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Firenze
Palazzo dei Congressi

WAVEFRONT SENSING IN THE VLT/ELT ERA
4TH EDITON

# SOUL MODAL GAIN MACHINE

## Optimization of SOUL control system

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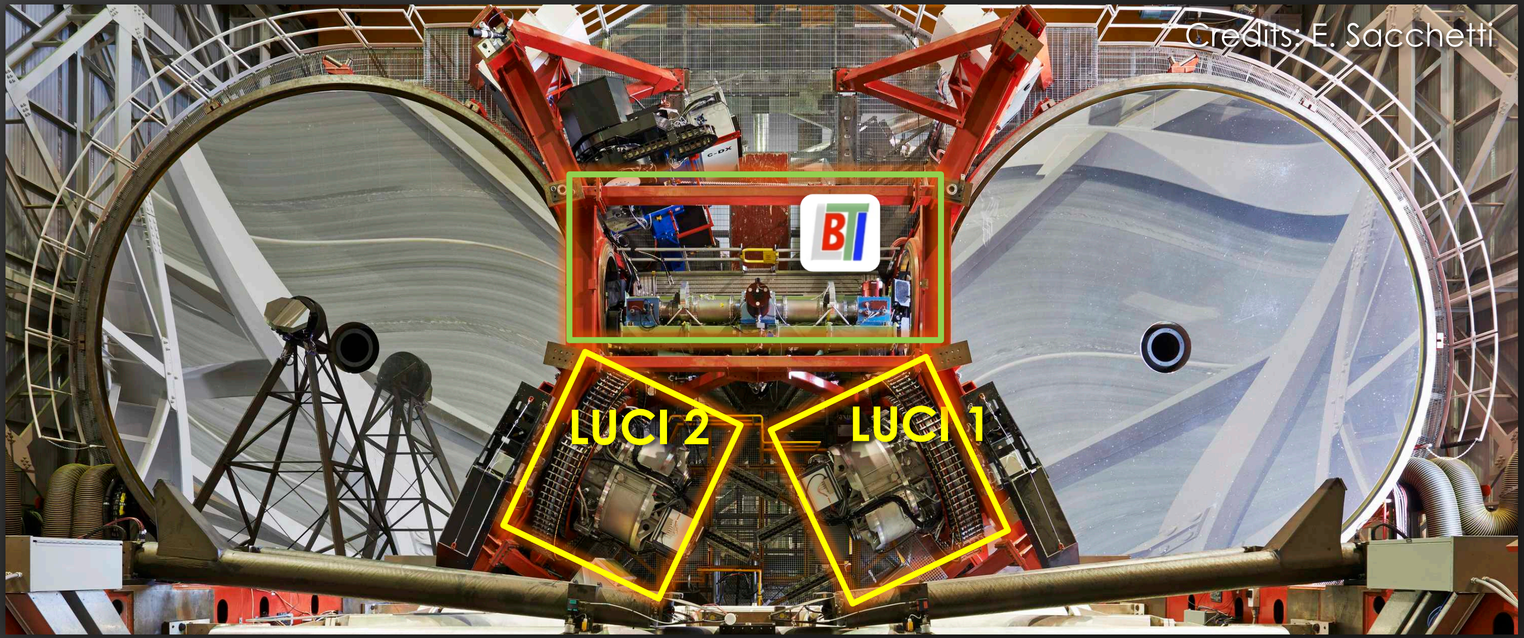
# SOUL




**SCAO systems**

**2x FLAO systems** (S. Esposito, PI)
LUCI1 & LUCI 2 (W. Seyfert, PI)
Diffraction limited Spectro-imager J-H-K

**2x systems feeding LBTI** (P. Hinz, PI - Ertel S.)
Imager L' M' - Fizeau interferometer - Nulling interferometer

Soon feeding **SHARK-NIR** and **V-SHARK**

## The SOUL upgrade

| | | |
|---|---|---|
| WFS detector | CCD39 ⇒ OCAM2k | |
| Camera Lens | 30x30 SA ⇒ 40x40 SA | |
| Tip/Tilt mirror<br>WFS electronics<br>ASM<br>RTC | } | Max. frame rate<br>1kHz ⇒ 2kHz |
| Control SW | Support for large # slopes and higher framerate | |

# SOUL – OPTIMIZATION

- SOUL, like FLAO, works on a **wide range of Guide Star magnitudes**, from Syrius down to R~18.
- An accurate **parameters optimization** is required to get the nominal performance.
- Typically AO systems change frame rate to adapt to flux regime, but PWFS can also change **pupil sampling.**
- SOUL approach:
  - EMCCD gain, Sampling, Loop frame rate and filter roots change in function of detected flux (no feedback from turbulence/vibration conditions).
  - Modulation amplitude is kept constant at $\pm 3\lambda/D$ (close to optimal, should be proportional to AO residual, but low sensitivity)
  - Number of corrected modes is always maximum available with the used sampling (control filters help here).
  - Control filters gains are optimized on line.

# SOUL – Parameters in function of flux

Optimization was initially performed in simulation and, then, during system commissioning (Pinna et al. 2015, 2016, 2019).

Parameters:

- Sampling (# s.a. = 40/detector binning)
- Loop frame rate
- EMCCD gain
- Modulation amplitude
- # corrected modes
- Integrator gain
- Forgetting factors (Agapito et al. 2019)

**Example of AO Supervisor Configuration Table**

| Rmag | flux | bin | freq | emGain | tt |
|---|---|---|---|---|---|
| -1.5 | 1.054E9 | 1 | 1700 | 1 | 3 |
| 0.0 | 2.65E8 | 1 | 1700 | 1 | 3 |
| 3.5 | 1.05E7 | 1 | 1700 | 10 | 3 |
| 4.5 | 4.20E6 | 1 | 1700 | 20 | 3 |
| 5.5 | 1.67E6 | 1 | 1700 | 30 | 3 |
| 6.5 | 6.65E5 | 1 | 1700 | 100 | 3 |
| 7.5 | 2.65E5 | 1 | 1700 | 100 | 3 |
| 8.5 | 1.05E5 | 1 | 1700 | 100 | 3 |
| 9.5 | 4.20E4 | 1 | 1700 | 300 | 3 |
| 10.5 | 1.67E4 | 1 | 1700 | 600 | 3 |
| 11.5 | 6.65E3 | 1 | 1250 | 600 | 3 |
| 12.5 | 2648 | 1 | 750 | 600 | 3 |
| 13.0 | 1671 | 1 | 500 | 600 | 3 |
| 13.0 | 1671 | 2 | 1000 | 600 | 3 |
| 14.0 | 665 | 2 | 800 | 600 | 3 |
| 14.5 | 420 | 2 | 750 | 600 | 3 |
| 14.5 | 420 | 4 | 1200 | 600 | 3 |
| 15.5 | 167 | 4 | 500 | 600 | 3 |
| 16.5 | 67 | 4 | 200 | 600 | 3 |
| 17.5 | 26.5 | 4 | 100 | 600 | 3 |
| 18.5 | 10.5 | 4 | 100 | 600 | 3 |

