Status and plans for CHARA/SPICA fringe tracking

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SPICA-FT project: Overview

- Scientific need: Reaching **low fringe contrast** or **faint magnitude** to observe scientific objects in the visible wavelengths

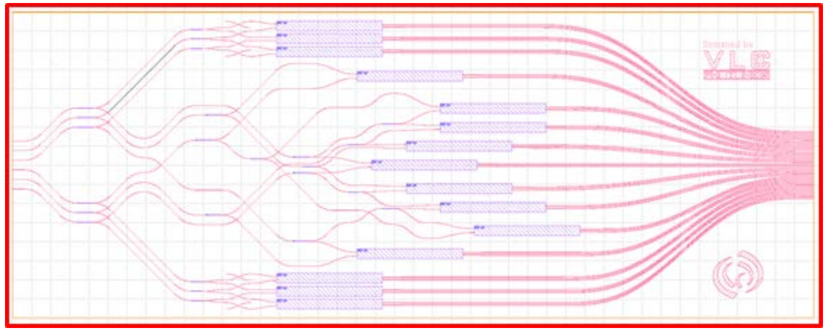
- Goal: Develop a **6T fringe tracker** for the **CHARA** interferometric array
  - MYSTIC K band, MIRCx H band
  - **SPICA H-band 6T-ABCD integrated optics** (IO) beam combiner
    - Flexibility of fibers and IO chip to easily interface SPICA-FT into MIRCx

- Top Level Requirements:
  - TLR 1: FT-SPICA must operate with **up to 6 telescopes**
  - TLR 2: FT-SPICA must track fringes for stars up to **magnitude R=8** which are **unresolved in H band** (corresponding to **magnitude H=7** for main sequence stars)
  - TLR 3: FT-SPICA must co-phase the 6 telescopes with :
    - **a precision of 90nm over a duration of 200ms (goal 2s)**
    - **a precision of 180nm over a duration of 30s**
  - TLR 4: **Robust** (against OPD vibration, flux drop out, low SNR, resolved baseline)
  - TLR 5: **Autonomous** (no decisions to be taken by the observer)

SPICA-FT testbed : Goals

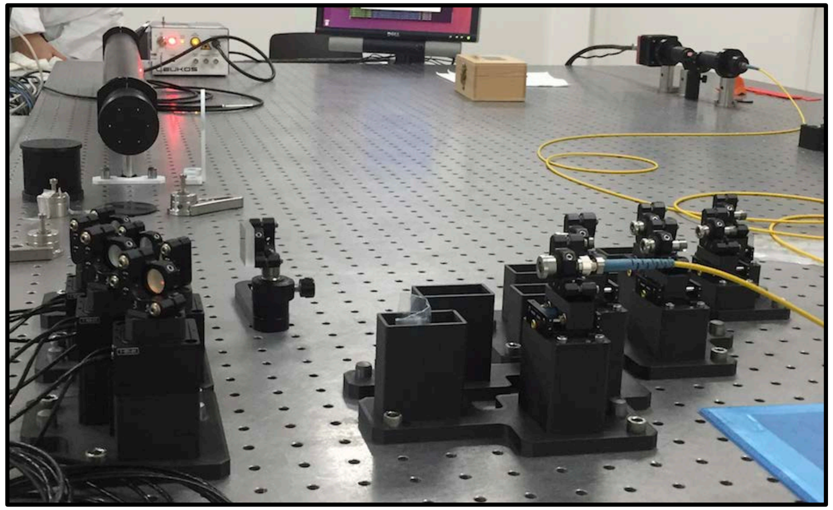
- SPICA-FT testbed implemented in Lagrange laboratory (Nice Observatory)

- 1st goal: **Interferometric tests of ABCD IO chips**
  - **Transmission** of each function
    - X coupler
    - Y junction
    - Phase shifter ($\pi/2$, π, $3\pi/2$)
  - Instrumental **visibility**
  - Instrumental **phase shift** between each pair of beams
  - Above parameters *wrt* **wavelength** and **polarization**



