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Interferometric sensitivity at VLTI

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Introduction

- We need higher limiting magnitudes
- We seem stalled around K=10-11 with the UTs
- We can
  - Use off-axis tracking in very special cases ?
  - Wait for detectors to improve ?
  - Say that improving sensitivity is useless because fainter targets are too unresolved ?

But we can also progress rapidly on:

- Incoherent and coherent data processing
- Cophasing and coherencing
- Off axis tracking, sky coverage and isopistonic angle
- …

There are science programs at higher magnitudes,
for *existing* and future interferometers!

Current « common sense »

- We process frame by frame (and channel by channel in AMBER) and average the results
  - Or we average coherent frames and channels with a FT
  - This is limited to SNR by frame and channels <~3
- The limiting magnitude is set by the capacity to detect fringes in one frame (~coherence time), or by the Fringe Tracker
- The limiting magnitude of any higher spectral resolution is set by the Fringe Tracker limit
- Fringe Tracker on sources fainter than K=10-11 is very uncertain
- Fainter sources would need much longer baselines.

Coherent, incoherent, intermediate

- Coherent integration of short exposures

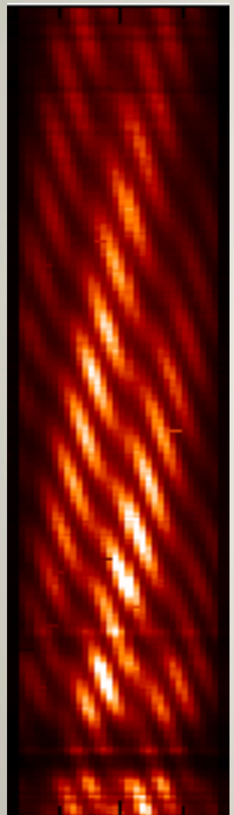
$$\frac{C}{\sigma_C} \simeq \frac{n_* t_{DIT} V}{\sqrt{n_T n_* t_{DIT} + n_p \sigma_{RON}^2 + n_T n_{th} t_{DIT}}} \sqrt{n_\lambda \frac{T_{EXP}}{t_{DIT}}}$$

  - Useless if $SNR_{frame}<1$
- Incoherent integration
  - When $SNR_{frame}<1$,
    varies like $SNR^2\ n^{1/2}$
  - Should be very inefficient

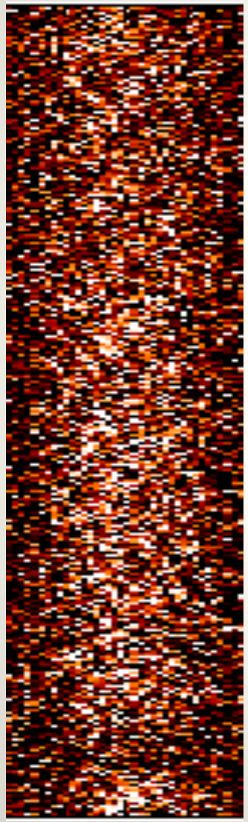
$$\frac{|C|^2}{\sigma_{|C|^2}} = \frac{\left(\frac{C}{\sigma_C}\right)^2}{\sqrt{N\left[1 + 2\left(\frac{C}{\sigma_C}\right)^2\right]}}$$

BUT

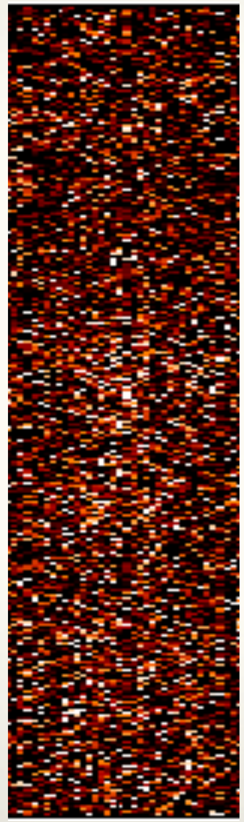
Blind mode observing and 2DFT processing



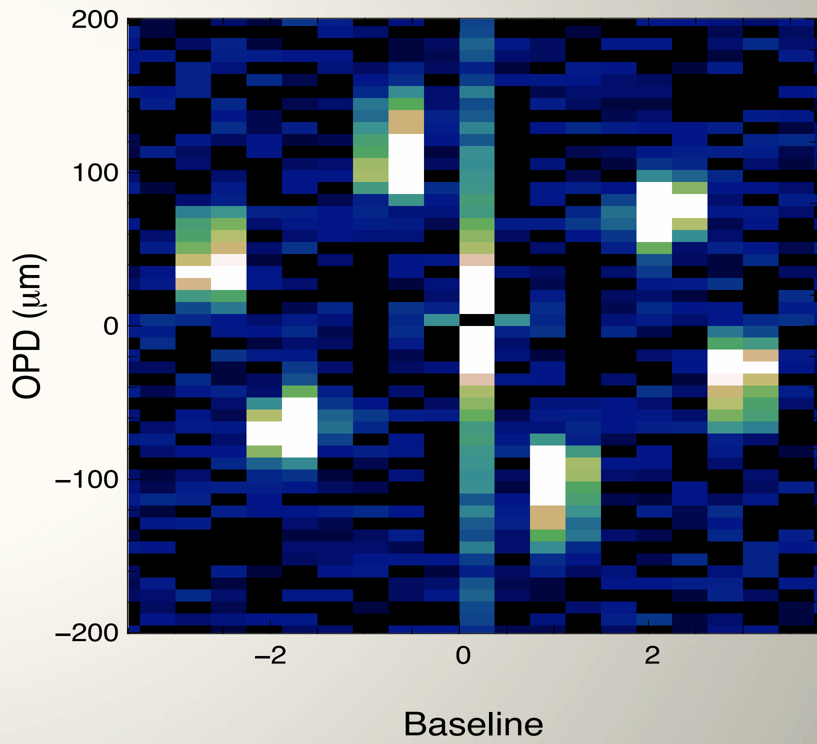
K=4



K=8.5



K=10



3C273 fringe peaks (10 s)

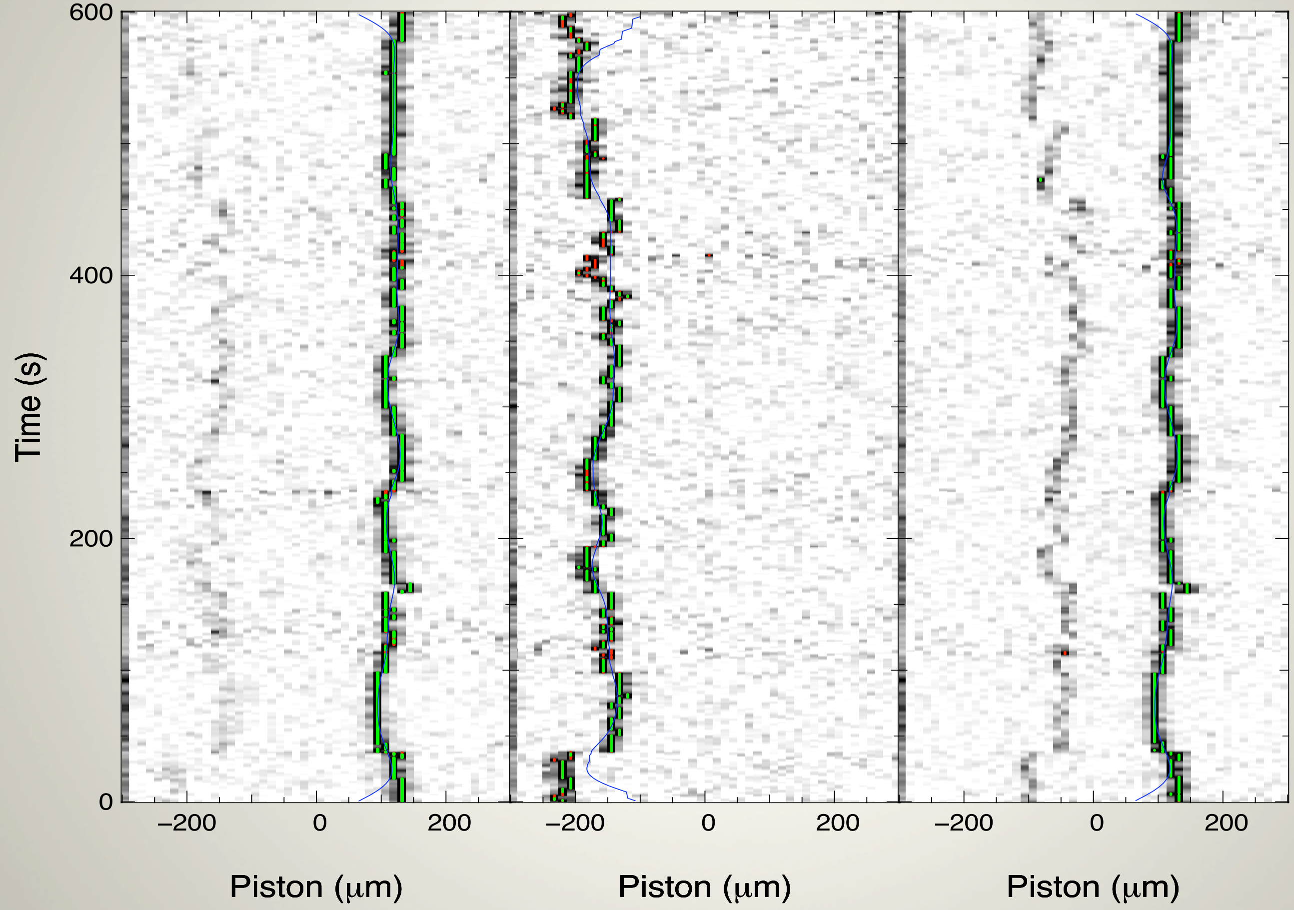
<|2DFT|^2> processing

- <|2DFT|^2> processing is:
  - A coherent addition of all spectral channels
  - An incoherent addition of 2D power or cross-spectra