# MODAL GAIN OPTIMIZATION

- PREVIOUSLY: TRIAL AND ERROR METHOD ON 3 SETS OF MODES
- THIS OPTIMIZATION IS INSPIRED BY "MODAL CONTROL OPTIMIZATION" FROM GENDRON&LÉNA 1994.
- CHARACTERISTICS OF OUR IMPLEMENTATION:
  - IT WORKS WITH **PSEUDO-OPEN LOOP MODES** (DESSENNE ET AL. 1998).
  - **PLANT** IS APPROXIMATED AS **PURE DELAY**, BUT ANY (MORE COMPLEX) LINEAR MODEL CAN BE USED.
  - IT COMPUTE GAINS OF IIR FILTERS (TYPICALLY A LEAKY INTEGRATOR).

$$\hat{g}_i = \min_{g_i} J_i$$

I^TH GAIN

$$J_i = \sum_{f=n/T}^{2/T} \Phi_i^{meas}(f) = \sum_{f=n/T}^{2/T} \|W_i(z)\|^2 \Phi_i^{pol}(f)$$

COST DEFINITION

$$W_i(z) = \frac{1}{1+\mathcal{H}_i\,(z)} = \frac{1}{1+C_i(z)P_i(z)}$$

CLOSED LOOP TF

$$C_i(z) \ = g_i C_i'(z)$$

CONTROL TF

INPUTS REQUIRED:

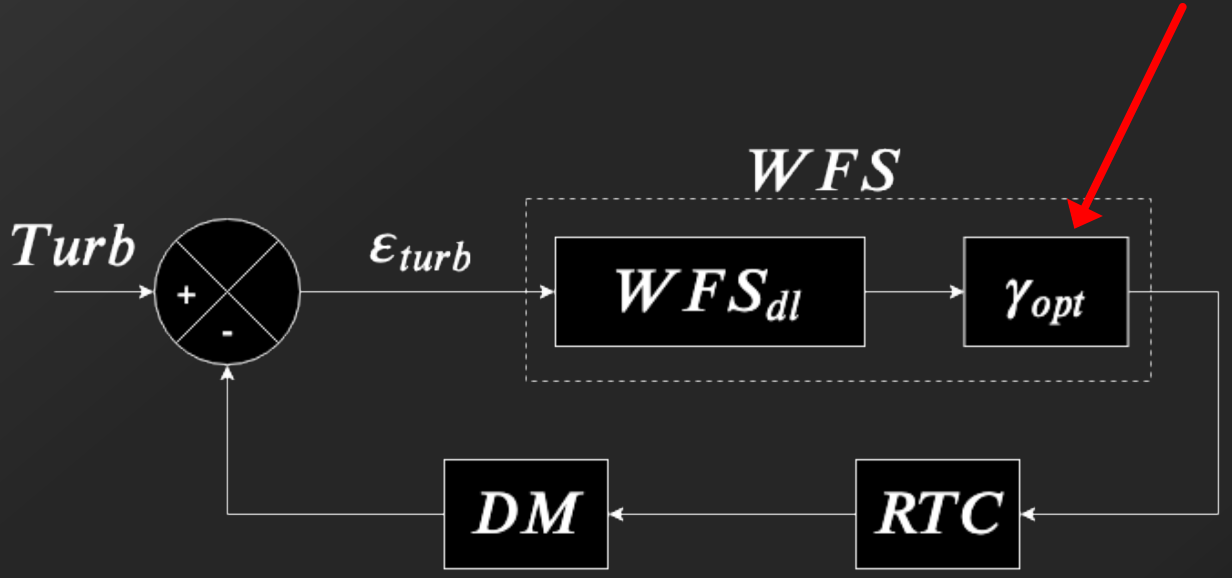
- PLANT TRANSFER FUNCTION, $P_i(z)$
- UNITARY GAIN IIR FILTER, $C_i'(z)$
- STABLE GAIN RANGE, $[g_i^{min}, g_i^{max}]$ → $g_i^{min}$ IS TYPICALLY 0; $g_i^{max}$ DEPENDS ON $C_i'(z)$ AND $P_i(z)$

# PYRAMID WFS AND OPTICAL GAIN (1)

- PYRAMID WFS IS NON-LINEAR WAVEFRONT SENSOR WHERE THE MEASURED SIGNALS DEPEND ON THE QUALITY OF THE ACHIEVED AO CORRECTION $\Longrightarrow$ AN ADDITIONAL PARAMETERS IS REQUIRED TO GET THE PLANT MODEL, THE PWFS OPTICAL GAIN:

