AMBER data reduction

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Goutelas – June 13th, 2006

The AMBER/VLTI instrument

Interferometer using single mode waveguides

↪ Spatial filtering of the turbulent wavefront

With a multiaxial "all-in-one" recombination scheme

↪ Fringes spatially coded on the detector

↪ All fringes coded together in the same interference pattern

For 2 or 3 telescopes, in the near infrared

↪ Resp. 1 or 3 baselines

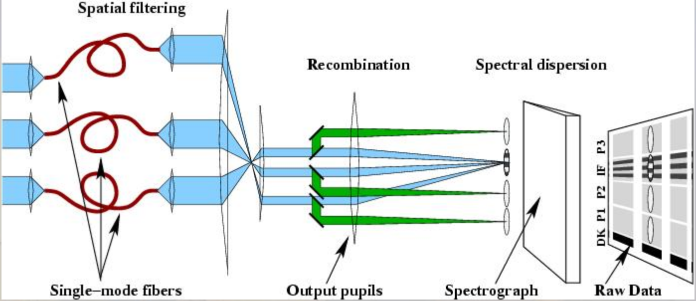
↪ In J (1.25μm), H (1.65μm) and K (2.2μm) bands

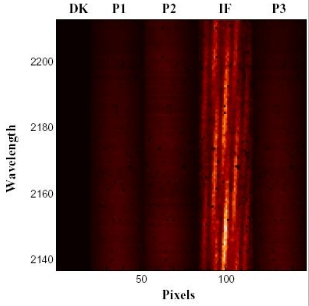
↪ Achieves an angular resolution of $\theta \sim$ 2mas

Allowing spectral dispertion

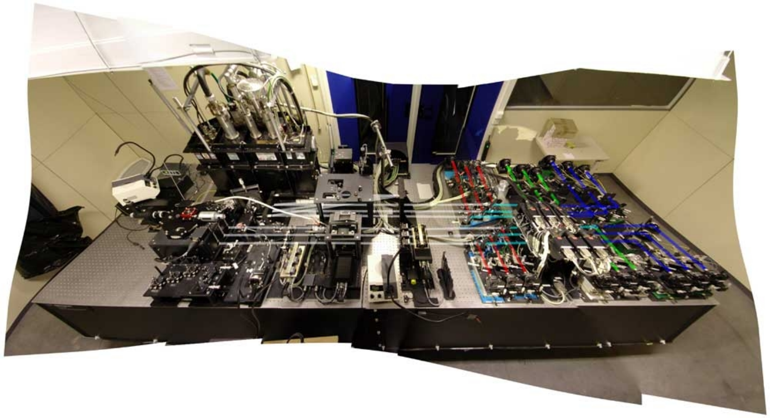
↪ $\mathcal{R} = 35, 1500, 10000$

The signal processing point of view





The beast



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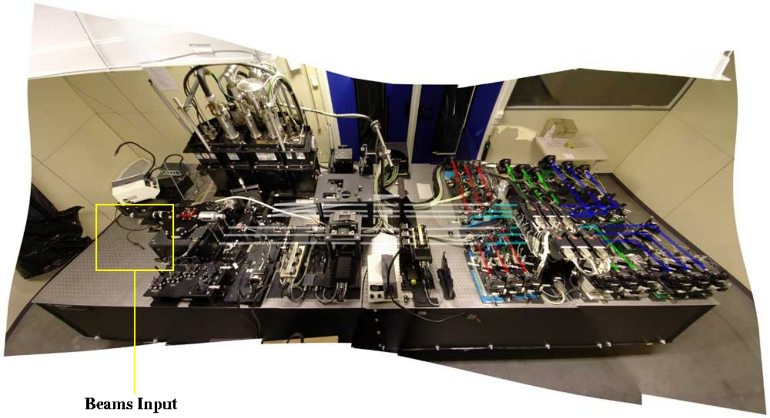

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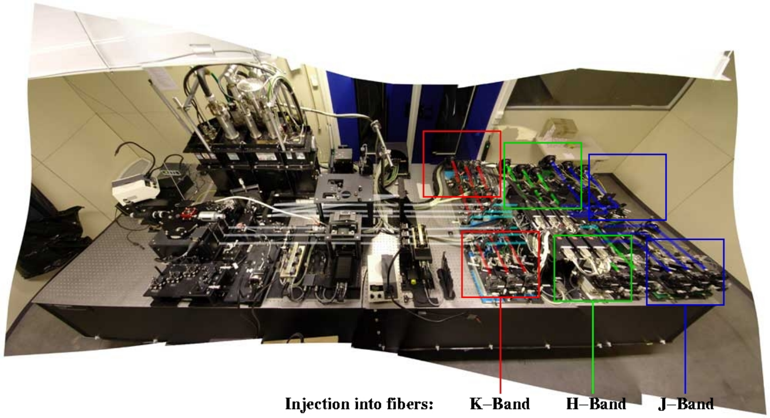

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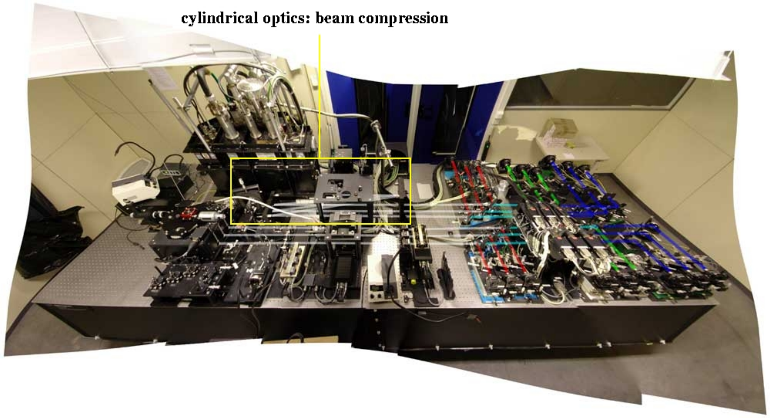