- 2nd goal: **Test/Debug several parts of the control software**
  - P2VM calibration
  - Phase sensor
  - OPD controller
  - State Machine
  - Servo-Loop

SPICA-FT testbed : Setup



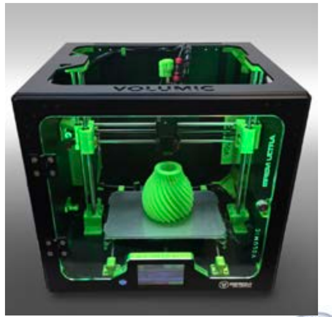
- Coherent white light source
- 6 coherent input beams
- 6 injection modules (manual tip-tilt + focus)
- 6 motorized shutters
- 6 DLs **slow piezo** translation stage
  - Mechonics, 30Hz, stroke 8mm, open loop
- 5 DLs **fast piezo** actuators (⇔ DLs CHARA)
  - Jena, 300Hz, stroke 38mm, close loop
- Spectrometer (R=30, 5 spectral channels)
- IR detector
  - PhotonFocus, 300 fps, 640x512 pixels of 15mm
- Opto-mechanical mountings in PETG + carbon
  - Manufactured by a 3D printer

Slow piezo stage:

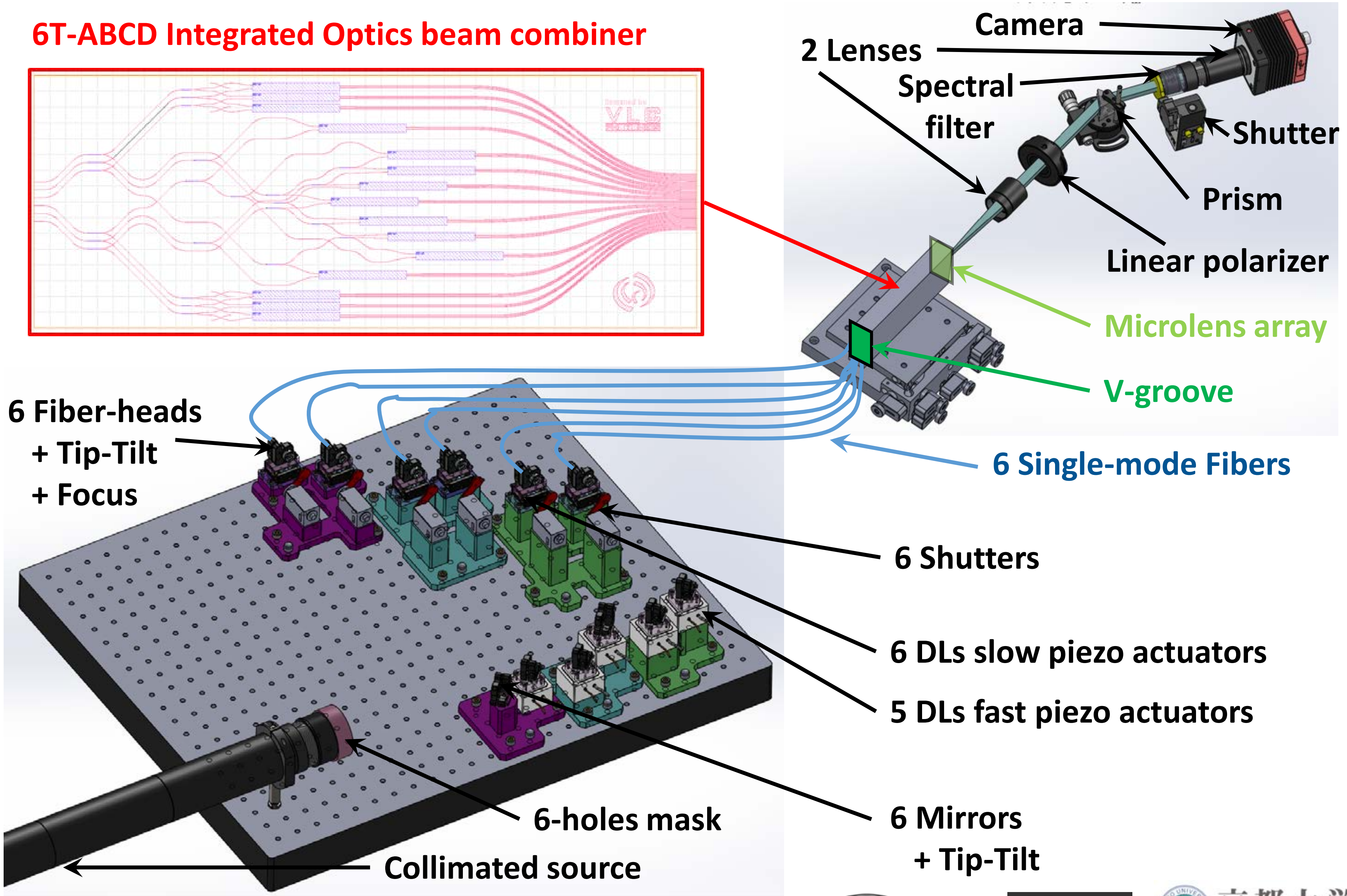
- **Correct the static OPD**
- **Apply slow OPD perturbations**

