Performances of MCAO on the E-ELT using the *Fractal Iterative Method* for fast atmospheric tomography

Michel Tallon[1], Clémentine Béchet[2], Isabelle Tallon-Bosc[1],
Miska Le Louarn[2], Éric Thiébaut[1], Richard Clare[2], Enrico Marchetti[2]

1 - Centre de Recherche Astrophysique de Lyon, France

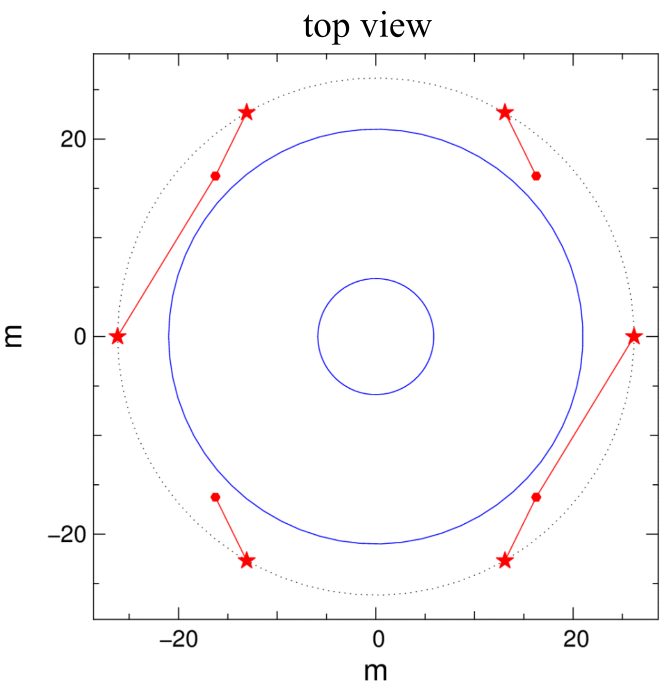
2 - European Southern Observatory (ESO), Germany

Outline

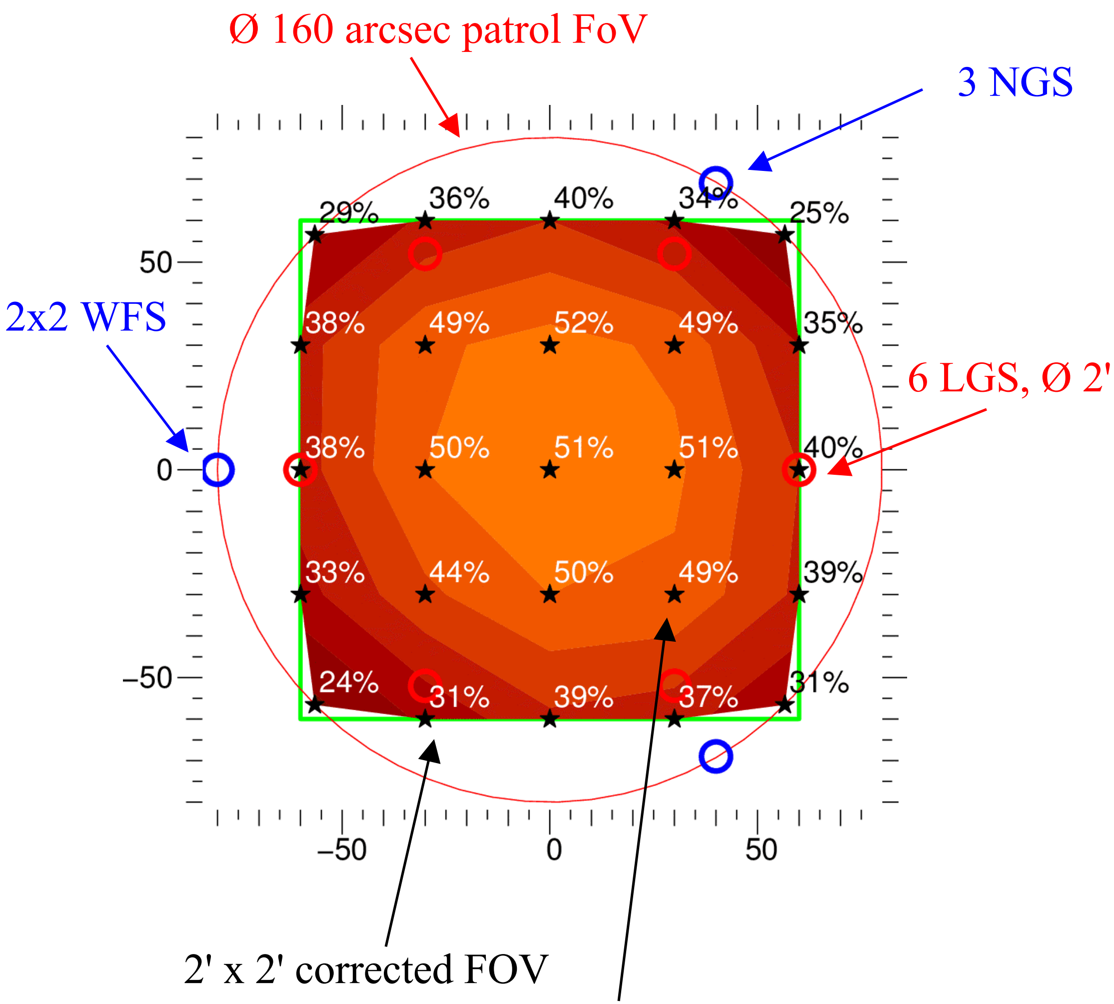
- "Experimental setup"
  - use MAORY configuration (E-ELT MCAO) as a test bench
  - ESO end-to-end simulator
- Short reminder on Fractal Iterative Method (FrIM)
- Calibrations & performances
  - noise levels, performances comparison
  - sensitivity of some FrIM parameters, number of iterations
- Some other effects
  - elongation, priors, Cn2 profile