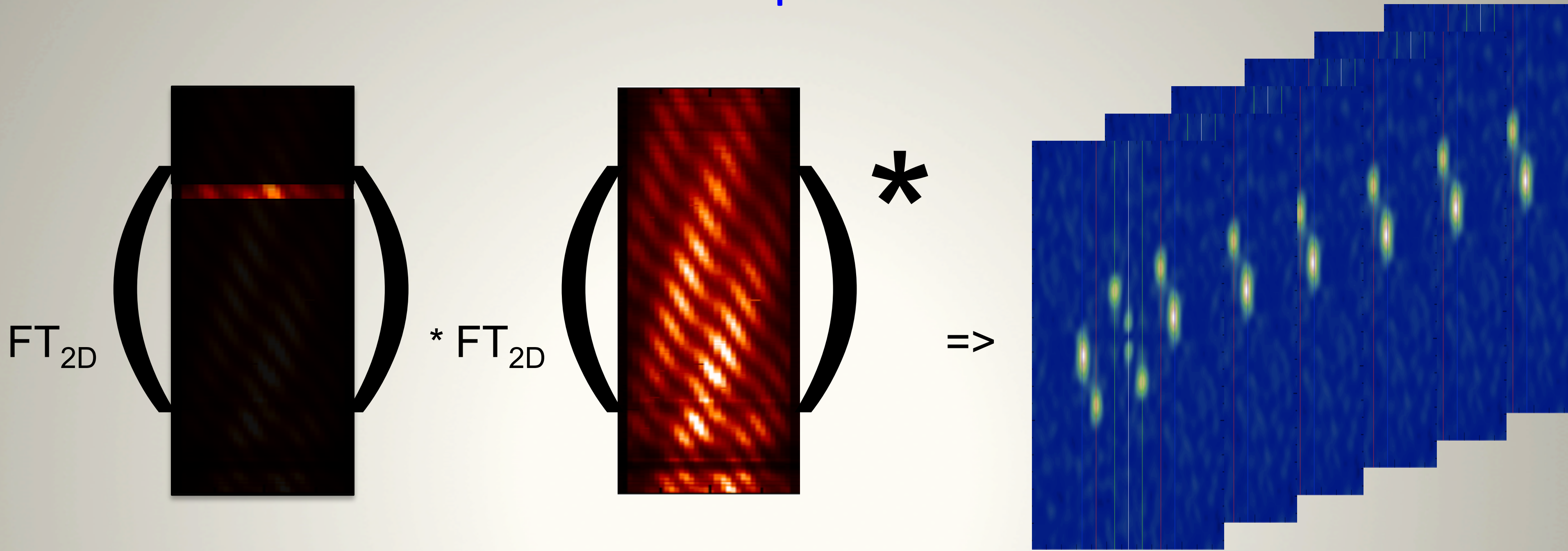
$$\frac{|C|^2}{\sigma_{|C|^2}} = \frac{n_\lambda \left(\frac{C}{\sigma_C}\right)^2}{\sqrt{N\left[1 + 2n_\lambda \left(\frac{C}{\sigma_C}\right)^2\right]}}$$

  - <|2DFT|^2> would increase coherence time
  - Higher order processing
    - Rebuilt a posteriori the successive derivatives of the piston track

Fringe peak monitoring and piston tracking AMBER K=10



TF2D measurement of complex coherent flux



⇒ Cross spectrum at σ yields:

$$W_\sigma^{ij}(\upsilon) = n_i n_j \Omega^{ij}(\sigma)\widehat{\Omega}^{ij}(\nu - p_a)e^{-2i\pi\sigma(\nu - p_a)}$$

⇒ Where $\Omega^{ij}(\sigma)$ is the "object" to be measured and calibrated:

$$\Omega^{ij}(\sigma) = n(\sigma)V_*^{ij}(\sigma)V_I^{ij}(\sigma)O_*^{ij}(\sigma)e^{\left[i\phi_*^{ij}(\sigma)+i\phi_I^{ij}(\sigma)+2ip_c(\sigma)\sigma\right]}$$

⇒if we have the ***Exact*** measure of piston p_a:

$$W_\sigma^{ij}(\nu = p_a) = n_i n_j \Omega^{ij}(\sigma)\widehat{\Omega}^{ij}(0) = n_i n_j \Omega^{ij}(\sigma)\int \Omega^{ij}(\sigma)\, d\sigma$$

performance of <|2DFT|^2> processing

With AMBER/UTs MR current detector: Ron=11e$^-$

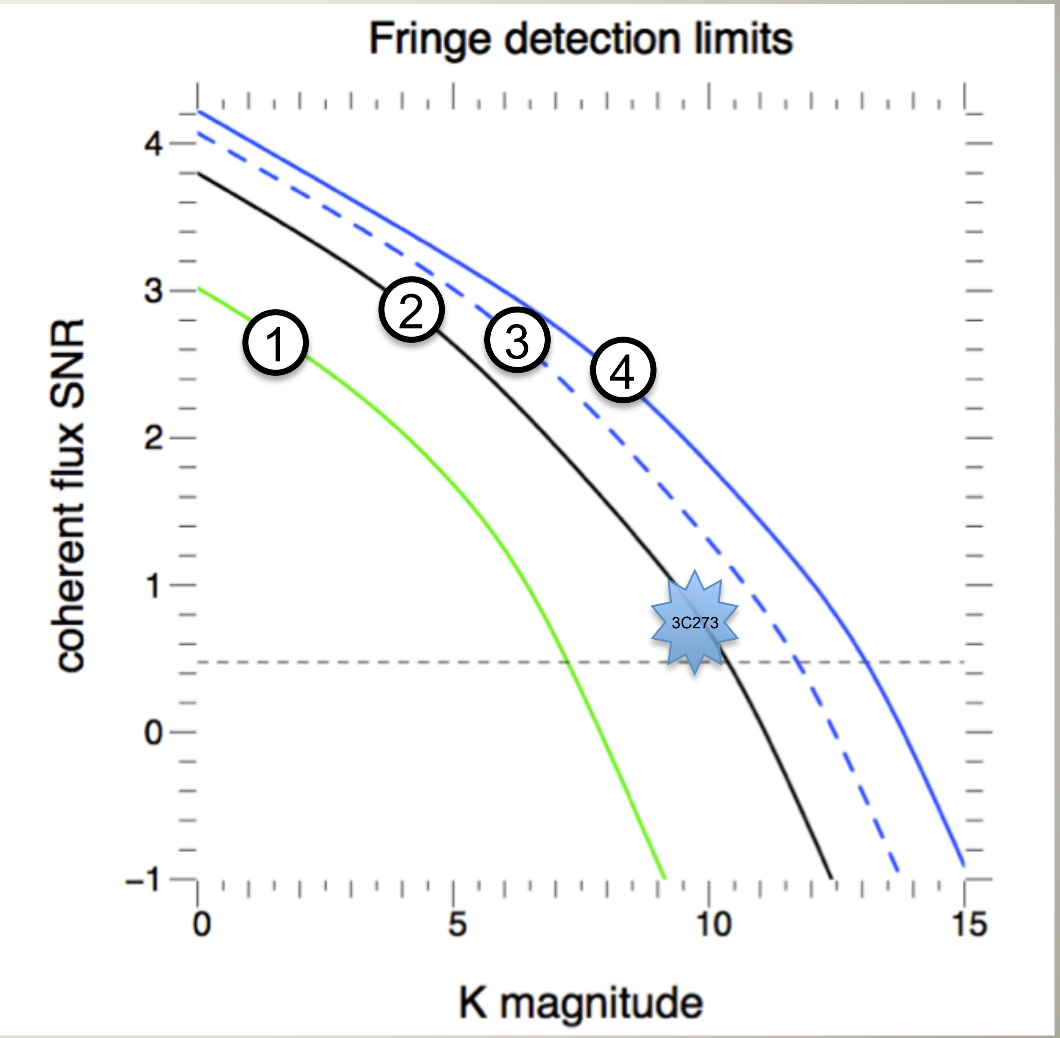
1: standard frame by frame processing (P2VM)

