Identification of system parameters during AO-corrected observations

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Outline

1. Context & constraints
   a) towards AOF and the ELTs
   b) examples of sensitivity to misregistrations
   c) main goals

2. Criterion for parameters identification
   a) AO equations
   b) estimation method

3. First numerical results
   a) simulations on AOF-size AO
   b) on-going and future work

1. Context & constraints

a) Towards Adaptive Optics Facility (AOF) @ the VLT

- deformable secondary mirror (DSM)
- large : 1170 actuators / 40x40 subapertures
- no calibration source before the DSM
- **adaptive telescopes** / non-stationnary AO systems
  - atmospheric parameters, like Cn2 profile evolution
  - **system parameters, like misregistrations**

⇒ requires new calibration strategies

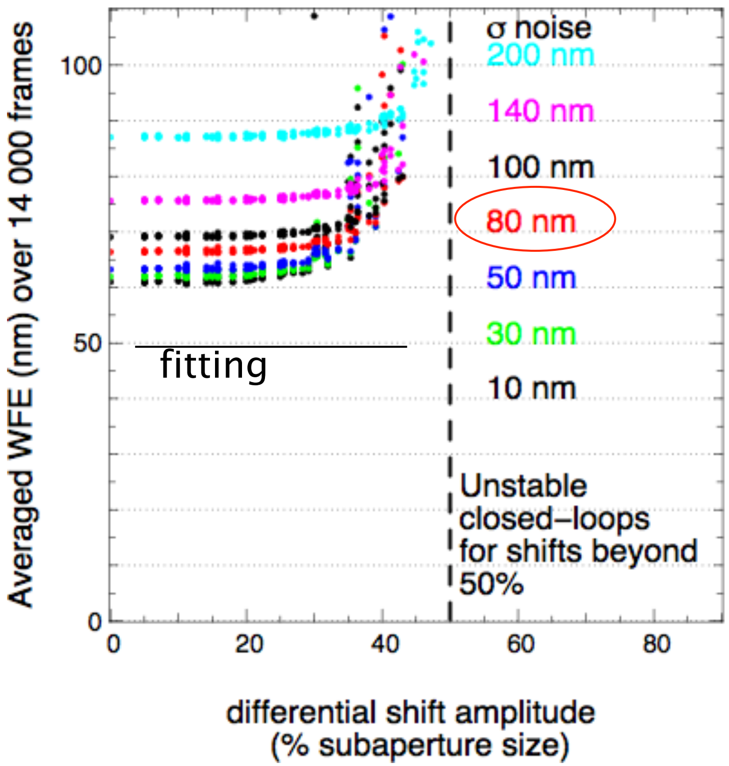
- pseudo-synthetic interaction matrix
- on-sky calibrations of long-term fixed parameters
- **on-sky identification during closed-loop AO at a minute-scale**