MAORY configuration / 1

- 40m class telescope = Ø 42m
- Deformable mirrors : 9296 actuators
  - 0 km : 85 x 85, spacing: 0.5 m
  - 4 km : 47 x 47, spacing: 1 m
  - 12.7 km : 53 x 53, spacing: 1 m
- Wavefront sensors : 60492 slopes
  - 6 LGS, 84 x 84 subap.
    - on a Ø 2 arcmin circle
    - 500 ph/subap.
    - RON 3e-
  - 2 NGS for tip/tilt, 1 NGS for 2 x 2 subap.
    - here on a Ø 2.7 arcmin circle, *edge of patrol field*
    - 500 ph/subap., H band
    - RON 5e-
- 500 Hz loop frequency
- Cn2 profile : 9 layers, r_0= 12.9 cm



MAORY-like configuration / 2



Strehl ratio in K on 5 x 5 PSF

Octopus as the end-to-end simulator

system definition

ESO Octopus end-to-end simuator

- detailed physical model
- measure slopes
- apply commands
- estimate Strehl ratios, etc.

slopes →

← commands

FrIM-3D

- geometric/analytic models (propagation, WFS, noises,..)
- read slopes
- compute commands (POLC or IMC)
- calibration needed for noise levels

Strehl ratios

FrIM reminder /1

- Solve reconstruction iteratively: $\widehat{\boldsymbol{w}} = \mathbf{R} \cdot \boldsymbol{d}$

noise cov. — a priori wavefront cov.

$$\underbrace{\left(\mathbf{S}^{\mathrm{T}} \cdot \mathbf{C}_{n}^{-1} \cdot \mathbf{S} + \mathbf{C}_{w}^{-1}\right)}_{\text{Matrix to be inverted}} \cdot \widehat{\boldsymbol{w}} = \mathbf{S}^{\mathrm{T}} \cdot \mathbf{C}_{n}^{-1} \cdot \boldsymbol{d}$$

layers — data

- Modified wavefront generator: $\boldsymbol{w} = \mathbf{K} \cdot \boldsymbol{u}$ ($\boldsymbol{u}$: *N* independent gaussian random values)

$$\mathbf{C}_{w}^{-1} = \langle \boldsymbol{w} \cdot \boldsymbol{w}^{\mathrm{T}} \rangle^{-1} = \mathbf{K}^{-\mathrm{T}} \cdot \mathbf{K}^{-1}$$

  – Number of operations for **K, K**$^{-1}$, … : ~ 6*N*
  – ***u*** are statistically independent modes.

- Solve in space of the statistically independent modes
  – Using change of variable: $\boldsymbol{w} = \mathbf{K} \cdot \boldsymbol{u}$

$$\left(\mathbf{K}^{\mathrm{T}} \cdot \mathbf{S}^{\mathrm{T}} \cdot \mathbf{C}_{n}^{-1} \cdot \mathbf{S} \cdot \mathbf{K} + \mathbf{I}\right) \cdot \boldsymbol{u} = \mathbf{K}^{\mathrm{T}} \cdot \mathbf{S}^{\mathrm{T}} \cdot \mathbf{C}_{n}^{-1} \cdot \boldsymbol{d}$$