2: <|2DFT|^2> processing achieved with current AMBER (10s incoherent integration)

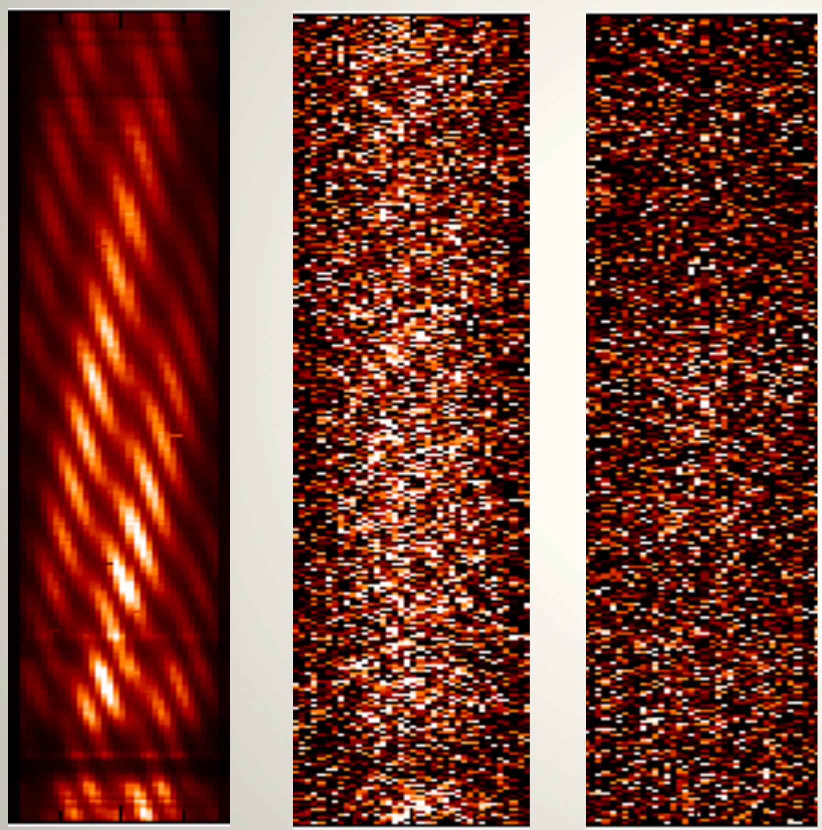
3: <|2DFT|^2> potential with corrected AMBER SFK

4: <|2DFT|^2> potential with OASIS bypass of SFK

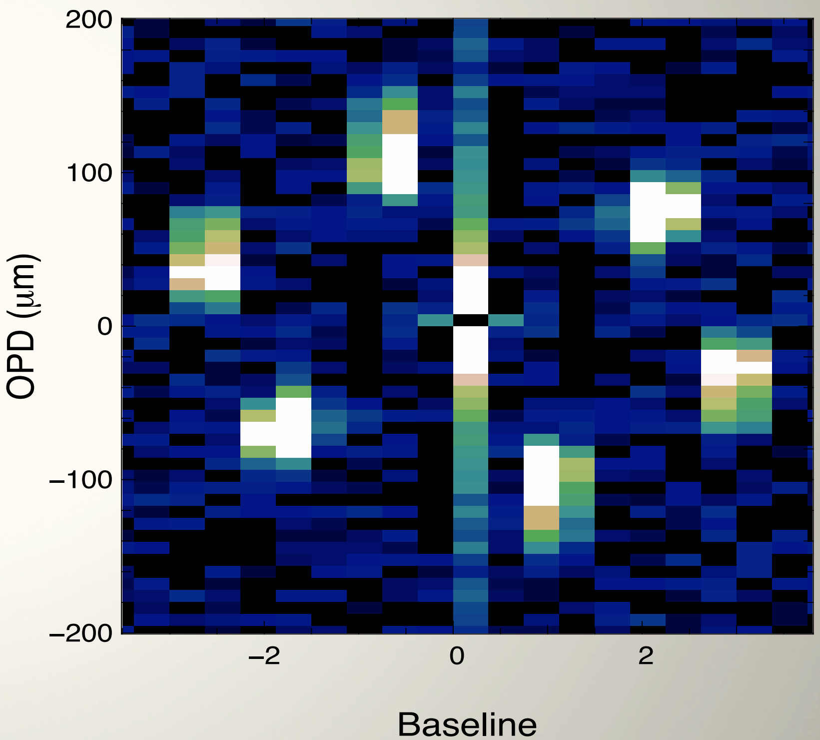
(1) and (2) are tuned on actual measures, (3) and (4) are deduced from (1) and (2) from transmission and number of pixels update



