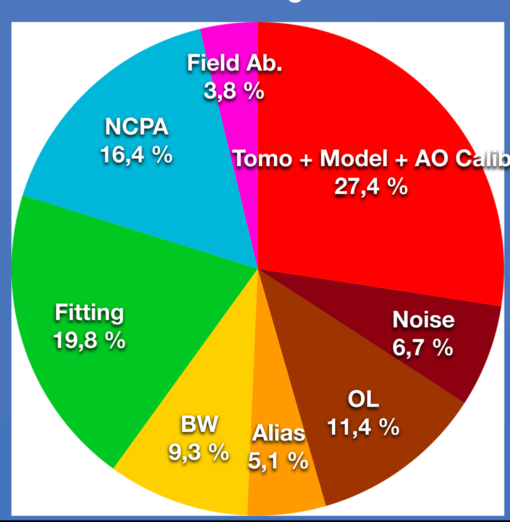
MOAO error budget @ 00h10mn



MOAO error budget @ 03h24mn



MOAO error budget @ 06h07



Error budget details

We detail the error budget obtained on 3 differents asterisms observed during the night (see left). For each, we computed on-sky slopes covariance matrices using a large data set of synchronized slopes (typically 5-10mn) recorded by all the WFS. Thanks to the Learn part of the Learn&Apply algorithm (3) we were able to retrieve turbulence parameters such as the Cn2 profile, geometric parameters and others calibration parameters needed in open loop. The Apply part allowed us to compute a tomographic reconstructor used to perform an optimized correction in the target direction (on-axis).

Thanks to the Truth Sensor (TS) placed after the deformable mirror, we measured the wavefront error while the MOAO loop was engaged. From the measurement we computed the on-sky error budget as follows:

Tomo+model:
From disengaged slopes, we compare wavefront reconstructed from off-axis WFS to the TS with no delay, unbiasing from noise propagation, and rescaled from seeing variations

Noise:
Compute noise from off-axis WFS (white noise temporal autocorrelation peaks on top of smooth turbu autocorrelatio,), propagate through reconstructor, compute effect of temporal filtering.

Open loop:
Difference between the sum of all the terms, and the error measured by the Truth Sensor (unbiasing from noise effect)

Aliasing & fitting:
Use determination of r0, with Kolmogorov a priori and basic analytical formulae. For aliasing, need to separate aliasing effects in altitude or ground

Bandwidth:
We simulate the loop filtering (with fractional delay and gain) and unbias from noise propagation (important !)

NCPA:
From SR measured in IR images recorded on calibration source by closing the loop on TS.

Field static aberrations:
off-axis aberrations subtracted in the MOAO loop and measured by TS.

Quick summary of the on-sky results

≈ 1/3 of the total error is due to tomography + open loop. The absolute value (between 160 and 270nm rms) is close to what expected in simulations.

≈ 1/4 due to static aberrations NCPA+Field ab. A particular effort will be made to reduce the NCPA during the Phase B run (Currently internal SR is only 70% at 1.65µm).

≈ 1/4 due to fitting error (OK with a 52+2 actuators)

< 1/5 due to others classical AO terms (BW, aliasing, noise...)

4- CANARY/EAGLE comparison

We present here a comparison between the error budget computed by numerical simulations and the one measured on-sky with CANARY. We aware that the comparison is extremely difficult to make since the 2 systems are different. In particular some of the error terms simulated for EAGLE were not identified in the error budget of CANARY. Nevertheless, we think this comparison attempt is interesting to show.

The CANARY error budget is computed at 06h07mn (see also section 3). For comparison purposes we sum up the tomographic error with noise, alias, model and AO calibrations errors because the spliting of the budget is different in CANARY and in EAGLE. The r0 measured for CANARY is 13cm. Simulated r0 value is 11.8cm for EAGLE and L0=25m. EAGLE was simulated using a Fourier code (4).

We also aware that the Cn2(h) is different for the 2 cases so that the tomographic error comparison is critical. A 9 layers Cn2 profile was used on the EAGLE simulation. EAGLE was simulated with a frequency of 250Hz while CANARY was running on-sky (for signal-to noise reasons) at 150Hz. This explains a greater BW error for CANARY.

