NGS APD tip-tilt : ARGOS commissioning Feb. 2015 run & preparation for next run

Gilles Orban de Xivry

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v 0.2

Contents

1 Introduction

We review the different calibration and operations performed concerning the APD during Feb. 2015 run, providing short procedure with it. We finish in estimating performances and sketching an optimization scheme for the framerate.

Some specifications (more see APD/Bonn unit documentation):

- Maximum counts in continuous 1.5Mcounts / seconds / APD, or **1500counts/m-seconds/APD**
- 4Mcounts/seconds/APD in burst mode
- FoV of quad-cell : $\sim 2''$

- Unrotated coordinates range from -23170 to 23170. Derotated is from -32767 to 32767 ($=2^{15}-1$).

Table 1: *Fiber #1 has the broken connector and was exposed to scattered light.*

Channels of APD unit	fiber #	"optic-wise"
4	2	3
3	1	4
2	3	2
1	4	1

In the following section, the APD #, correspond to the channel of the APD

2 Aperture Wheel

We perform a scan of the aperture 1, the large aperture. From which we infer :

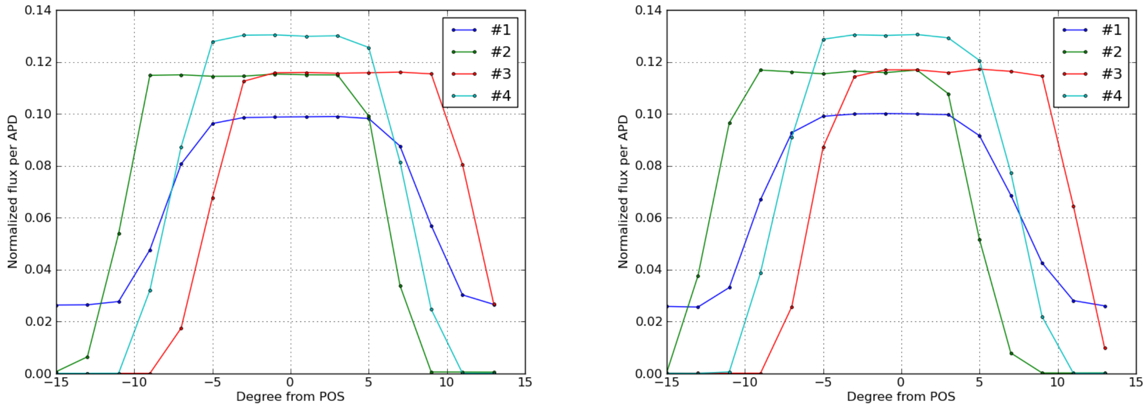

Figure 1: Aperture wheel position POS1 center calibration.

- Physical geometry w.r.t. center of rotation of the wheel is : (top) #2, (bottom) #3, (closer to center) #1, (father from center) #4.
- the aperture position is well centered.

3 Calibrations: dark, flat, noise & zeropoint

3.1 Dark

Procedure :

- Aperture wheel to "close"
- acquire a large number of counts and average, and convert to counts/seconds.

The error on the mean is $\sigma^2_{<>} = \frac{\sigma^2}{N_{\text{frames}}}$. Thus to have an error of 1 counts at 1Hz, one need to acquire $N_{\text{frames}} = 500$ for a dark noise of 250 counts/seconds, thus ~ 8 minutes of data.

Results is given below Tab. 2.

Table 2: Dark level measured and used at the beginning of the Feb.2015 run.

APD	#1	#2	#3	#4
dark [counts/seconds]	45172	378	115	133

Note that the FPGA logic can not handle large number and the product of dark counts and integration time can not exceed 4096.

Results taken at the end of Feb.2015 run with the noisy channel "shielded" Tab. 3.

Table 3: Dark level measured and used at the end of the Feb.2015 run after "shielding" of the fiber exposed to scattered light.

APD	#1	#2	#3	#4
dark [counts/seconds]	369	359	111	130

3.2 Flat

Procedure :

- Using the FLAO internal light source with ND2 (3?) filter,
- Using the large aperture from the wheel (the center had to be found before see previous section),
- Large defocus of the FLAO board in order to get a spot size of $>2''$(which means a defocus of the board by $>$18mm, see footnote later).
- acquisition of a large number of counts, average and normalization to the maximum QC value, so that one APD has a relative efficiency of 100%.