$$P(z) = \frac{1}{\hat{\gamma}_{opt}} z^{-d}$$

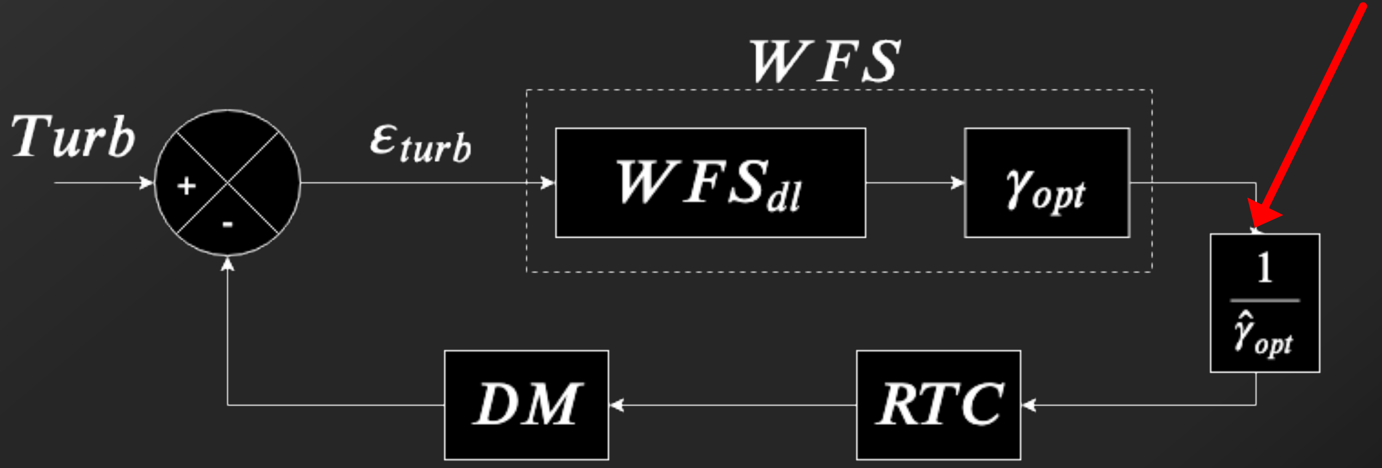
BUT …



# PYRAMID WFS AND OPTICAL GAIN (2)

- In 2015 we developed for FLAO+LUCI (Esposito et al. 2015) a NCPA compensation tool that comprises PWFS optical gain estimation.
- Then, we use the same algorithm to get a optical gain compensated PWFS and so we revert the Plant model to a pure delay:

$$P(z) = z^{-d}$$



# PLANT TRANSFER FUNCTION

HENCE, WE MODEL PLANT AS $P_i(z) = z^{-d_i}$, SO A PURE DELAY. DELAY $d_i$ IS THE SUM OF:

- INTEGRATION TIME (0.59 - 10MS)
- DETECTOR READ-OUT TIME (ROI 120X120PIXEL ⟹ 0.24 – 0.17MS)
- RTC LATENCY (0.50MS, 0.06MS DURING DETECTOR READ-OUT)
- HALF OF DM SETTLING TIME (~0.60 – 1.00MS)

WE COMPUTE IT WITH NOMINAL VALUES AND WE VERIFY IT FROM CLOSED LOOP DATA ESTIMATING THE TRANSFER FUNCTION NATURAL FREQUENCY.

NOTE: DELAY CHANGES MODALLY BECAUSE DM SETTLING TIME IS NOT EQUAL FOR EACH MODE, LOW ORDER MODES ARE SLOWER (RICCARDI ET AL. 2008).

# MGM – Other Characteristics

Gain applied in the RTC at step $k$ :

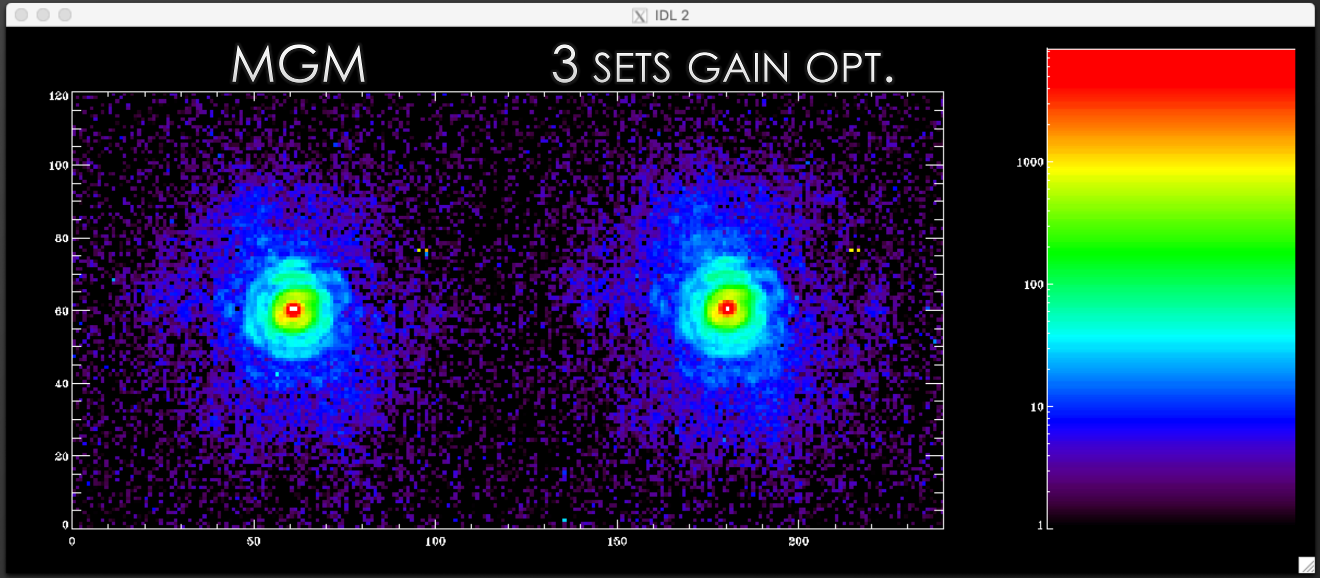
$$g_i^{RTC}(k) = (1-\rho)g_i^{RTC}(k-1) + \rho\alpha\hat{g}_i(k)$$

- Robustness for dealing with model errors (safety margins and limit increment rate):
  - Maximum gain, $g_i^{max}$, is reduced from theoretical one by 5%
  - A factor $\alpha$ ($\alpha < 1$, typically $\alpha = 0.9$) reduces the gain which minimizes the cost function, $\hat{g}_i$
  - Gain increment limited w.r.t. previous step: factor $\rho$ ($\rho < 1$, typically $\rho = 0.5$)
- MGM and PWFS optical gain compensation algorithm are coordinated:
  - Updates are synchronized
  - Optical gain variation (new over previous one) is used to rescale final filters gain vector
- We add a supervisor that monitors the closed loop and, for example, reduces the filters gain if the DM forces saturate too often.