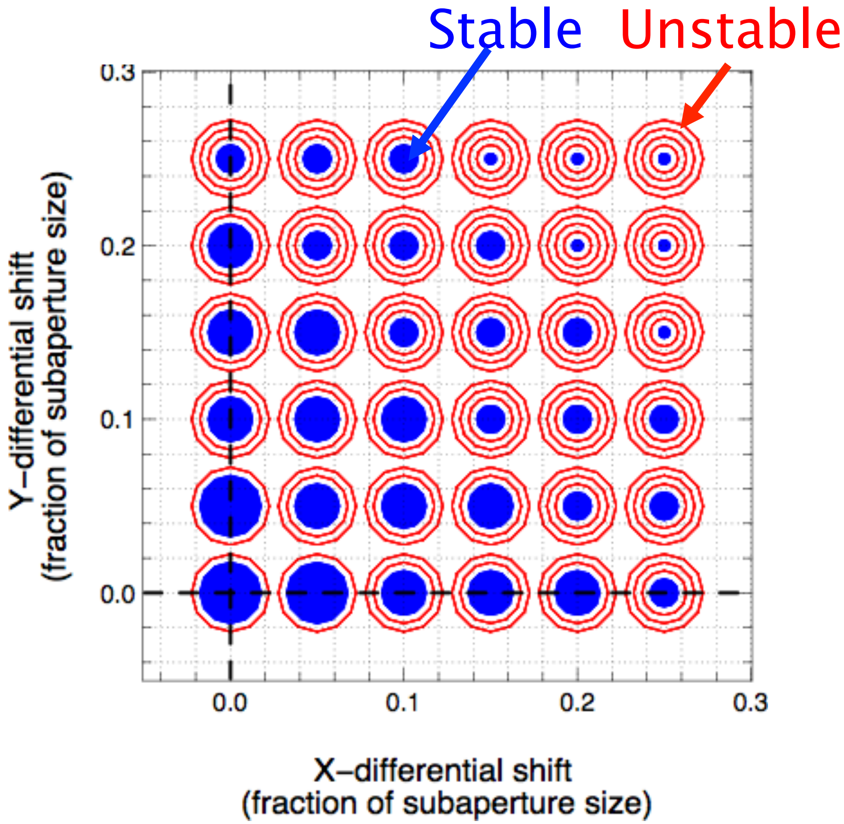
1. Context & constraints

b) examples of sensitivity to misregistrations

2D-shifts and rotation of the DM w.r.t. the WFS alignments

AOF-size SCAO but « square aperture » and Fried geometry

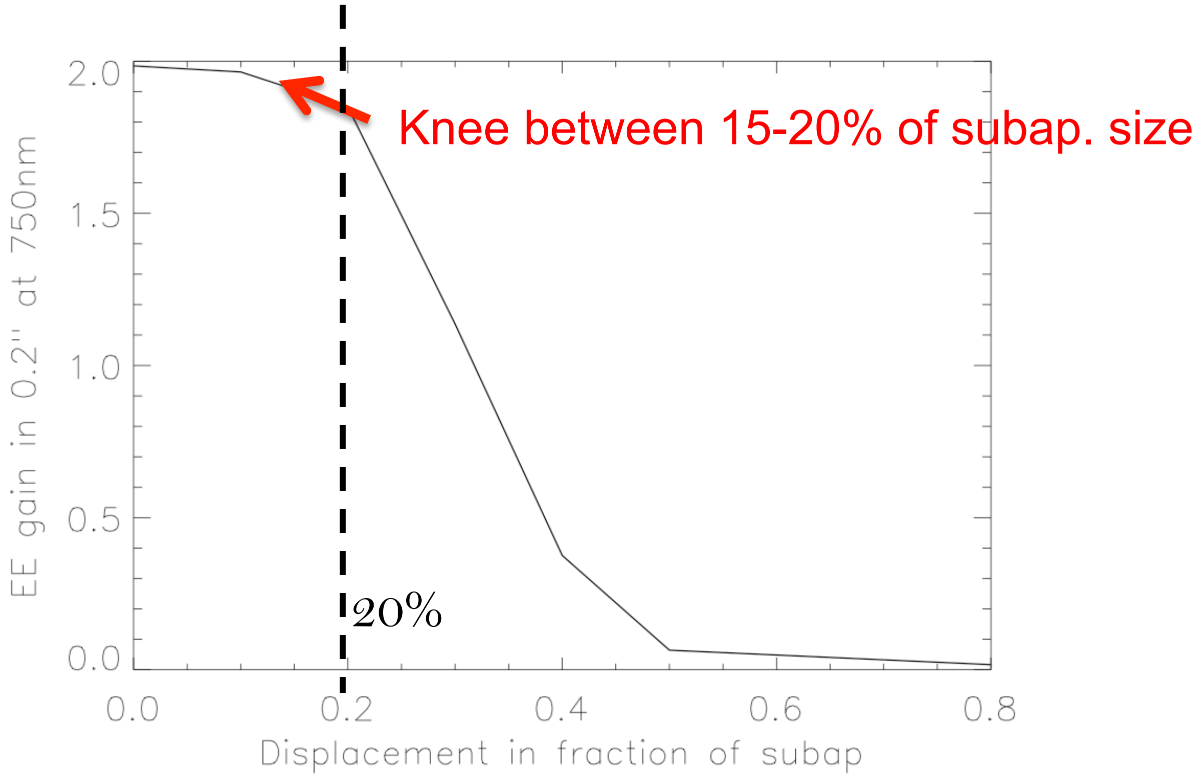




1. Context & constraints

b) examples of sensitivity to misregistrations

from AO performance analysis report of GALACSI (LTAO with AOF)



Remember:
For a given system, it depends on the reconstruction and control algorithms