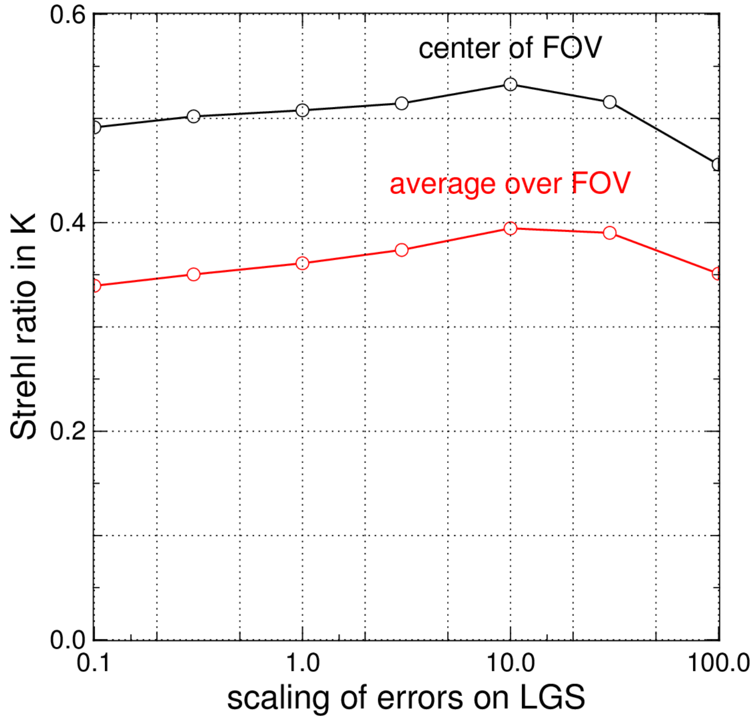
FrIM reminder /2

- Iterative method: preconditioned conj. grad.
  - Jacobi, or so-called "optimal" preconditioner
- Number of iterations independent of *N* (# deg. of freedom)
  - ~ 3 iterations in closed-loop
  - *O(N)*
- Minimum variance yields: $\widehat{\boldsymbol{a}} = \mathbf{F} \cdot \mathbf{E} \cdot \mathbf{R} \cdot \boldsymbol{d}$

  projection on DMs ($\mathbf{F}$) — temporal extrapolation ($\mathbf{E}$) — reconstructor ($\mathbf{R}$)

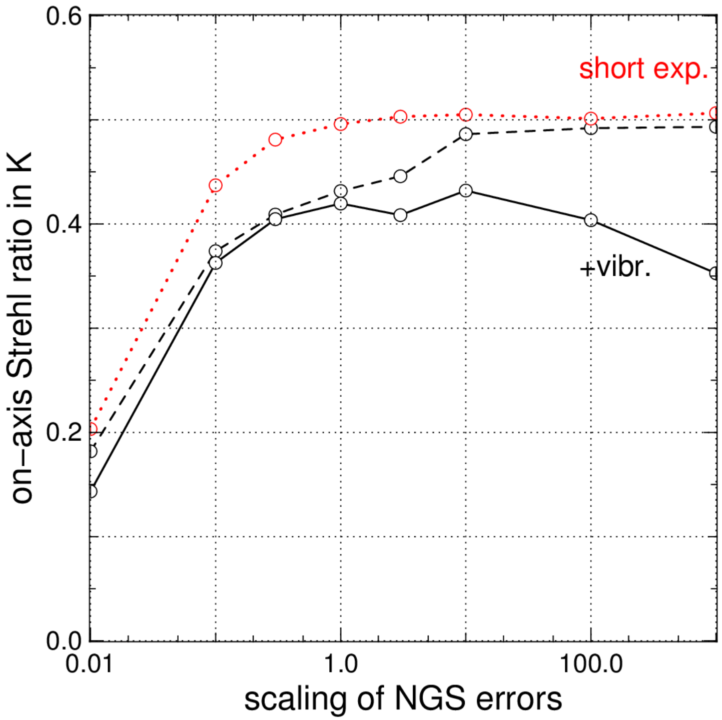
- In the following:
  - **E** : not used at the moment
  - **F** simplified : 3 layers at same altitudes as the DM
    - same as reference control method on Octopus (interaction matrix)
    - minimal amount of calculations and latency for RTC

