MAORY LGS WFS trade-Off: Truncation and Regularization, and a few tricks

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What is the best size for the FOV of the sub-apertures of a LGSWFS ?

- I asked my bro-law who knows everything, this is his answer:

FOV =

ARCSEC

■ ■ ■ ■ ■

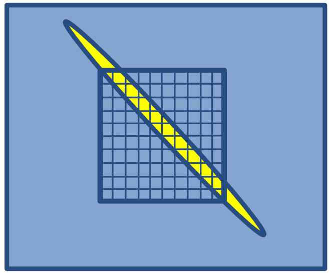
NOT SO BAD ! JUST WRONG BY A FACTOR OF 2 OR SO…

What size for MAORY LGSWFS FOV ?

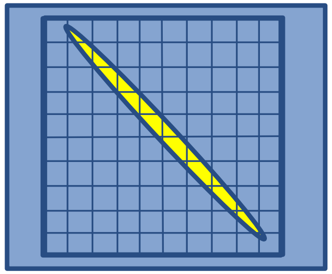
We want computation time < 10000 years
With Q-OCTOPUS

→ Quantization of FOV

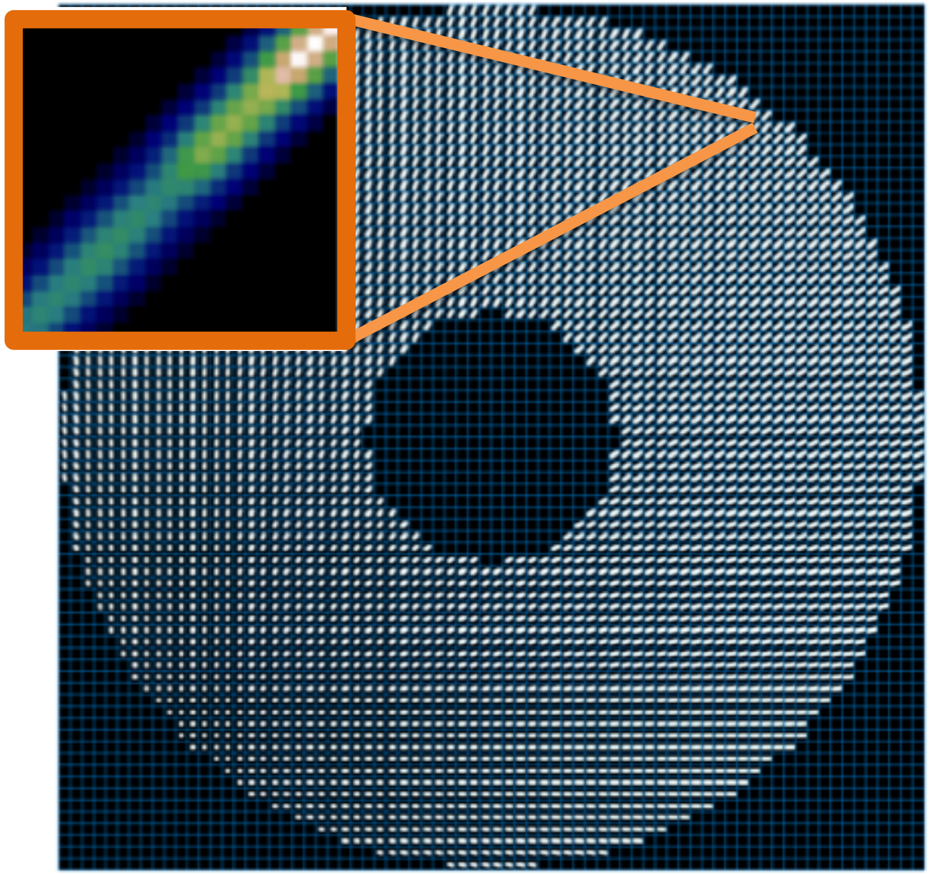
$$| \text{FOV} \rangle = \alpha \, | 10 \rangle + \beta \, | 15 \rangle + \gamma \, | 20 \rangle \quad \text{arcsec}$$



TRUNCATED ☹



UNDERSAMPLED ☹



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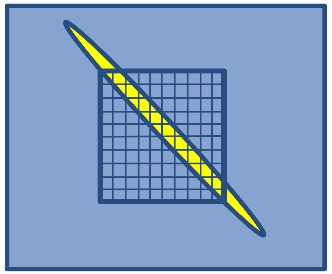
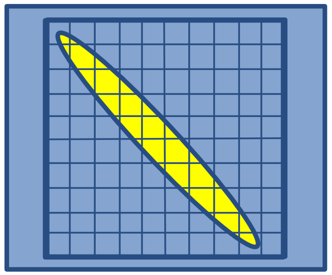
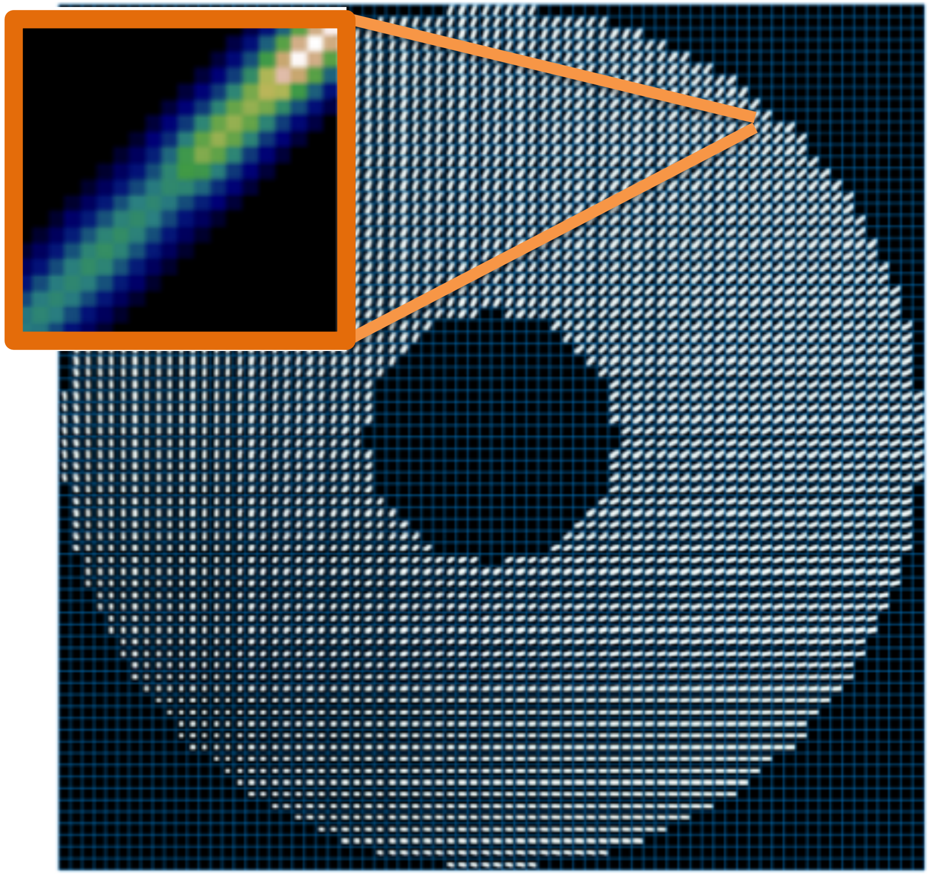


TRUNCATED ☹

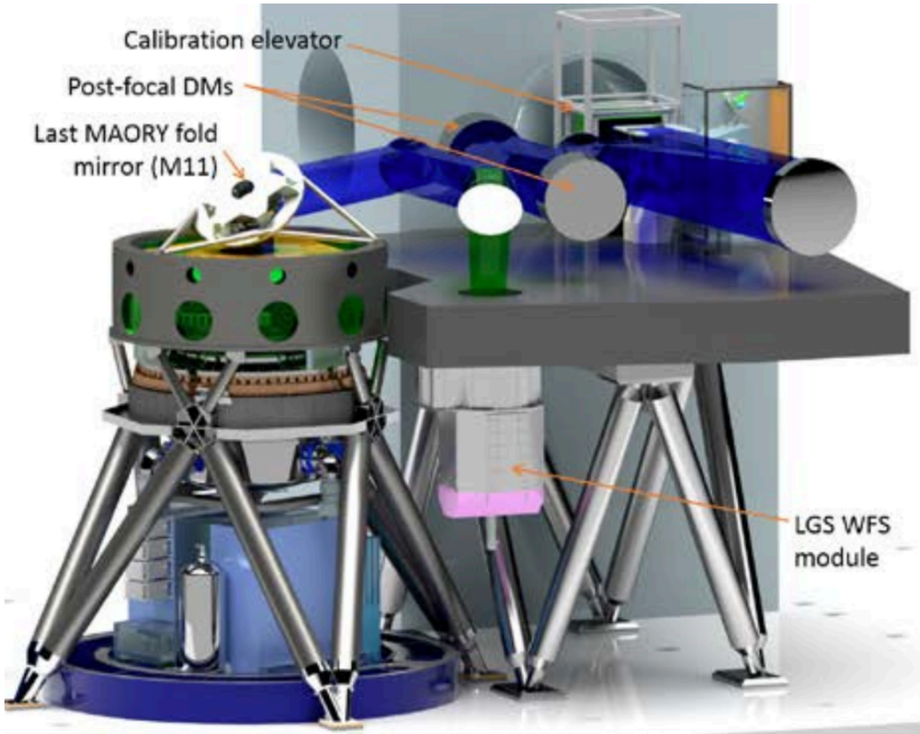


SPOT ENLARGED
ALL GOOD ☺



MAORY simulation case

Target SR(K) = 60% for simulations
(in center of FOV)



- 6 LGS WFS @ 45" radius
  - **Flux=470 photons** / sub-aperture (percentile 90%)
- 2 Post-Focal DMs
- **LISA → 10x10 pixels / sub-aperture**
  - **RON=3**
- 3 NGS WFSs looking at bright stars
- 35 layers profile, r**0=0.157m** @ zenith L0=25 m
- Turbulence profile:
  - **Cn2 mean**
  - **Cn2 bad** (percentile 90%)
- Na profile:
  - **Na Mean**: Multi-Peak
  - **Na Bad**: Top-Hat-Peak,
- POLC-MMSE reconstruction 6 layers : OCTOPUS+FRIM

