Towards a 6-beam fringe tracker for SPICA

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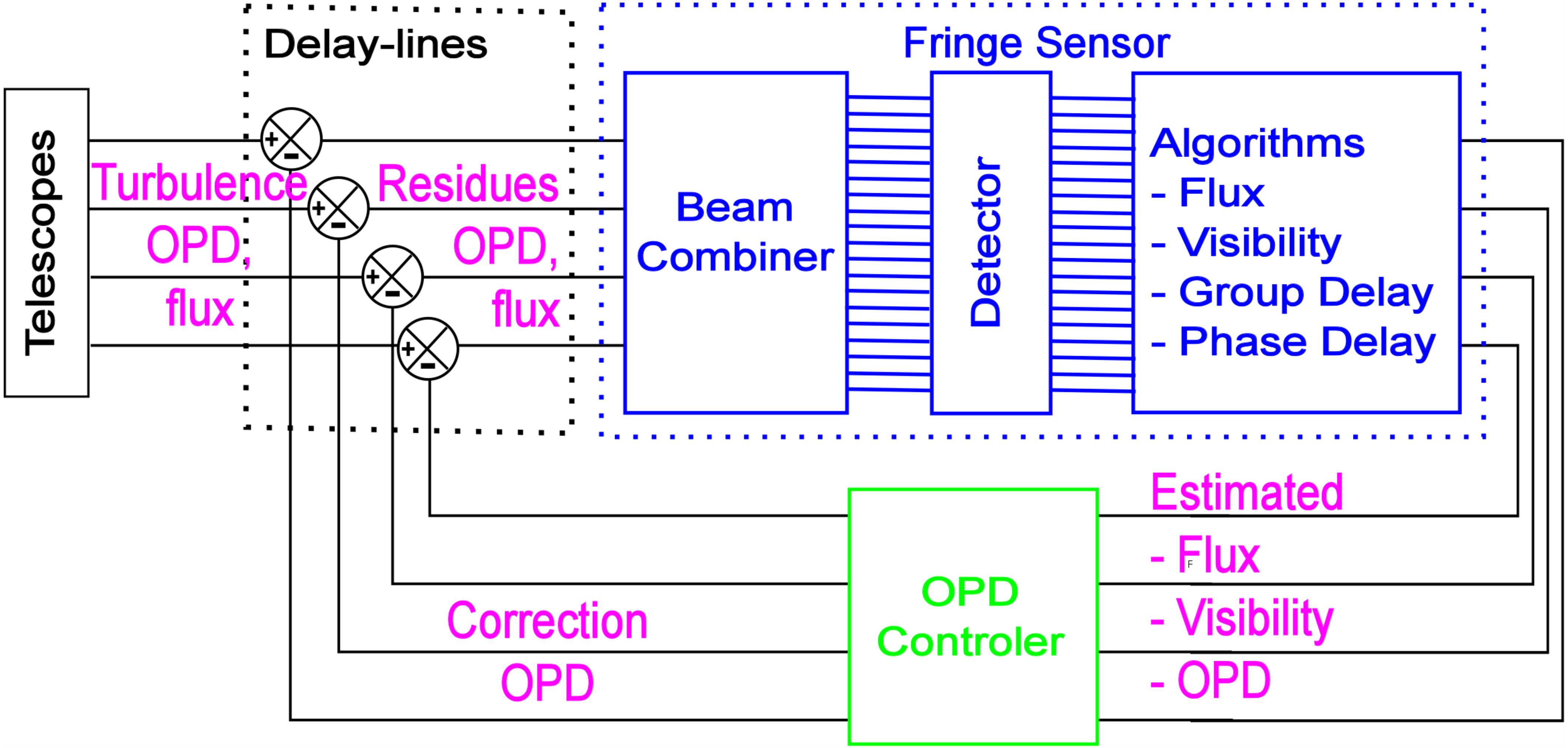
Outline of the talk

- Why a « new » fringe tracker ?
- Optimizing a Fringe Tracker
- A tool for loop simulation : COH_LIB

1) Why a new fringe tracker ?