Fast piezo actuators:

- **P2VM calibration**
- **Apply fast OPD perturbations**
- **Apply fast OPD corrections**

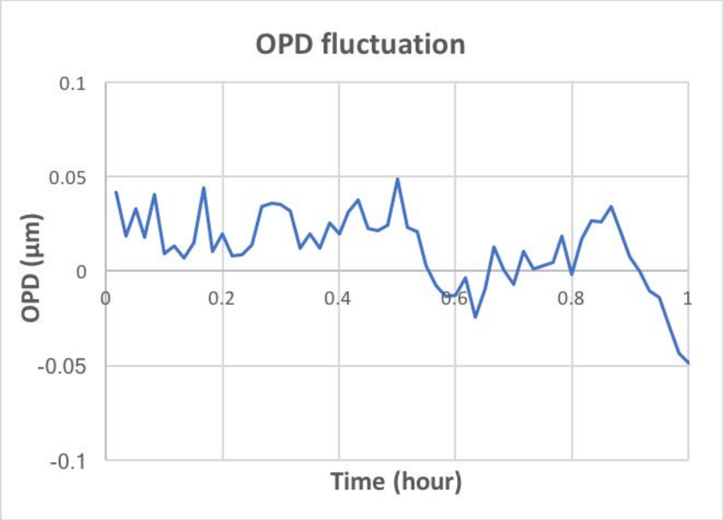


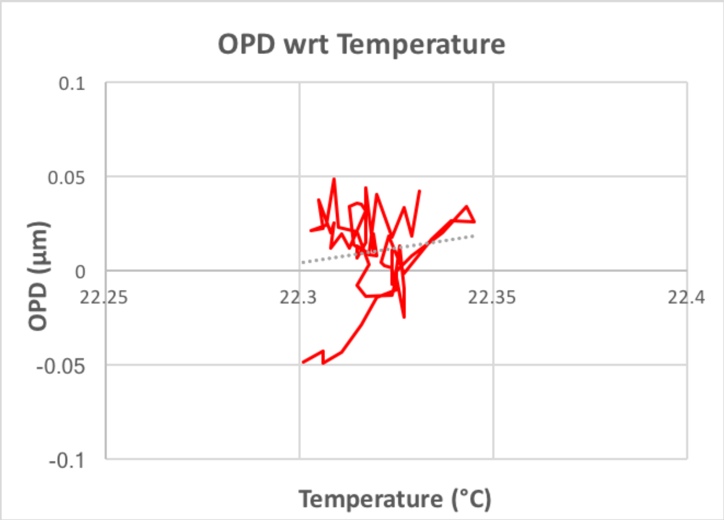
SPICA-FT testbed : Scheme

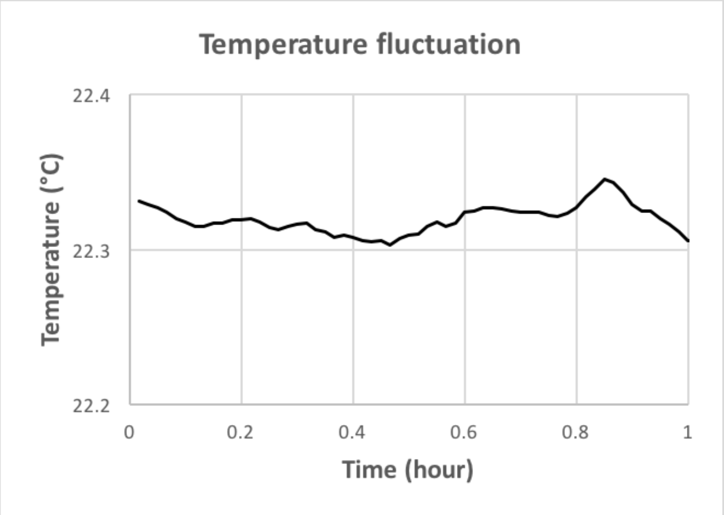


SPICA-FT testbed : Stability

- OPD stability *wrt* time & temperature (measured with a SIOS interferometer)







OPD drift : 20 nm RMS over one hour

Temperature fluctuation : 0.01 °C RMS

Flux injection : highly **stable**

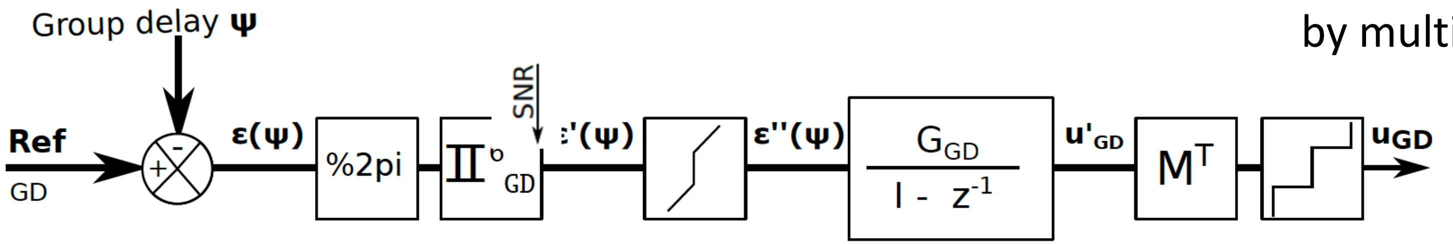
Observables & Setups

Observable	Computation	Integr.	$N_{Gravity}$	N_{Spica}
Flux	extracted from the P2VM	N_λ	4	6
Visibility	extracted from the P2VM providing complex coherent flux (unnormalized V)	DIT	6	15
Phase delay (PD)	derived from the P2VM correction of dispersion (phase curvature) no unwrapping	N_λ	6	15
Phase variance (SNR)	deduced from the P2VM + pixels variance variance of the coherent flux amplitude	5 DIT N_λ	6	15
Group delay (GD)	derived from the P2VM correction of dispersion (phase curvature) no unwrapping	40 DIT	6	15
Closure phase	argument of the averaged bispectrum estimated from PD and GD	N_λ 300 DIT	4	20
Independent closure			3	10