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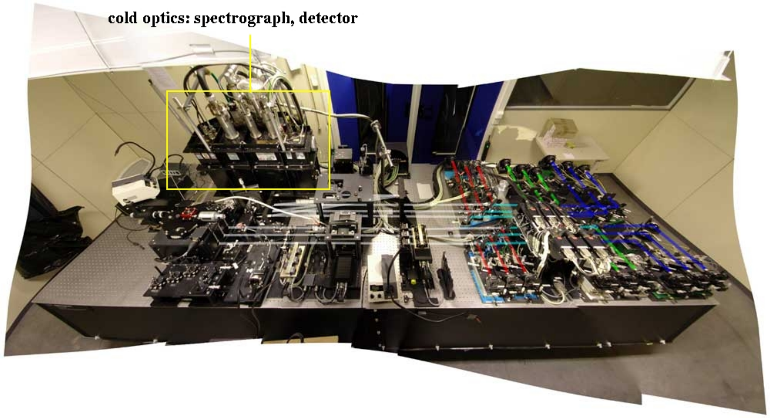

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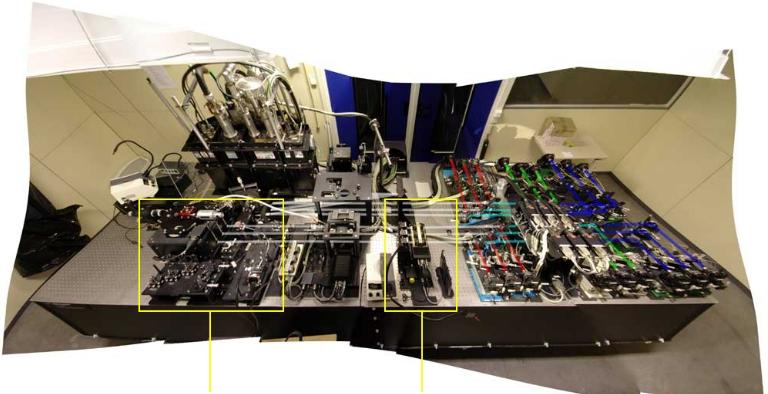

Calibration and Alignement Unit (CAU)

The AMBER/VLTI instrument

Interferometer using single mode waveguides

With a multiaxial "all-in-one" recombination scheme

for 2 or 3 telescopes, with spectral dispertion

The AMBER/VLTI instrument

Interferometer using single mode waveguides

What is their effect on the interferometric signal?

How can we use this in the data reduction process?

With a multiaxial “all-in-one” recombination scheme

for 2 or 3 telescopes, with spectral dispertion

The AMBER/VLTI instrument

Interferometer using single mode waveguides

What is their effect on the interferometric signal?
How can we use this in the data reduction process?

With a multiaxial "all-in-one" recombination scheme

What is the proper AMBER interferometric equation?
What is specific about it?

for 2 or 3 telescopes, with spectral dispertion

The AMBER/VLTI instrument

Interferometer using single mode waveguides

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How can we use this in the data reduction process?

With a multiaxial “all-in-one” recombination scheme

What is the proper AMBER interferometric equation?

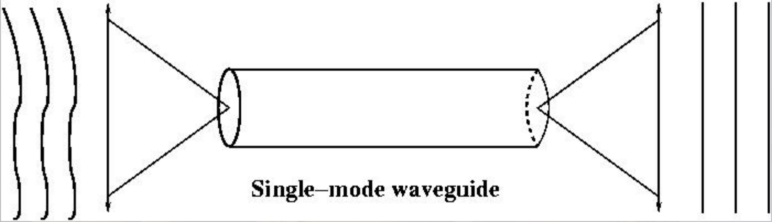
What is specific about it?

for 2 or 3 telescopes, with spectral dispertion

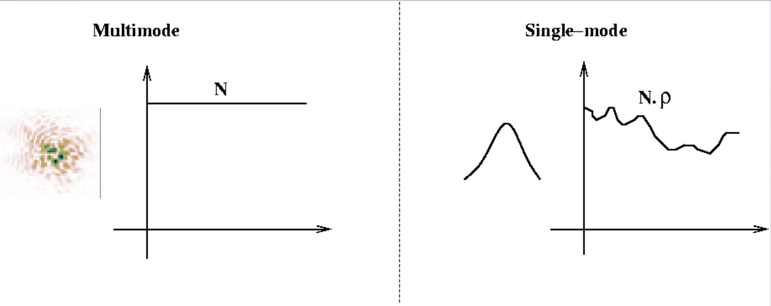
What are the observables of AMBER?

How to estimate them?