LGS SH WFS design: trade-off space

LGS SPOT SHAPING

REGULARISATION

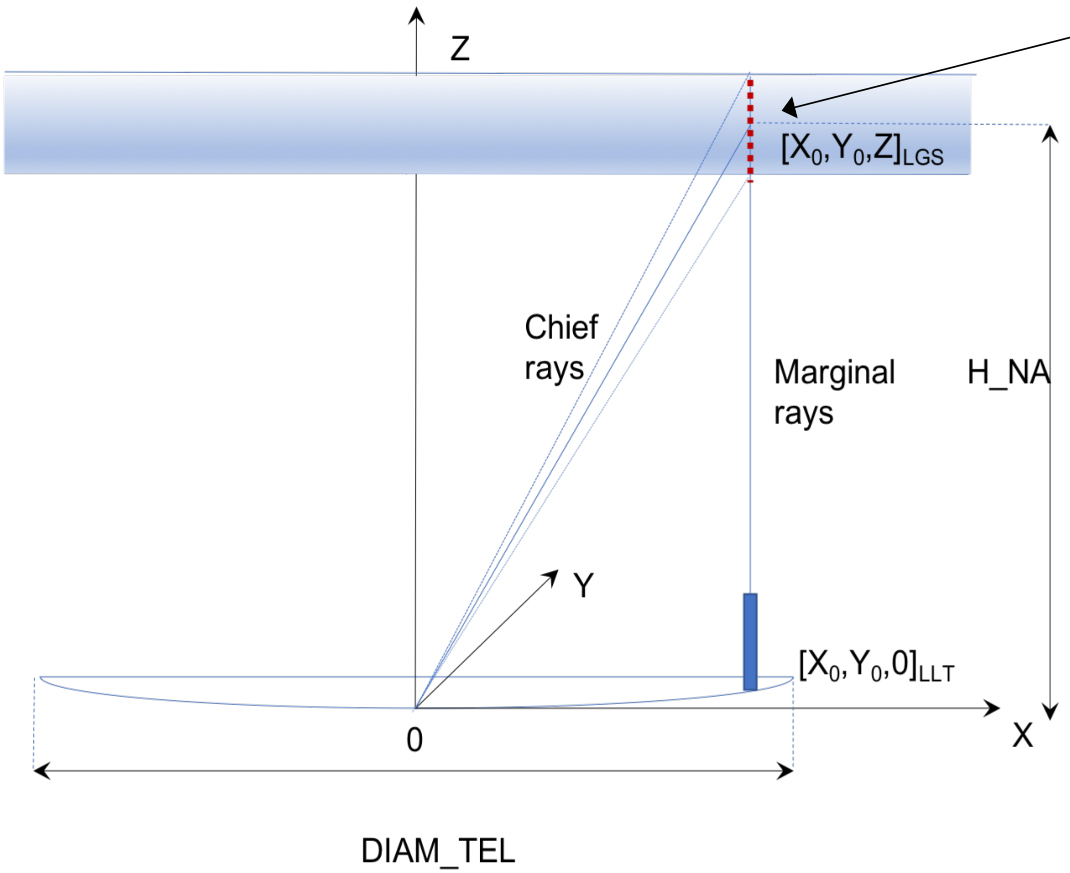
Trade-off philosophy

- Optimization under constraint
- Keep it **simple** !
- Favour **robustness**
- **Avoid** when possible the necessity for **calibration or prior knowledge**
- Prefer **static tuning** to online update

CLASSICAL CoG
THRESHOLDING
WINDOWING

NON-LINEARITY
QUASI STATIC BIAS
NOISE

When Na profile varies (and turbulence WF=0)
A LGS SH in the Telescope sees only Tip-Tilt and Defoc



Each point **j** with intensity $\mathbf{I_j}$ in LGS cigare is seen from M1 as Wavefront with only 3 components

$Z1_j=Tip_j$

$Z2_j=Tilt_j$

$Z3_j=Focus_j$

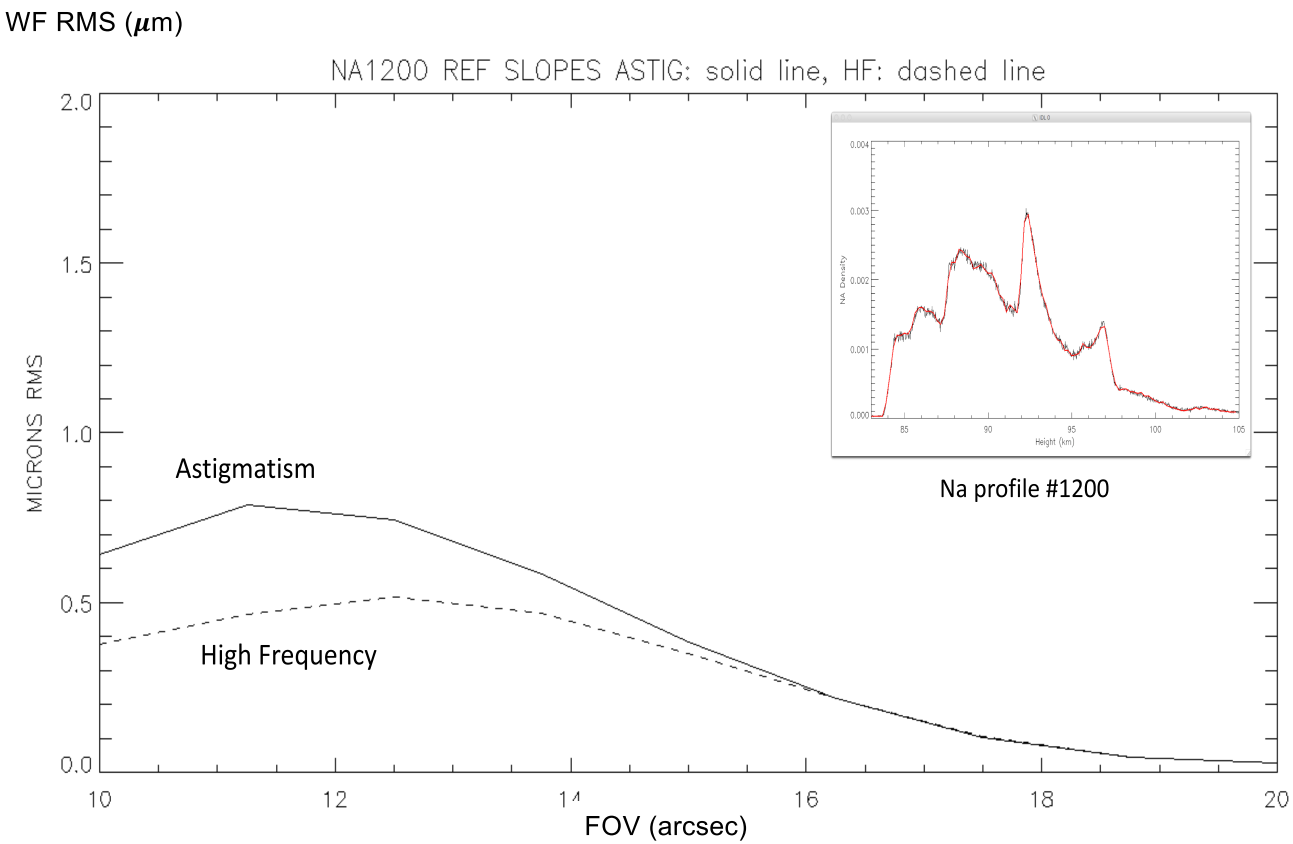
The LGS SH measures the ponderated linear combination of the 3 Zi_j

Only TT and Defoc = $F(I_{Na})$
AND THOSE ARE FILTERED!

$$\mathbf{WF}(I_{Na}) = 1/N \sum_{j=0}^{N} \sum_{i=1}^{3} I_j\, \mathbf{Zi_j}$$

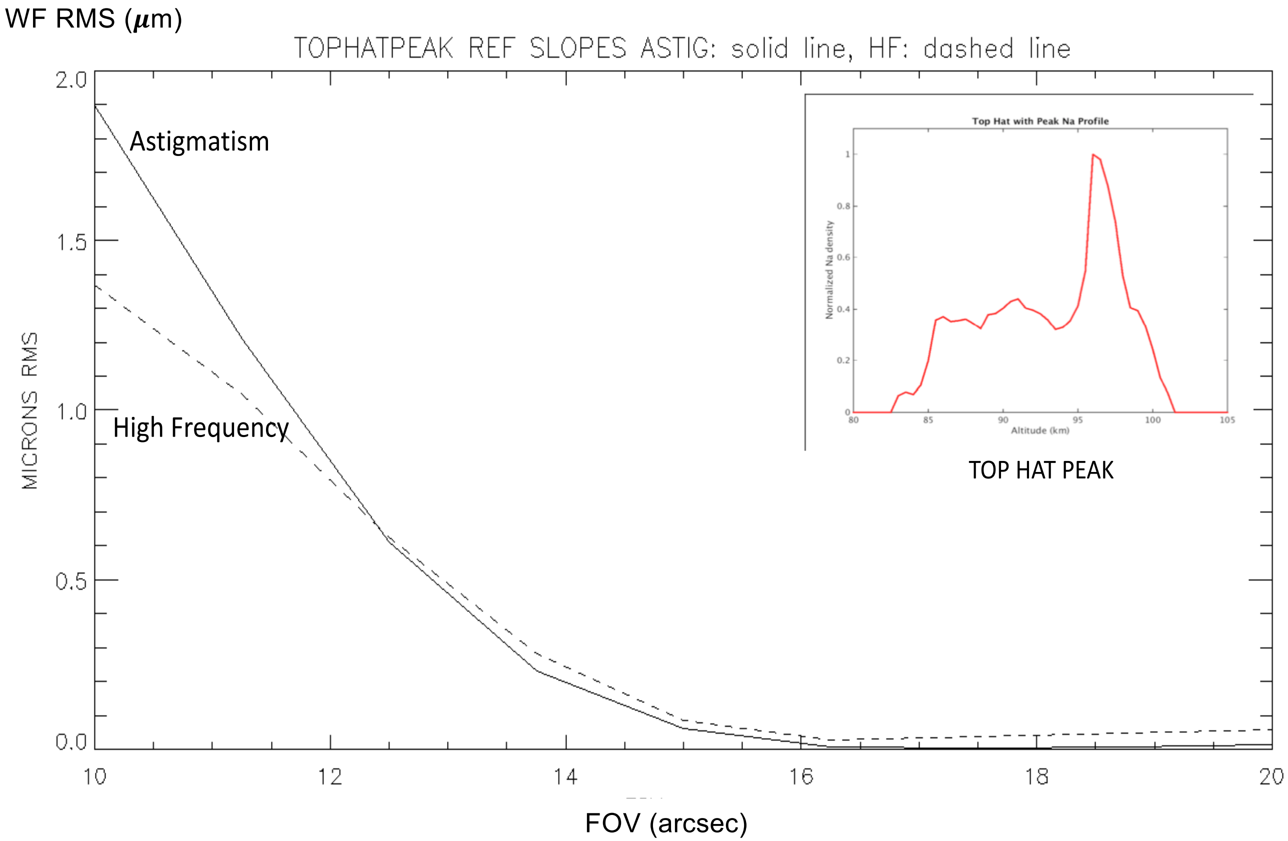
Q-Static Bias: Single LGS Recons^{ted} WF for Flat WF