# DAY TIME RESULTS

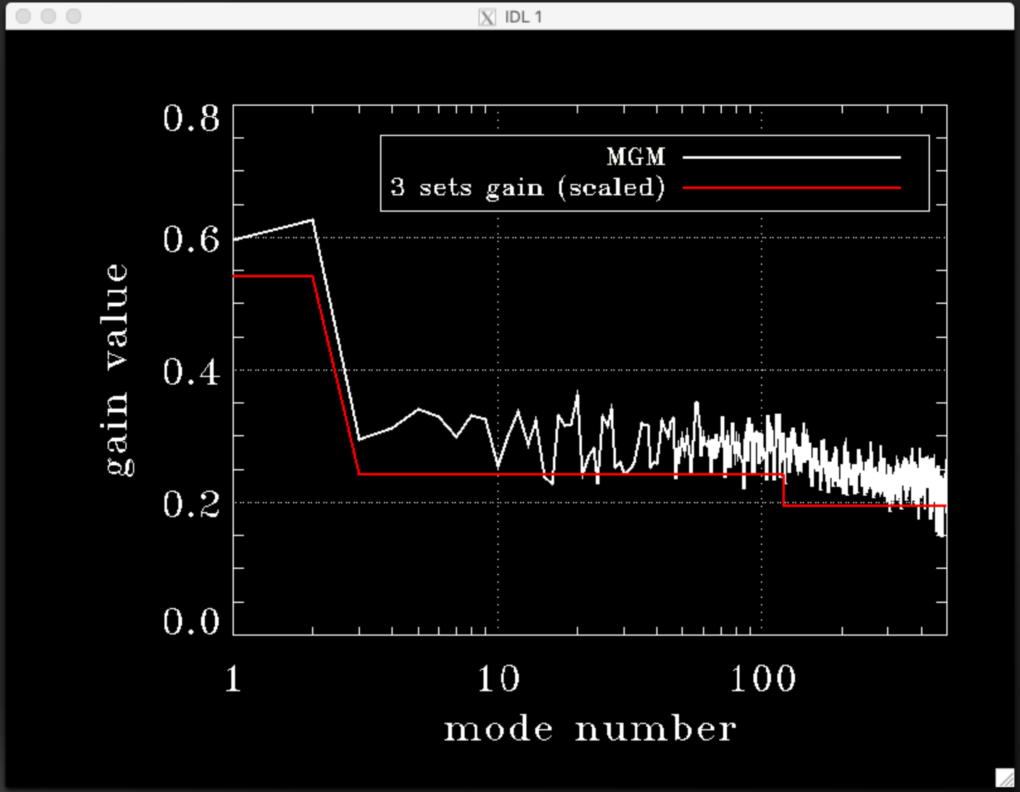
20190409

40x40s.a., 1kHz, seeing 0.6", R=11.9




SR(H)=66% SR(H)=60%

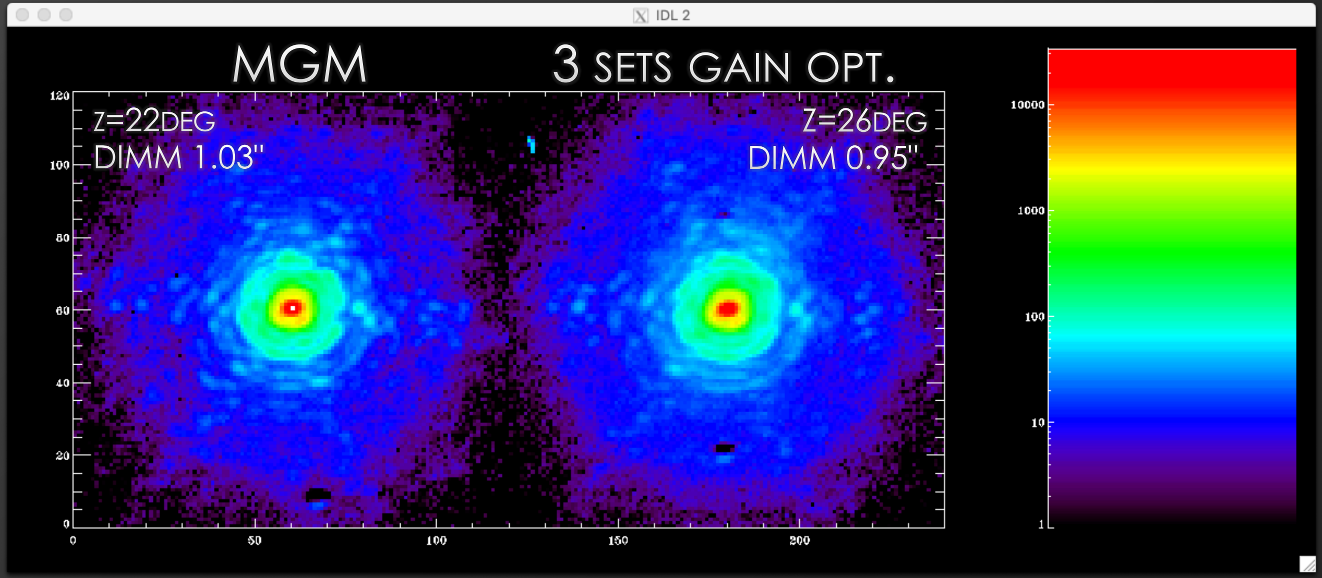
(No LUCI NCPA compensation)



# ON SKY RESULTS

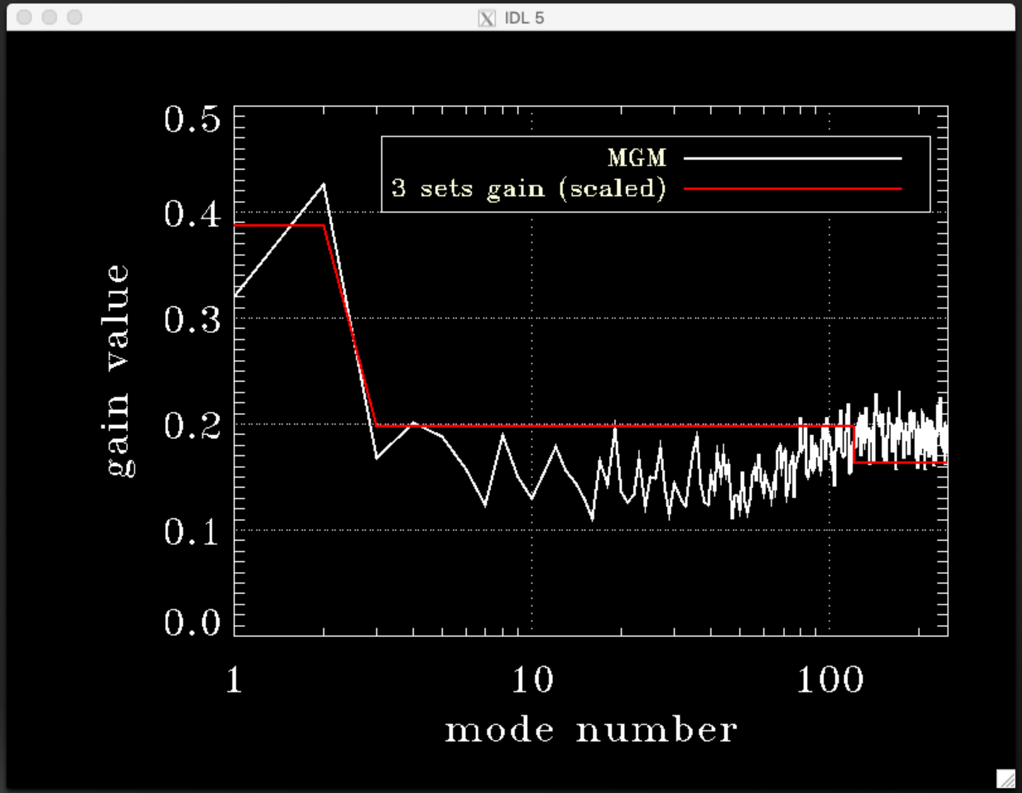
20190709

40x40s.a., 1.2kHz, R=11.5




SR(FeII)=61%  SR(FeII)=57%

(No LUCI NCPA compensation)

