Numerical simulations of an Extreme AO system for an ELT

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With help from Austrian AO Team & Frim3D Team
Introduction

Full end to end modeling (“Octopus”) of AO
- Shifting phase screens
- Diffractive WFS model
- Measurements for each subap
- Reconstructor
- DM shape $\rightarrow$ residual phase
- Closed loop

Goals of the study:
- Demonstrate that our full XAO model works and is tractable for a 42m telescope
- Investigate XAO PSF as provided by the simulator
- Compare reconstructors (“Austrian in-kind contribution to accession to ESO”)
  - This lead also to some MCAO results which will be presented as well
XAO system parameters

- 42m telescope, with central obstruction, no spiders, no segments, no wind shake.
- Pyramid sensor @700nm, with modulation
- 200x200 “sub-apertures” $\rightarrow \sim 20\text{cm}$
- 3 kHz, 2 frames delay.
- Seeing: 0.8”, Tau0: $\sim 3\text{ms}$
- No Woofer - tweeter: PYR sees all turbulence when loop is open (worst case for PYR linearity)
- Pupil: 2000 pixels $\leftrightarrow 42\text{m}$
- PSFs calculated at K-Band (unless otherwise noted)
- Static aberrations not considered, only “basic” atmospheric AO errors
- Temporal control: Simple integrator
- PYR module written by Ch. Verinaud
Modulation

- Simulation tool allows to modulate PYR (square pattern)
- Larger modulation is more computation time intensive:
  - 2 \( \lambda / D \) of modulation \( \rightarrow \) 16 points
  - 6 \( \lambda / D \) of modulation \( \rightarrow \) 48 points
- Modulation is fully parallelized
- Still time consuming: 3h (mod 2) - 7h (mod 6) for 500 iterations
- Allows to increase linearity range of PYR measurements
- Different modulations change behavior of PSF, even if Strehls are very similar
Modulation & Strehl (high flux)

→ Modulation of 4 is chosen
PSF structure
PSF structure

Scale is simulation pixels (5.3 mas/pix)
Impact of modulation at high flux
Next we study the impact of modulation on the limiting magnitude

- 2.8e of RON
- Optimize loop gain for each flux
- At low flux, amount of regularization when building command matrix is increased
- Framerate optimization not yet done (i.e. running slower to get less effect from RON).
$d_{subap\ size}$
$V_{characteristic\ wind\ speed}$
$T_{delay}$
$r_0$, the Fried parameter

$$\sigma^2_{fitting} = 0.26 (d/r_0)^{5/3},$$
$$\sigma^2_{delay} = 6.88 (VT/r_0)^{5/3},$$
Loop closing at low flux

Doesn’t seem too problematic, although much slower than in typical SH case.
J, H, K PSF comparisons

- K Band; S=0.965
- H Band; S=0.936
- J Band; S=0.898

Radius [mas]
K Band

Constant sampling in lambda/D units
H Band

Constant sampling in lambda/D units
J Band

Constant sampling in lambda/D units
Comparing Cure(D) and MVM

- Idea: See how different 2 reconstruction algorithms are from the PSF point of view.

- Use **same** Measurements to calculate commands:
  - With the standard MVM w/ Interaction matrix inversion (+ some regularization)
  - Cure(D)

- Commands are sent to the **same simulation**, with same input phase screens, noise,…

- Only difference is the reconstructor everything else in the simulation stays the same.
Cure(D)

- Fast reconstruction algorithm developed by the Austrian AO Team (AAO)
- MVM is used as a “reference” case against which Cure(D) is tested.
  - Modal interaction matrix + ad-hoc regularization
- Initial “poor” performance of Cure compared to MVM pushed improvements in Cure → now almost identical performance, BUT many less FLOPs!
- Shows importance of the performance benchmark
- “CuRe - Fast wavefront reconstruction algorithm for extremely large telescopes”, Rosensteiner, M., JOSA A, in press
- ”Cumulative Wavefront Reconstructor for the Shack-Hartman Sensor”, M. Zhariy, A. Neubauer, M. Rosensteiner, R. Ramlau, Inverse Problems and Imaging, accepted
Cure without pre-processing

with help from the Austrian AO Team
Cure with pre-processing

with help from the Austrian AO Team
CureD, D=1 (Domain decomp.)

with help from the Austrian AO Team
CureD, D=3 (Domain decomp.)

with help from the Austrian AO Team
Evolution of Cure(D) vs MVM

Very first comparison  After some months of hard work of AAT (pre-processing of data, CureD)
MAORY-like MCAO configuration

- Continue comparisons of reconstructors
- MCAO is also part of the test cases
- In addition to Cure (MCAO→Kaczmarz), we also test Frim3D
  - “A Kaczmarz type iterative reconstructor for Multi-Conjugate Adaptive Optics”, AO4ELT2, Ramlau & Rosensteiner
- 99% same config (still a few discrepancies with NGS sensors, but impact should be minor)
MAORY-like configuration

- 6 Sodium LGS (84x84 WFS)
  - “High flux”
  - Spot elongation neglected for the moment (planned)
  - 90km, fixed
  - 2’ (diameter) circle, no central LGS
- 3 NGS
  - one 2x2 (for fast focus + TT)
  - two 1x1 (TT only)
  - “High flux”
- 3 DMs
  - 0 (full) 4km (2 *spacing) 12.7km (2 *spacing)
- Corrected FOV: 2.8’ (Diameter)
- 25 PSF star measure Strehl (K-band) in FOV
- Seeing: 0.8’’
- 9 layer atmospheric model (none of the reconstructors uses intermediate layers)
MCAO results

- Frim3D has best performance (for now?)
  - Good way to regularize
  - Difference on-axis and close to it
- MVM and Kaczmarz extremely close
- How to improve performance?
  - Reconstruct more layers and the project on DMs
  - Frim3D: different gain for NGS and LGS
  - […]
- → Very good results showing consistency, and that gaining significantly on computing power is possible.

- Would be interesting to add other reconstructors to the comparison (MCAO and/or XAO, MOAO, LTAO, …)
  - A beauty contest of reconstructors?
  - IDL, Matlab, yorick interfaces already exist to use Octopus
Conclusions

- Our simulation software is ready and capable for XAO on the E-ELT
- It is also ready for MCAO on the E-ELT
  - Spot elongation was not considered here, but has been shown to work with MVM and Frim3D.
- Importance of reference points when creating new reconstructors – there are many parameters to tweak, and it’s reassuring to have independent methods yielding very similar results
  - Performance is hard to know even with analytic / semi-analytic models (which often lack precisely the parameters you want to optimize)
- Comparisons will continue
  - LTAO, MOAO
  - Spot elongation (already done with Frim, to be done with Cure)
- Other algorithms are being developed by AAO
- Also comparison with RTC implementability (//, pipeline, …).