1. Context & constraints

c) main goals

1. **estimation accuracy requirements**
   - AOF driver : better than 10% subaperture size
   - AO performance analysis report of GALACSI (LTAO with AOF)

2. **no additional disturbance introduced**
   - no impact on astrophysical data
   - fully exploit AO data

3. **numerical update of interaction matrix (IM) and control matrix (CM)**
   - identification ~ every minute
   - not moving the DM, but updating the pseudo synthetic IM/CM
   - only when misregistrations are larger than a threshold (lost frames)

2. Criterion for parameters identification

a) AO equations

- measurement equation

propag. & sensing model — interaction matrix — measurement noise

$$\boldsymbol{d}_k = \mathbf{S} \cdot \boldsymbol{w}_k - \mathbf{G}(\boldsymbol{p}) \cdot \boldsymbol{a}_k + \boldsymbol{e}_k$$

AO closed-loop data — turbulent atmosphere — DMs commands

  - ➢ parametric model for the interaction matrix
  - ➢ Note: time index different from usual writing -> clearer for identification

- control law in AOF real-time computer (tau = AO correction delay)

$$\boldsymbol{a}_{k+\tau} = \alpha \boldsymbol{a}_{k+\tau-1} + \beta \boldsymbol{a}_{k+\tau-2} + \gamma \mathbf{C} \cdot \boldsymbol{d}_k$$

2. Criterion for parameters identification

a) AO equations

- measurement equation

$$\boldsymbol{d}_k = \mathbf{S} \cdot \boldsymbol{w}_k - \mathbf{G}(\boldsymbol{p}) \cdot \boldsymbol{a}_k + \boldsymbol{e}_k$$

$$\boldsymbol{d}_k = -\mathbf{G}(\boldsymbol{p}) \cdot \boldsymbol{a}_k + \boldsymbol{z}_k$$

➢ parametric model for the interaction matrix

with $\boldsymbol{z}_k = \underbrace{\mathbf{S} \cdot \boldsymbol{w}_k}_{\text{contribution of turbulent atmosphere}} + \underbrace{\boldsymbol{e}_k}_{\text{measurement noise}}$

- measures the system parameters *through* the applied commands
- « noise » includes: turbulence and AO usual measurement noise

2. Criterion for parameters identification

b) criterion for parameters estimation

$$\boldsymbol{d}_k = -\mathbf{G}(\boldsymbol{p}) \cdot \boldsymbol{a}_k + \boldsymbol{z}_k$$

⇒ **non-linear fitting method**

$$f(\boldsymbol{p}) = \frac{1}{2} \sum_{k=1}^{N} (\boldsymbol{d}_k + \mathbf{G}(\boldsymbol{p}) \cdot \boldsymbol{a}_k)^{\mathrm{T}} \cdot \mathbf{C}_{\boldsymbol{z}}^{-1} \cdot (\boldsymbol{d}_k + \mathbf{G}(\boldsymbol{p}) \cdot \boldsymbol{a}_k)$$

???

2. Criterion for parameters identification

b) criterion for parameters estimation

$$\boldsymbol{d}_k = -\mathbf{G}(\boldsymbol{p}) \cdot \boldsymbol{a}_k + \boldsymbol{z}_k$$

$\Rightarrow$ **non-linear fitting method**

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???

main issues:

- on-sky **calibration** approaches do not apply, since we do not choose the applied commands
- applied commands are almost the inverse of the turbulence (which is now a « noise » source) => strongly correlated