- Gentle Na profile

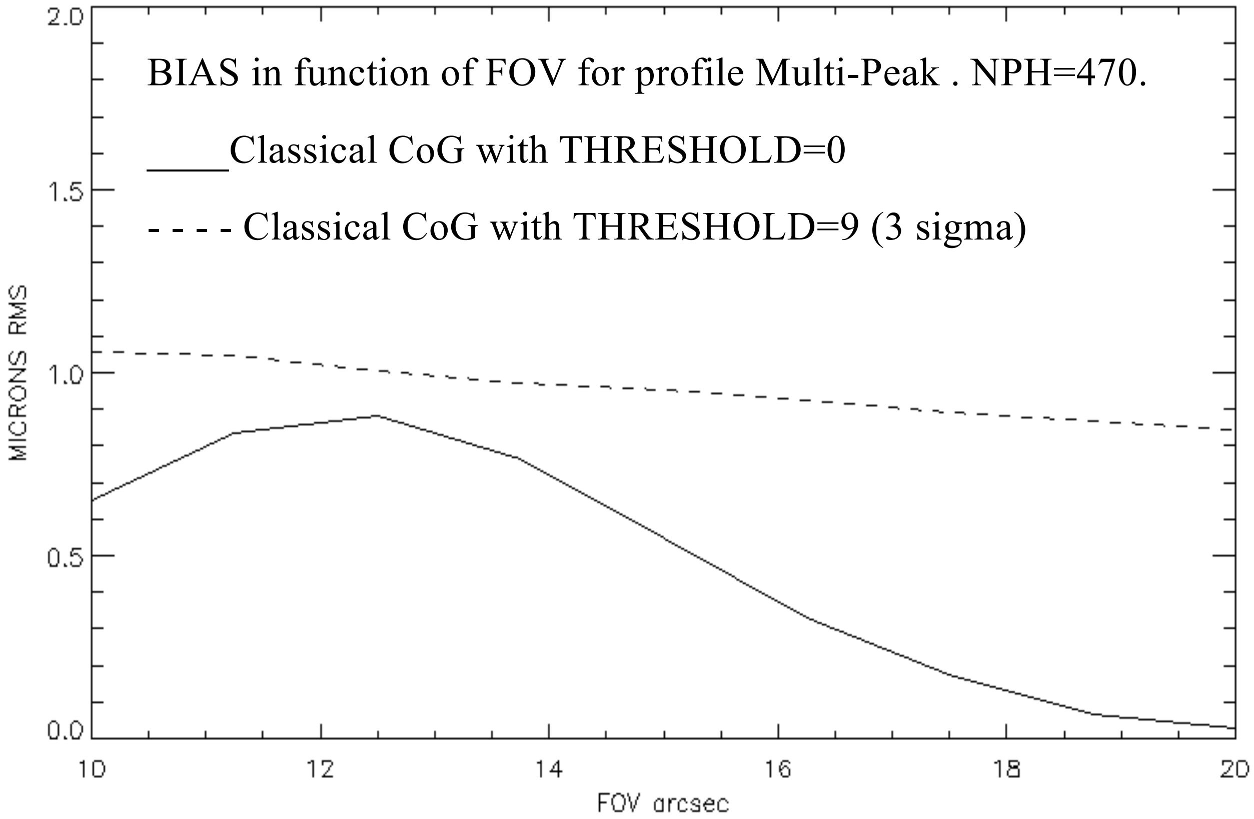


Q-Static Bias: Single LGS Recons^{ted} WF for Flat WF

- Extreme Na profile (depends from which perspective)



Q-static bias: impact of CoG+THRESHOLD



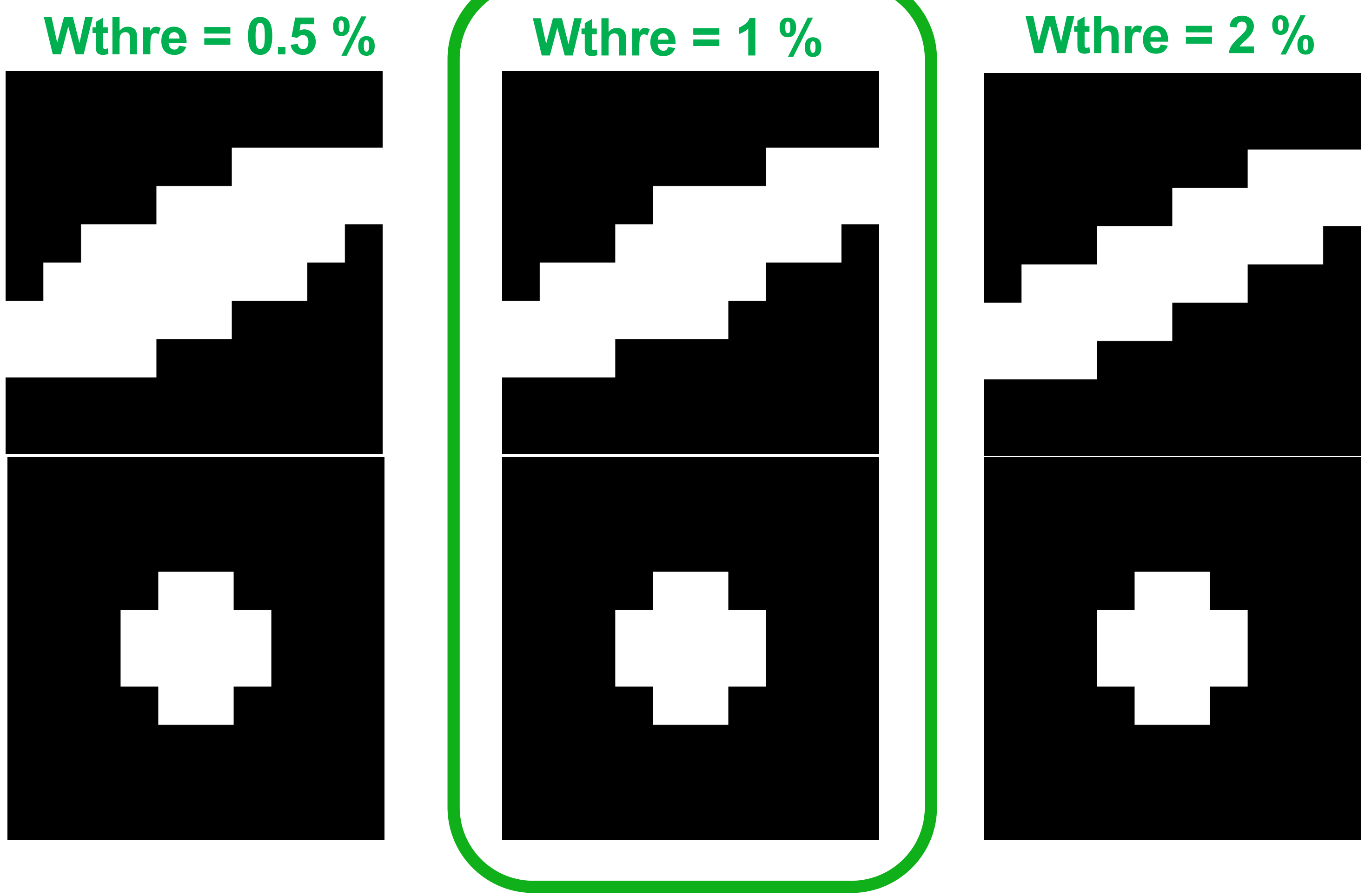
Using a CoG with THRESHOLD to reject RON is equivalent to truncating the Spots.

All benefits of having a small Bias at large FOV are lost

Binary windows to damp RON

Binary windows for most elongated spots in function of parameter Wthre

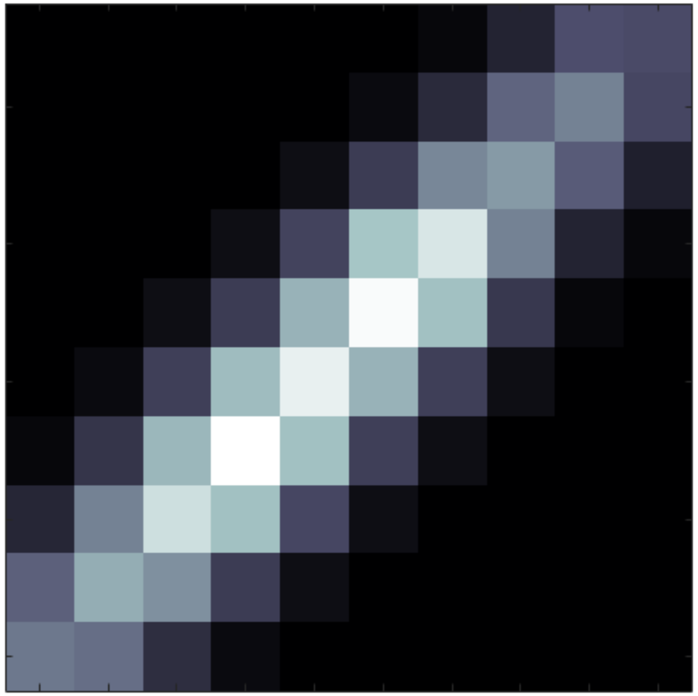
Binary windows for NON elongated spots in function of parameter Wthre



(User's) Choice of Truncated sub-apertures: **Projection Regularization** (tG: threshold, Gauss. model)

Parameters tuning recipe:

1. Noise variance: $\boldsymbol{\sigma_n}$ uniform in P
2. Elongation: $\boldsymbol{\beta}$ non uniform in P
3. Elongation discard threshold: ***tG***



$$[\mathbf{C}_n]^{-1}_{2\times 2,\mathrm{cut}} = \frac{\eta}{\sigma_n^2\,\beta^2}\begin{pmatrix}\beta_2^2 & -\beta_1\beta_2 \\ -\beta_1\beta_2 & \beta_1^2\end{pmatrix}$$