Results thus obtained is given in Tab. 4. **The dichroic used at FW1 creates a back reflection about 1-2$''$away from the main spot. To mitigate this in the flat measurement, the FLAO board was defocussed much more than 18mm.**

Table 4: Relative efficiency measured at the beginning of Feb.2015 run.

APD	#1	#2	#3	#4
relative flat [%]	70	100	65	96

3.3 Noise

The APD having essentially zero readout noise, the variance of the signal is thus essentially Poisson noise, $\sigma^2 = N_{\text{counts}}$

In Fig. 2, we plot the variance of the total number of counts versus the raw total number of counts.

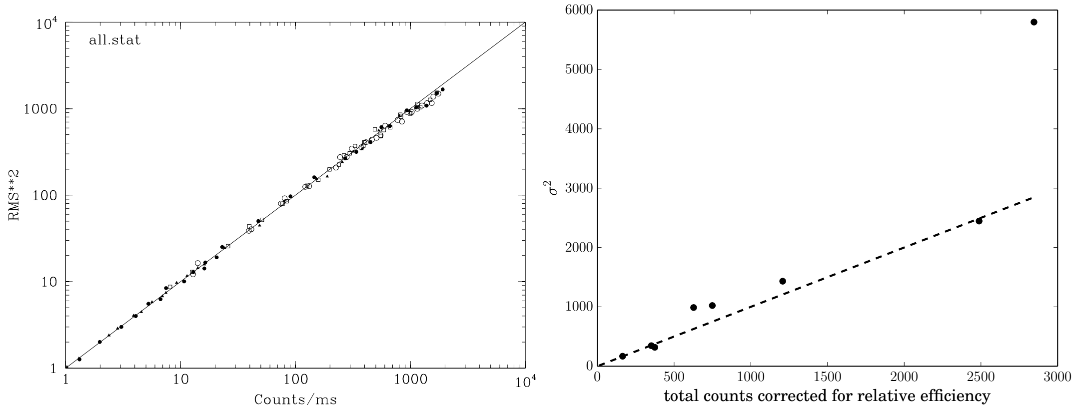

Figure 2: (Left) lab measurements under flat illumination for each channel independently. Credit : Jesper Storm. (Right) at LBT with focussed illumination and based on the total number of counts for which each channel is previously corrected by the relative efficiency between the channels (different integration time: either 1kHz or 100Hz).

3.4 Zeropoint calculation

We estimate the zeropoint allowing the conversion between f [counts/seconds] on the APD to the star magnitude m, in the same photometric system than the Pyramid *i.e.* approx. R-band,

$$m = -2.5 \log f + zpt \tag{1}$$

Procedure. The procedure is simply as followed, and is done in daytime and nighttime,

- calculate the mean total raw counts per seconds from the snaphsots data (counts provided by the BCU), and subtract the dark,
- record the star magnitude provided by the Pyramid gui,
- invert the equation.

Results is provided in Fig. 3, and is obtained using the dichroic 50/50. The real guide star magnitude is then $\text{mag}_{50/50}$ - 0.75, assuming the Pyramid is not taking into account the usage of the dichroic 50/50 in its magnitude computation (if so, no convertion is needed). The zeropoint for real guide star is also obtained by subtracting 0.75. Improvement can be done using more daytime measurement (no sky subtraction needed), and get a better average magnitude from the Pyramid gui.

4 Interaction matrix & reconstructor

A tip-tilt interaction matrix acquisition based on introducing disturbance on the ASM appears to be unpractical due to vibration of the telescope reducing the accuracy of the measurements. In the end, we choose to calibrate the APD tip-tilt with respect to the Pyramid tip-tilt using the FLAO internal light source and verify that this match the theoretical expectation.