2. Criterion for parameters identification

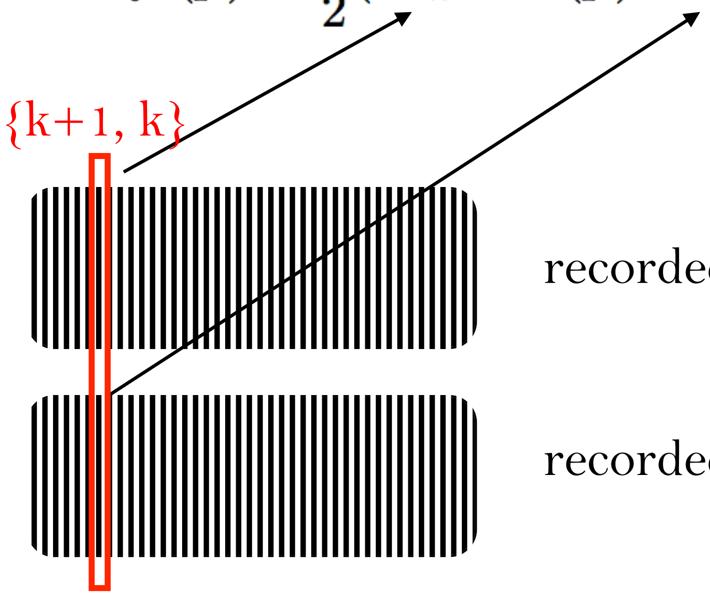
b) Criterion for parameters estimation

$$\boldsymbol{d}_k = -\mathbf{G} \cdot \boldsymbol{a}_k + \boldsymbol{z}_k \longrightarrow \begin{aligned} \delta\boldsymbol{d}_k &= \boldsymbol{d}_{k+1} - \boldsymbol{d}_k \\ &= -\mathbf{G} \cdot \delta\boldsymbol{a}_k + \delta\boldsymbol{z}_k \end{aligned}$$

⇒ **non-linear fitting method**

⇒ aim is to have decorrelated signal and noise (commands increments w.r.t. turbulence increments)

$$f_1(\boldsymbol{p}) = \frac{1}{2}(\delta\boldsymbol{d}_k + \mathbf{G}(\boldsymbol{p}) \cdot \delta\boldsymbol{a}_k)^{\mathrm{T}} \cdot \mathbf{C}_{\delta z}^{-1} \cdot (\delta\boldsymbol{d}_k + \mathbf{G}(\boldsymbol{p}) \cdot \delta\boldsymbol{a}_k)$$



recorded AO data history

recorded AO commands history

2. Criterion for parameters identification

b) Criterion for parameters estimation

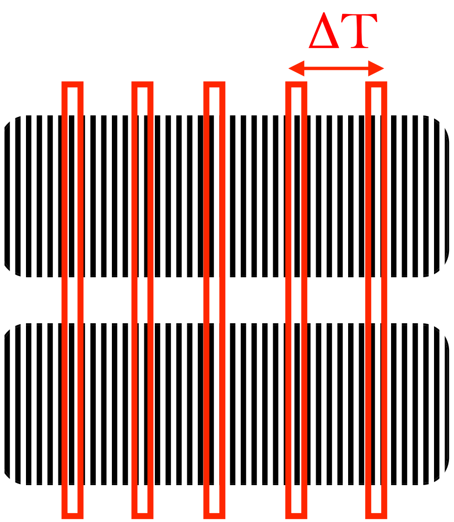
$$\boldsymbol{d}_k = -\mathbf{G}\cdot\boldsymbol{a}_k + \boldsymbol{z}_k \quad \longrightarrow \quad \begin{aligned}\delta\boldsymbol{d}_k &= \boldsymbol{d}_{k+1} - \boldsymbol{d}_k\\ &= -\mathbf{G}\cdot\delta\boldsymbol{a}_k + \delta\boldsymbol{z}_k\end{aligned}$$

⇒ **non-linear fitting method**

⇒ aim is to have decorrelated signal and noise (commands increments w.r.t. turbulence increments)

$$f_{N,\Delta T}(\boldsymbol{p}) = \frac{1}{2}\sum_{k=1}^{N}(\delta\boldsymbol{d}_{k\Delta T} + \mathbf{G}(\boldsymbol{p})\cdot\delta\boldsymbol{a}_{k\Delta T})^{\mathrm{T}}\cdot\mathbf{C}_{\delta z}^{-1}\cdot(\delta\boldsymbol{d}_{k\Delta T} + \mathbf{G}(\boldsymbol{p})\cdot\delta\boldsymbol{a}_{k\Delta T})$$

$$\boldsymbol{p}^* = \mathrm{Arg\ min}_p\ f_{N,\Delta T}(\boldsymbol{p})$$



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main difficulties :

- on-sky **calibration** approaches do not apply, since we do not choose the applied commands
- very good AO correction mainly means poor signal-to-noise ratio for identification