- SPICA context
  - Main science case : diameter measurements for ~1000 G-K stars, **6 ≤ mag V ≤ 8**.
  - Observation in the visible with **6** AO-corrected beams
- High-level requirements for the FT:
  - 6 beams ⇒ up to 15 baselines ⇒ many configurations ! (4T ⇒ « only » 3-6 baselines)
  - Single-mode operation
  - Goal : OPD residue $\lesssim \lambda_{VIS} / 6$ (coherent integration) or $\lesssim$ few μm (short exposures)
  - Fringe Sensor (FS) in the J, H, K bands ⇒ inverse situation wrt usual
  - Predictive state machine (as demonstrated with Gravity)
  - Availability of E-APD detectors ⇒ evaluate new concepts
- Summary: make the best FS ! (efficient, simple, cheap?,....)

2) Overview of a Fringe Tracker



2) The Fringe Sensor: a) the beam combiner

- Many degrees of freedom
  - Bulk optics / Integrated Optics chip
  - Pairwise combination / all in one / sub-groups (hierarchical) / …
  - ABCD vs AC
  - Photometric channels ?
  - ~~Temporal modulation~~ vs Spatial modulation ? 1D vs 2D ?
  - Group delay: Dispersion ~~vs large amplitude modulation~~
- But in any case
  - LINEAR propagation of the electric field E from the input to the output
  - Not linear in OPD but in exp(i ϕ), $\phi = 2\pi\ \delta\sigma$, $\sigma = 1/\lambda$

⇒ Any single-mode beam combiner can be modeled by a matrix $M[NP, NA]$
NP = number of pixels NA=number of apertures

2) The Fringe Sensor: b) the detector

- Converts the continuous electric field $E(\boldsymbol{x})$ to discrete measured intensity I_p
- Optical frequency ⇒ quadratic detection, support = pixels sensitivity $P_p(\boldsymbol{x})$

$$I_p = \langle |E(\boldsymbol{x})|^2 \, P_p(\boldsymbol{x}) \rangle + noise$$

- Consequences:
  - No longer linear in field
  - Single-mode interferometry, where $b = (a, a')$ and a is the sub-aperture index, $\leq NA$:

$$I_p = \cdots = \sum_b \beta_b^{inst} \beta_b^{obj} B_{bp}$$

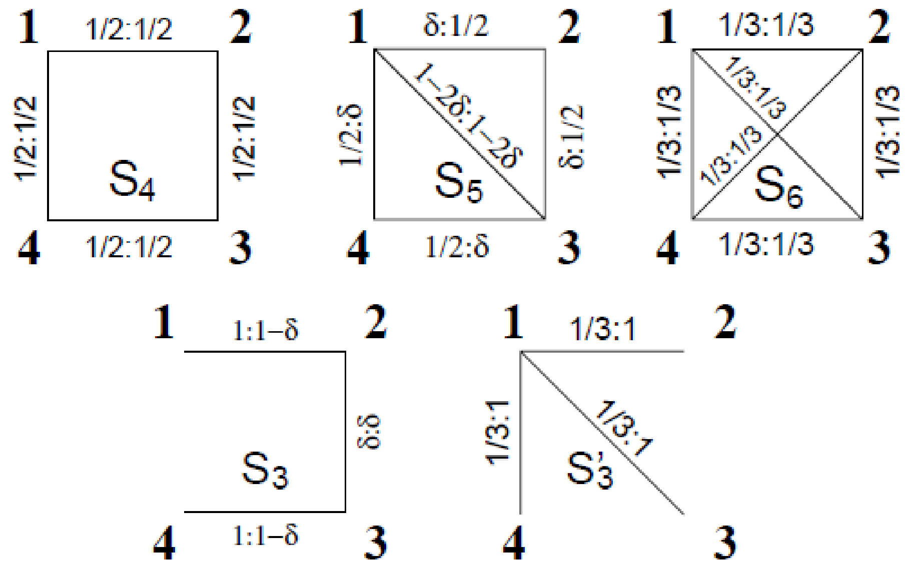
  - The output intensity is still linear, with respect to object β^{obj} and instrument β_b^{inst} coherence vectors
- « V2PM » formalism (Lacour, 2008) B=V2PM = f(M) is a matrix$[NP, NA^2]$