Calibration of noise / LGS



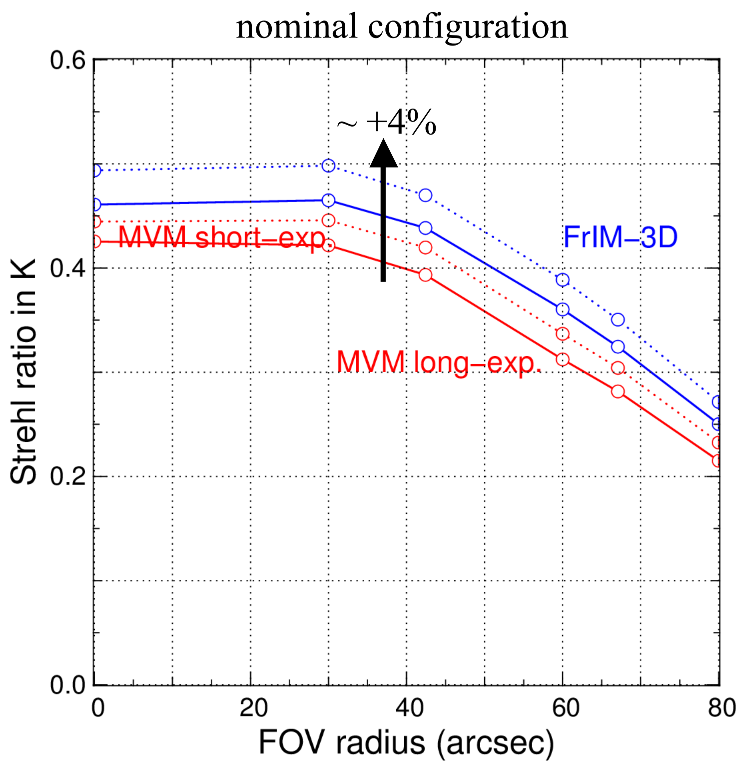
- No matching model of errors on data
  - ⇒ calibration needed
- For a quick calibration:
  - 100 loops
  - LGS can measure tip/tilt => NGS data negligible
  - no spot elongation
- Scaling at optimum: ~ x10

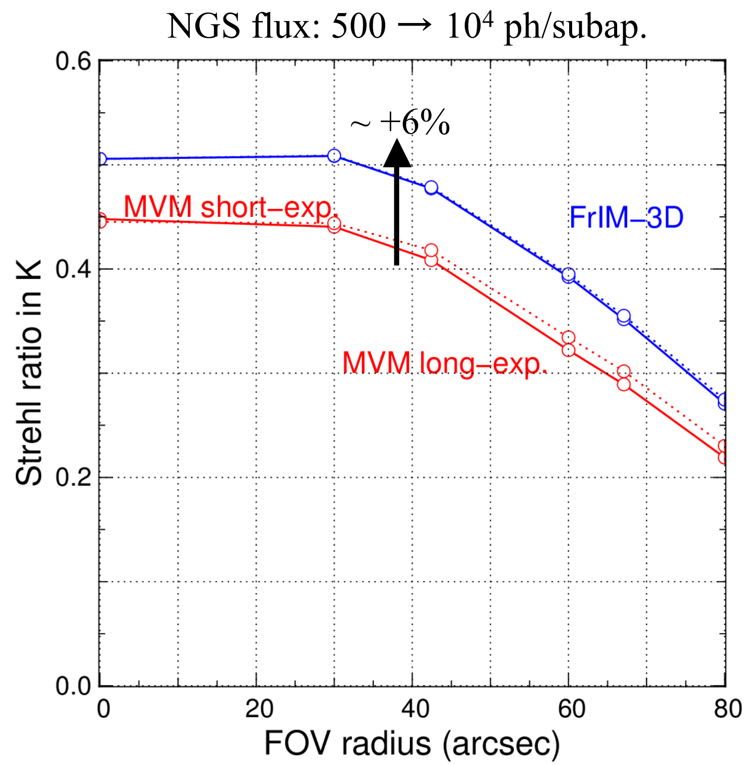
Calibration of noise / NGS



- No matching model of errors on data
  ⇒ calibration needed for NGS
- For a quick calibration:
  - 100 loops
- But : no signal on low orders !
- Vibration added on the telescope
  - tip/tilt = circular path in the focal plane
  - Ø 1 λ/D