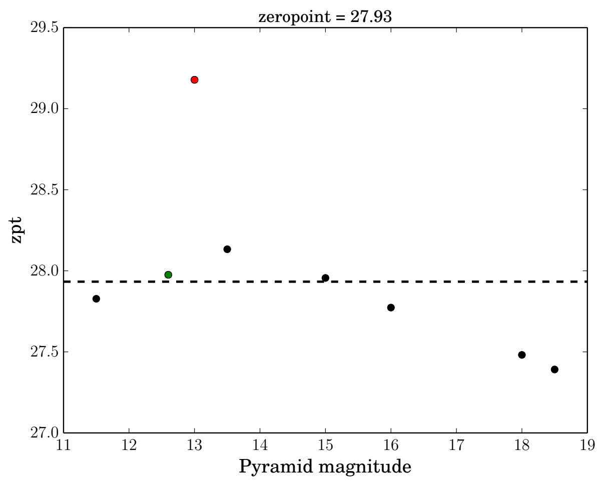

Figure 3: Calculated zeropoint in function of the star magnitude provided by the Pyramid gui, using the dichroic 50/50. The black dot are daytime data, the green is one good nighttime data, the red is another nighttime point showing special noise behavior, see Fig. 2

For that purpose we first check the response of the APD for different PSF sizes, calculate the expected order of magnitude of the reconstructor and finally perform the cross-calibration using the pyramid as a reference.

4.1 Sweep across APD

- Defocus of the FLAO board (4.5-9mm) to obtain a reasonable PSF size (between 0.5″to 1″).[1]
- shift of the FLAO board in x / y direction, by steps of e.g. 0.3mm (0.5″)

Results in shown in Fig. 4.

4.2 Theoretical calculation

The "order of magnitude" reconstructor can be calculated as follow.

- Assuming a spot of 0.5″ falling on the quad-cell, the maximum tilt measured is ∼0.25″, corresponding to a tilt value of ∼23k from the tip-tilt computer.
- A tilt angle of 0.25″, correspond to ($0.25\ 4.8\ 10^{-6}\ 8.2 =$)∼10$\mu$m PtV tilt, or a 2.5$\mu$m tilt rms wf, and so a 1.25μm rms surface, unit of the modes used by the RTC
- the reconstructor values are thus of order :

$$\sim \frac{1.25\ 10^{-6}}{23\ 10^{3}} \sim 5.4\ 10^{-11}[\text{m rms wf surf}]/\text{counts}$$

[1]Relating the focus with the spot size :

- The pixel scale of a $f_{\#}15$ is 0.6mm/″,
- The blur diameter from defocus is $B_d = \dfrac{\Delta z}{f\#} = 8\text{PtV}f_{\#}$, thus a 1″ spot corresponds to $\Delta z = 9mm$,
- This can also be converted into wavefront (could be applied to the ASM), using

$$\text{PtV}_{\text{focus}} = \frac{\Delta z}{8(f_{\#})^2} = \frac{\text{RMS}}{0.289} = \frac{\text{RMS surf.}}{0.578}$$

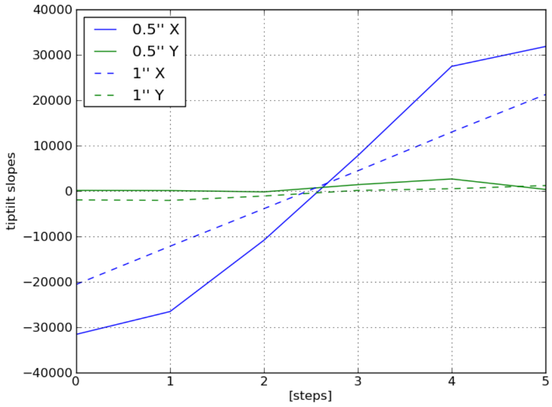

Figure 4: x/y scan of the APD for 0.5″ and 1″ spot size. The steps are supposedly of 0.5″. The difference between 0.5″ and 1″ is as expected. *If moving 0.5" from the center with a spot of 0.5", one expect to saturate the signal reaching [23170-32767] depending of the de-rotation angle.*

4.3 Final solution

By equaling the tip-tilt modes measured by the pyramid (using the `getTrueModes` command) and the APD, one gets

$$\mathbf{m}_{\text{pyr}} = \mathbf{R}_{\text{apd}}\mathbf{s}_{\text{apd}} \tag{2}$$