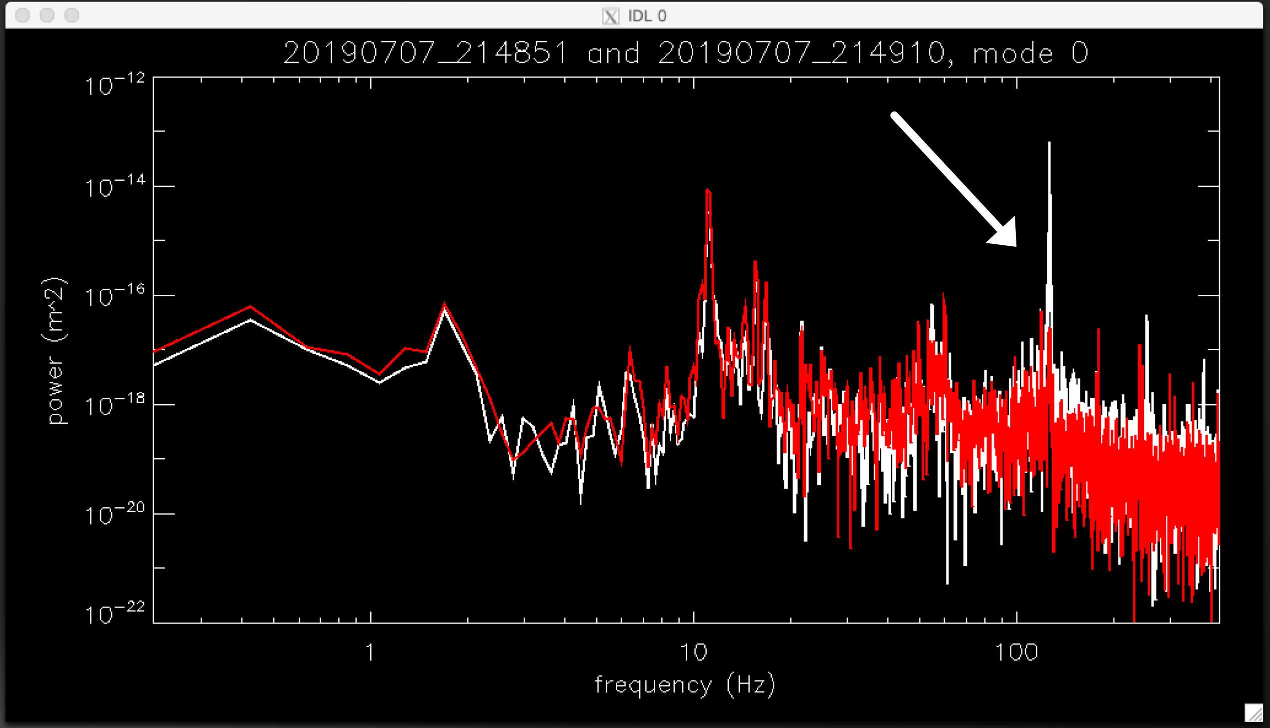


# 127Hz Vibration

TT Gain

1. 0.188, 0.242
2. 0.231, 0.276

- During our test we note a bi-stable behavior of Tip/Tilt gain, oscillating between two values separated by ~20%.
- When TT gain raise we see a strong vibration at 127Hz ⟹ we found a Control-Structure-Interaction
- We verified that this can happen for frame rates between 700 and 1700Hz
- FLAO was not able to excite it because closed loop bandwidth is significative lower with natural frequency around 80Hz



# 127HZ VIBRATION

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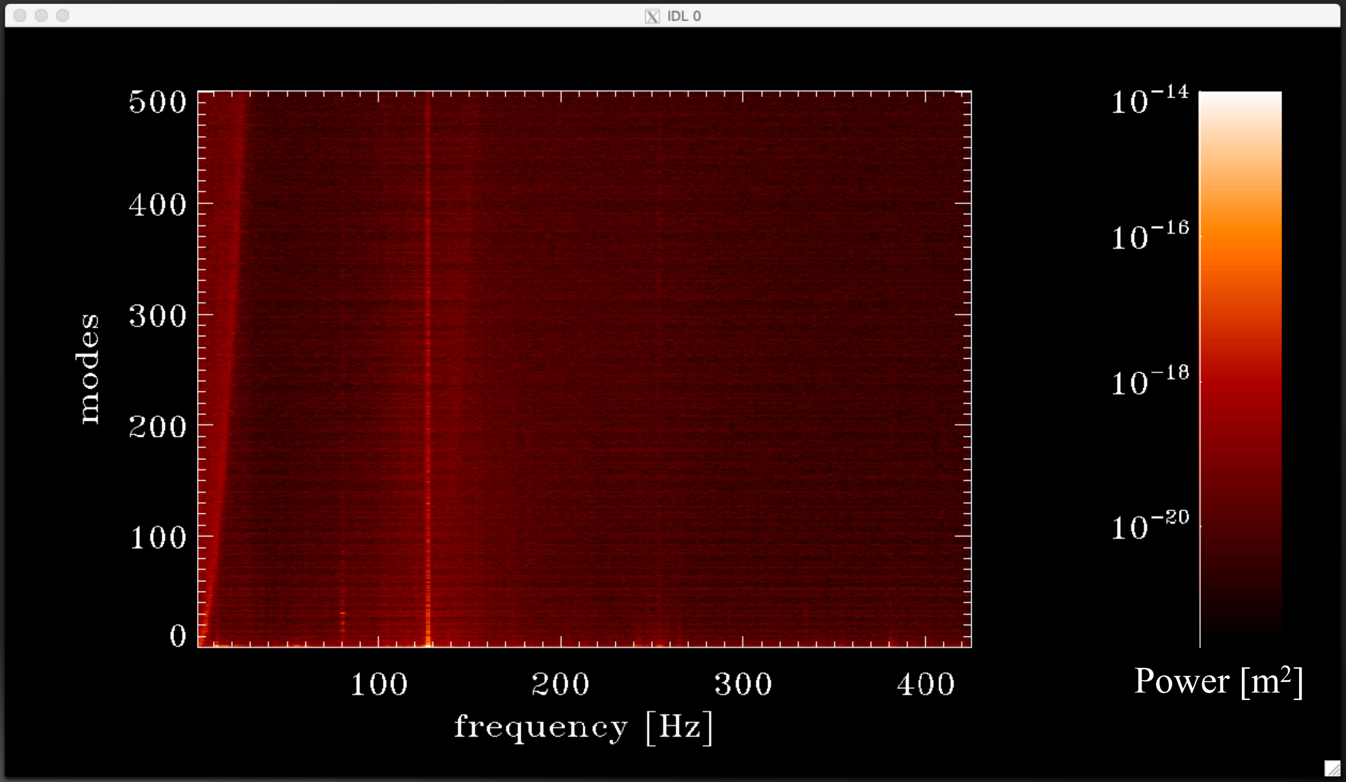
2D PSDs