2) The Fringe Sensor: c) Flux algorithm

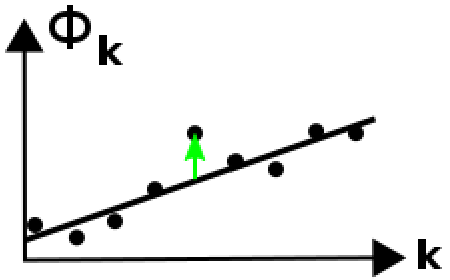
- Direct if dedicated photometric channels
- For a FS, better if photometric channels are avoided
- Can be possible from interferometric channels
  - Asymmetric beam combination (Monnier PASP 2001): A'C' + temporal modulation
  - Asymmetric A'B'C'D' modulation (Persée beam combiner, Houairi 2009)
    [4 I_p for 4 unknown β_p parameters ⇒ fully reversible if beam combiner well designed]
  - Derive aperture flux from all baselines, if enough baselines (Gravity 4T x 6 baselines)
- Fully linear (intensity to intensity)
  ⇒ no real issues other than V2PM conditionning

2) The Fringe Sensor: c’) Phase Delay algorithm

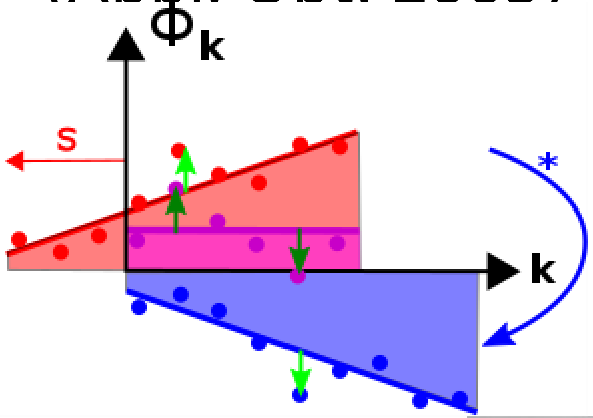
- Intensity to delay: things get worse…
- Classical solution : 2 beam interferometry, sum over all spectral channels $\Rightarrow$ single ABCD-like demodulation $\Rightarrow$ 1 coherence $\Rightarrow$ OPD estimation
- $NA > 2$, non redondant (organized baselines, ABCD groups): cf previous case. Need to convert OPDs to delay on each arm: linear operation (Cf Baron JOSA-A 2008, Houairi SPIE 2008)
- Redundant case
    - Generaly avoided since inverse problem harder
    - But real-time solutions exist
    - Less pixels
    - No IO chip
    - Investigation begun during 2GFT study



2) The Fringe Sensor: c'') Group Delay algorithm

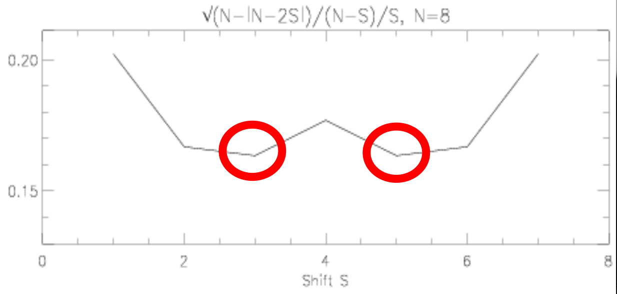


- Dispersed fringe approach:
  ABCD in each spectral channel (σ_k linear with index k)
  $\Rightarrow Z_k = A_k \exp(2i\pi\sigma_k\delta) + noise$
- Based on E. Pedretti shifting algorithm $Y = \langle Z_{k+S} Z_k^* \rangle_k$ (Appl. Opt. 2005)