Performing movement in the x- and y- directions of the FLAO board, one gets two equations than can thus be inverted to obtain the reconstructor of the APD :

$$\mathbf{R}_{\text{apd}} = [\mathbf{m}_{\mathbf{x};\text{pyr}}|\mathbf{m}_{\mathbf{y};\text{pyr}}]\ [\mathbf{s}_{\mathbf{x};\text{apd}}|\mathbf{s}_{\mathbf{y};\text{apd}}]^{-1} \tag{3}$$

Procedure

- create a spot of size $\sim 1''$ by defocusing the FLAO board,
- make sure to have the K-mirror activated on the pyramid side,
- set tip-tilt unit to 'zero-angle' to 0, and the 'rotate angle' to the current LUCI rotator angle (if not done automatically by the arbitrator),
- center the spot both on the APD and on the Pyramid as a starting position,
- scan the APD by offsetting the FLAO board by steps of $\sim 0.5''$in x, and record the APD tip-tilt and true modes tip-tilt,
- fit a line to the tip-tilt APD slope and Pyramid modes,
- repeat the procedure for y direction,
- apply Eq. 3

The results is :

$$\mathbf{R}_{\mathbf{tt}} = \begin{bmatrix} 1.9e-11 & -3.2e-12 \\ -2.1e-12 & 1.6e-11 \end{bmatrix} \tag{4}$$

valid for a zero-angle of 180°(and for the APD connector configuration).

Dark and flat are not guaranteed to have been properly configured during this calibration (and later operation of the Feb. 2015 run), due to a software bug.

5 Operation, performances & optimization

5.1 Operation

Procedure

- acquire star on the APD
- close the loop with very low gain (*tracking*), after convergence increase the gain
- co-center the tip-tilt star on the pyramid by modifying the offset of piezo mirror (performing the modulation)

5.1.1 Acquisition

A star on the Tech viewer "hot spot" provides normally the star within the APD FoV allowing to start the loop.

Nevertheless, we acquire the "hot spot" for the QC by closing the loop on the APD star and recording the CCD47 (Tech Viewer) pixel position :
BIN2: [254; 270]px, modulation offset = [-2.0, 0.1]V, rotator angle = 361°, K-mirror angle = 89.5°

5.1.2 Tip-tilt mirror to pyramid loop

One want to convert True modes in tip-tilt mirror voltages for any de-rotator (and thus resp. K-mirror) angles, such that

$$\mathbf{v} = \mathbf{IM}\ \mathbf{m} \tag{5}$$

The interaction matrix is a function of the de-rotator angle θ and is simply expressed as

$$\mathbf{IM} = \begin{bmatrix} \cos(\theta-\theta_0) & -\sin(\theta-\theta_0) \\ \sin(\theta-\theta_0) & \cos(\theta-\theta_0) \end{bmatrix} \mathbf{IM}_{\theta_0} \tag{6}$$

with θ_0 the derotator angle at the acquisition of the $\mathbf{IM}_{\theta_0}$.

Procedure

- record the LUCI rotator angle, and enable the K-mirror,
- interaction matrix acquisition by changing ±0.2V on the piezo mirror (to avoid saturation of the true modes),

Results:

$$\mathbf{IM}_{\theta_0} = \begin{bmatrix} 900456.6 & -1340939.8 \\ -857577.8 & -454516.2 \end{bmatrix} \tag{7}$$

for $\alpha_0 = 266°$, the K-mirror angle= $-0.5\alpha_{LUCI} + 304°$ (bin 2).

5.2 Performances & optimization

5.2.1 First comparison with Pyramid WFS in daytime?

see commissioning diary ... to be repeated

5.2.2 Analytical calculation

We estimate in the following the current and expected signal to noise and jitter achievable with the unit. We also draft a framerate optimization from analyticaly formulation using Olivier and Gavel (1994). Namely we consider the measurement noise and the finite bandwith noise to find the optimum sampling frequency/integration time.