Interferometry with single-mode waveguides



Interferometry with single-mode waveguides



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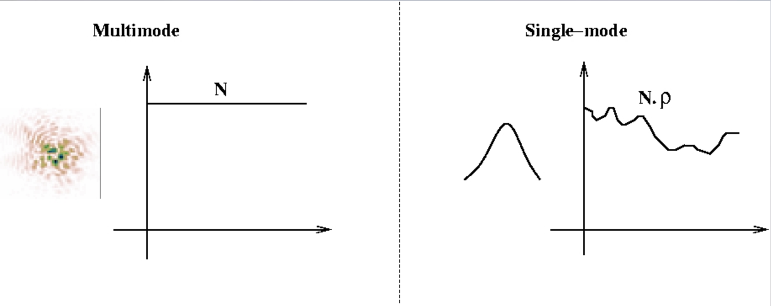


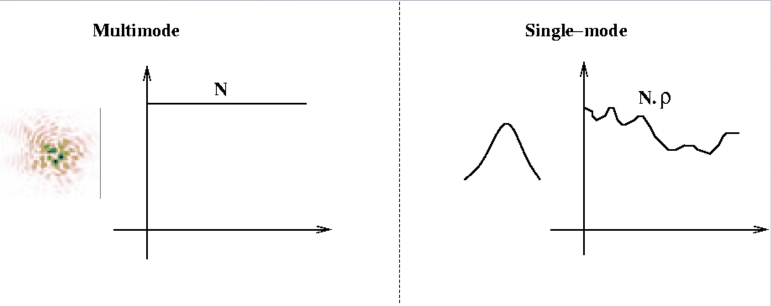
At the fiber's output

↪ The shape ot the signal is deterministic

↪ Phase fluctuations → Intensity fluctuations

Coupling coefficient depends on: turbulence and source's extent

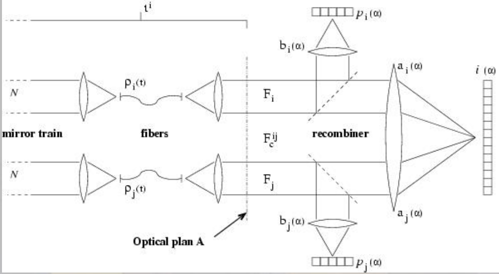
Interferometry with single-mode waveguides

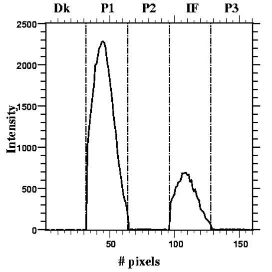


What do we measure: the modal visibility

- $\hookrightarrow$ $V_{ij} \propto \mathrm{TF}[O_\star(\alpha)L^{ij}(\alpha)](f_{ij})$
- $\hookrightarrow$ Field of view: $\Theta \sim \frac{\lambda}{D}$
- $\hookrightarrow$ The modal visibility is biased
- $\hookrightarrow$ For compact sources: $V_{ij} \sim V_{obj}$, $\frac{\Delta V}{V} < 10^{-3}$

Deriving the AMBER interferometric equation





Step I: One beam lit

Interferometric channel: $i_k = F^i a_k^i$

Photometric channel: $p_k^i = F^i b_k^i$

Conventions

k in index: pixel coordinate

i, j in exponent: telescope(s)number(s)

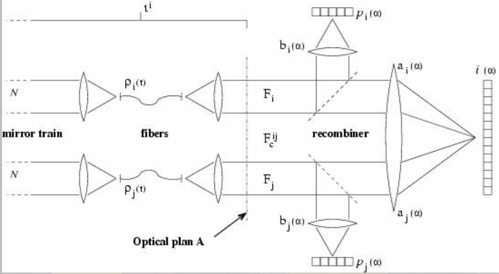
Definitions

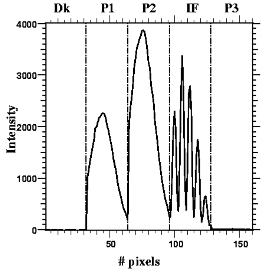
$F^i = Nt^i$

photometric flux

a_k^i, b_k^i: intensity profile

Deriving the AMBER interferometric equation





Step II: two beams lit

Interferometric channel:

$$i_k = F^i a_k^i + F^j a_k^j + \sqrt{a_k^i a_k^j} C_B^{ij} \mathrm{Re}\left[F_c^{ij} \mathrm{e}^{i(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})}\right]$$

Definitions

$$F_c^{ij} = 2N\sqrt{t^i t^j} V^{ij} \mathrm{e}^{i(\Phi^{ij} + \phi_p^{ij})}$$

coherent flux

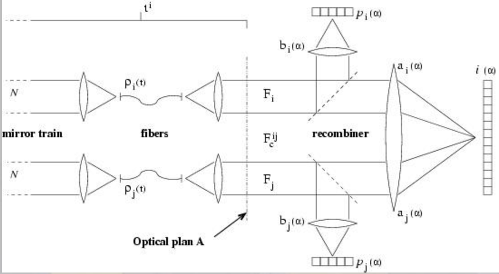
C_B^{ij}, Φ_B^{ij}: polarization

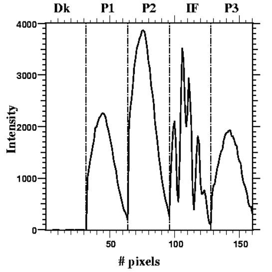
ϕ_s^{ij}: instrumental phase

α_k: sampling

f^{ij}: frequency coding

Deriving the AMBER interferometric equation





Step III: all pairs of beams

Interferometric channel:

$$i_k = \sum_{i}^{N_{tel}} F^i a_k^i + \sum_{i<j}^{N_{tel}} \sqrt{a_k^i a_k^j} C_B^{ij} \mathrm{Re}\left[F_c^{ij} \mathrm{e}^{i(2\pi\alpha_k f^{ij}+\phi_s^{ij}+\Phi_B^{ij})}\right]$$