- What is the optimal spectral shift S ?
  - Small value: large dynamic (synthetic wavelength)
  - Large value: better accuracy (larger differential phase) but less phasors averaged ⇒ more noise ?
  - S is software-tunable ⇒ to be optimized for tracking
- Simple analytical model → noise is proportional to

$$\frac{1}{S^2}\frac{N_S}{(N-S)^2}\frac{\sigma_n^2}{A^2} \quad \text{where} \quad N_S = N - |N-2S|$$



- Optimum values for S ⇒ new *mustache* theorem ?

Photo by Weegee (Arthur Fellig)/International Center of Photography/Getty Images)

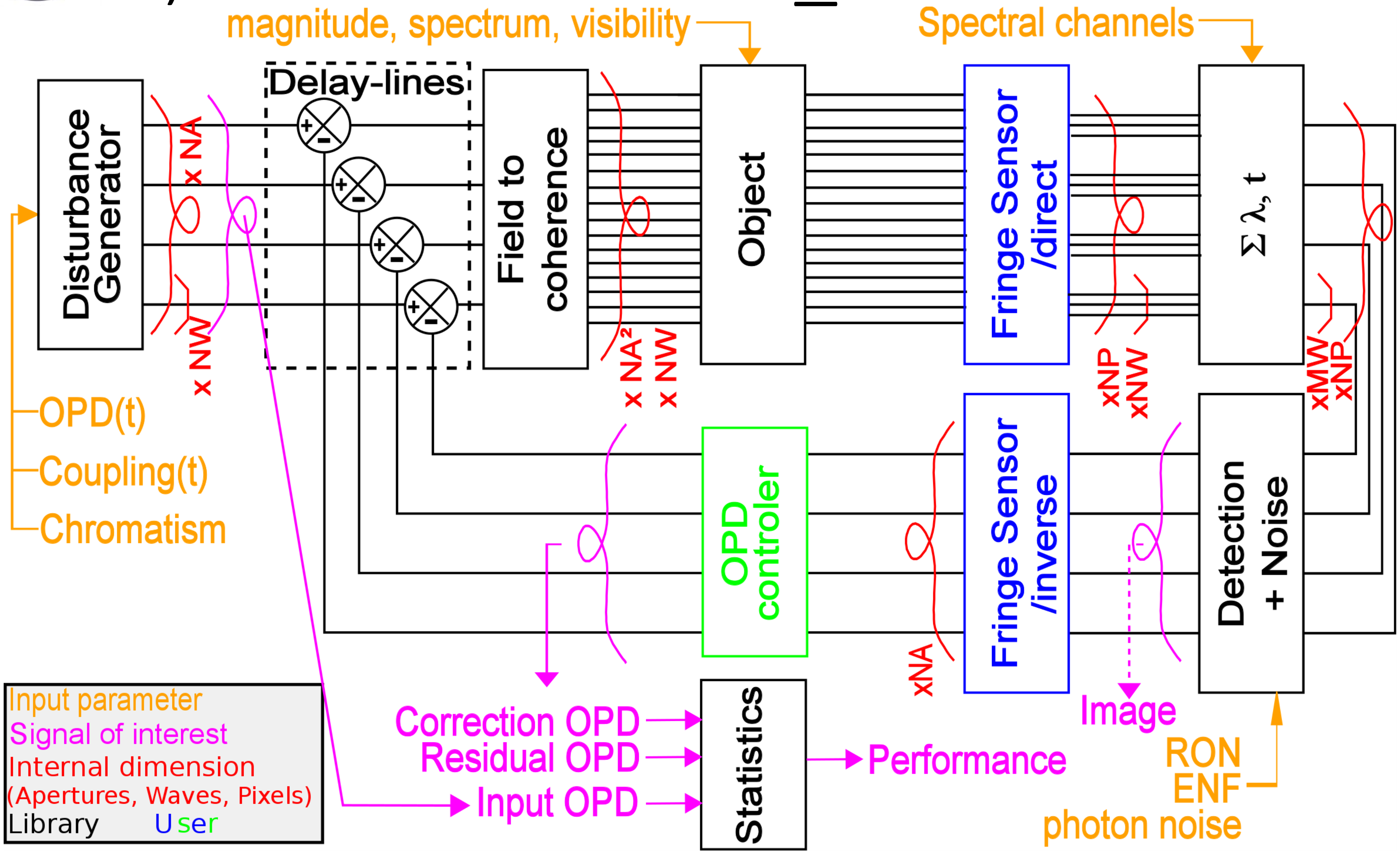
2) The OPD controler

- Basic version : integrator
- Advanced version : predictive OPD model
  - Kalman filter
  - ARMA
- « Clever » : adaptive behavior
  - No flux in one arm⇒ use model rather than measurements
  - Poor visibility ⇒ recenter (from GD), search for fringes
- Consequences
  - Non linear
  - Time-domain evaluation

3) Our simulation tool: COH_LIB

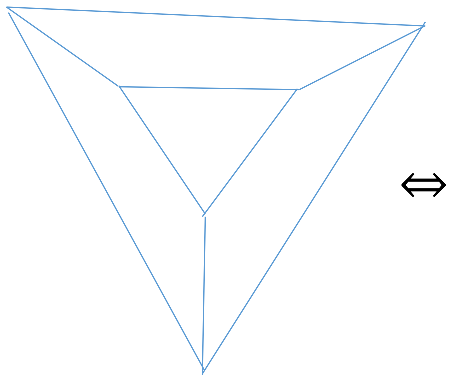
- Non linear control ⇒ temporal domain simulation
- Based on coherence propagation ⇒ linearity of the beam combiner = matrix
- Modular set of IDL routines :
  - Generic: turbulence, delay lines, detector, loop, statistics,…
  - User specific: FS, controler
- Initiated in ~2007 and already used for:
  - 2GFT ESO study
  - Gravity FT development
- Currently upgraded
  - Features, functions, documentation,…
  - Definition of new FS
  - Definition of relevant performance criteria

3) Overview of COH_LIB



3) The already-defined FSs for 6-beams

- Based on pairwise ABCD combinations (1line = 1 ABCD modulator)
- Uniform amplitude splitting (preliminary approach)