Signal-to-noise ratio The SNR computation is

$$\mathrm{SNR} = \frac{N_{ph}}{\sqrt{(N_{ph} + N_{bkg} + N_{dark})}} \tag{8}$$

with N_{ph} number of detected photons from the source, *i.e.* the raw counts from the source. Thus $N_{ph} + N_{dark} + N_{bkg}$ is simply the number of raw counts.

We can thus plot the expected SNR versus the NGS star magnitude, computed by $mag = -2.5 \log(N_{\mathrm{ph}} \times 2) + zpt$, where we multiply N_{ph} [counts/seconds] by 2 to take the dichroic 50/50 into account. Result is given in Fig. 5 comparing SNR with the noisy channel, and the expected SNR after "shielding".

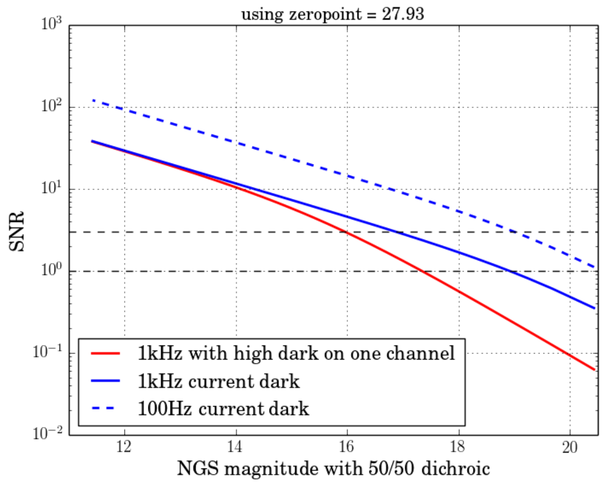

Figure 5: Signal-to-noise ratio versus real NGS magnitude obtained using the 50/50dic, a zpt=27.93, $F^2 = 1.38$ and the measured darks.

Measurement noise. The one-axis rms tilt error that is due to the SNR is given by

$$\sigma_{\mathrm{SNR}} = \frac{3\pi}{16} \frac{1}{\mathrm{SNR}} \frac{\lambda_T}{D} \chi \tag{9}$$

with

$$\chi \equiv [2/\kappa \tan^{-1}(\kappa/2)]^{1/2} \quad \text{with} \quad \kappa \equiv f_s/f_C$$

for a single closed feedback loop with bandwith f_C and sampling frequency f_s, see Appendix A of Oliver and Gavel (1994) for more details.

Temporal noise. The one-axis rms tilt error that is due to the finite closed-loop bandwith is given by

$$\sigma_{\mathrm{BW}} = \frac{f_{\mathrm{Tyler}}}{f_C} \frac{\lambda_T}{D} \tag{10}$$

with

$$f_T = 0.331 D^{-1/6} \lambda_T^{-1} \left[\sec \xi \int_0^\infty C_n^2(z) V_w^2(z) dz \right]^{1/2} \tag{11}$$

Jitter Those two formula can be used to calculate the jitter error function in function of the NGS magnitude :

$$\sigma^2 = \sigma_{\mathrm{SNR}}^2 + \sigma_{\mathrm{BW}}^2 \tag{12}$$

$$e_{\mathrm{jitter}} = \sqrt{2}\sigma \tag{13}$$

with e_{jitter} the rms error on the tip and tilt.

With the following parameters :

- Tyler frequency $f_T = 2.8Hz$, obtained using the Bufton velocity profile and a C_n^2 profile H-V 10/10 ($r_0 = 10cm$ and FWHM=1.26″at 500nm)

- $\lambda_T = 750nm$, $\mathrm{FWHM_{tt}} = 0.8''$ ($r_{0;\mathrm{tt}} = 24$cm; taking into account a longer wavelength and mild improvement from the AO),

- $D = 8.2$, $\xi = 0$, $\kappa = f_s/f_c = 10$

The results are plotted in Fig. 6 (Left) where we compare $f_s = [1000, 100, 10]$Hz and the two dark current "configuration". Up to 100Hz, the measurement error dominates the error budget, only at lower sampling frequency is the temporal error quickly rising. At this point we should note that we did not include any vibration, a simple way to account for it is by increasing the tilt-tracking frequency, e.g. from 2.8Hz to 13Hz (if the vibration is strongly dominating at that frequency), in which case one obtains Fig. 6 (Right).