2. Criterion for parameters identification

b) Criterion for parameters estimation

$$\boldsymbol{d}_k = -\mathbf{G} \cdot \boldsymbol{a}_k + \boldsymbol{z}_k$$

$\Rightarrow$ **non-linear fitting method**

$$\begin{aligned} \delta \boldsymbol{d}_k &= \boldsymbol{d}_{k+1} - \boldsymbol{d}_k \\ &= -\mathbf{G} \cdot \delta \boldsymbol{a}_k + \delta \boldsymbol{z}_k \end{aligned}$$

$$f_{N,\Delta T}(\boldsymbol{p}) = \frac{1}{2} \sum_{k=1}^{N} (\delta \boldsymbol{d}_{k\Delta T} + \mathbf{G}(\boldsymbol{p}) \cdot \delta \boldsymbol{a}_{k\Delta T})^{\mathrm{T}} \cdot \mathbf{C}_{\delta z}^{-1} \cdot (\delta \boldsymbol{d}_{k\Delta T} + \mathbf{G}(\boldsymbol{p}) \cdot \delta \boldsymbol{a}_{k\Delta T})$$

advantages:

- o weighting $\mathbf{C}_{\delta z}^{-1}$ is much closer to a diagonal matrix (even if 2 times the measurement noise level)
- o $\delta \boldsymbol{z}_{k\Delta T}$ and $\delta \boldsymbol{a}_{k\Delta T}$ not much correlated (because AO correction delay)
- o But is $\mathbf{G}(\boldsymbol{p}) \cdot \delta \boldsymbol{a}_{k\Delta T}$ informative enough?