Optimizing spectro-interferometry for 2DFT

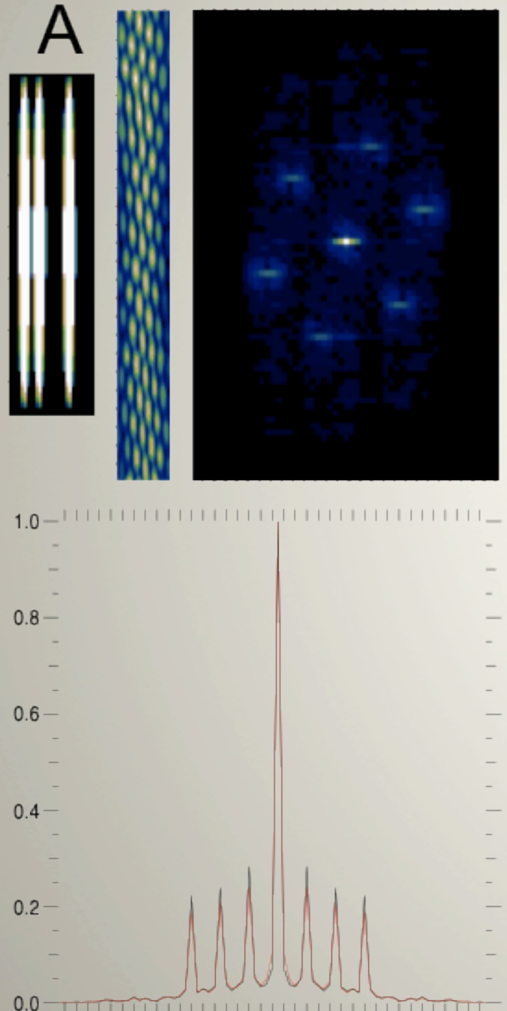


K=4 K=8.5 K=10

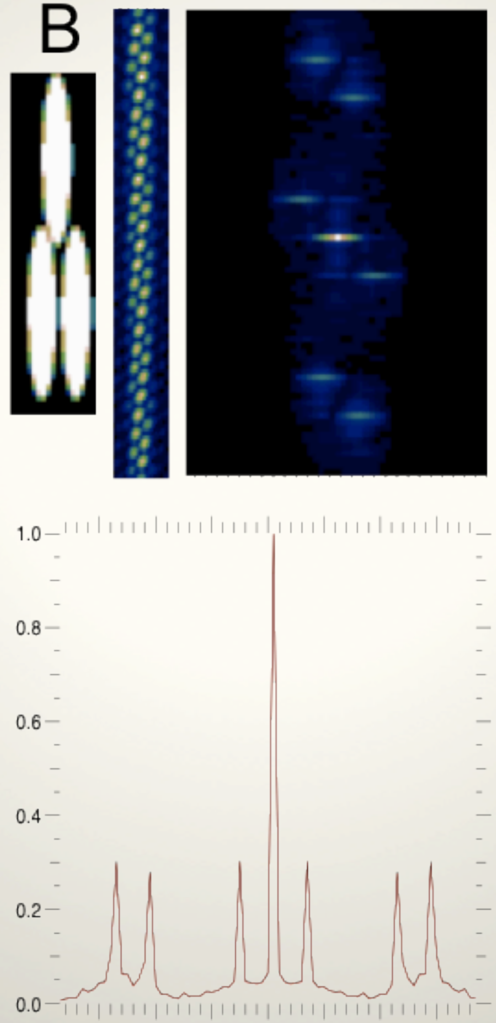


Saving pixels in spectro-interferometry

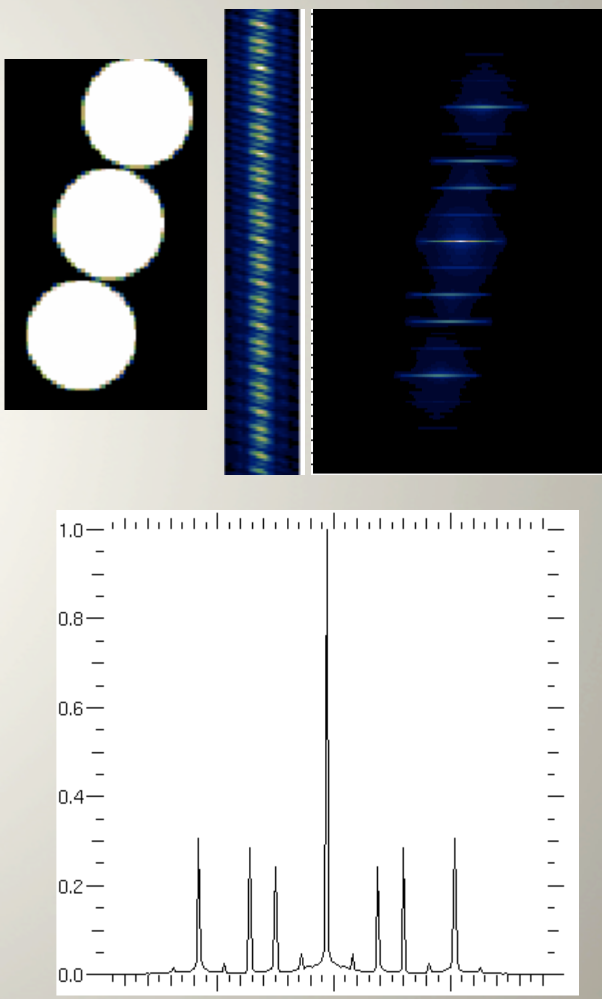
32 pixels/channel



12 pixels/channel

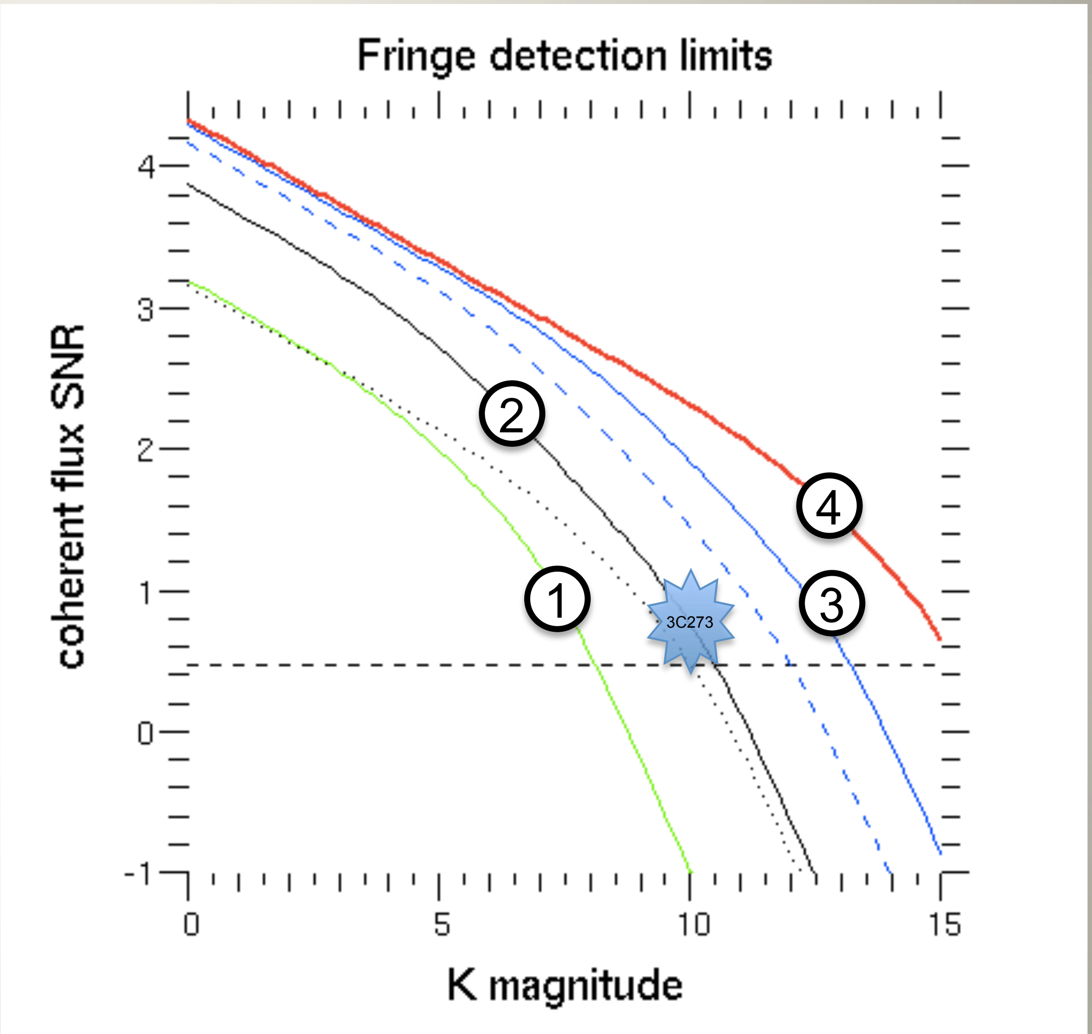


4 pixels/channel



performance of <|2DFT|^2> processing

- 1: current standard AMBER processing, MR=1500
- 2: <|2DFT|^2> processing with current AMBER
- 3: <|2DFT|^2> processing with improved AMBER but current detector (11e$^-$)
- 4: <|2DFT|^2> processing with new instrument and SELEX detector (3e$^-$)



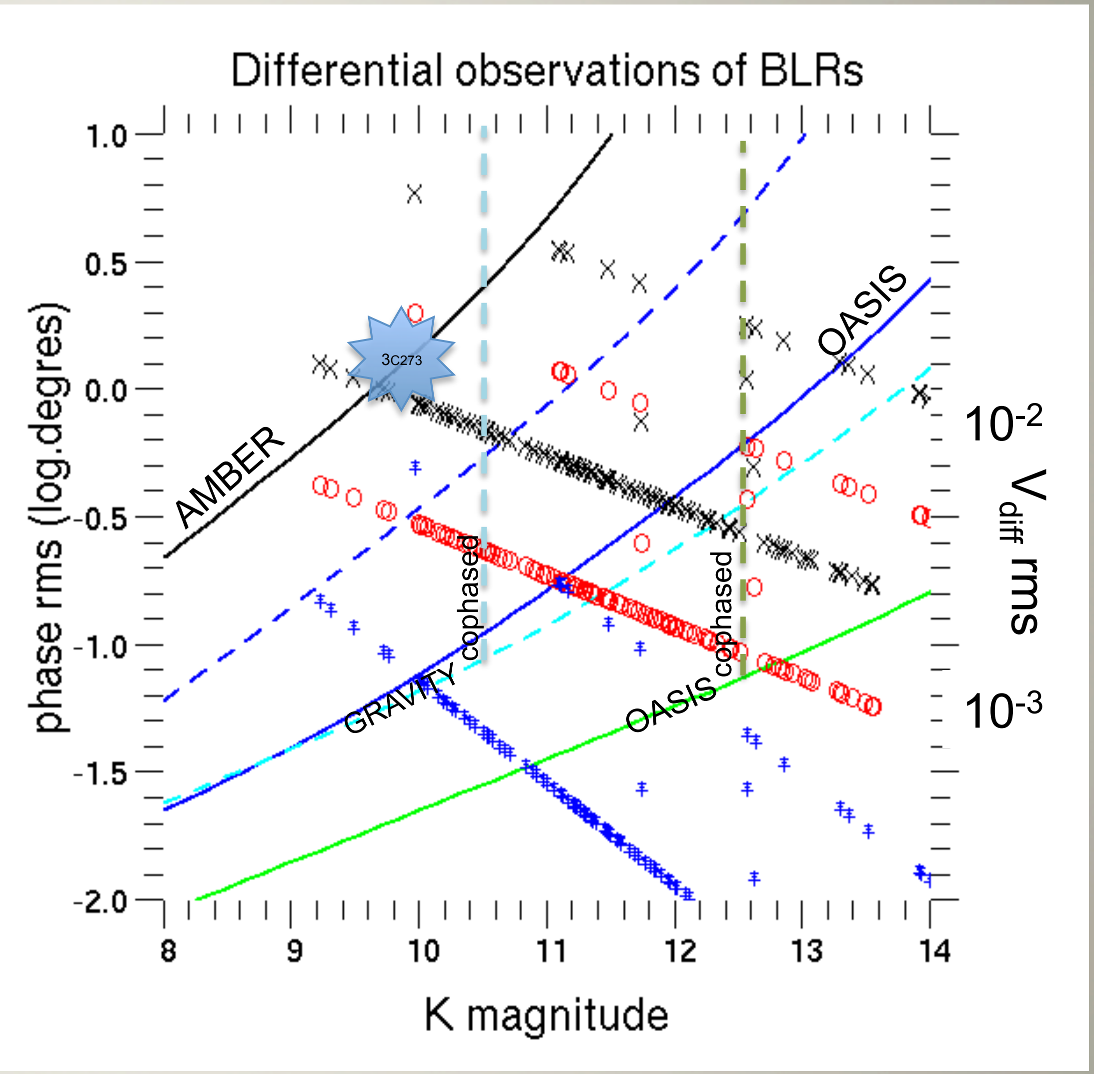
BLRs: a program for high magnitudes in MR