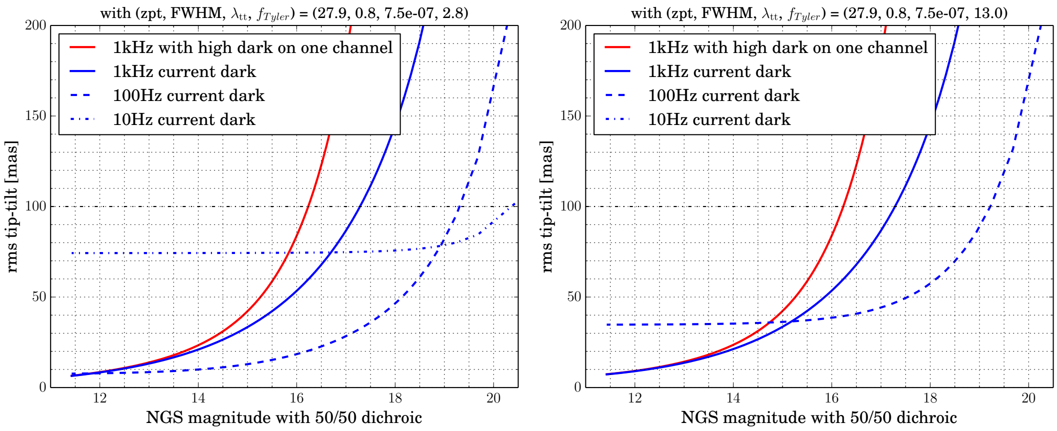

Figure 6: (Left) using the Tyler tilt-tracking frequency for standard model paramenters, $f_T = 2.35$Hz. (Right) considering a tilt-tracking frequency driven by the vibration at 13Hz.

It is immediately clear that the more complicated parameter to retrieve is the characteristic tilt-tracking frequency.

The optimum sampling frequency/integration time. Oliver and Gavel (1994) computed the optimum closed-loop frequency (assuming a pure photon noise SNR) :

$$f_C = 8\left[\frac{f_T r_0}{3\pi\chi D}\left(\frac{\Gamma_0}{\kappa}\right)^{1/2} 10^{-m/5}\right]^{2/3} \tag{14}$$

with Γ_0 the photon-detection rate at $m = 0$ and m the magnitude of the tilt reference star.

Converting this to the sampling frequency in term of $\mathrm{SNR_{per\ sec}}$, one obtains :

$$f_s = 8\kappa^{2/3}\left[\frac{f_T r_0}{3\pi\chi D}\mathrm{SNR_{per\ sec}}\right]^{2/3} \tag{15}$$

$$\propto \kappa\ f_T^{2/3}\ \theta_{\mathrm{seeing}}^{2/3} \tag{16}$$

(dependence in κ is not exact). We plot the optimum sampling frequency for two different (f_T, κ), in Fig. 7 and Fig. 8. The optimum frequency is of course only sensitive at faint stars / low frame rate where the rms tilt error can change quickly in function of f_s.

Note on κ : 1) the tip-tilt is asynchronous so the loop delay can be between [1-2ms], meaning that κ can vary substantially, e.g.. 10-15. 2) the loop gain changes the BW, thus κ.