3. Numerical results

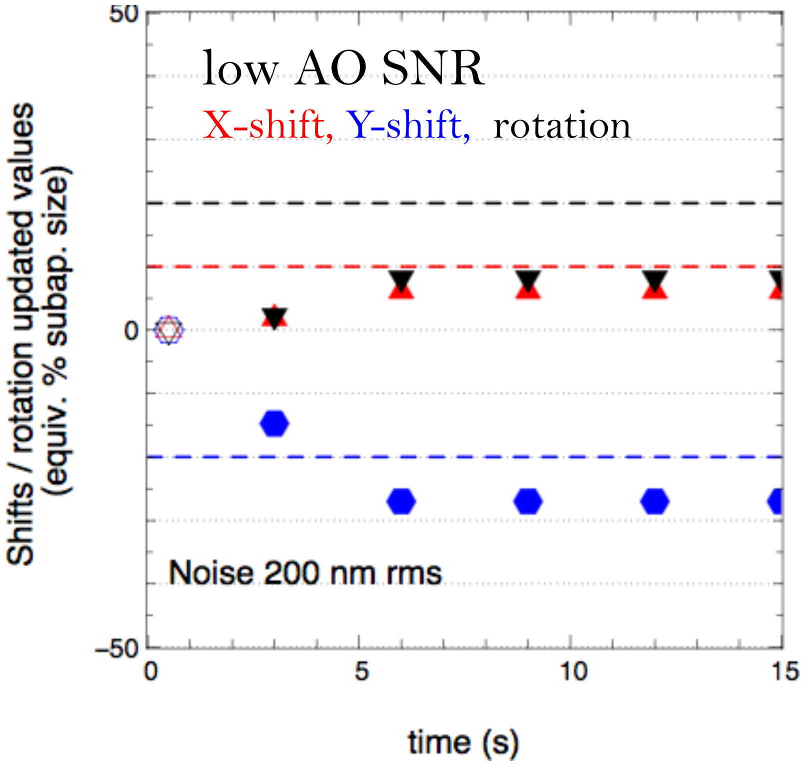
a) Simulations

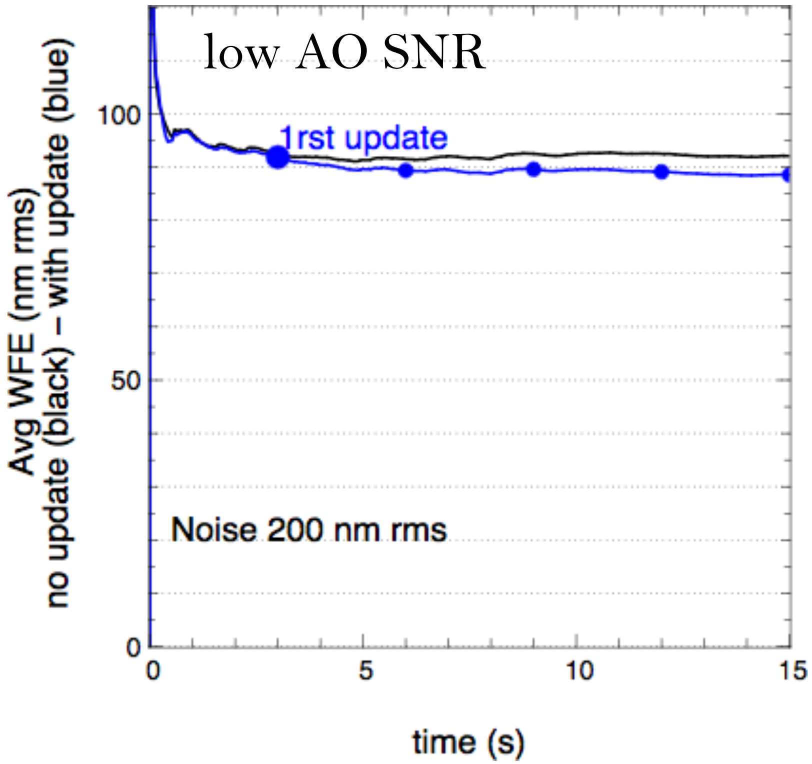
- first checks with simulations of a 40x40 « square aperture » SCAO
  - parameters = 2D-shifts and rotation angle
  - ΔT = 23 frames
  - N = 130
  - residuals do not include information from subapertures on the edges
  - Levenberg-Marquardt algorithm modified with « Trust region » approach
  - 2 iterations
  - large # residuals but computations are easy to highly parallelize

$$f_{N,\Delta T}(\boldsymbol{p}) = \frac{1}{2}\sum_{k=1}^{N}(\delta \boldsymbol{d}_{k\Delta T} + \mathbf{G}(\boldsymbol{p})\cdot \delta \boldsymbol{a}_{k\Delta T})^{\mathrm{T}} \cdot \mathbf{C}_{\delta z}^{-1} \cdot (\delta \boldsymbol{d}_{k\Delta T} + \mathbf{G}(\boldsymbol{p})\cdot \delta \boldsymbol{a}_{k\Delta T})$$

3. Numerical results

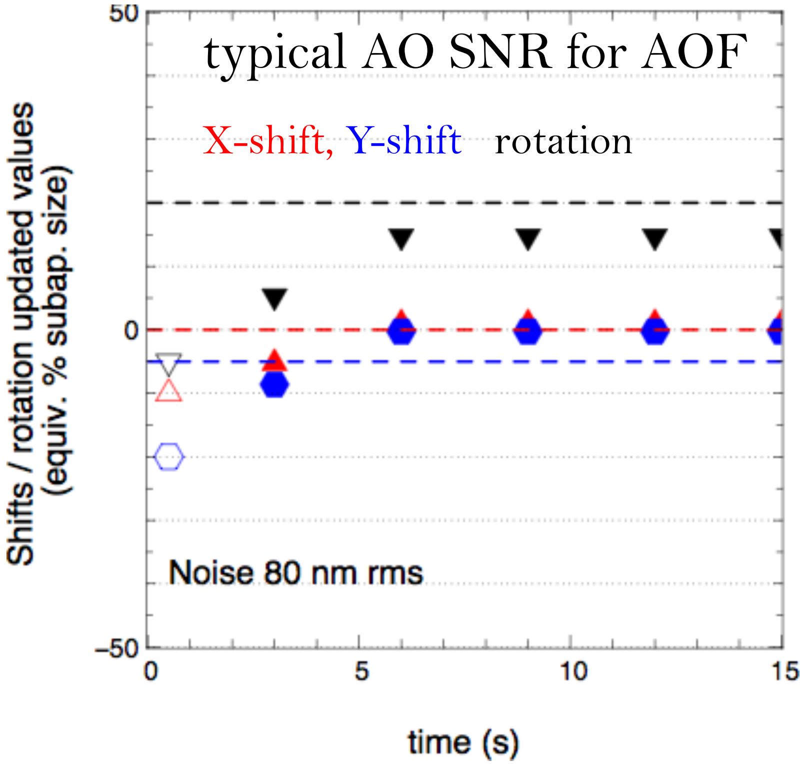
- ✓ medium initial misregistrations
- ✓ convergence of the method
- ✓ improved parameters knowledge by identification
- ✓ remaining error related to the threshold chosen for effective update of the CM
- ✓ small benefit observed in terms of WFE (measurement noise dominates)