1 h of observation, R=1500

X : differential phase from R_{in} diameter
(IR reverberation mapping, extrapolated)

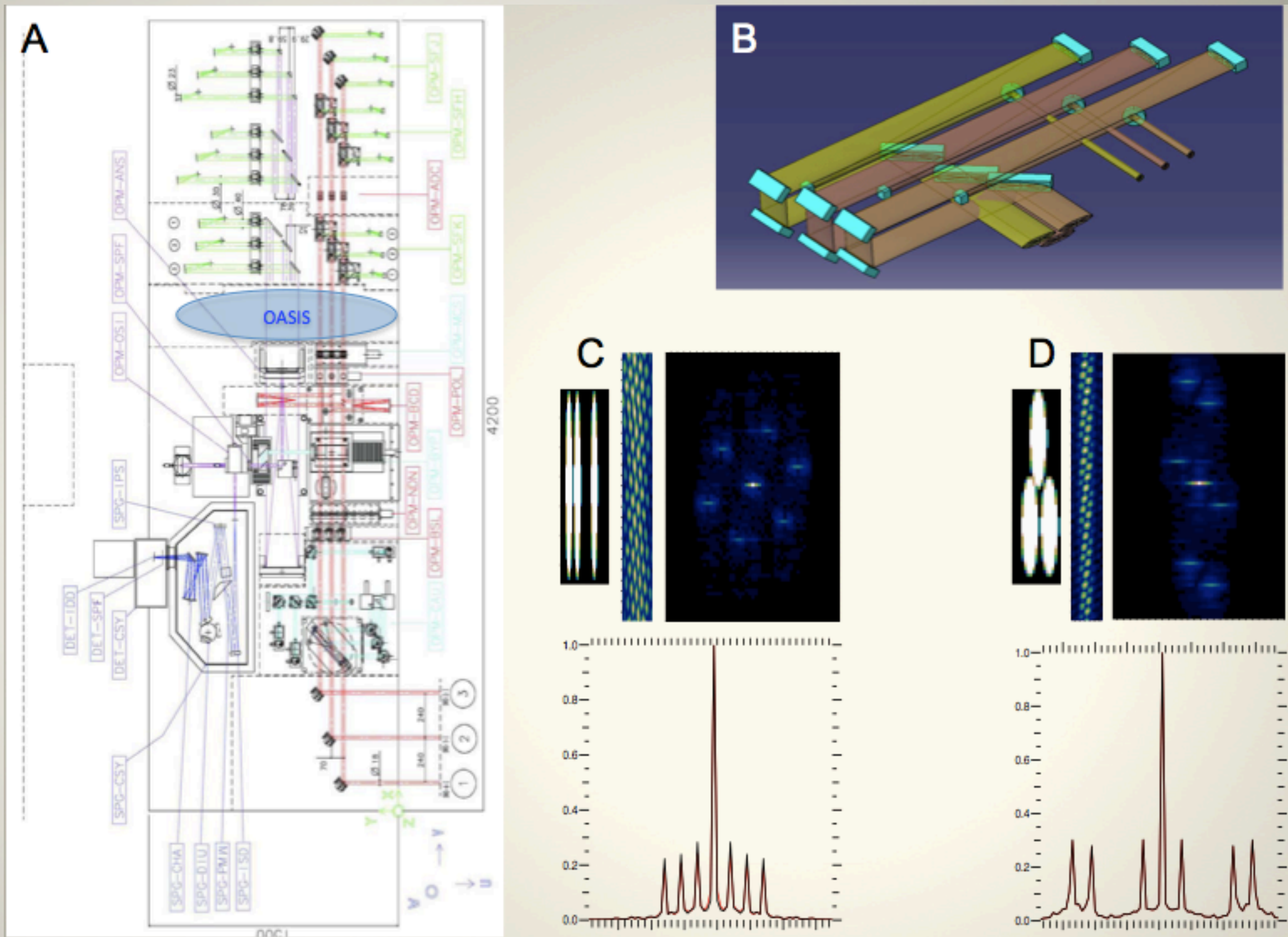
O : differential phase from RM radius
(H_β RM extrapolated)

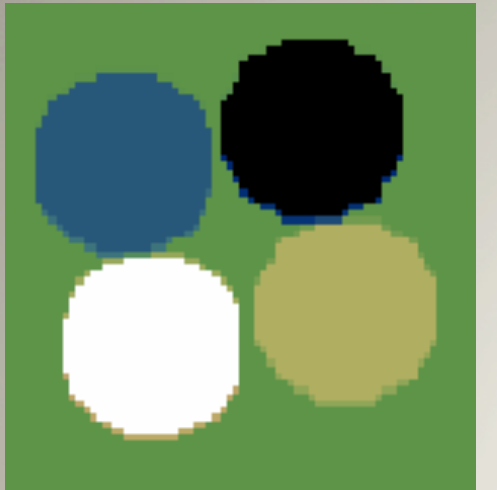
* : differential visibility from R_{in} and R_{BLR}<<R_{in}



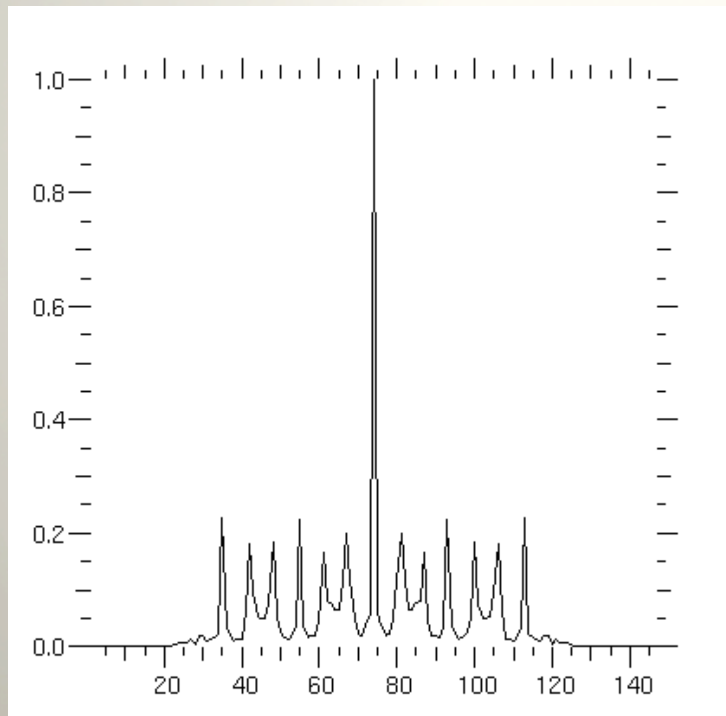
OASIS

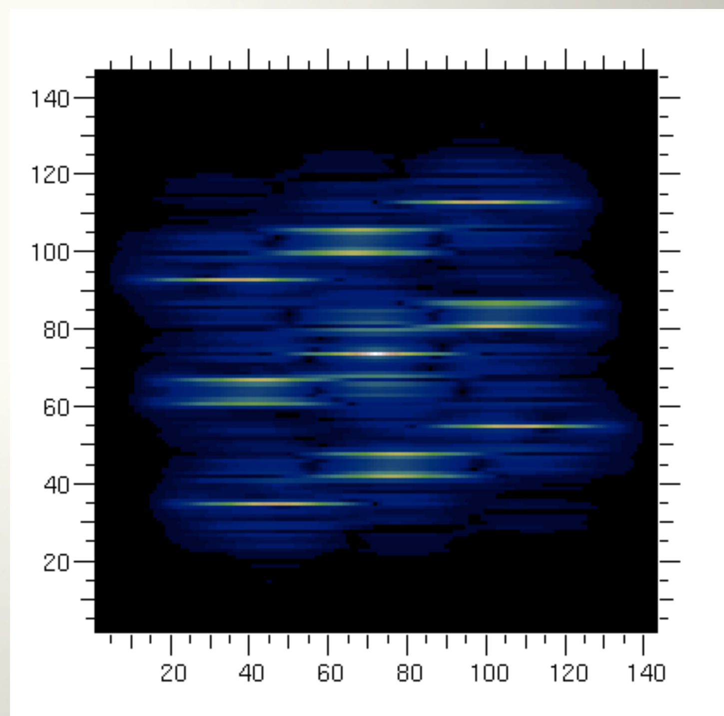
Optimizing
Amber for
Spectro
Interferometry and
Sensitivity

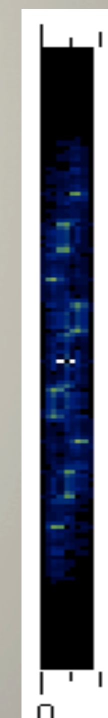




4T spectro-interferometer
with only 8 pixels / spectral channel for all baselines