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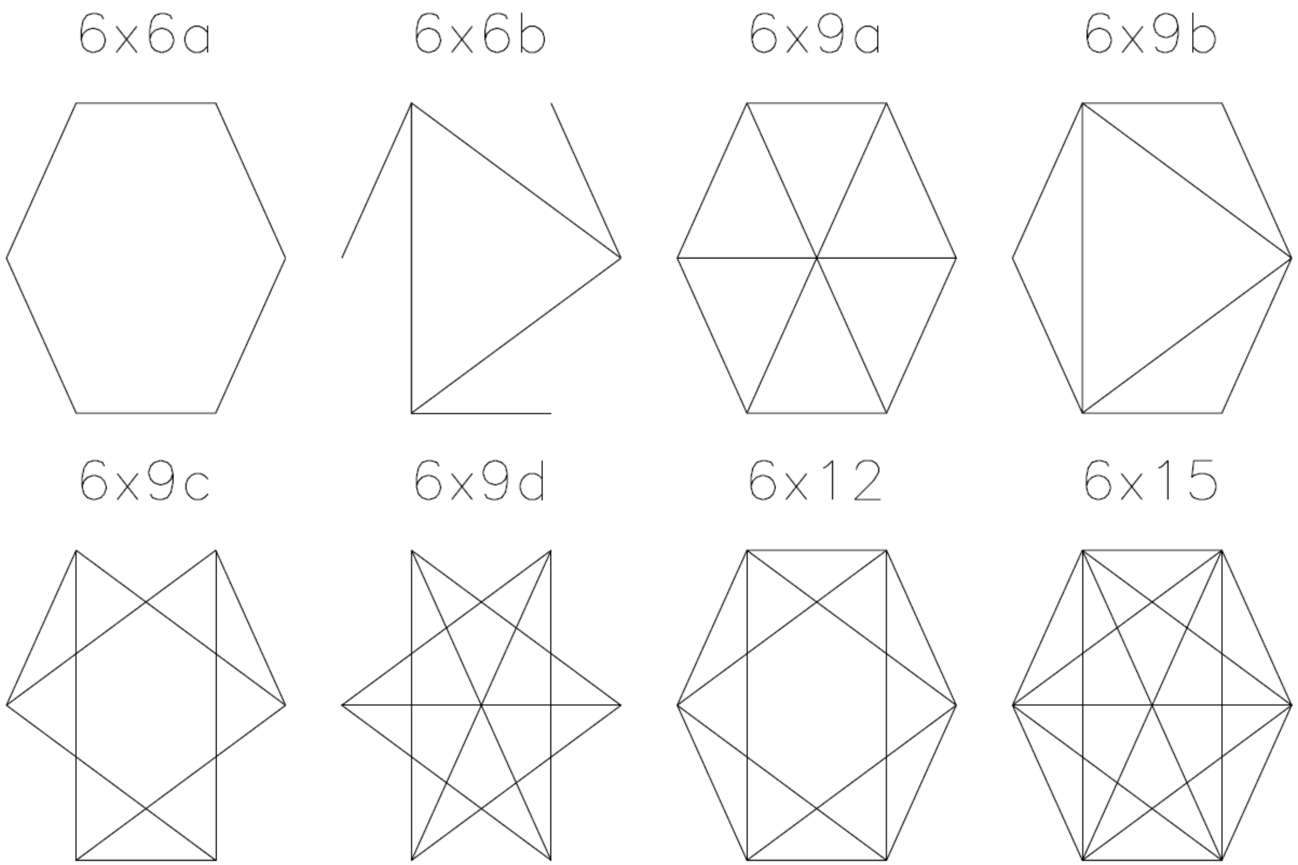
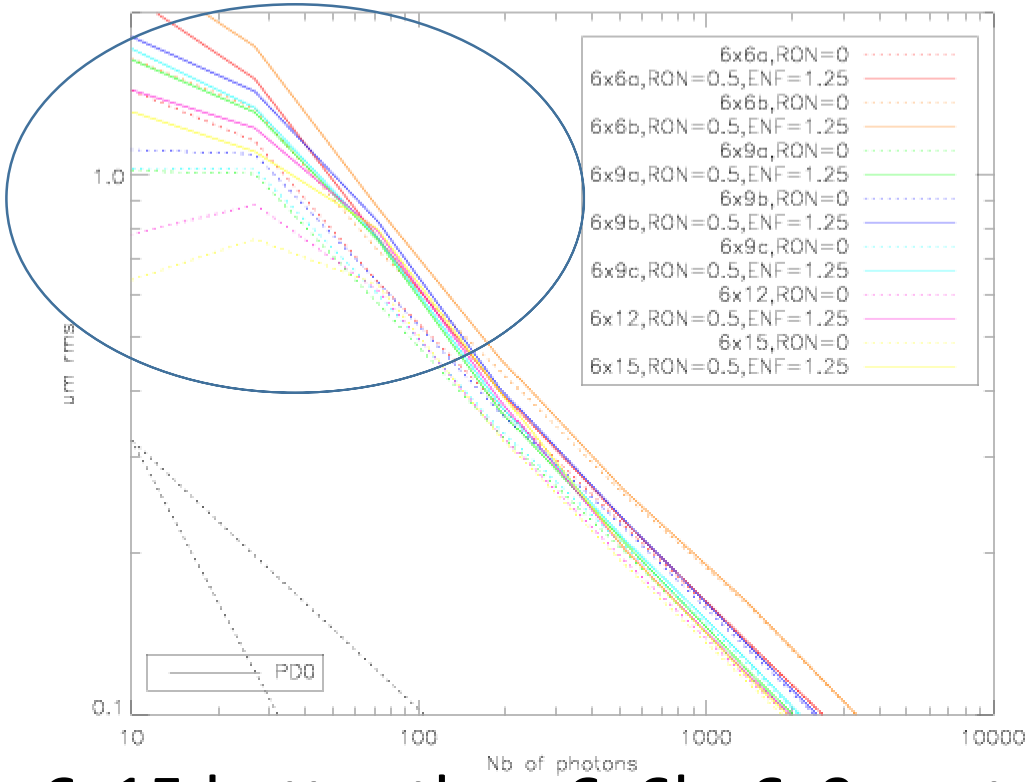