Definitions

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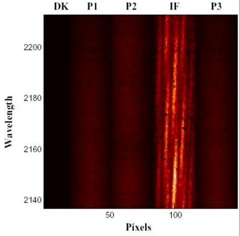
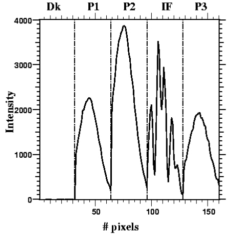
Analyzing the AMBER interferometric equation

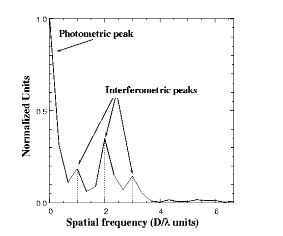
the AMBER interferometric equation

$$i_k - \overbrace{\sum_i^{N_{tel}} F^i a_k^i}^{DC\ component} = \overbrace{\sum_{i<j}^{N_{tel}} \sqrt{a_k^i a_k^j}\, C_B^{ij}\, \mathrm{Re}\left[F_c^{ij}\, \mathrm{e}^{i(2\pi\alpha_k f^{ij}+\phi_s^{ij}+\Phi_B^{ij})}\right]}^{AC\ component}$$

$$p_k^i = F^i b_k^i \qquad \left(P^i = F^i \sum_k^{N_{pix}} b_k^i\right)$$







Analyzing the AMBER interferometric equation

the AMBER interferometric equation

$$i_k - \overbrace{\sum_{i}^{N_{tel}} F^i a_k^i}^{DC\ \ component} = \overbrace{\sum_{i<j}^{N_{tel}} \sqrt{a_k^i a_k^j} C_B^{ij} \mathrm{Re}\left[F_c^{ij} \mathrm{e}^{i(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})}\right]}^{AC\ \ component}$$

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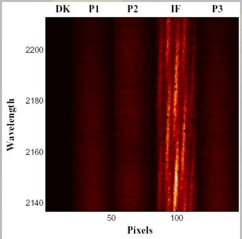

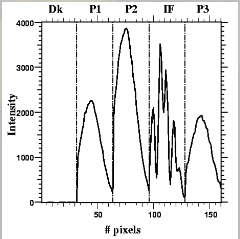

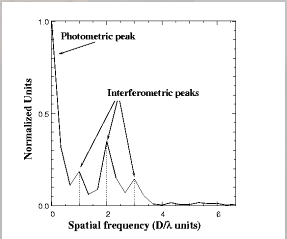

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A linear relationship between the measurements and the complex visibilities can be derived

Analyzing the AMBER interferometric equation

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A linear relationship between the measurements and the complex visibilities can be derived

- Need to estimate the DC component
  The fraction of flux that goes from photometry to DC

$$P^i v_k^i = F^i a_k^i$$

Analyzing the AMBER interferometric equation

the AMBER interferometric equation

$$\underbrace{i_k - \sum_{i}^{N_{tel}} F^i a_k^i}_{DC\ component} = \underbrace{\sum_{i<j}^{N_{tel}} \sqrt{a_k^i a_k^j} C_B^{ij} \mathrm{Re}\left[F_c^{ij} e^{i(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})} \right]}_{AC\ component}$$

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A linear relationship between the measurements and the complex visibilities can be derived

- Need to know characteristics of the intrument
  The shape of the interferogram: the carrying waves

$$c_k^{ij} = C_B^{ij} \frac{\sqrt{a_k^i a_k^j}}{\sqrt{\sum_k a_k^i a_k^j}} \cos(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})$$

Analyzing the AMBER interferometric equation

the AMBER interferometric equation

$$i_k - \overbrace{\sum_{i}^{N_{tel}} F^i a_k^i}^{DC\ \ component} = \overbrace{\sum_{i<j}^{N_{tel}} \sqrt{a_k^i a_k^j} C_B^{ij} \mathrm{Re}\left[F_c^{ij} \mathrm{e}^{i(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})}\right]}^{AC\ \ component}$$

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A linear relationship between the measurements and the complex visibilities can be derived

- Need to know characteristics of the intrument
  The shape of the interferogram: the carrying waves

$$d_k^{ij} = C_B^{ij} \frac{\sqrt{a_k^i a_k^j}}{\sqrt{\sum_k a_k^i a_k^j}} \sin(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})$$

Analyzing the AMBER interferometric equation

the AMBER interferometric equation

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A linear relationship between the measurements and the complex visibilities can be derived

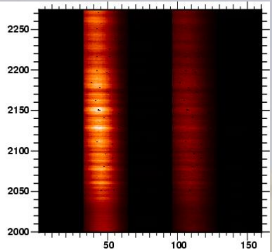
- Requires a calibration of the instrument: $v_k^i, c_k^{ij}, d_k^{ij}$

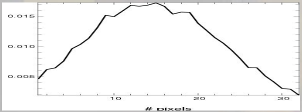
AMBER data reduction steps

- Modelling the interferogram in the detector plane
- In 5 steps:
  1. Cosmetic *(flatfield, sky...)*
  2. Calibration of the instrument:
     - ↪ *fraction of flux* v_k^i
     - ↪ *carrying waves* c_k^{ij}, d_k^{ij}
  3. Estimation of the photometric F^i and coherent fluxes F_c^{ij}
  4. Estimation of the observables
  5. Biases correction

Calibration of the instrument

the v_k^i functions





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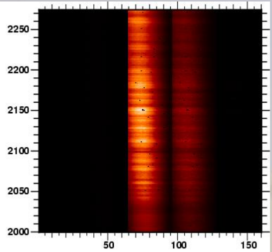