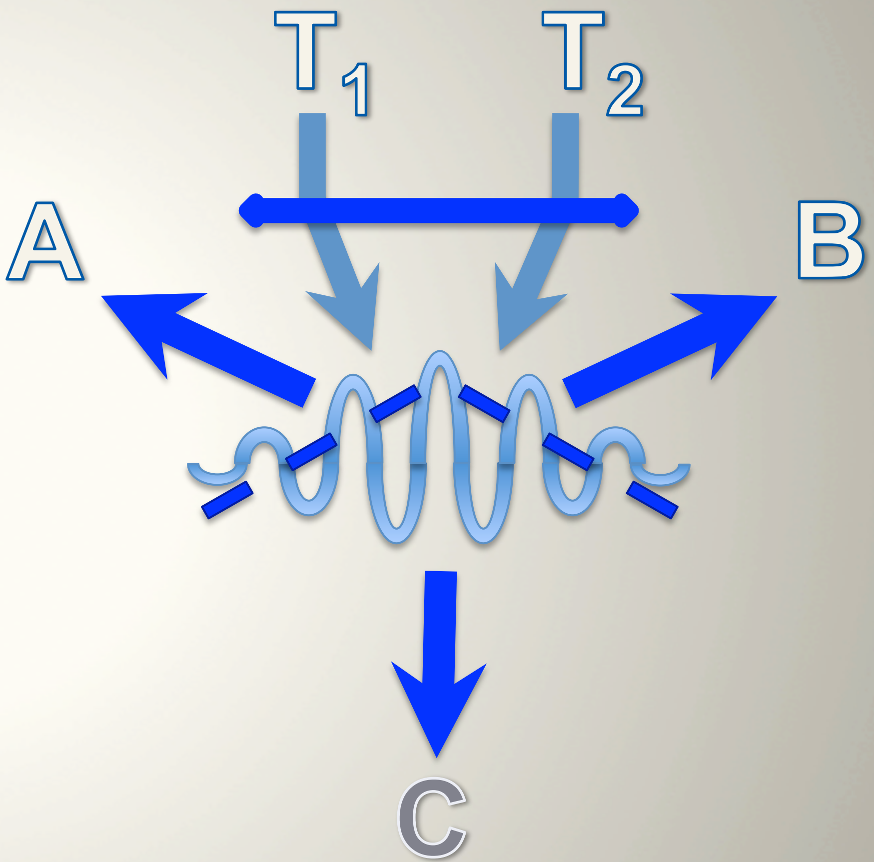
Cophasing

- When cophasing is possible, it improves strongly accuracy of measures
- We can improve:
  - The control law
    - Kalman filtering
    - Better exposure time optimization from better atmospheric optics knowledge
    - The injection of vibration information in the fringe tracking loop
    - Better cophasing-coherencing transitions
  - The concept
    - Minimize the number of pixels
    - Break the conflict between number of apertures and sensitivity (flux divided by N_T-1 or total noise of $N_T(n_*+n_{th})$ flux).
  - Two proposals in that direction
    - The Nova Fringe Tracker
    - Hierarchical Fringe Tracking

Hierarchical cophasing:

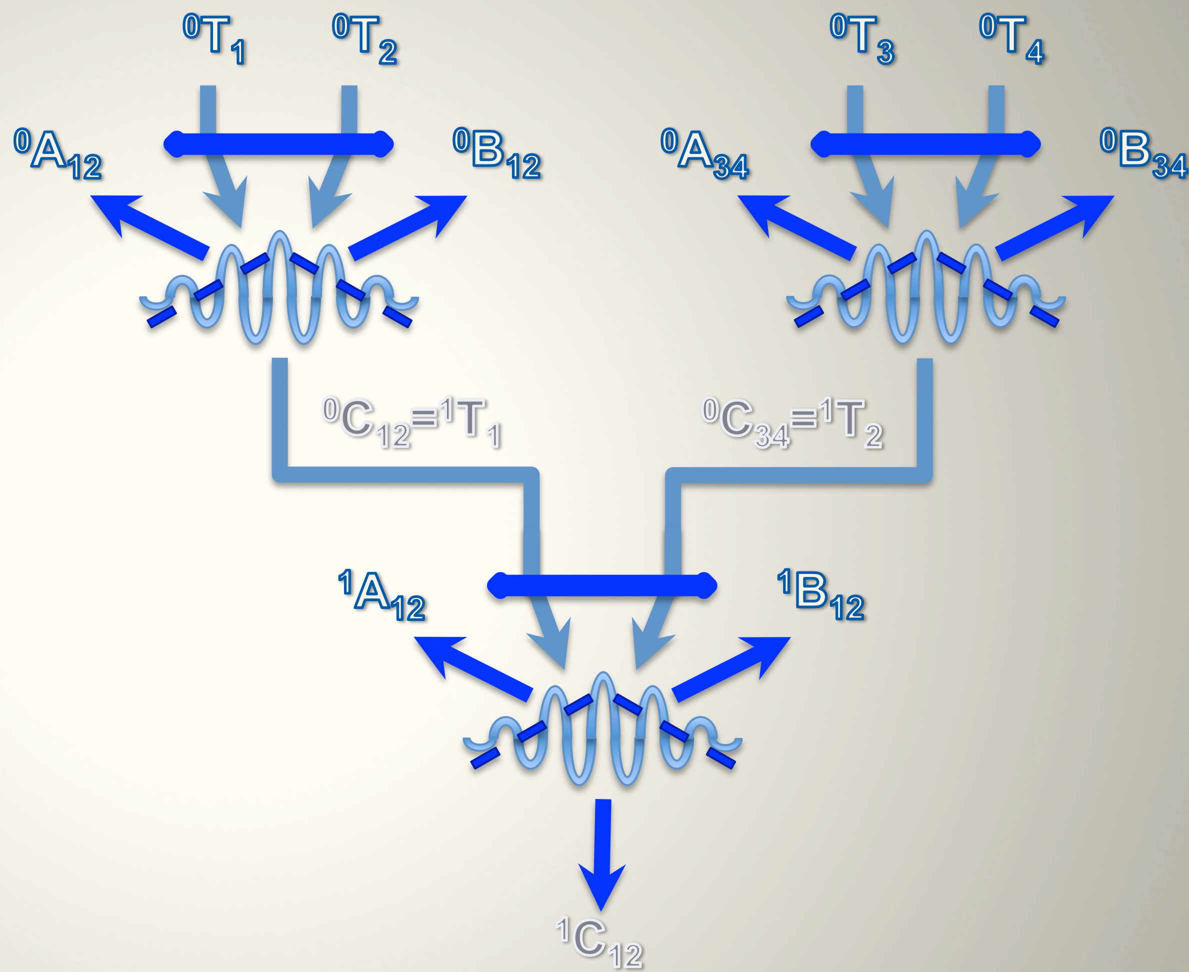
the 2T spatial filter

- When T1 and T2 are cophased, « all » the flux is transmitted.
- The beam C behaves like a spatial filtered beam from a single cophased telescope
- When T1 and T2 are out of phase, the flux in A, B and C allows to compute the piston
- All the flux from T1 and T2 is used to cophase them.



Hierarchical cophasing

- Each cophased pair behaves like a single telescope



Hierarchical Cophasing

- For the first level, the SNR is the maximun one for 2T
- For the lower pairs, the SNR increases if C>0.5(A+B+C)
- Each FT drives one delay line

$^{2}A_{12}$, $^{2}B_{12}$, $^{2}C_{12}$ $\rightarrow$ $^{2}\delta_{12}$, $^{1}C_{12}$, $^{1}C_{34}$

$^{i}A_{lk}$, $^{i}B_{lk}$, $^{i}C_{lk}$ $\rightarrow$ $^{i}\delta_{lk}$, $^{i-1}C_{lk}$, $^{i-1}C_{lk}$