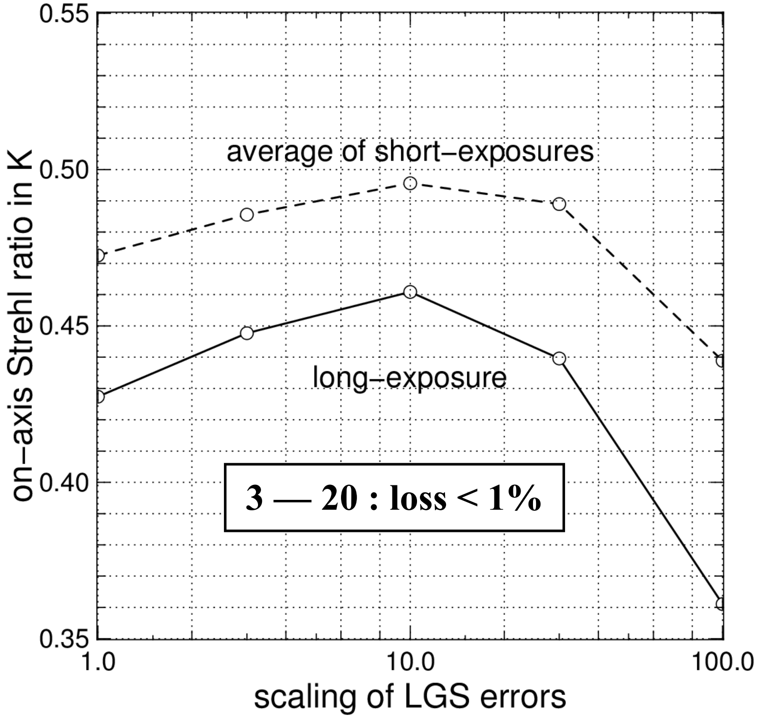
Performances & comparison

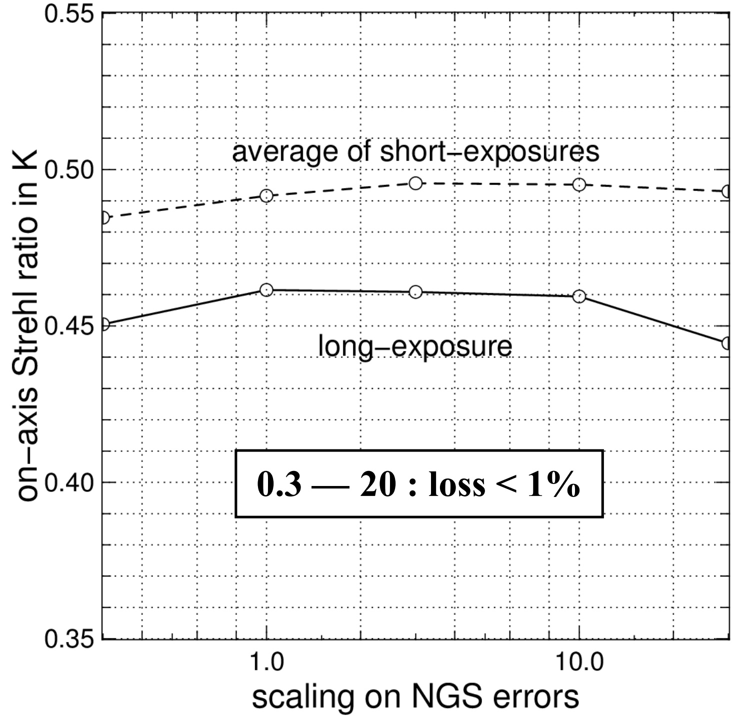




- Comparison with reference method on Octopus: "MVM"
  - use of interaction matrix, modal filtering, priors, different gains LGS/NGS, …
- ~ same difficulty with PSF stabilization (plate scale modes)
  - cause: NGS noise level

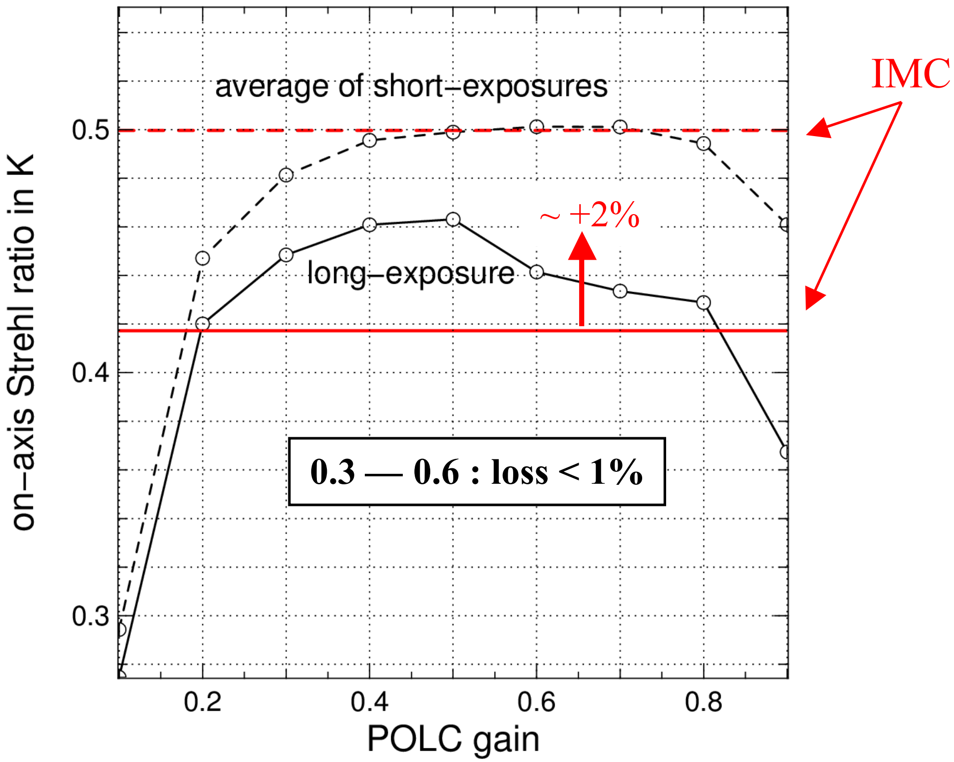
Sensitivity to calibrated values





- Performances not very sensitive to scaling mismatch
- Model of the noises would be helpfull