C_n: Measurements covariance

Michel Tallon and Clementine Bechet, 2009

OCTOPUS UNITS

- $\boldsymbol{\sigma_n}$: noise on slopes (no elong): **nm**
  - NPH,RON, FWHM (transverse)
- **βmax:** elong. max **km**
  - 10 km → ~10 arcsec
- **tG** **tG / X%**
  - tG such X% sub-ap truncated
  - (note real Values in plots are in other units that are unprocatical)

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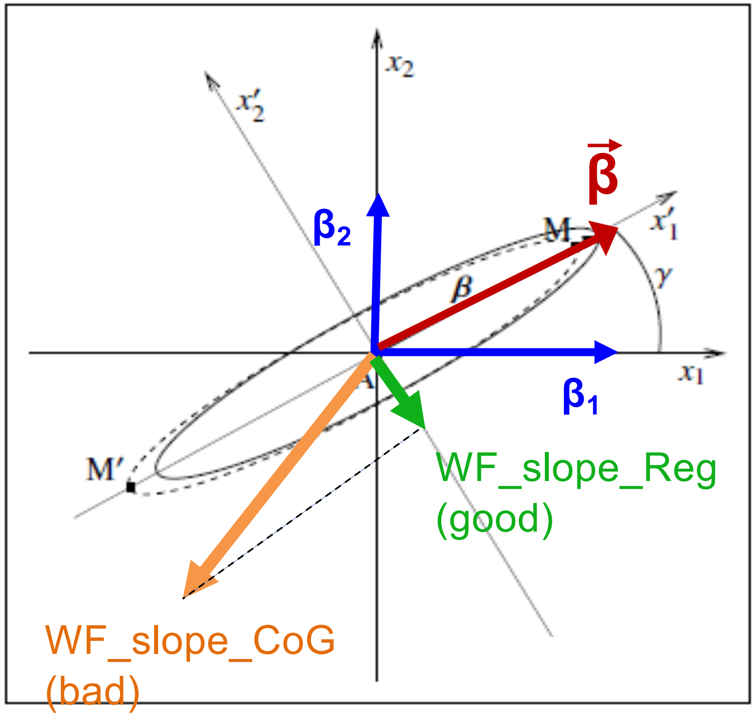

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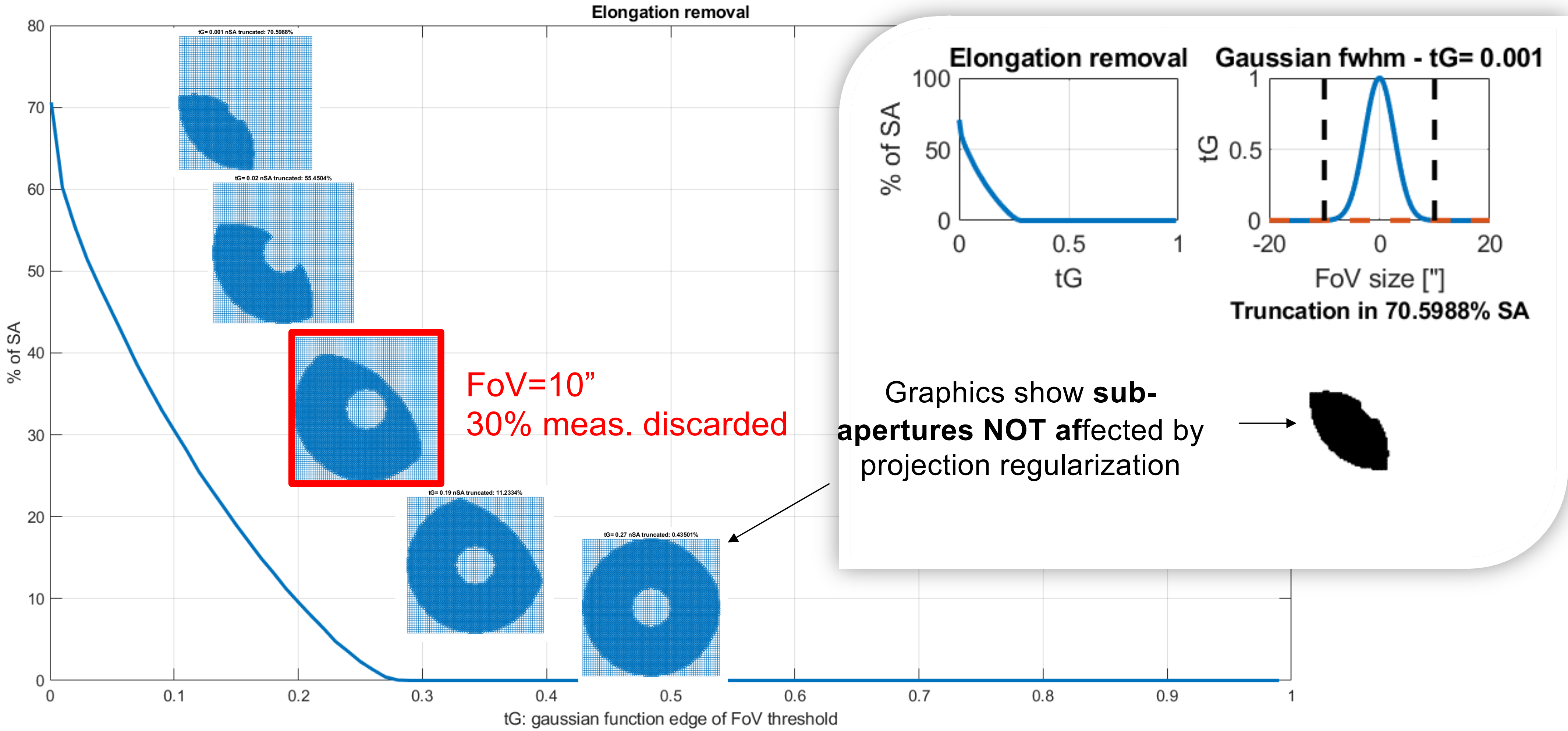
Optimising tG:

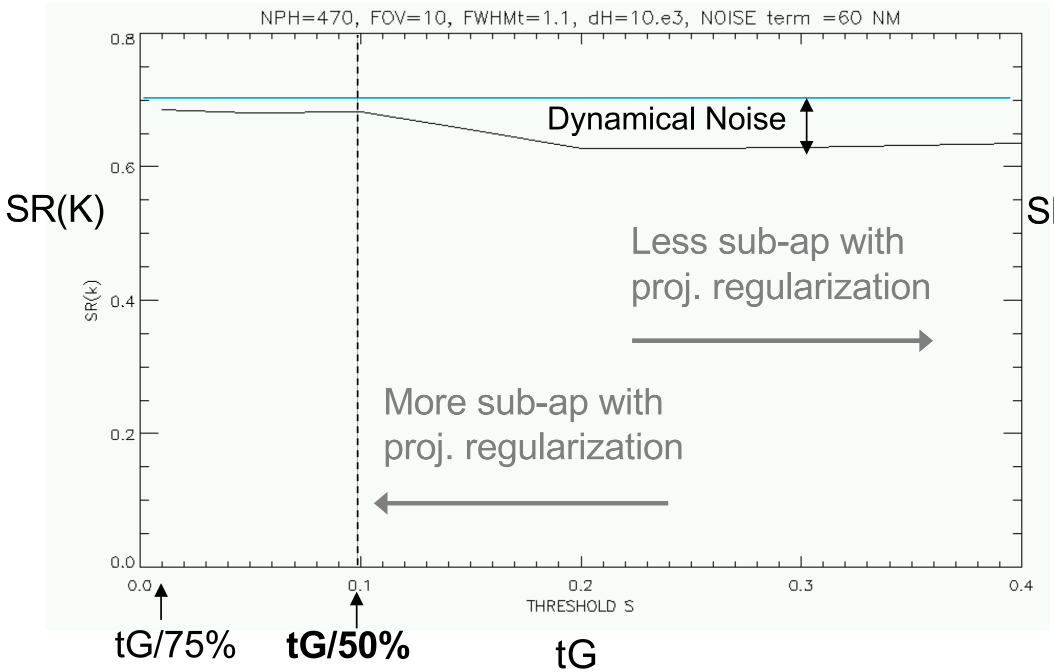
Select Sub-apertures on which to apply the projection regularization



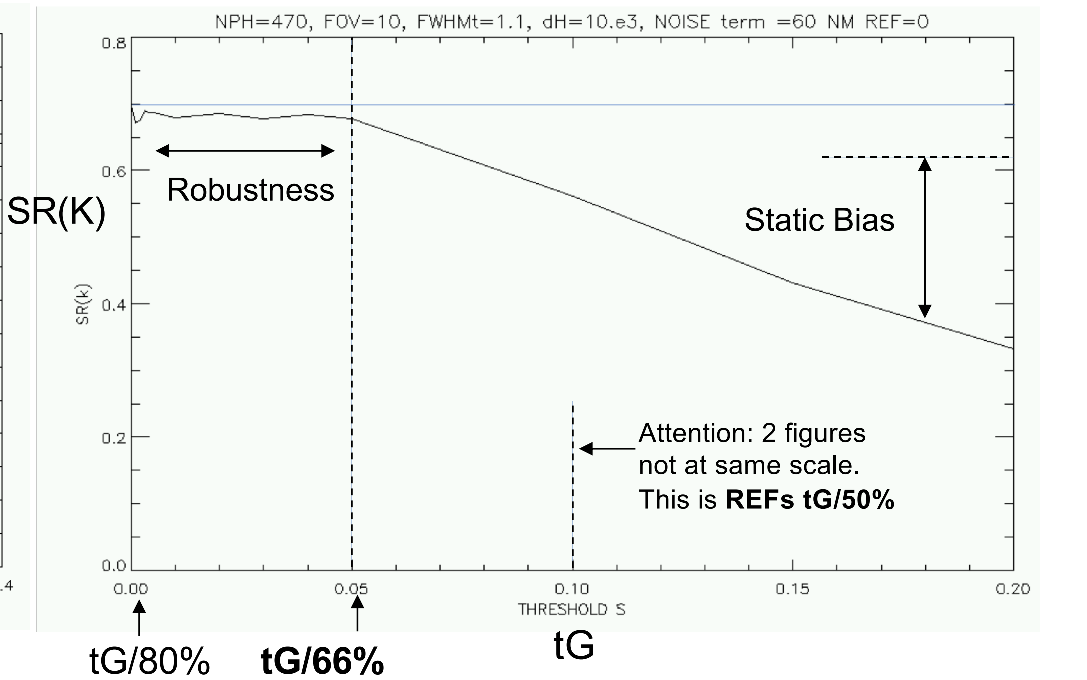
Optimization of tG

- Truncation induces dynamical noise and static bias: **tG fixes both…**

FOV=10, Na Multi-Peak, **REFs** (bias calibrated)