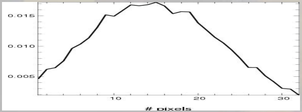

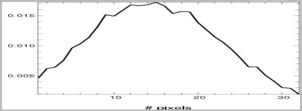

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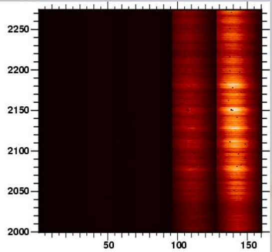

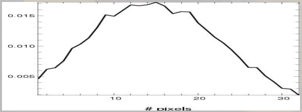

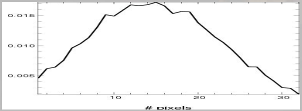

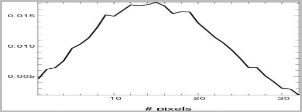

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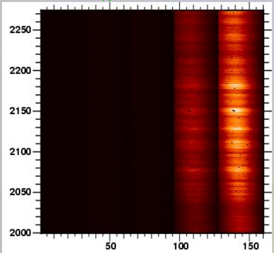
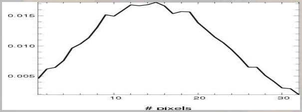
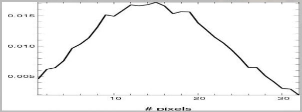
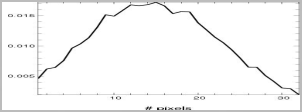
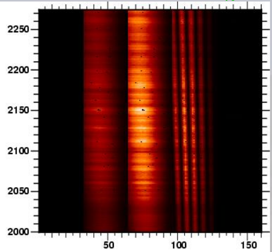


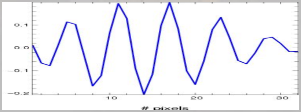






the carrying waves c_k^{ij}, d_k^{ij}





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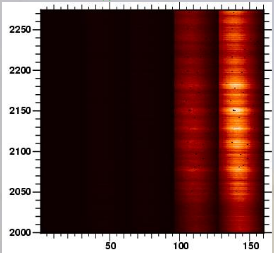

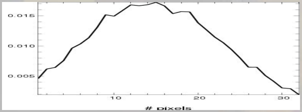

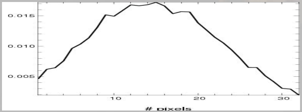

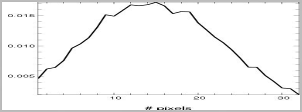

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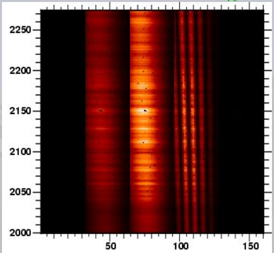

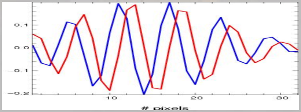

Calibration of the instrument

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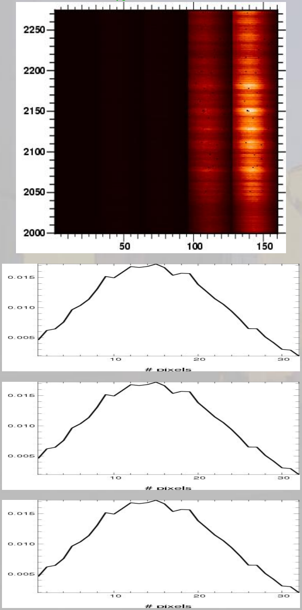

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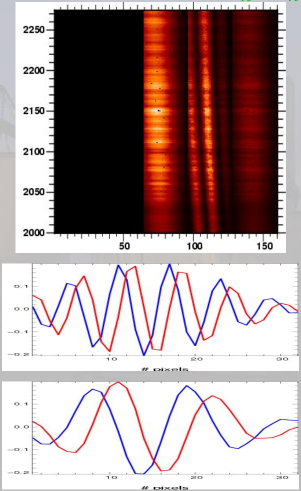
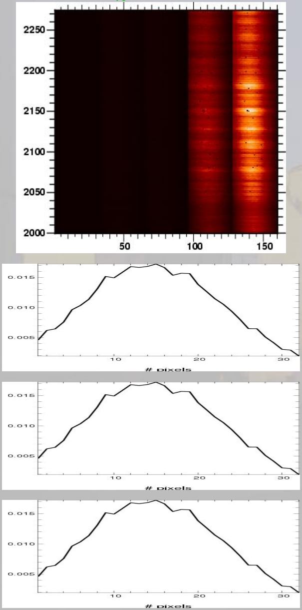
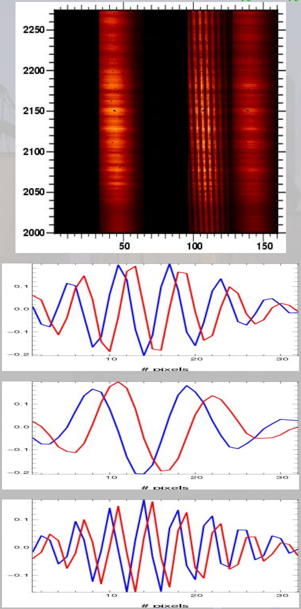


Calibration of the instrument

the v_k^i functions



the carrying waves c_k^{ij}, d_k^{ij}



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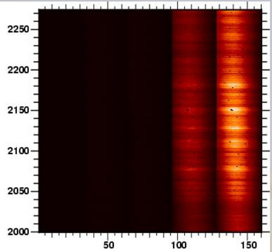