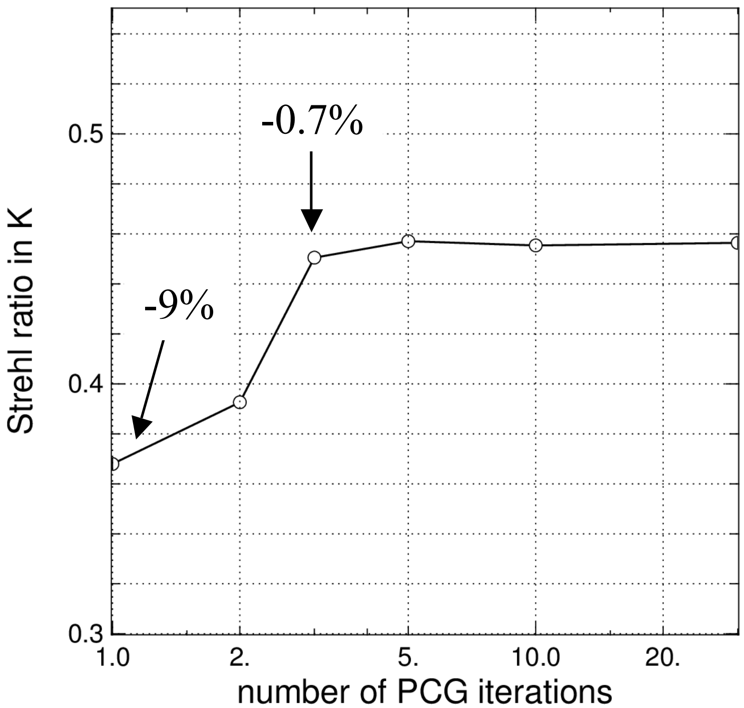
Sensitivity to POLC gain & IMC



- POLC gain does not need to be very accurate.
- LGS (short exp.):
  - IMC is as good as POLC
- NGS (long exp.):
  - improvement is 2% only from IMC
- Needs for a lower gain for low-order modes.

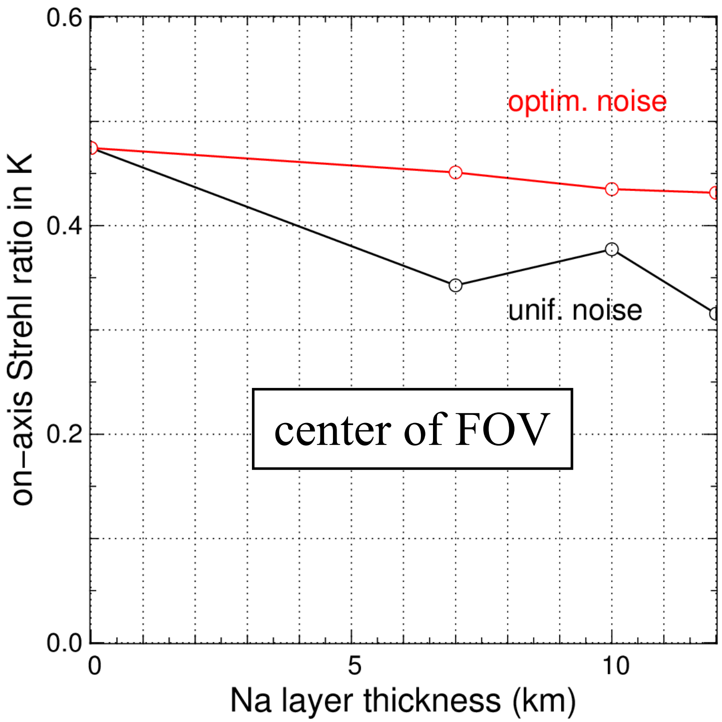
POLC = pseudo-open loop control
IMC = internal model control