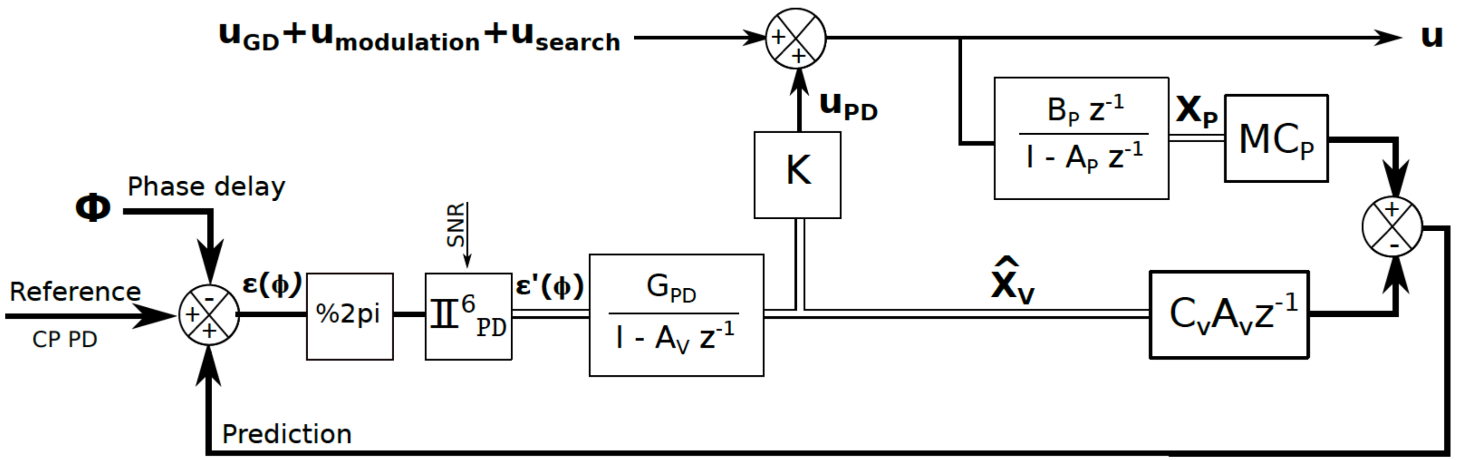
Item	$N_{Gravity}$	N_{Spica}
Degrees of freedom	3	5
Inputs Outputs	4 24	6 60
V2PM P2VM	10x24 24x10	21x60 60x21
Spectral channels Polarization	5 2	5 1

Lessons learnt from GRAVITY-FT

- **Dual control** : **Group Delay** (GD) & **Phase Delay** (PD) based on a Kalman filter
  - The GD controller is robust (sliding average of 40 DIT) for providing coherencing by multiples of λ.



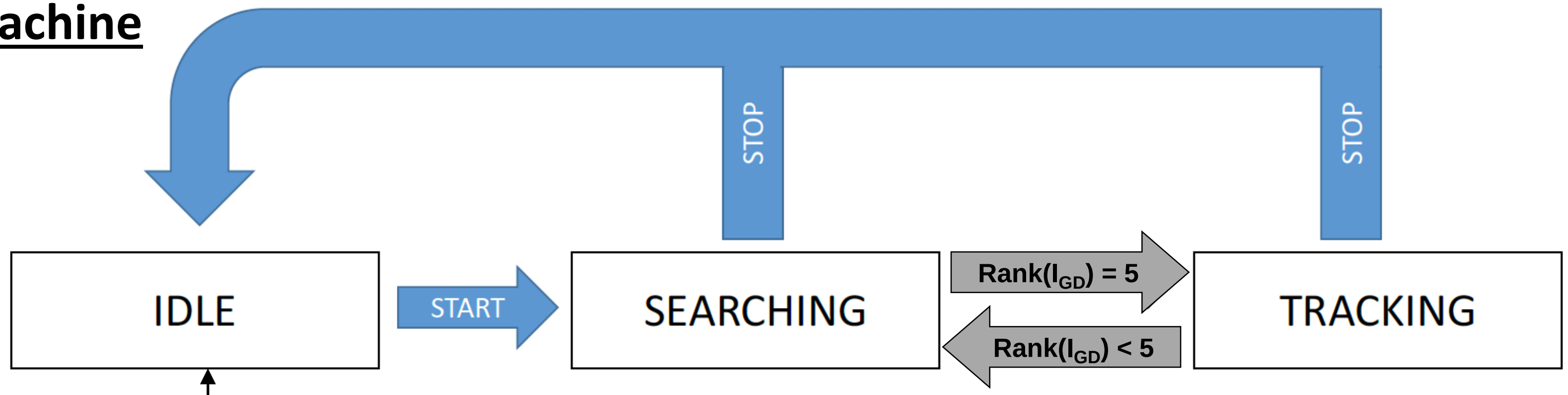
  - The PD controller is fast for providing cophasing