FOV=10, Na Multi-Peak, **REF0** (bias NOT calibrated)



FOV=10. SR Performance in function of tG (threshold S). Optimum value between 0.1 and 0.01 [50%-75%]. BETA=10. KM, NOISE=60 nm. **REFs.**

FOV=10. W1%. SR Performance in function of tG (threshold S). Optimum value between 0.05 and 0.001 [66%-80%] . BETA=10. KM, NOISE=60 nm. **REF0.**

Performance: simulations

- **With Regularisation values in table below:**
- Determined for for NPH=470, RON=3
- σ_n and β fixed analytically and KEPT CONSTANT
- **tG** can be put to 100% and KEPT CONSTANT
  - →Simulations show a Loss of SR < 2% (worst case)

For all the following simulations results:

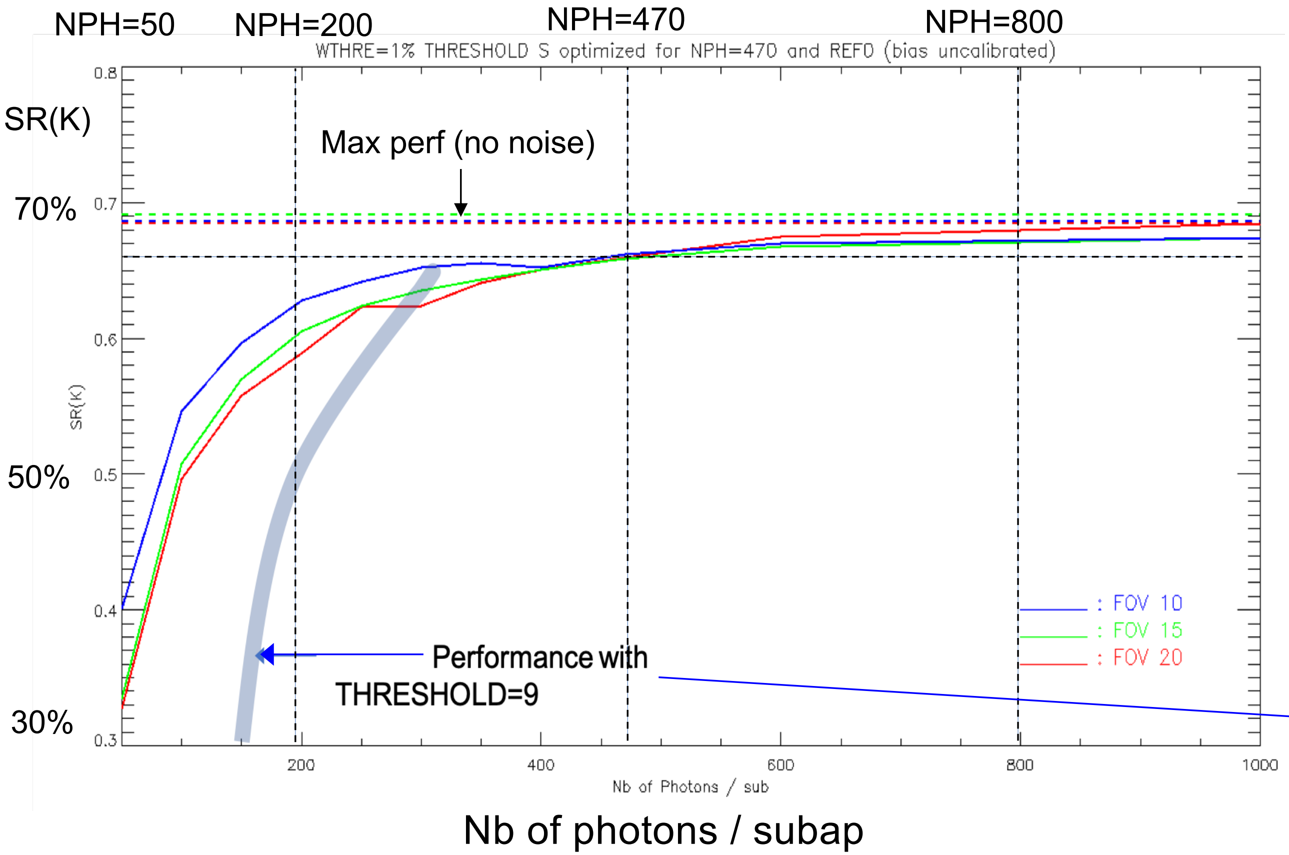
Binary Windowing Wthre=1% fixed

REF0 (bias NOT calibrated)

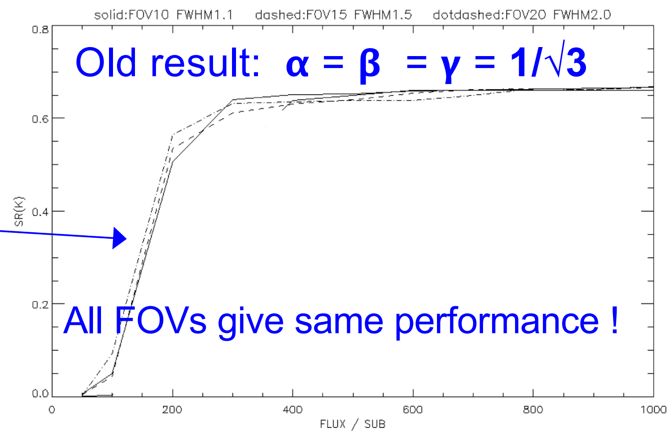
	FOV=10 arcsec	FOV=15 arcsec	FOV=20 arcsec
σ_n	50 nm	60 nm	80 nm
β_{max}	10 km	10 km	10 km
tG %	66%	66%	0%

Performance: LGS flux

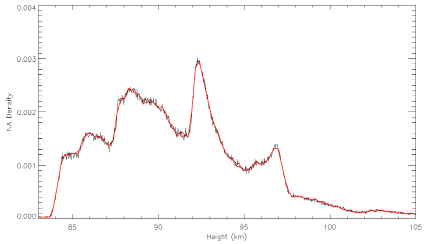
REF0 (bias NOT calibrated)



- **50 %** of the time : **SR>68%** (NPH>800),
- FOV=20 : Max Perf at High Flux
- FOV=10: Best Perf at Low Flux
- **90%** of time **SR loss less than 3%** (NPH>470)
- Perf. still SR>50% for NPH=100 !

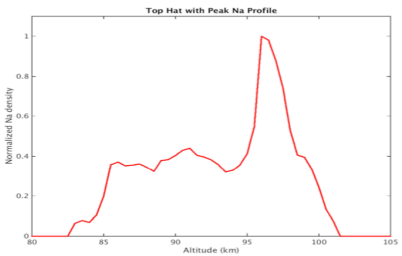


Performance, Impact of Bad Na Profile



MULTI PEAK

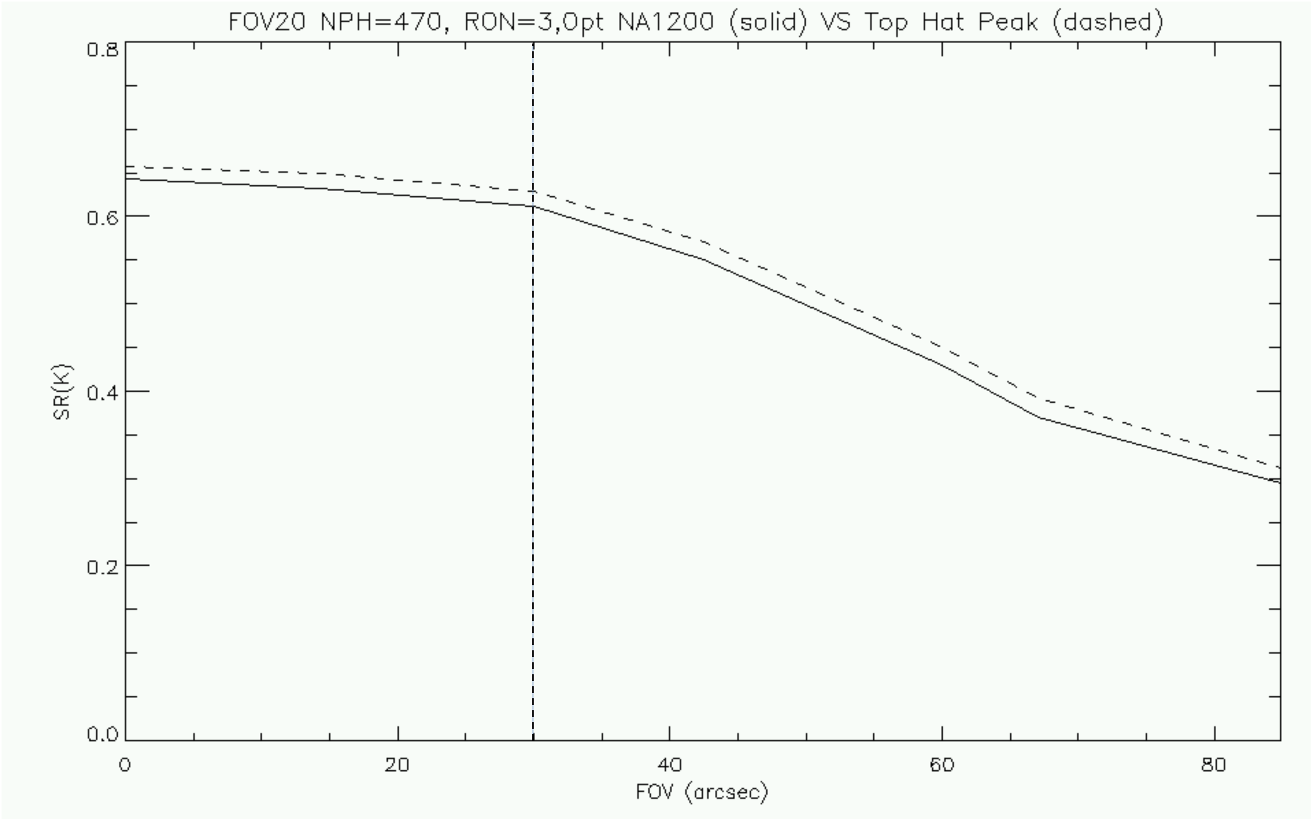
Mean Na profile _____



TOP HAT PEAK

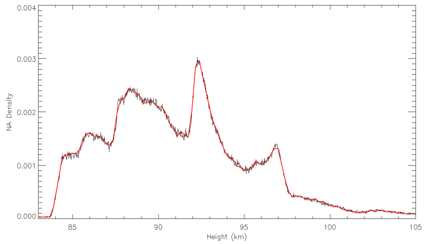
Bad Na profile - - - -

- FOV=20 arcsec 😀 I like point sources !