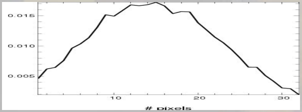

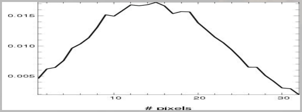

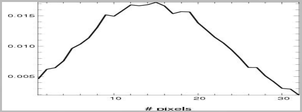

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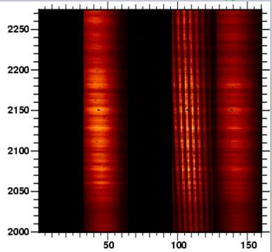
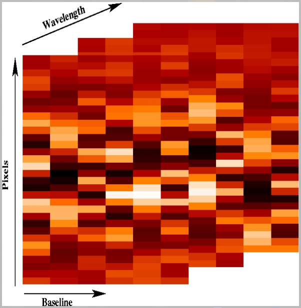




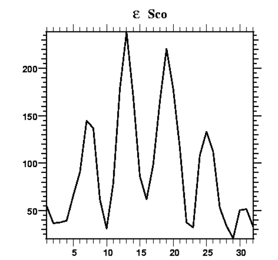
Photometric and coherent fluxes

$$i_k = \sum_i^{N_{tel}} F^i a_k^i + \sum_{i<j}^{N_{tel}} \sqrt{a_k^i a_k^j} C_B^{ij} \mathrm{Re}\left[F_c^{ij} \mathrm{e}^{i(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})} \right]$$

Photometric fluxes

$$F^i a_k^i = P^i v_k^i$$

$$mk = i_k - \sum_i^{N_{tel}} P^i v_k^i$$



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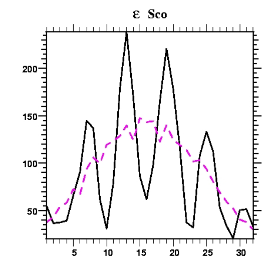

Photometric and coherent fluxes

$$m_k = \sum_{i<j}^{N_{tel}} \sqrt{a_k^i a_k^j} C_B^{ij} \mathrm{Re}\left[F_c^{ij} \mathrm{e}^{i(2\pi\alpha_k f^{ij} + \phi_s^{ij} + \Phi_B^{ij})} \right]$$

Photometric fluxes - DC substraction

$$F^i a_k^i = P^i v_k^i$$

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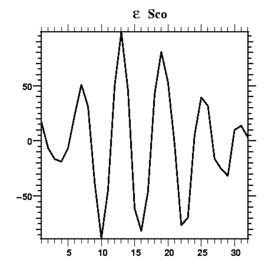

Photometric and coherent fluxes

$$m_k = \sum_{i<j}^{N_{tel}} \sqrt{\sum_k a_k^i a_k^j} \left(c_k^{ij} \mathrm{Re}\left[F_c^{ij}\right] + d_k^{ij} \mathrm{Im}\left[F_c^{ij}\right] \right)$$

Coherent flux

$$m_k = \sum_{i<j}^{N_{tel}} c_k^{ij} R^{ij} + d_k^{ij} F_c^{ij}$$

$$R^{ij} = \sqrt{\textstyle\sum_k a_k^i a_k^j} \mathrm{Re}\left[F_c^{ij}\right]$$

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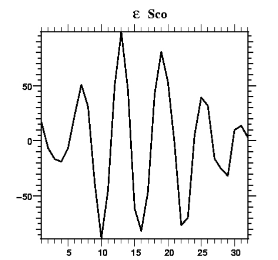

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Coherent flux - Inverting the V2PM

$$m_k = \underbrace{\left[c_k^{(i,j)}, d_k^{(i,j)} \right]}_{V2PM} \begin{bmatrix} R_{ij} \\ I_{ij} \end{bmatrix}$$

$$R^{ij} = \sqrt{\sum_k a_k^i a_k^j} \mathrm{Re}\left[F_c^{ij}\right]$$

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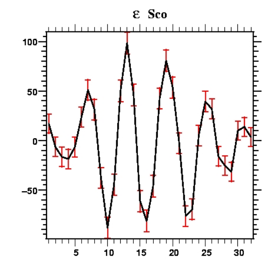

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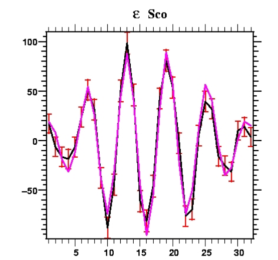


The AMBER observables

$$F_c^{ij} = 2N\sqrt{t^i t^j} V^{ij} \mathrm{e}^{i(\Phi^{ij} + \phi_p^{ij})}$$

- the modulus of the visibility
  characteristic size of the source
- the phase $\longrightarrow$ *presence of atmospheric piston*

1. the closure phase @ 3 telescopes
   geometry/asymmetries
2. the differential phase @ spectral resolution
   displacement of the photcenter vs. the wavelength

The phase

$$C^{ij} = R^{ij} + iI^{ij} = \sqrt{\sum_k a_k^i a_k^j} 2N\sqrt{t^i t^j} V^{ij} \mathrm{e}^{i(\Phi^{ij} + \phi_p^{ij})}$$