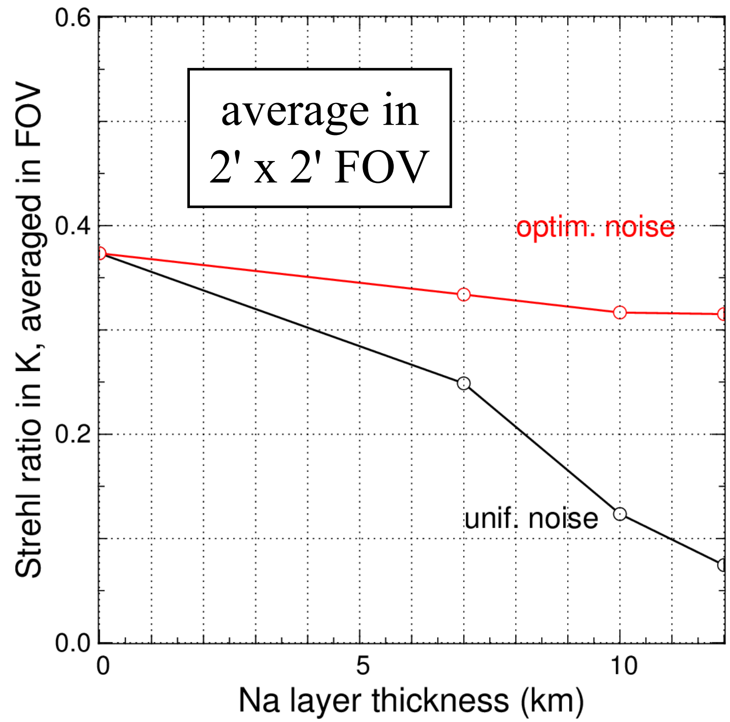
Number of PCG iterations



- Preconditioned conjugate gradient for reconstruction
- losses:
  - 3 iterations : < 1%
  - 1 iteration : ~ 10 %
- => 3 iterations is still enough.

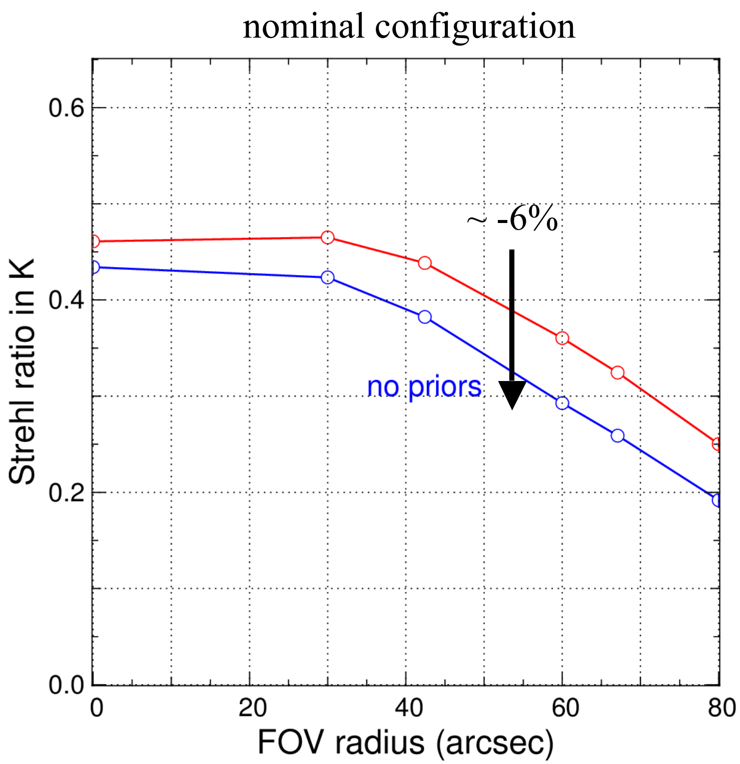
Effect of spot elongation

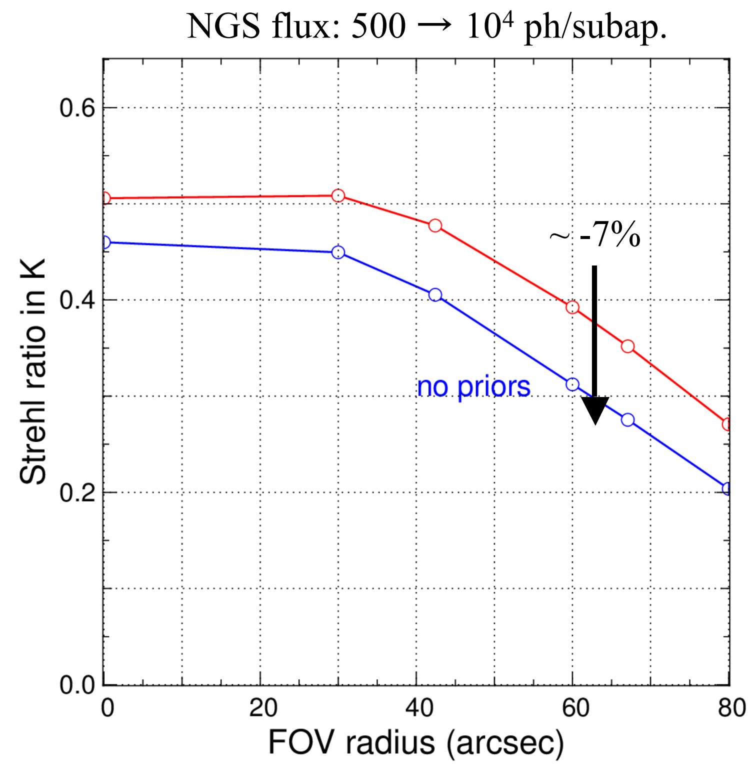




- LGS centroiding with CoG, and RON=0
- Noise model not optimized yet
  - assume : variance proportional to elongation