3) First COH_LIB results

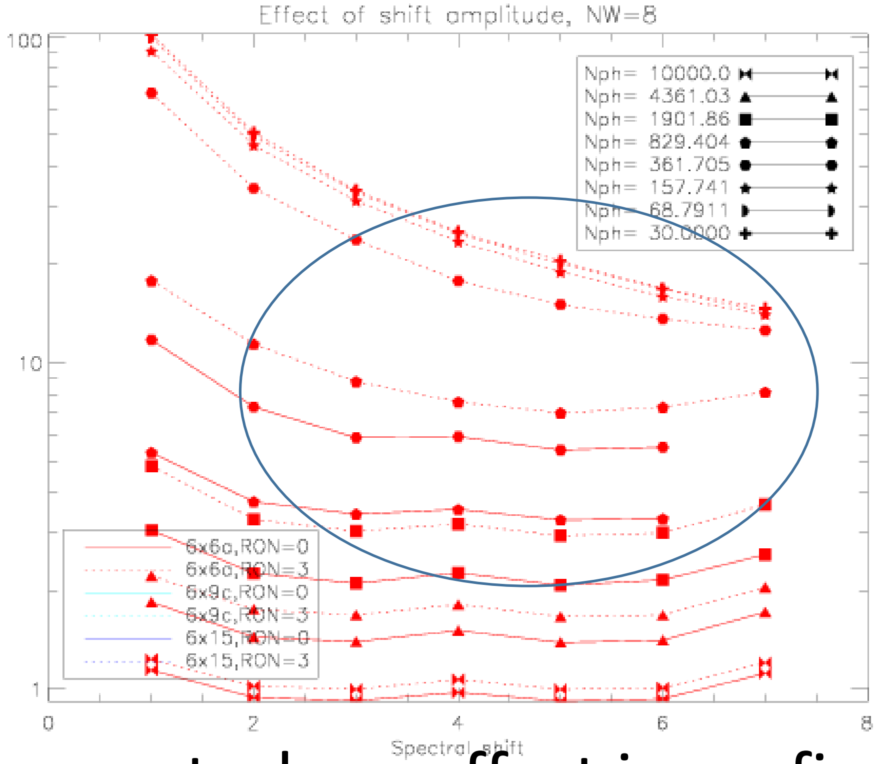
- Bad behavior observed at low flux (SNR test not implemented yet)

- Measurement noise vs nb of photons



- 6x15 better than 6x6b, 6x9c not bad

- Optimal shift for GD algorithm



- The « mustache » effect is confirmed !

Conclusion

- Optimal 6T FT: not so trivial
  - Find best architecture
  - In link with algorithms
  - Need for a state machine
- Necessity of a time-domain end-to-end simulator
- COH_LIB simulation tool to be completed soon
- First results (high flux): more baselines better than few baselines

Next steps:

- Identify the best (at least : not too bad) 6T Fringe Tracker
- Answer questions: NxABCD or all-in-one ? ABCD or AC ? Other setups ?