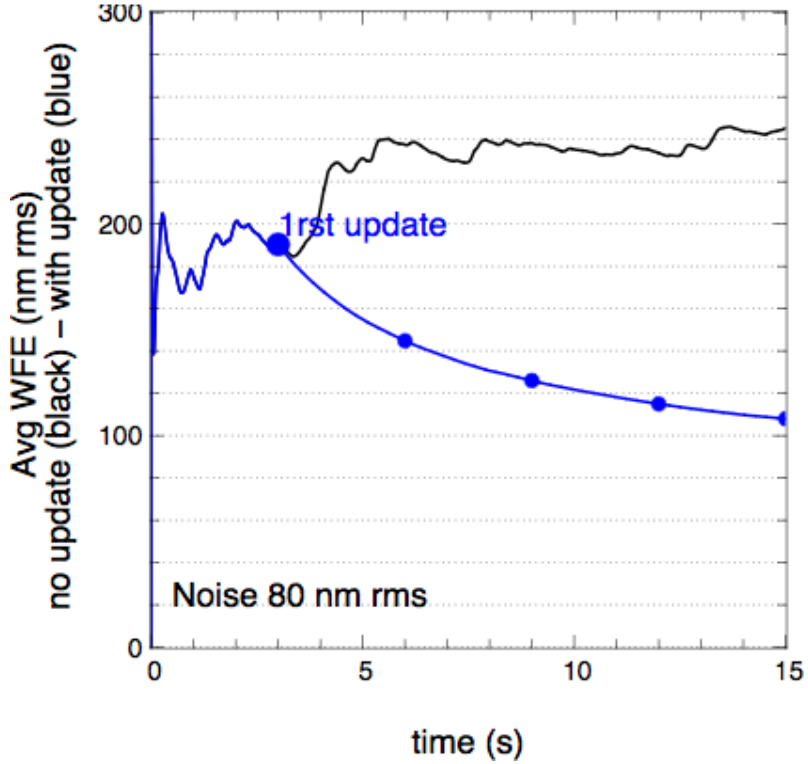




3. Numerical results

- ✓ very large initial misregistrations
- ✓ requires 0.1 integrator gain to close the loop
- ✓ convergence of the method
- ✓ stabilization of the AO correction
- ✓ significant benefit in terms of WFE