Cn2 mean

Performance: impact of bad Na Profile



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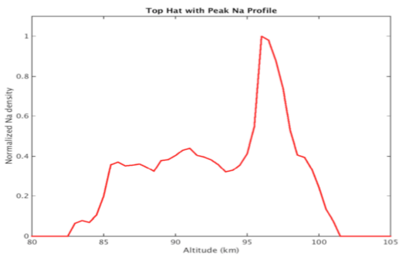
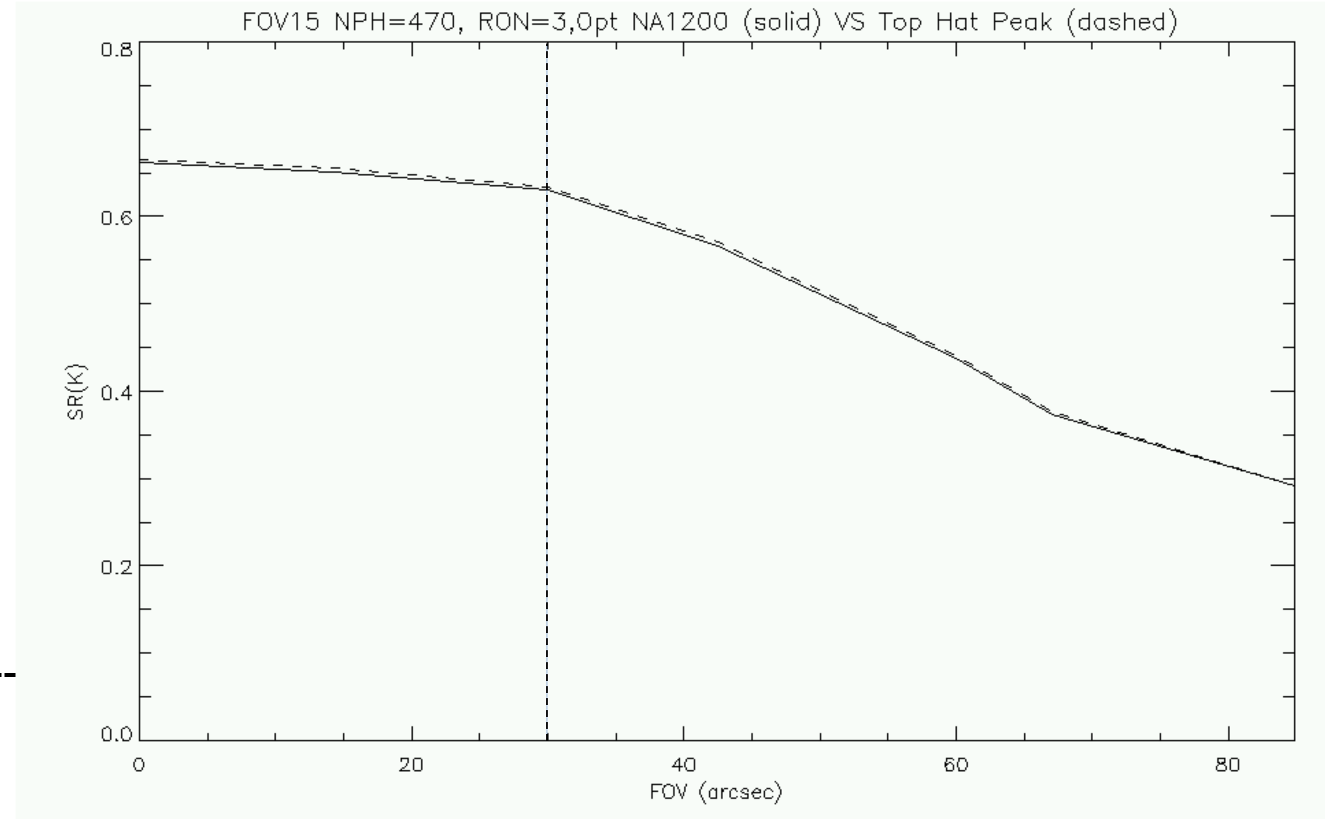


TOP HAT PEAK

Bad Na profile --------

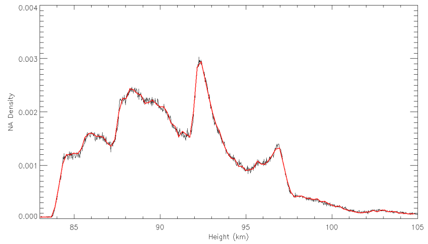
- FOV=15 arcsec

même pas peur



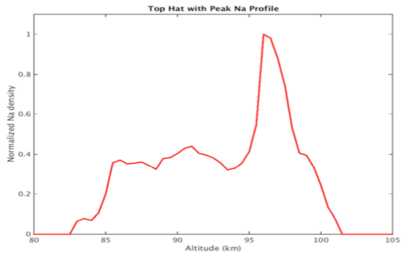
Cn2 mean

Performance: impact of bad Na Profile



MULTI PEAK

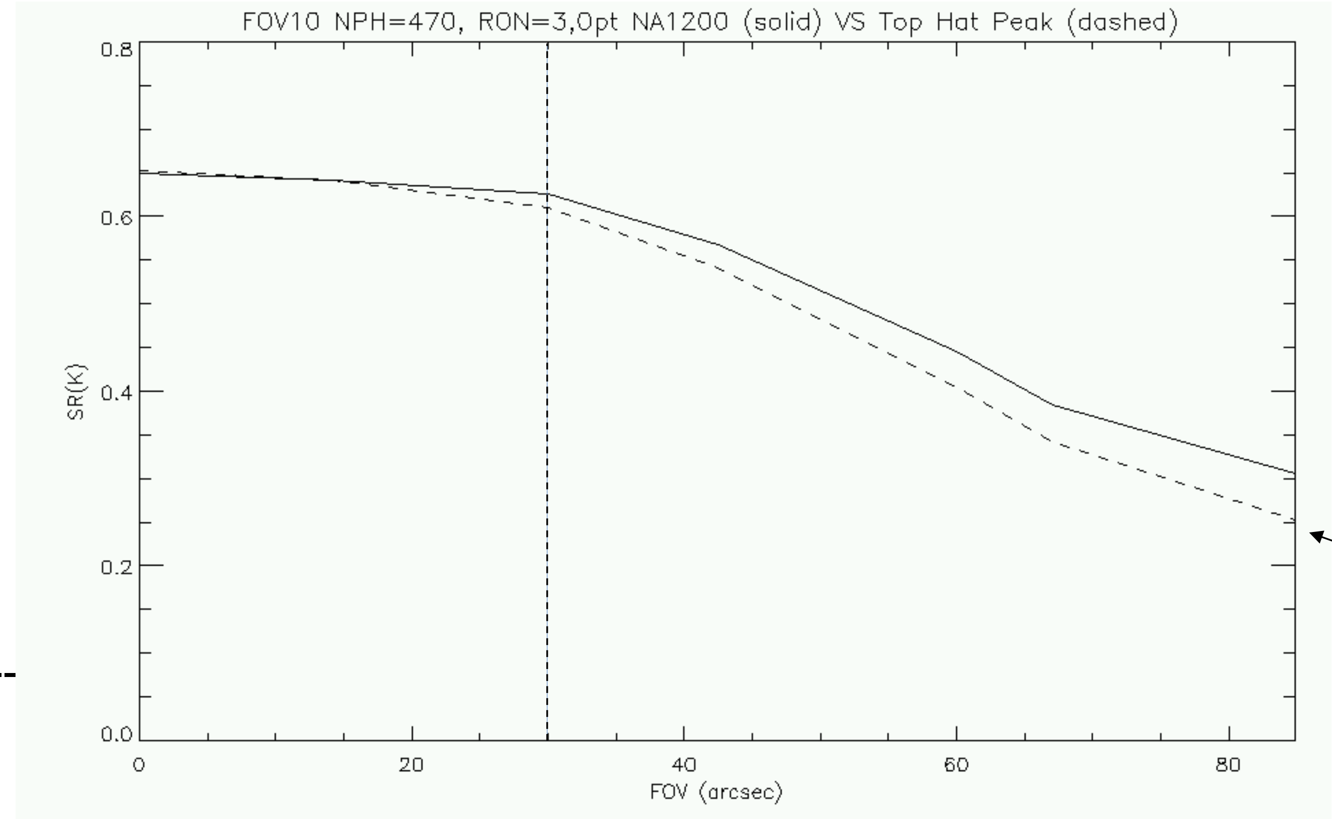
Mean Na profile _____



TOP HAT PEAK

Bad Na profile -------

- FOV=10 arcsec 🙁 I don't like to make suffer NGS WFSs



Cn2 mean

Not recovered by tG optimization

Conclusions / Recommendations

- **Main Result**: Fix all the regularization parameters once for all to a “reasonable value” and you are near optimality in 90% of time
- **If you wish to do better** then I recommend:
  - $\boldsymbol{\sigma_n}$: update it if you want to be optimal at low flux
- Be careful with spot lateral width sampling: **non-linearity**
- **On the Quasi-Statics**: Regularization plays an (too?) enormous role…
- → Having no Quasi-Static Bias at all would be certainly an asset for Non Common Path Aberrartions compensation

Towards Decoherence of MAORY

$$| \text{FOV} \rangle = \alpha\, |10\rangle + \beta\, |15\rangle + \gamma\, |20\rangle \quad \text{arcsec}$$

- FOV = 10 arcsec
- α ↑: Good at low flux Spot well sampled
- α ↓: Strong Static Bias Needs Regularization Not good at adverse Na profiles