……

$L_1 = 0$

$L_2 = L_1 + {}^{0}\delta_{12}$

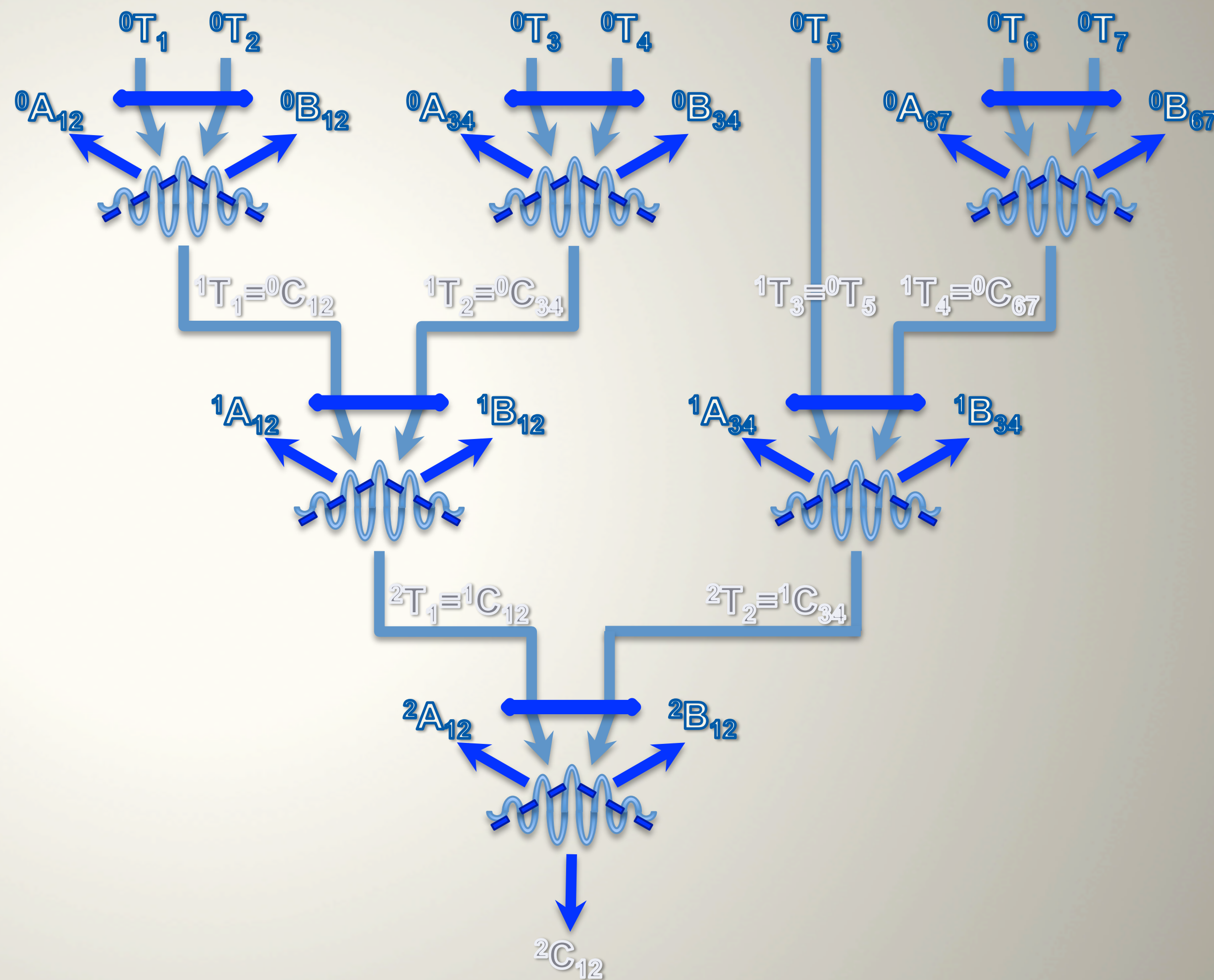
$L_3 = {}^{1}\delta_{12}$

$L_4 = L_3 + {}^{0}\delta_{34}$

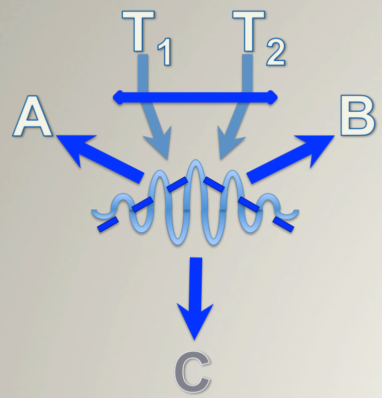
$L_5 = {}^{2}\delta_{12}$

$L_6 = L_5 + {}^{1}\delta_{34}$

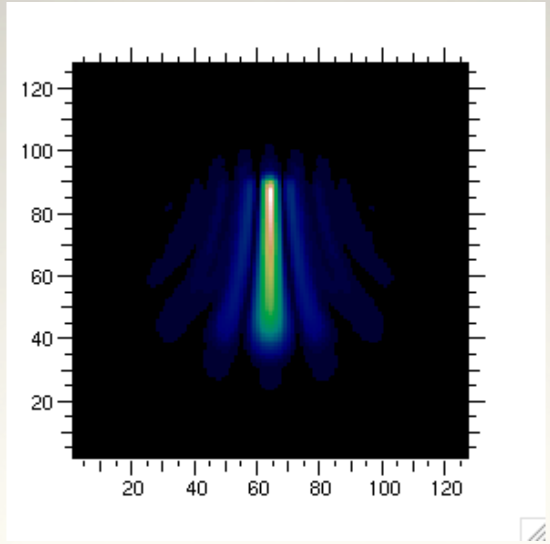
$L_7 = L_6 + {}^{0}\delta_{67}$

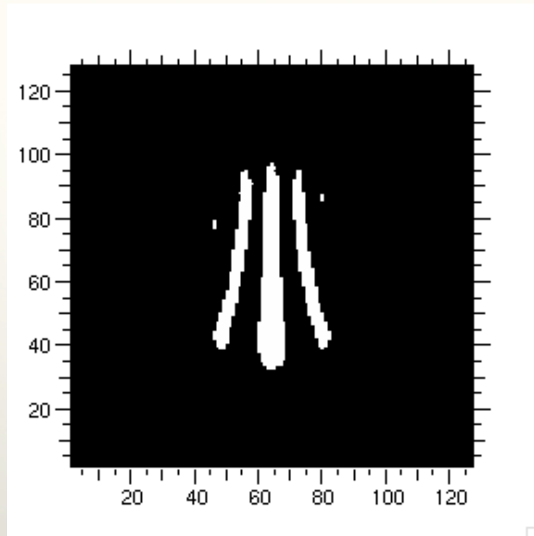


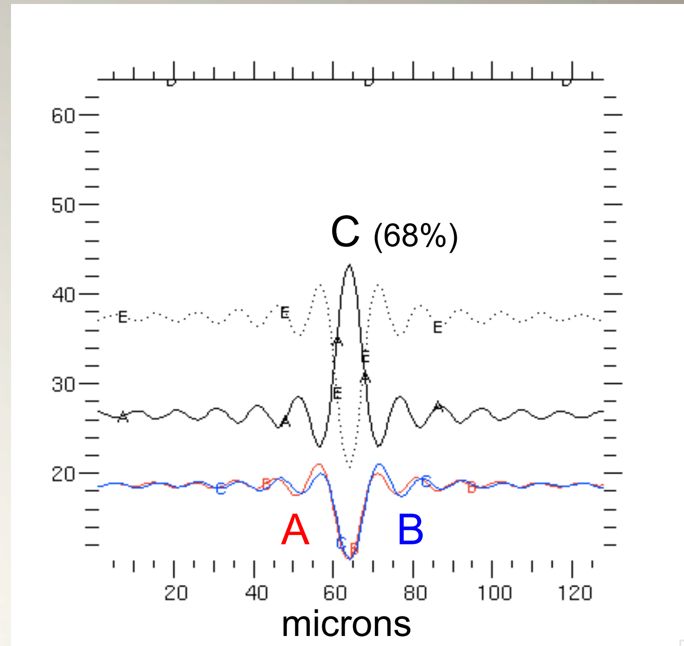
It might work

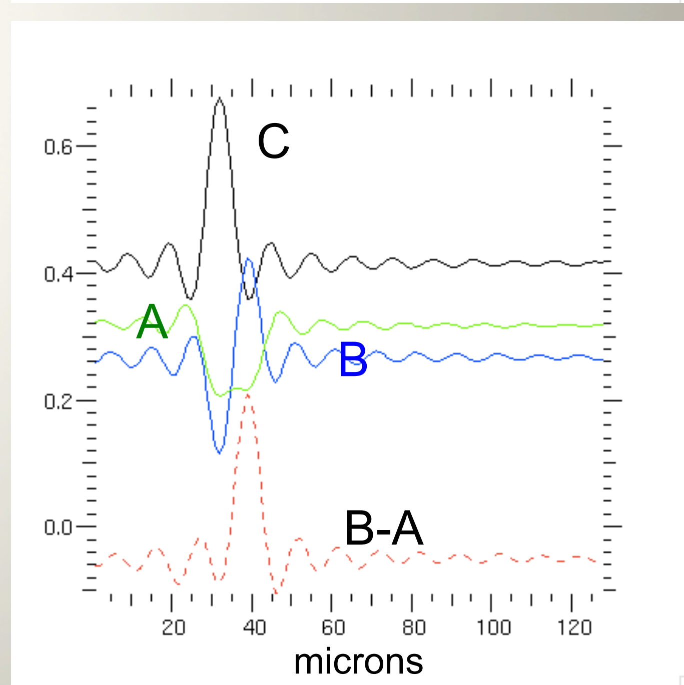


- C transmits 70 to 80% when cophased
- C, B-A, etc… can be set in quadrature
- The typical width of C(p) whith J-H-K is 8 μm ➔ good coherencing
- Research program with UCA Marrakech