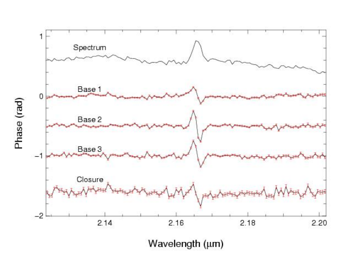
The closure phase

$$\phi_p^{ij} = \phi_p^i - \phi_p^j$$

$$\widetilde{B}^{123} = \langle C^{12} C^{23} C^{13*} \rangle$$

$$\widetilde{\phi_B}^{123} = \mathrm{atan}\left[\frac{\mathrm{Im}(\widetilde{B}^{123})}{\mathrm{Re}(\widetilde{B}^{123})}\right]$$

$$\widetilde{\phi_B}^{123} = \Phi^{12} + \Phi^{23} - \Phi^{13}$$



The differential phase

$$\widetilde{W_{12}^{ij}} = \left\langle C_{\lambda_1}^{ij} {C_{\lambda_2}^{ij}}^* \right\rangle$$

$$\widetilde{\Delta\phi_{12}^{ij}} = \mathrm{atan}\left[\frac{\mathrm{Im}\left(\widetilde{W_{12}^{ij}}\right)}{\mathrm{Re}\left(\widetilde{W_{12}^{ij}}\right)}\right]$$

$$\phi_\lambda^{ij} = 2\pi\delta^{ij}\sigma + Cst$$

$$\Delta\phi_{12}^{ij} = \phi_1^{ij} + 2\pi\left(\sigma_2 - \sigma_1\right)\delta^{ij}$$

In the continuum: $\delta^{ij} = \delta_p^{ij}$

In lines: $\delta^{ij} = \delta_o^{ij} + \delta_p^{ij}$

The phase

$$C^{ij} = R^{ij} + iI^{ij} = \sqrt{\sum_k a_k^i a_k^j} 2N\sqrt{t^i t^j} V^{ij} \mathrm{e}^{i(\Phi^{ij} + \phi_p^{ij})}$$

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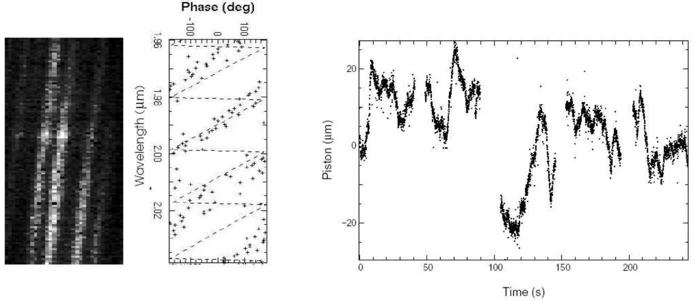

The squared visibility

By definition

$$|V^{ij}|^2 = \frac{|F_c^{ij}|^2}{4F^iF^j}$$

- Visibility V_c^{ij} the internal source (CAU)
- Quadratic bias: photon and detector noise
- Loss of spectral coherence: finite coherence length $\mathcal{L}_c$
- Atmospheric jitter

The squared visibility

By definition

$$|V^{ij}|^2 = \frac{{R^{ij}}^2 + {I^{ij}}^2}{4 P^i P^j \sum_k v_k^i v_k^j}$$

- Visibility V_c^{ij} the internal source (CAU)
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The squared visibility

By definition

$$\frac{|V^{ij}|^2}{{V_c^{ij}}^2} = \frac{{R^{ij}}^2 + {I^{ij}}^2}{4 P^i P^j \sum_k v_k^i v_k^j}$$

- Visibility V_c^{ij} the internal source (CAU)
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The squared visibility

Estimation

$$\frac{\widetilde{|V^{ij}|^2}}{{V_c^{ij}}^2} = \frac{\left\langle {R^{ij}}^2 + {I^{ij}}^2 \right\rangle}{4 \left\langle P^i P^j \right\rangle \sum_k v_k^i v_k^j}$$

- Visibility V_c^{ij} the internal source (CAU)
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The squared visibility

Estimation

$$\frac{\widetilde{|V^{ij}|^2}}{{V_c^{ij}}^2} = \frac{\left\langle {R^{ij}}^2 + {I^{ij}}^2 \right\rangle - \text{Bias}\left\{ {R^{ij}}^2 + {I^{ij}}^2 \right\}}{4 \left\langle P^i P^j \right\rangle \sum_k v_k^i v_k^j}$$

- Visibility V_c^{ij} the internal source (CAU)
- Quadratic bias: photon and detector noise
  $\text{Bias}\left\{R^2 + I^2\right\} = \sigma_R^2 + \sigma_I^2$

  $R = \sum_{k=1}^{N_{pix}} \zeta_k m_k, \quad I = \sum_{k=1}^{N_{pix}} \xi_k^b m_k$

  $\sigma_R^2 = \sum_k (\zeta_k)^2 \sigma^2(m_k); \; \sigma_I^2 = \sum_k (\xi_k)^2 \sigma^2(m_k)$

  $\sigma^2(m_k) = \overline{i_k} + \sigma^2 + \sum_{i=1}^{N_{tel}} \left[\overline{P_i} + N_{pix}\sigma^2\right] (v_k^i)^2$
- Loss of spectral coherence: finite coherence length $\mathcal{L}_c$
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The squared visibility

Estimation

$$\frac{\widetilde{|V^{ij}|^2}}{{V_c^{ij}}^2} = \frac{\left\langle {R^{ij}}^2 + {I^{ij}}^2 \right\rangle - \text{Bias}\left\{ {R^{ij}}^2 + {I^{ij}}^2 \right\}}{4 \left\langle P^i P^j \right\rangle \sum_k v_k^i v_k^j} < \rho_p^2 >$$