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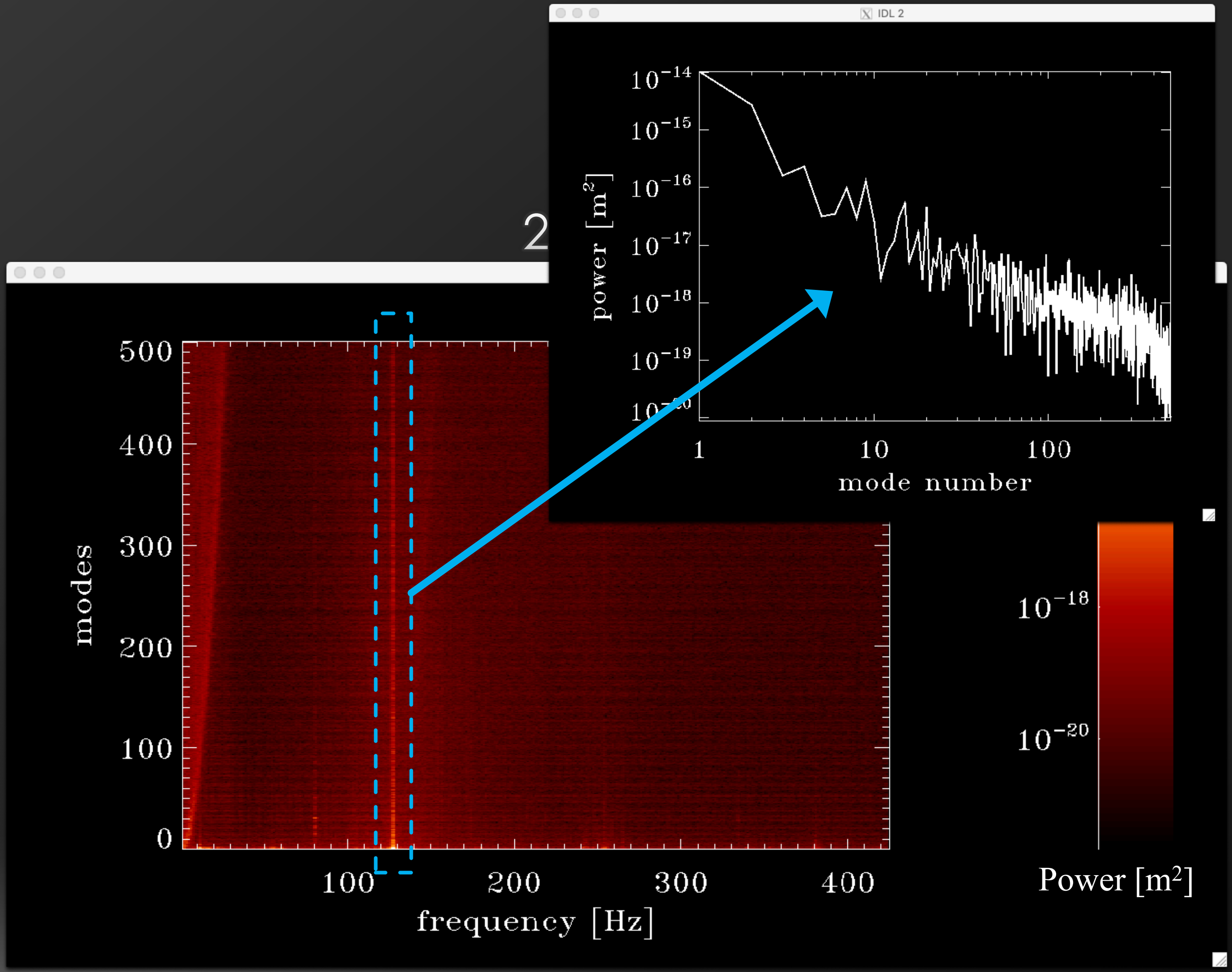
MAINLY TIP TILT, BUT A BIT OF 2ND AND 3RD RADIAL ORDER