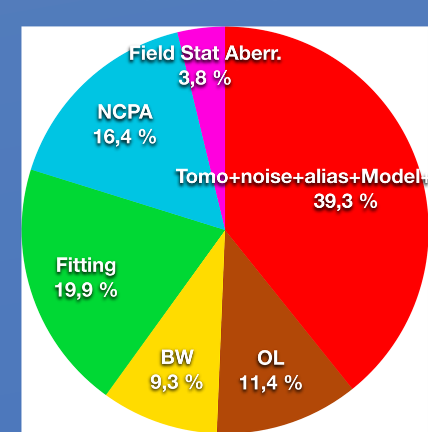
Telescope static high order aberrations of the WHT were measured at less than 30 nm rms. Since the CANARY Phase A was a Natural Guide Stars (NGS) run, there are no LGS anisplanetism error and for sake of clarity we put the chromatism error to 0 for both.

The expected performance of EAGLE is slighly optimistic when compared to the one measured with CANARY. Notice that for CANARY the performance on-sky was not fully optimized during the first run.

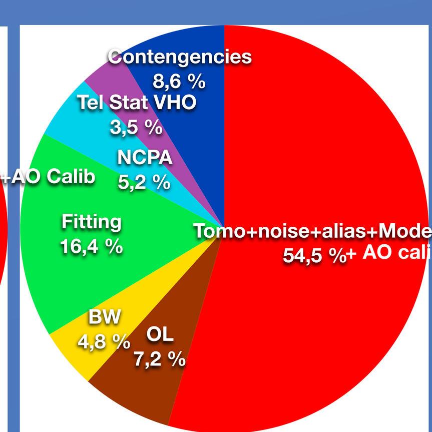
We see a good agreement of the tomographic+alias+noise term between the EAGLE simulation and CANARY (232 instead of 237nm rms). In the EAGLE simulations underestimated the field static aberration error was totally underestimated.

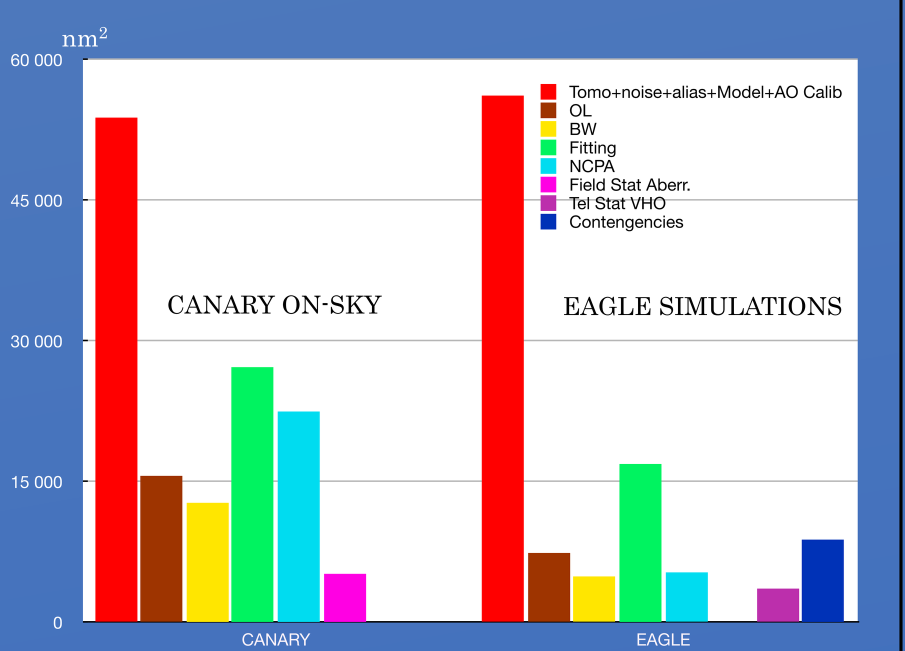
	CANARY ON-SKY	EAGLE SIMULATIONS
tomo+noise+alias + Model + AO Calib	232	237
OL	125	86
BW	113	70
Fitting	165	130
NCPA	150	73
Field aberr.	72	0
Tel stat VHO	0 (<30)	60
Contengencies	0	94
Chromatism	0	0
LGS Aniso	0	0
Total error (nm rms)	370	321

CANARY ON-SKY



EAGLE SIMULATIONS





(1) Gendron et al., "MOAO first on-sky demonstration with CANARY", A&A 529, L2 (2011)

(2) Gendron E. et al. "Toward MOAO on the ELT: the CANARY program", this conference

(3) Vidal F., Gendron E., Rousset G., "Tomography approach for multi-object adaptive optics", Vol. 27, pp253, JOSA-A (2010)

(4) Rousset G. et al. "EAGLE MOAO system conceptual design and related technologies", Proc of SPIE, Vol. 7736 (2010)

(5) Cuby J.G., "Science requirements for EAGLE", This conference