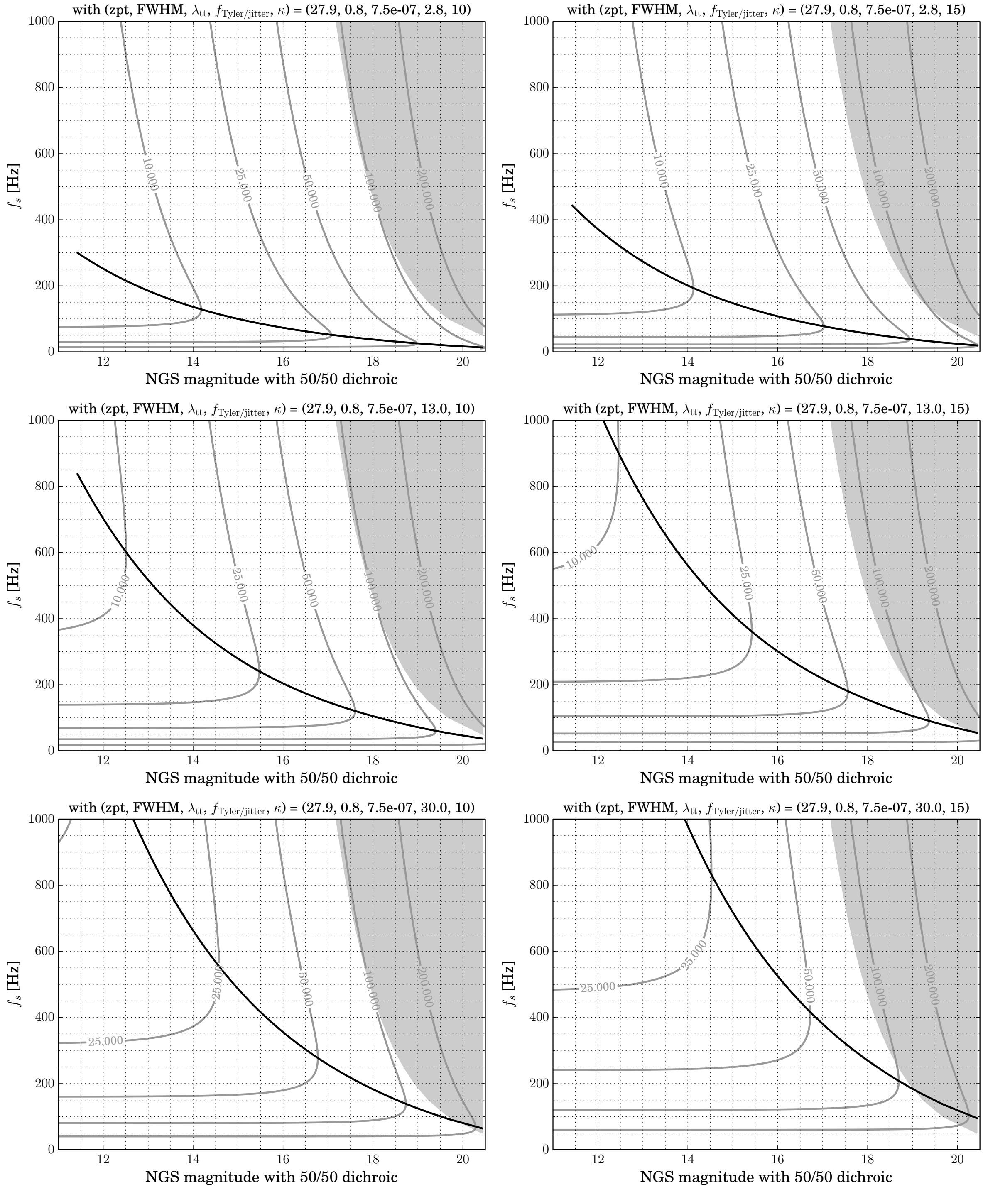

Figure 7: Optimum sampling frequency. FWHM=0.8 ″of the tip-tilt star falling on the APD. Rows are plot for $f_{Tyler/jitter} = [2.8, 13, 30]Hz$. Columns are for $\kappa = [10-15]$. Jitter RMS in [mas] are indicated by grey curves. The shaded area is area with counts $< 10 counts$ total.