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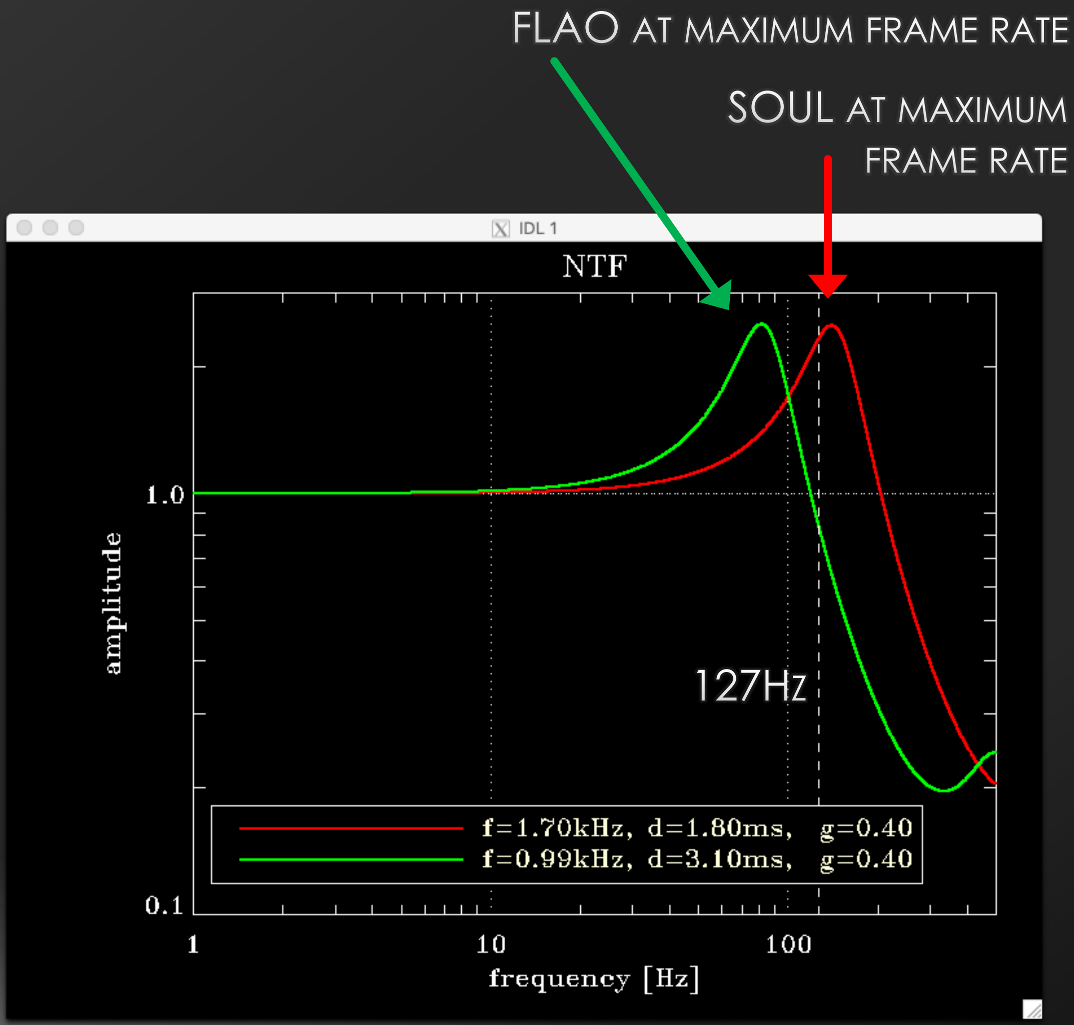
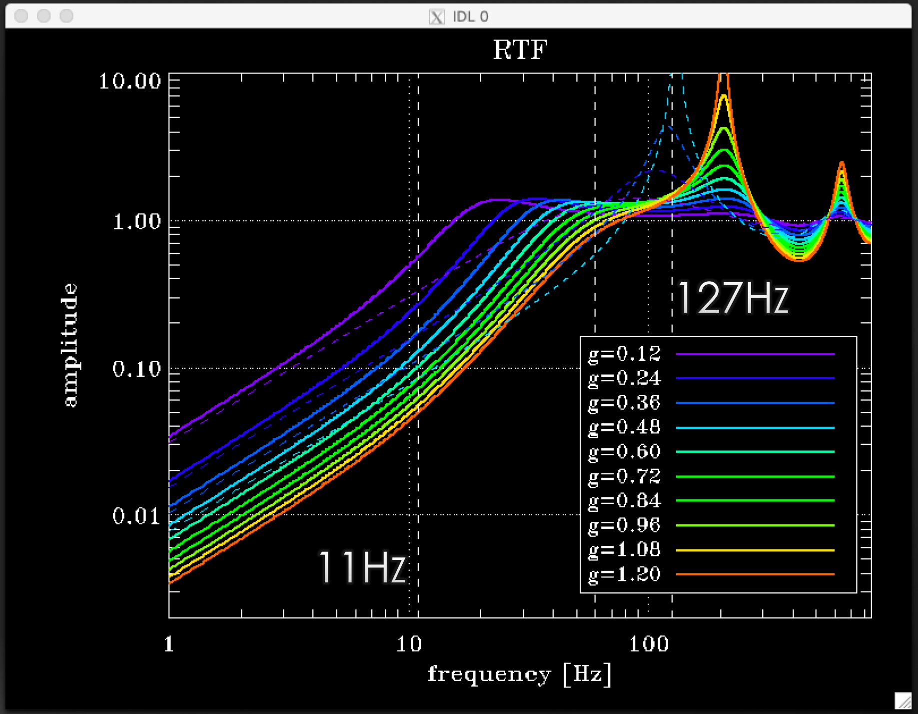


# 127Hz Vibration Control Solution

- We design, by means of a numerical optimization with stability constraint (Agapito et al. 2012), some IIR filters for Tip/Tilt modes with low Closed Loop TF amplitude at 127Hz and "good" rejection of typical LBT vibrations (main peak at ~10Hz, Kulcsar et al. 2012).
- We get 4 filters for 1700Hz, 1350Hz, 1000Hz and 750Hz, fully compatible with system RTC and MGM.
- Gain vector can be changed on the fly, while filtering is fixed during AO operations.




1700Hz filter

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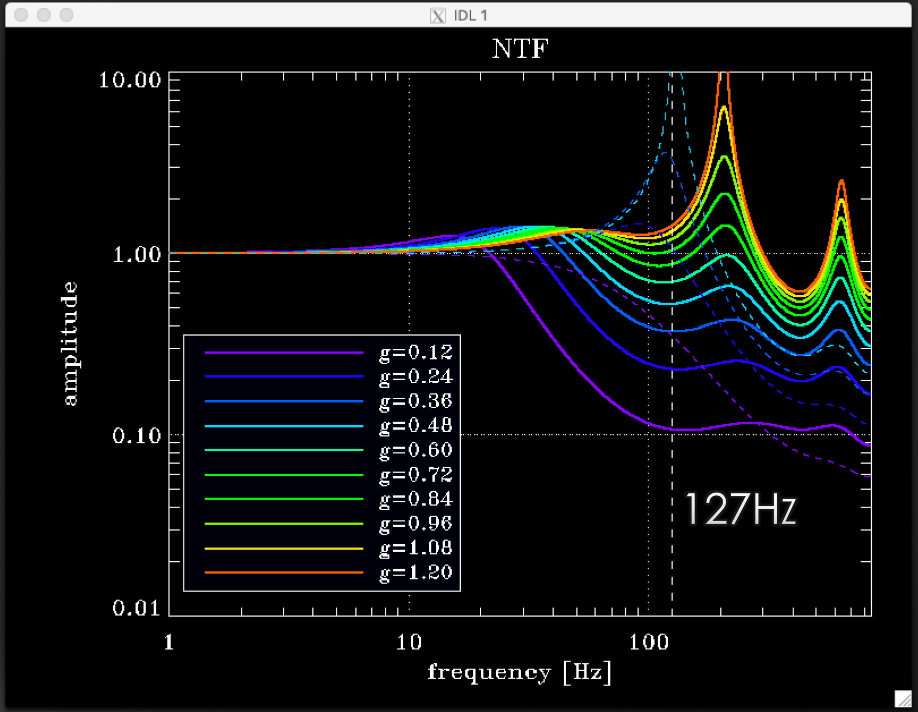
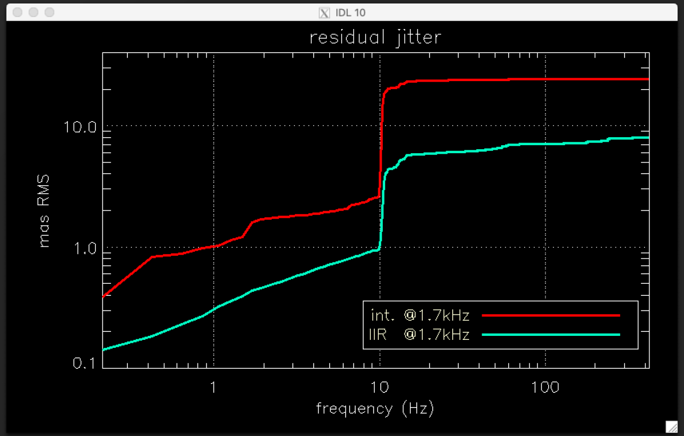