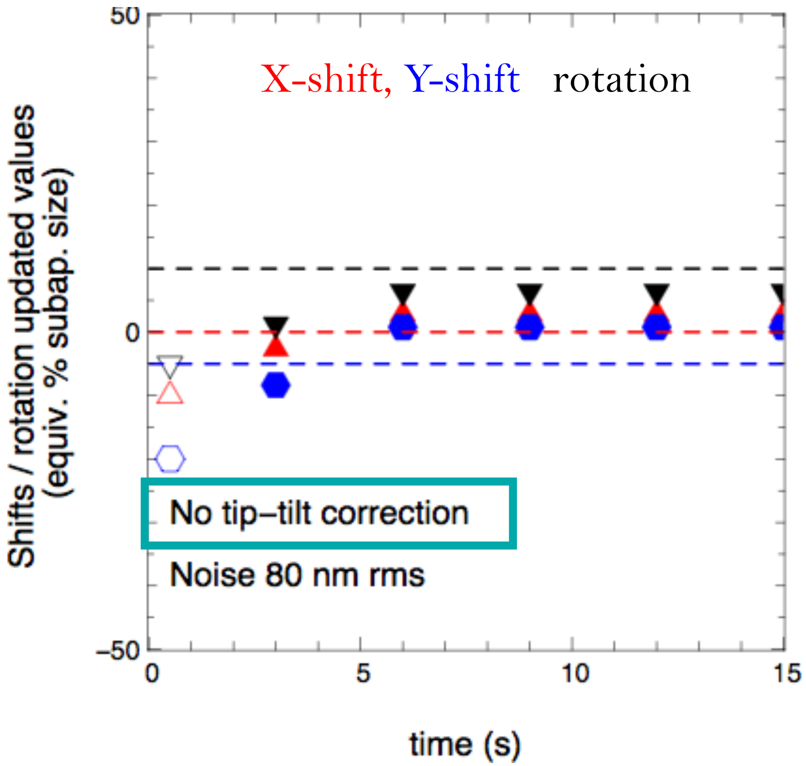




3. Numerical results

a) Simulations

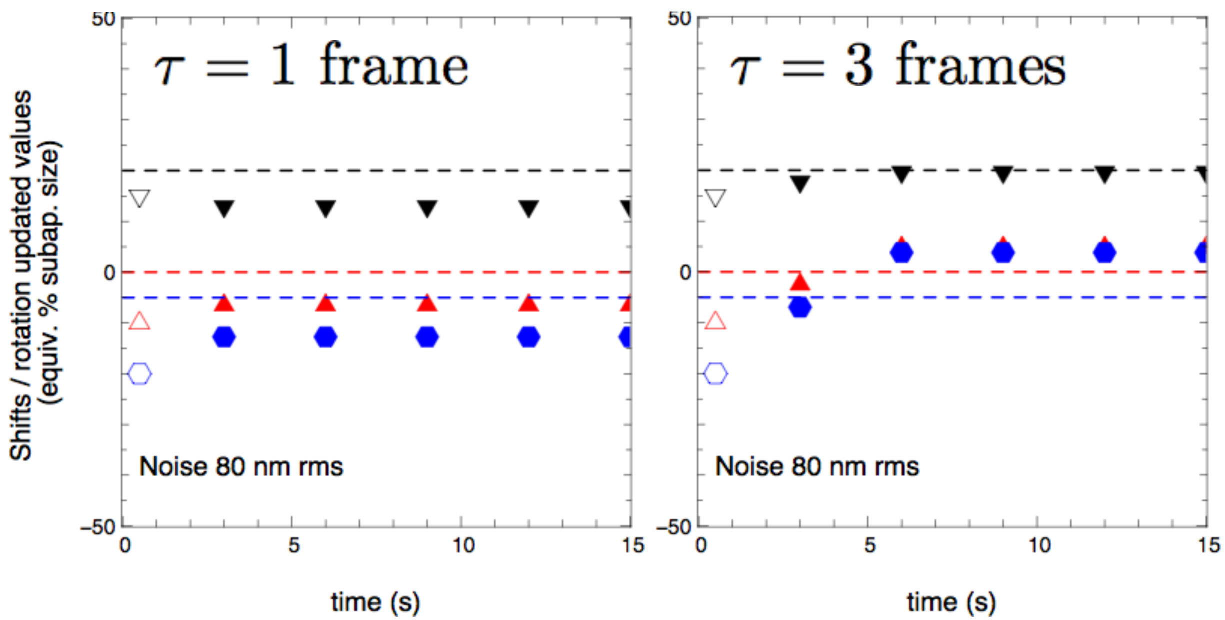
- o first checks with simulations of a 40x40 « square aperture » SCAO
  - ➢ estimation accuracy => ongoing theoretical analysis
  - ➢ closed-loop CM update after parameters identification
  - ➢ LGS-related issue: not considering the tip-tilt correction



3. Numerical results

a) Simulations

- first checks with simulations of a 40x40 « square aperture » SCAO
  - estimation accuracy => ongoing theoretical analysis
  - closed-loop CM update after parameters identification
  - LGS-related issue: not considering the tip-tilt correction
  - robustness to delay assumption error



estimation changes. Which diagnostic?

=>the criterion is minimum for the true delay value

3. Numerical results

b) on-going and future work

- simulations of AOF exact system (influence functions of its DM, no Fried geometry)

- confirm parallel theoretical analysis on estimation accuracy, w.r.t
  - atmospheric conditions,
  - noise level,
  - control parameters,
  - fitting parameters (ΔT, N, # of iterations, …)

- multi-LGS identification (LTAO & GLAO of the AOF)

Conclusion

- global estimation approach to identify system misregistrations during closed-loop AO-corrected observations

- goals driven by AOF requirements
  - estimation accuracy (~ 10% subaperture size for shifts)
  - numerical update of the CM when large misregistrations appear

- originality & assets
  - no additional disturbance => fully exploits AO data
  - computationally reasonable
  - can handle undetermined TT (low-orders) from LGS
  - robustness to uncertainty on AO-correction delay

- results
  - accuracy theoretical analysis on-going
  - first promising simulations results (& some NAOS data analysis)