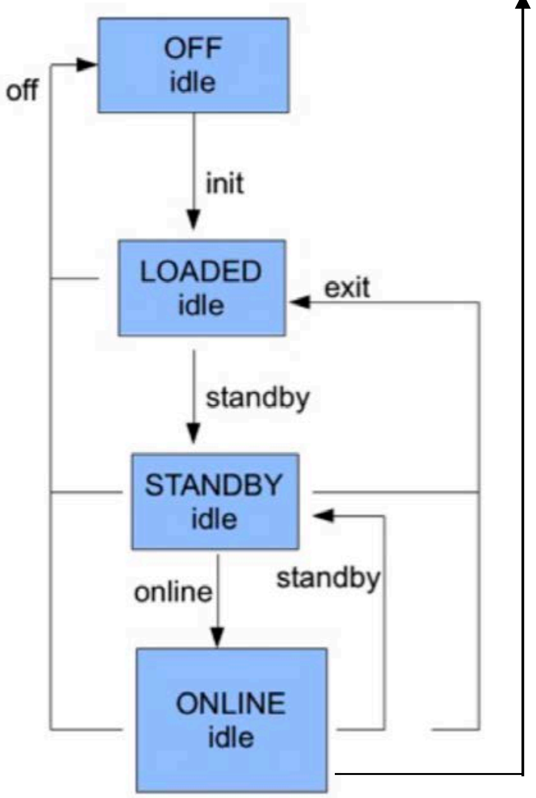


  - In case of high SNR, the Kalman filter determines and predicts the states of both atmospheric and vibrational perturbation for optimal correction at a fraction of λ.
  - In case of low SNR, the Kalman filter relies on its predictive model which, in the worst case, can be as simple as a constant value.

Lessons learnt from GRAVITY-FT

- **State machine**





- The **rank** of the matrix I^6_{GD} is what drives the decision-making of the state machine
  - The number of non-zero eigenvalues decreases if the system can't track all telescopes
  - For 6-telescopes, 5 (over 6) eigenvalues are non-zero
- The state machine has 3 states: **IDLE**, **SEARCHING, TRACKING**
  - When the operator starts the FT, it switches to SEARCHING
  - If the rank of I^6_{GD} matrix is 5, the FT goes to TRACKING
  - In both states, the GP and PD controllers are running
  - The system is still tracking on baselines with sufficient SNR which are not modulated by the saw-tooth function

GRAVITY-FT Observation sequence

Modulation synchronized with the 5s DIT science camera (high spectral resolution)