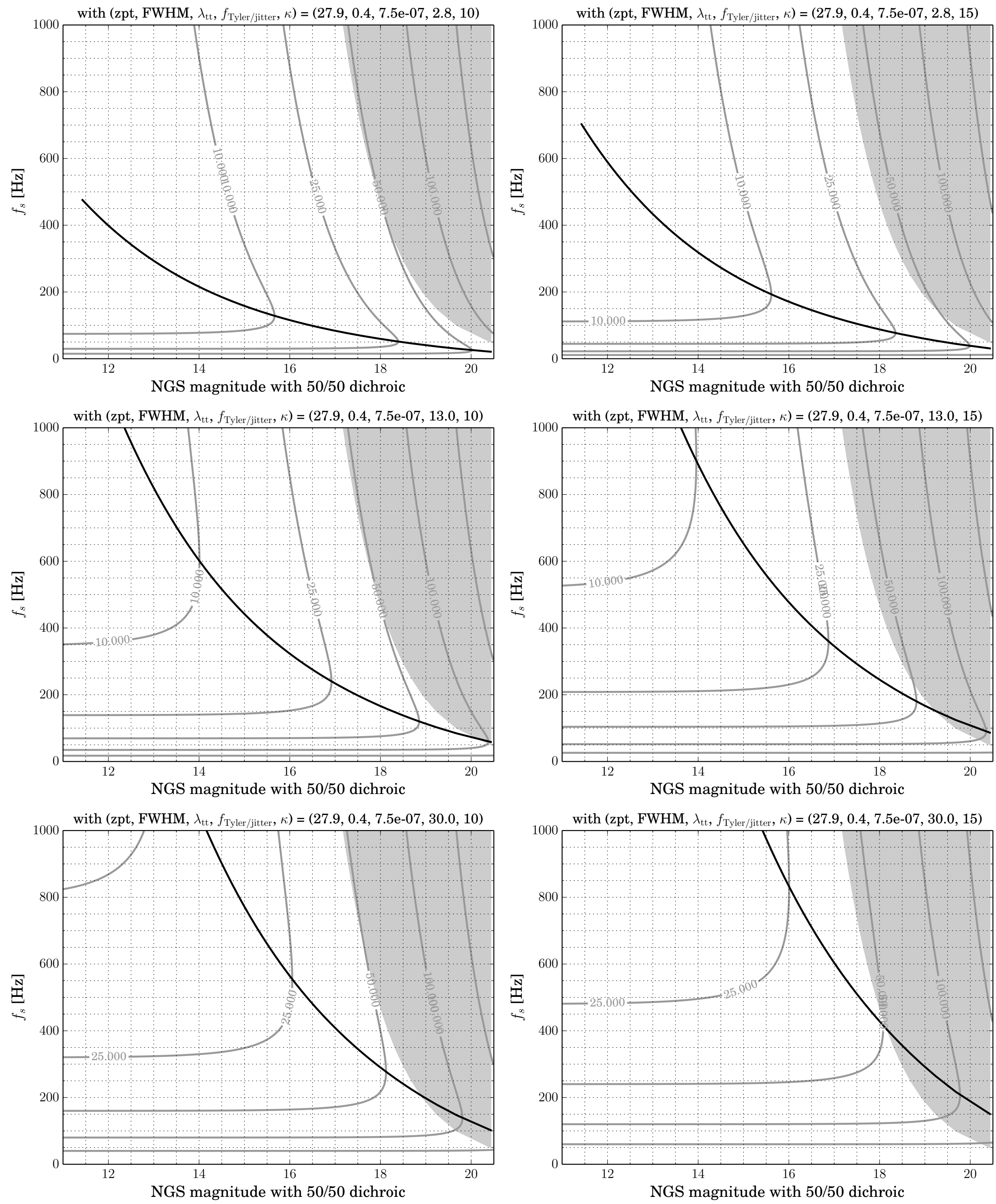

Figure 8: Optimum sampling frequency. Same as Fig. 7 with FWHM=0.4″of the tip-tilt star falling on the APD.

6 Notes for future commissioning

- Measure the precise distance of the secondary spot on the Tech Viewer, and measure the flux ratio + check with mirror specs.
- Acquire new dark with proper accuracy.
- Acquire new flat.
- repeat Aperture Wheel calibration for all aperture wheel positions.
- test tip-tilt with faint star (high magnitude).
- calibrate the parametrization optimization.
- re-acquire σ^2 - raw counts using flat illumination and doing it individually for each channel,
- re-acquire the zpt
- re-acquire reconstructor
- ...

Parametrization for implementation

- $f_T \propto V_{\mathrm{wind}}, \theta_{\mathrm{wind}}$
- r_0 from seeing with conversion factor from the DIMM seeing...