- Visibility V_c^{ij} the internal source (CAU)
- Quadratic bias: photon and detector noise
- Loss of spectral coherence: finite coherence length $\mathcal{L}_c$
  $\rho_p = \left| \widehat{\mathcal{F}} \left(\pi \frac{\delta_p + \delta_o}{\mathcal{L}_c} \right) \right|$
- Atmospheric jitter

The squared visibility

Estimation

$$\frac{\widetwidetilde{|V^{ij}|^2}}{{V_c^{ij}}^2} = \frac{\left\langle {R^{ij}}^2 + {I^{ij}}^2 \right\rangle - \text{Bias}\left\{ {R^{ij}}^2 + {I^{ij}}^2 \right\}}{4\left\langle P^i P^j \right\rangle \sum_k v_k^i v_k^j} < \rho_p^2 >$$

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- Loss of spectral coherence: finite coherence length $\mathcal{L}_c$
  $\rho_p = \left| \text{sinc}\left(\pi \frac{\delta_p + \delta_o}{\mathcal{L}_c} \right) \right|$
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The squared visibility

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$$\frac{\widetilde{|V^{ij}|^2}}{{V_c^{ij}}^2} = \frac{\left\langle {R^{ij}}^2 + {I^{ij}}^2 \right\rangle - \text{Bias}\left\{ {R^{ij}}^2 + {I^{ij}}^2 \right\}}{4 \left\langle P^i P^j \right\rangle \sum_k v_k^i v_k^j} < \rho_p^2 > \; < \rho_{jit}^2 >$$

- Visibility V_c^{ij} the internal source (CAU)
- Quadratic bias: photon and detector noise
- Loss of spectral coherence: finite coherence length $\mathcal{L}_c$
- Atmospheric jitter
  Fringe motion during the integration time:
  Must be calibrated on reference source

Error of the visibility

Semi-empirical formula

$$\frac{\sigma^2(|V^{ij}|^2)}{\overline{|V^{ij}|^2}^2} = \frac{1}{M}\left[\frac{\sigma^2(|C^{ij}|^2)}{\overline{|C_{ij}|^2}^2} + \frac{\sigma^2(P^iP^j)}{\overline{P^iP^j}^2}\right]$$

Error of the visibility

Semi-empirical formula

$$\frac{\sigma^2(\widetilde{|V^{ij}|^2})}{\widetilde{|V^{ij}|^2}^2} = \frac{1}{M}\left[\frac{\left\langle |C^{ij}|^4\right\rangle_M - \left\langle |C^{ij}|^2\right\rangle_M^2}{\left\langle |C^{ij}|^2\right\rangle_M^2} + \frac{\left\langle {P^i}^2 {P^j}^2\right\rangle_M - \left\langle P^i P^j\right\rangle_M^2}{\left\langle P^i P^j\right\rangle_M^2}\right]$$

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Semi-empirical formula

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Empirical computation

Bootstrapping!

Error of the visibility

Semi-empirical formula

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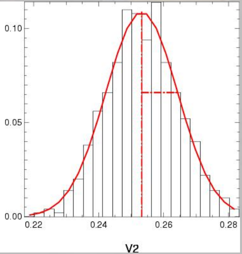
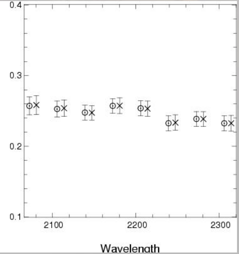
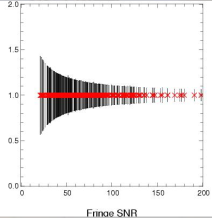




Current limitations

- VLTI status: vibrations along the ,
  - ↪ no fringe tracker, low limiting magnitude
  - ↪ Potentially non stationnary: absolute calibration?



- Careful check of evolution of the transfer function *(more than 1 calibrator)*
- Fringe selection + jitter dispersion
- Strong effort from ESO to identify/suppress sources of vibration

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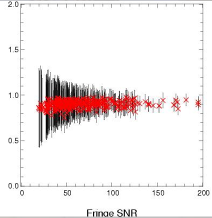

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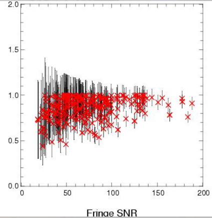

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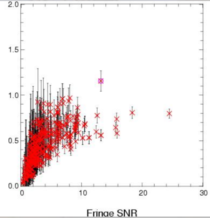

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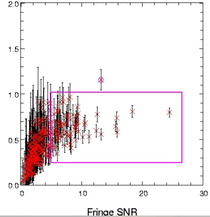

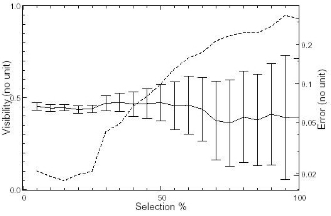

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In summary

The AMBER data reduction process:

- fit of the interferogram in the detector plane
  $\hookrightarrow$ allows fourier fringe peaks overlaping
- uses *a priori* of the instrument: $v_k^i, c_k^{ij}, d_k^{ij}$
  1. requires a calibration step $\Leftrightarrow$ the "P2VM" computation
  2. the calibration matrix needs to be accurate and stable
- $[M] = [MV2P][V] \rightarrow$ Inversion of the calibration matrix
- the observables are:
  1. the modulus of the visibility: *spatial extent*
  2. the closure phase @ 3 telescopes: *geometry/asymmetries*
  3. the differential phase @ spectral resolution: *kinematics*

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