Detection of low SNR fringes by the controller

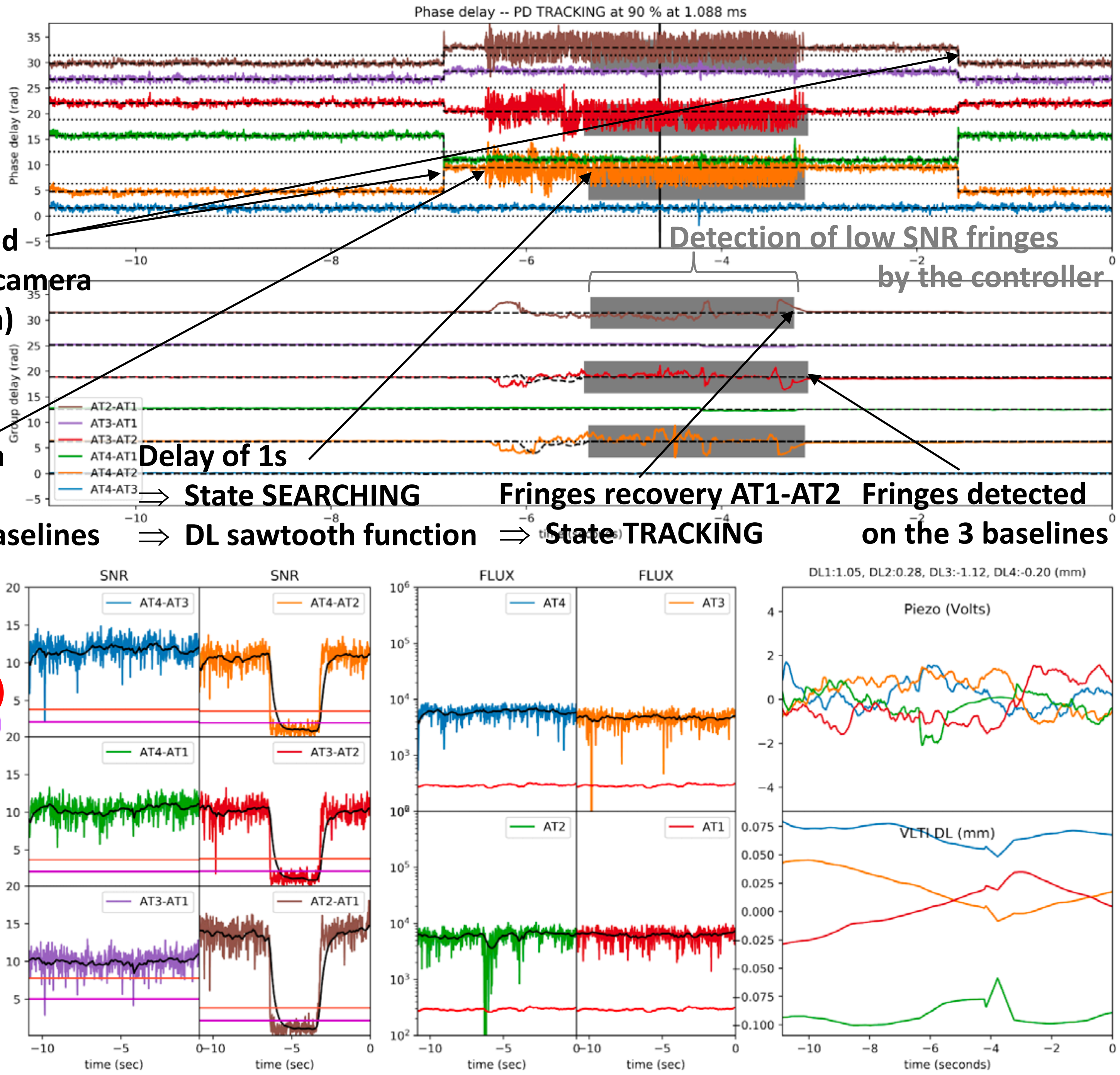
Glitch on AT2 AO system + loss of the fringes
⇒ Stop tracking on 3 baselines
⇒ State TRACKING still

Delay of 1s
⇒ State SEARCHING
⇒ DL sawtooth function

Fringes recovery AT1-AT2
⇒ State TRACKING

Fringes detected on the 3 baselines

GD threshold ($1/\sigma_{GD}$)
PD threshold ($1/\sigma_{PD}$)



Injected piston in H *wrt* R band

- Definition:
  - Piston across a pupil plane : Piston_t = average(atan[Pupil_t]) *$\lambda/2\pi$
  - Piston injected into a SM fiber :**Piston_t = atan ($\int$ Pupil_t x Gaussian dxdy) *$\lambda/2\pi$**
  - Gaussian = fundamental mode of the SM fiber, transposed in the pupil plane

- Issues :
  - RMS(Pupil_t) is worst in R band than in H band
  - Injected piston is a function of the wavelength

- Results: TBD…

What's next ?

- Integration and test of the IO chip in the testbed
    - IO chip to be aligned with the V-groove and the micro-lenses array
    - IO chip characterization
    - P2VM calibration
    - Phase sensor
    - OPD controller
    - State Machine
    - Servo-Loop

- Development and test of a fringe tracking sensor & control system
    - Group delay control
    - Phase delay control (PID first, Kalman filter next)

- *Injected* piston in H *wrt* R band (to be continued…)