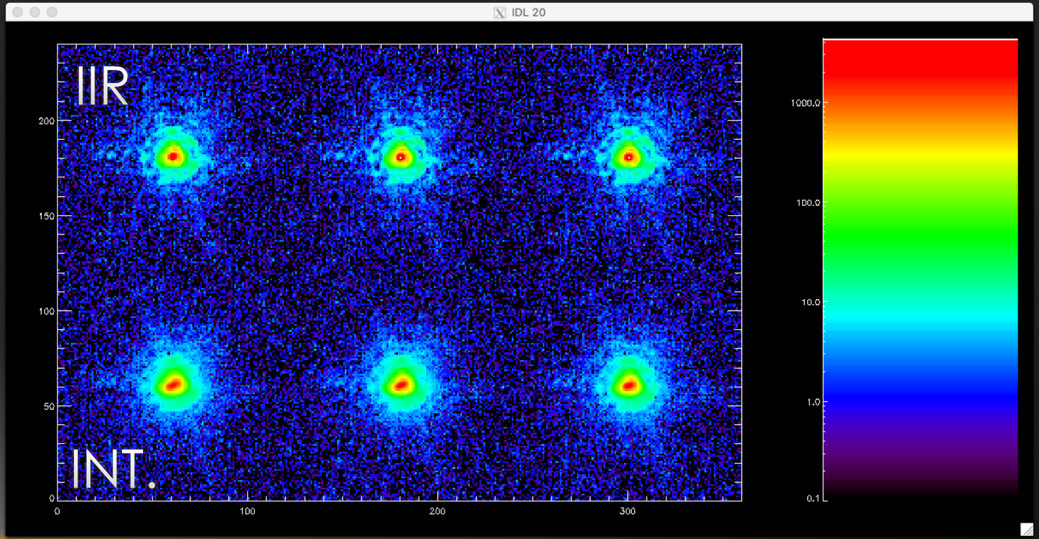

1700Hz filter

# 127HZ VIBRATION CONTROL SOLUTION TEST

- First daytime test was successful:
  - TT jitter 8mas RMS (vs 24mas)
  - SR(H band) to 70% (vs 40%, LUCI NCPA not corrected)
- Next week these filters will be used during nighttime commissioning
- MGM SW updated to manage IIR filters and will be tested soon

1700Hz filter
Day time test



# CONCLUSION

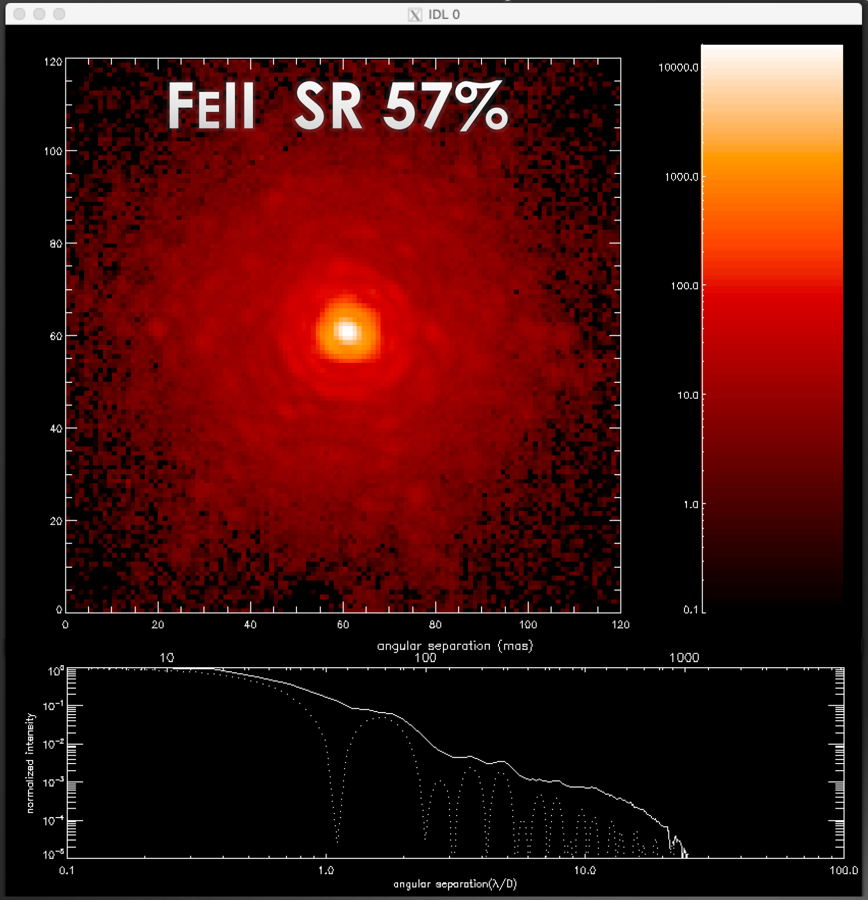
SPHERE NOMINAL
R13.5@0.6''
SR(H)=48.5%

ON SKY
(2019/07/09 06:40:42)

G 205-43
R13.5
S=0.93''

20x20 S.A.
870Hz
250 MODES

LONG EXP = 40 x 2.0s (NO SHIFT &ADD)




SIMUL.: R13.5, S=0.93'', AVE VIBR.
SR = 53% (FLAO 25%)