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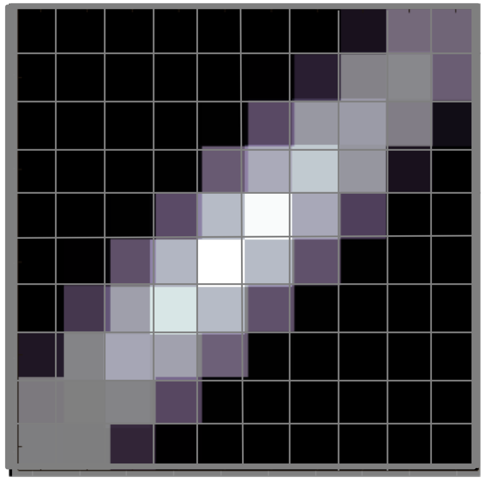
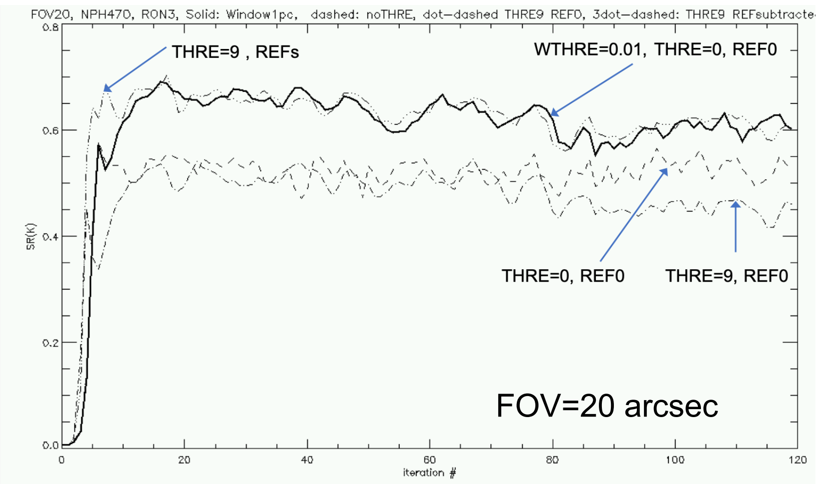
- FOV = 20 arcsec ~~γ ↑ closest to 42~~
- γ ↑: No Static Bias No need of Regularization Performing in All Conditions
- γ ↓: Needs spot shaping

- FOV = 15 arcsec
- β measures the SWISS probability

Reject RON with windowing

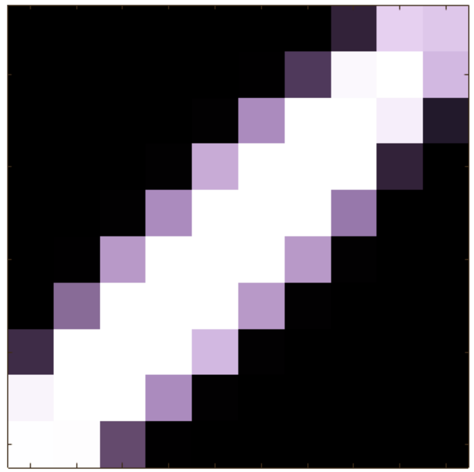
- 10x10: lots of pixels with big leverage on slopes
- → **Binary Windows:**
  - Pixels with No signal → 0 (threshold few ~1-2 %)
  - Add pixels with value 1 to Centro-Symmetrize the Window
- Idea: **Fixed Windows adapted to all conditions**
  - Spot width, Na profiles, Jitter, NCPA offsets…
  - If needed some borderline pixels can be Weighted



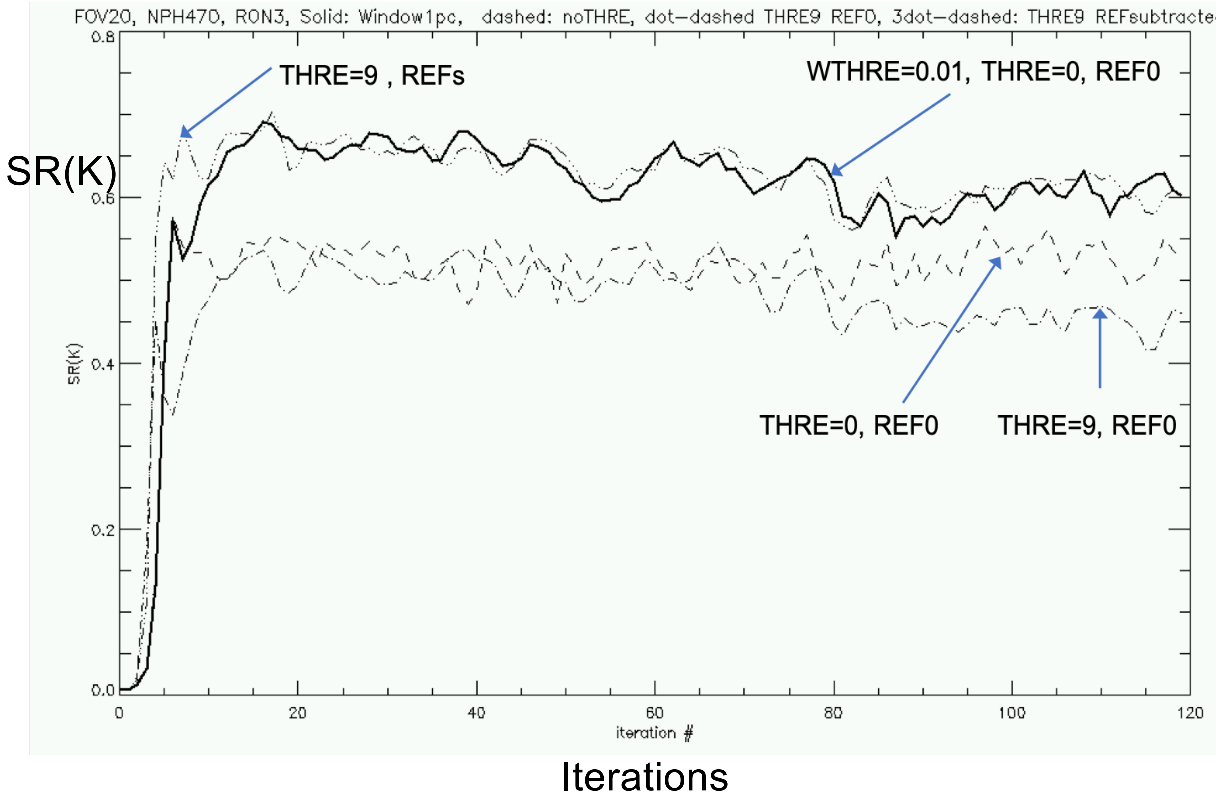


REFs: Bias Calibrated
REF0: Bias NOT Calibrated
W1%: Bin. Window Thre=0.01

SR (W1%, REF0): 66%
SR(THRE=9, REFs): 66%
SR(THRE=9,REF0): 47%



Performance: Windowing VS Thresholding

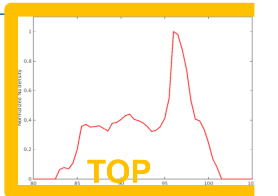


Solid line in bold: Performance of FOV=20 with REF0 and windowing W1%. Dashed line: REF0 and no thresholding (RON not attenuated). Doted-Dashed: REF0 and application of thresholding (no zero BIAS hurts). 3-Dotted Dahsed: Classical threshold with Bias calibrated.

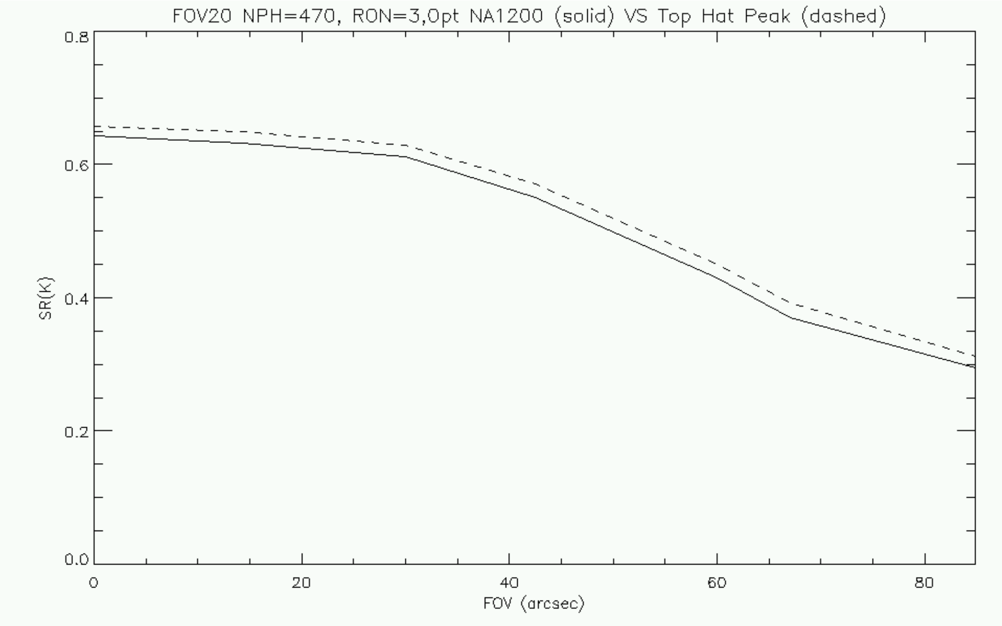
- SOLID LINE: Windowing W1%, REF0
- All other lines are without windowing
- The only case that performs as good as windowing is Thresholding+ REFs
- Other curves' performance is either dominated by RON or by the BIAS
- **→ Windowing is used for the rest of the study**

Mettre def de REFs REF0

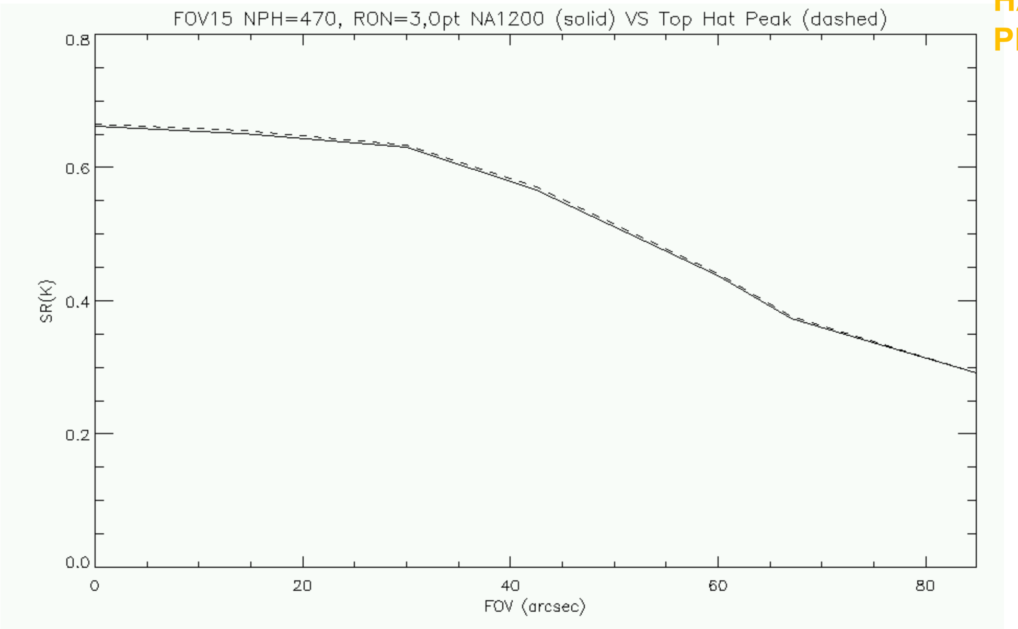
Performance: “adverse” Na Profile



- Profile Top-Hat-Peak VS Multi-Peak at “Optimum” Regularization
- Slightly better pref: with FOV=20: Spot is “point-like”