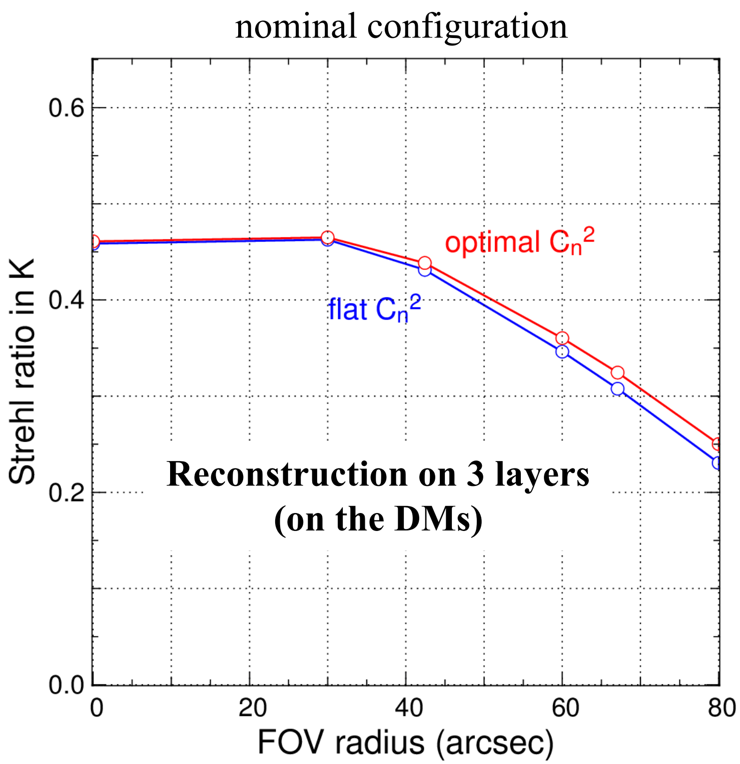
Usefulness of priors ?

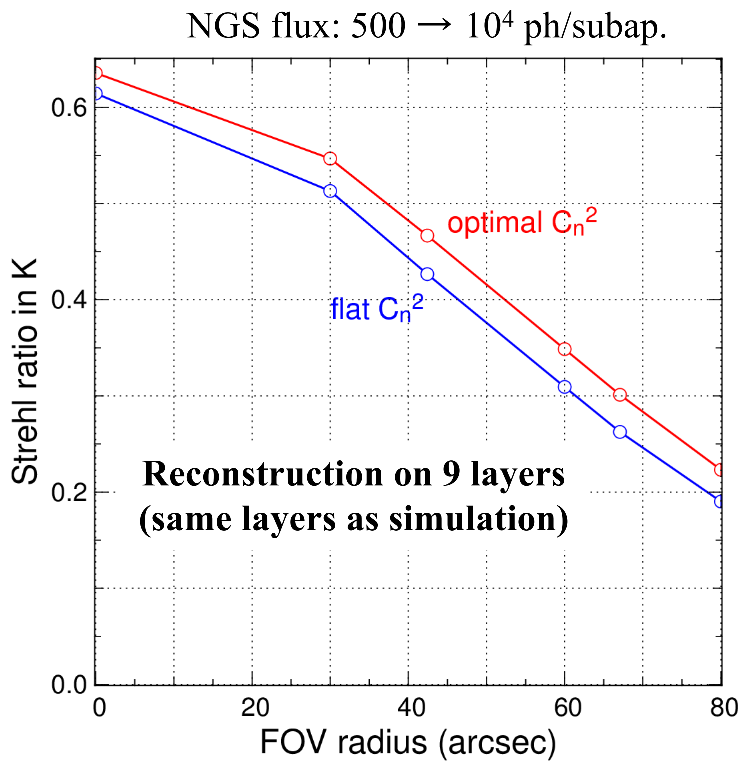




- Without priors:
  - minimum norm solution in fractal space
  - stopped before convergence ~ regularization

Sensitivity to priors on Cn2 weights





- Priors on Cn2 weights have very limited effect
  - especially when tomographic error is dominent
- Number/altitude of layers is significant

Conclusions

- First results of FrIM in closed-loop for MCAO
  - good quality of the reconstruction achieved
  - confirm that 3 iterations are enough for reconstruction
  - the losses for < 3 iterations are lower than expected
- Next steps
  - Improvements expected with a "better use of NGS photons"
    - different gains on low-order modes
    - split tomography
    - …
  - Revisit of the iterative optimization (→ RTC implementation)
  - Need of better noise models