Sky coverage

- FT variance = $(\lambda/n)^2$

(n from required accuracy, n=6 enough for differential measures)

= Fundamental noise variance

(from nb pixels, flux/baseline, exposure time, bandpass)

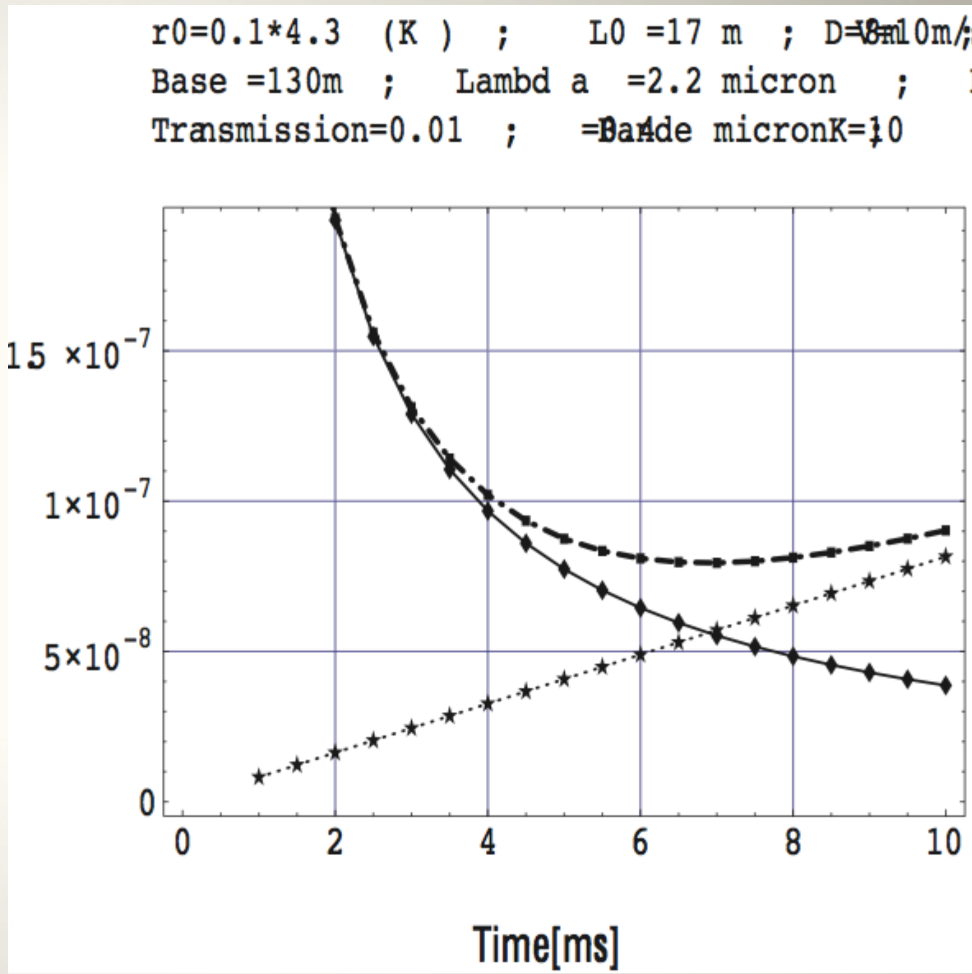
+ Loop error

(*dominated by the integration and the lag between measure and correction)*

+ Anisopistonic error

(set by the local seeing, 10 as at Paranal for $\lambda/10$)

Optimum exposure time in Paranal,
For a GRAVITY-PIONIER FT,
after vibration correction,
is **3 ms < τ < 7ms**



Elhalkouj et al., A&A 2014, submitted

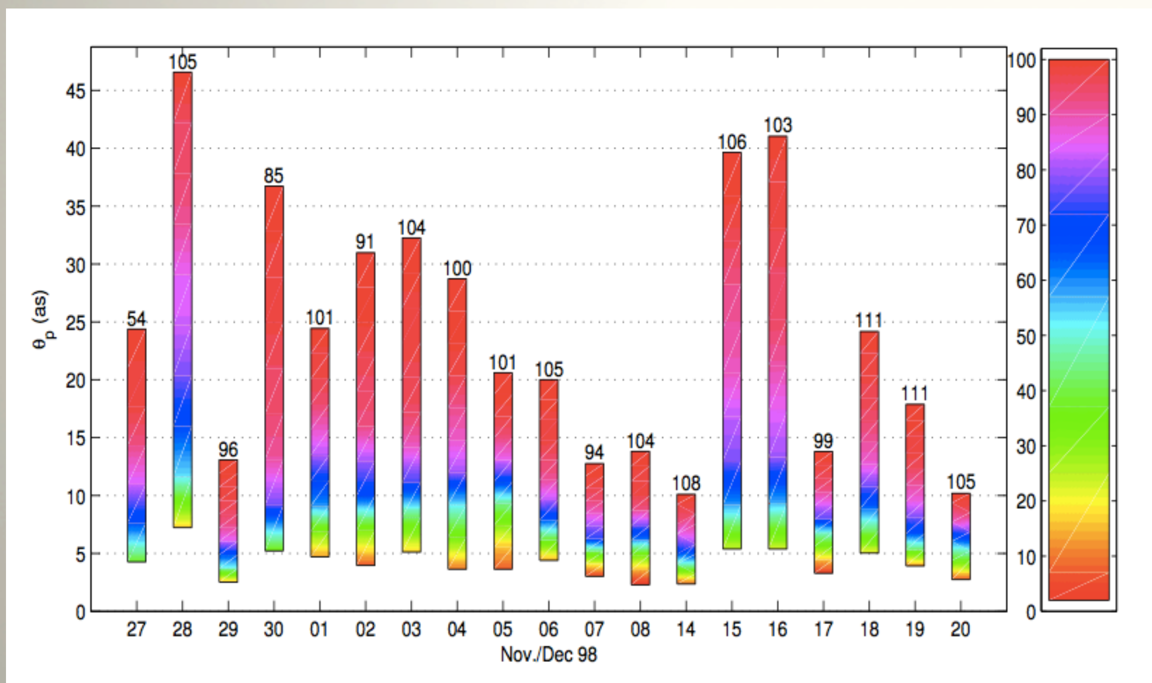
Sky coverage

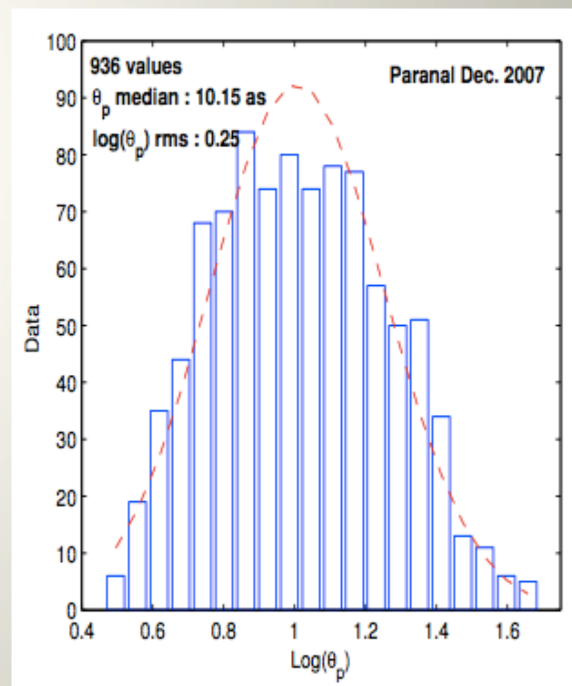
- FT variance = $(\lambda/n)^2$ (n from required accuracy, n=6 enough for differential measures)

  Fundamental noise variance (nb pixels, flux/baseline, exposure time, bandpass)

  \+ Loop error (dominated by the integration and the lag between measure and correction)

  \+ Anisopistonic error (set by the local seeing, ~10 as at Paranal for $\lambda/10$)





Ziad et al., A&A 2014, submitted

Sky coverage
(preliminary numbers)

Fringe Tracker	caracteristics	K limit	Sky coverage at GP (10 as)	Sky coverage at 20° G Latitude
GRAVITY-PIONIER	4 px, 2*N/3 phot, K band, 5 channels, 1% transmission,1 ms	10.5	0.4%	16%
Nova FT	2 px, 2*N/2 phot, J-H-K band, 3 channels, 1% transmission,1 ms	12	5%	>100%
Hierarchical FT	4 px, 2*0.7N phot, J-H-K band, 1 channel, 1% transmission,1 ms	12.5	~7%	>100%

Conclusion

- Sensitivity of spectro-interferometry is not limited by Fringe Tracking
- Optimized, simple, spectro-interferometric instruments could achieve K>14 with UTs and K>10 with Ats
- nDFT processing can be applied to PIONIER and GRAVITY and go beyond FT limit
- Cophasing improves the accuracy when available
- There is room for progress in FT and sky-coverage for off axis tracking
- We should maintain a very active R&D program on FT on and off axis