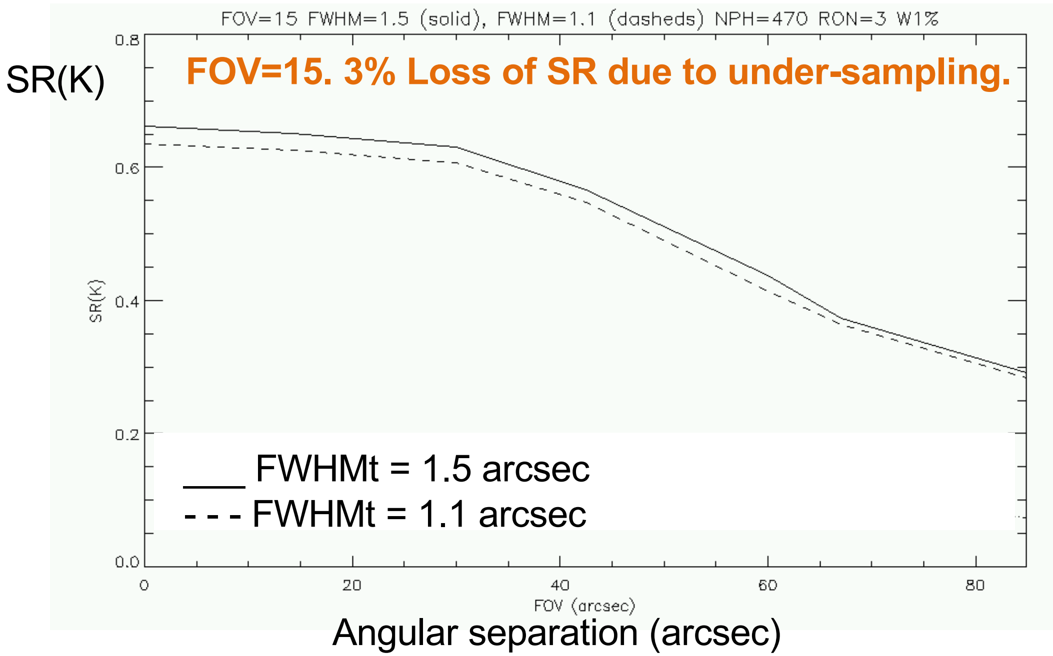
SR in function of angular separation. CN2 mean. FOV=20 NPH=470, RON=3, W1%, Optimum regularisation parameters (Table 1). Solid line: profile NA1200. Dashed line: Profile Top-Hat-Peak

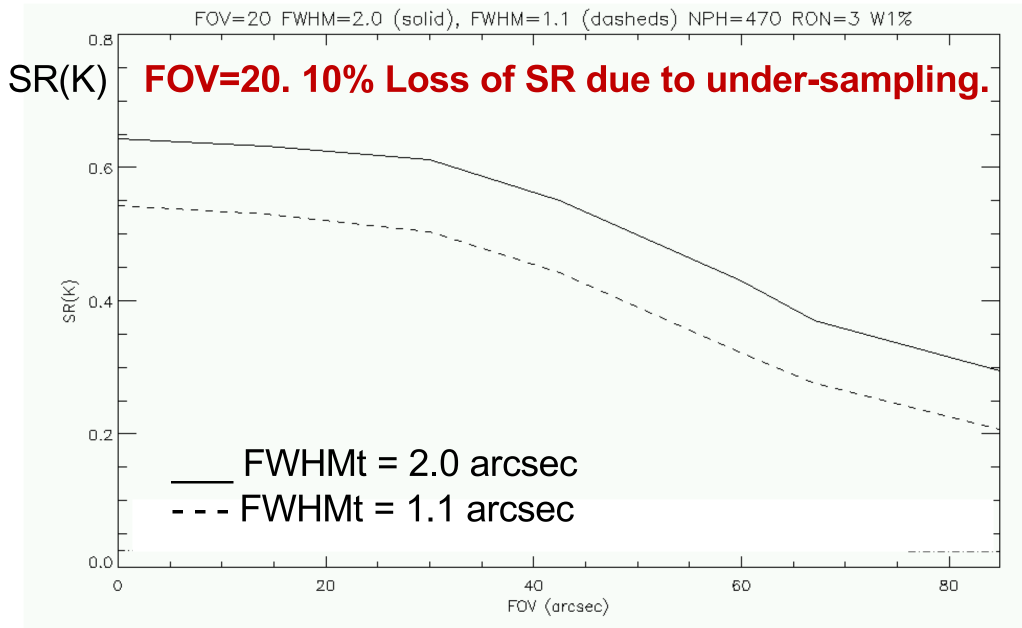


SR in function of angular separation. CN2 mean. FOV=15 NPH=470, RON=3, W1%, Optimum regularisation parameters (Table 1). Solid line: profile NA1200. Dashed line: Profile Top-Hat-Peak.

Spot enlargement to reduce non-linearity

- FWHMt = Lateral LGS spot size in Sodium layer at uplink
- Optimal reconstructor as defined later
- **For the rest of the study the LGS Spot is enlarged such that sampling is 1 pixel / FWHMt**





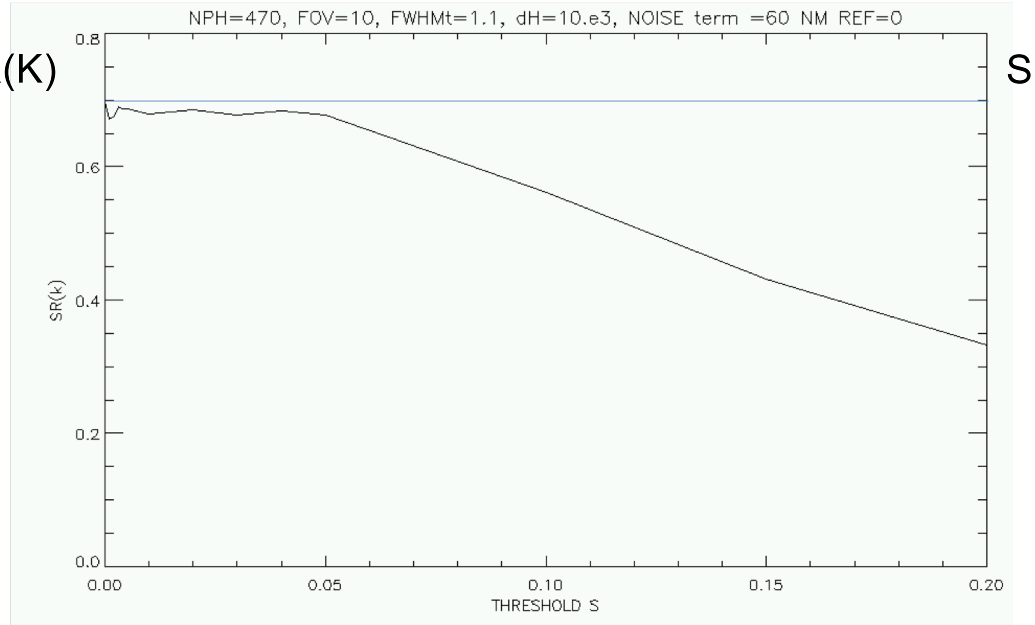
Angular separation (arcsec)

Optimization of tG: Threshold ?

- tG can also “fix” Static Bias due to Thresholding but needs to regularize harder

FOV=10, Na Multi-Peak, **Wthre1%**

SR(K)

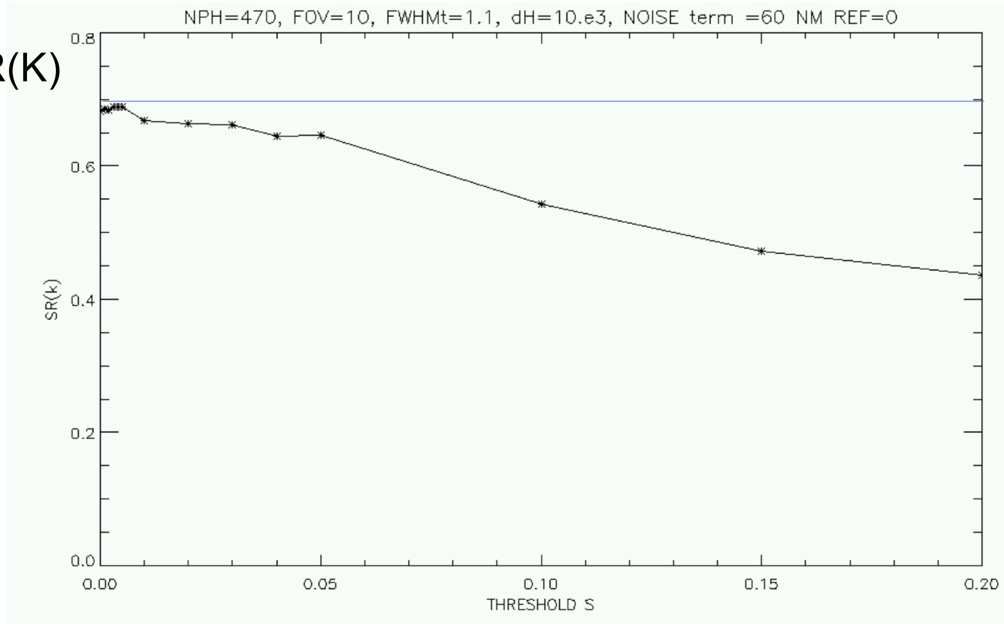


tG

FOV=10. **W1%.** SR Performance in function of tG (threshold S). Optimum value between 0.05 and 0.001 [66%-80%] . BETA=10. KM, NOISE=60 nm. **REF0.**

FOV=10, Na Multi-Peak **THRESHOLD=9**

SR(K)



tG

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