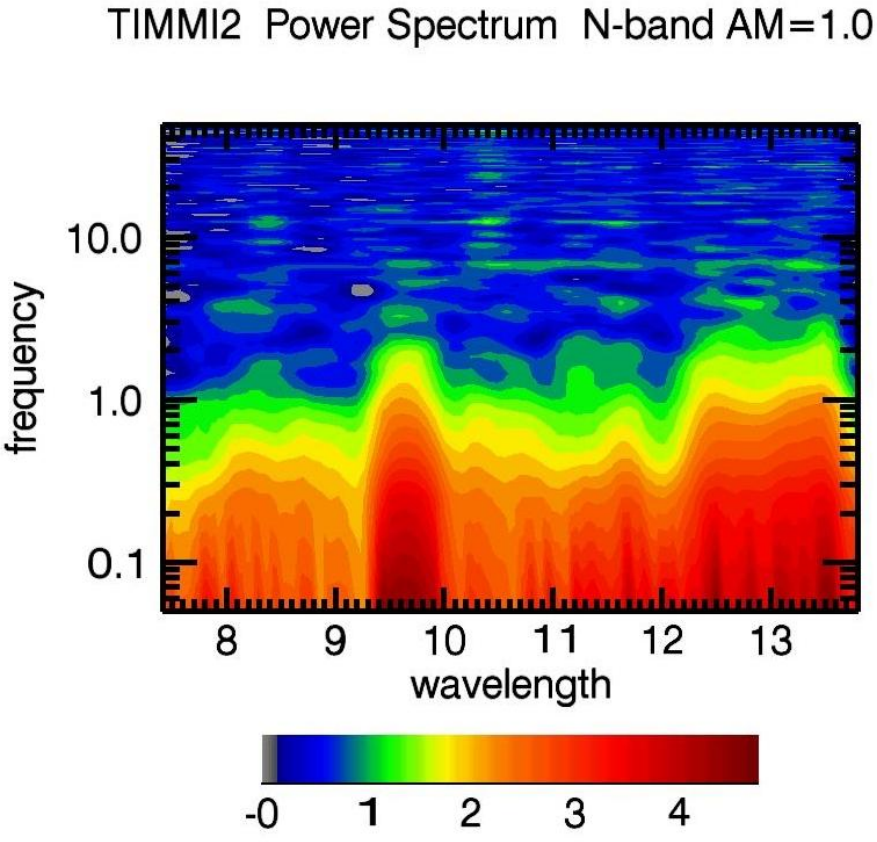
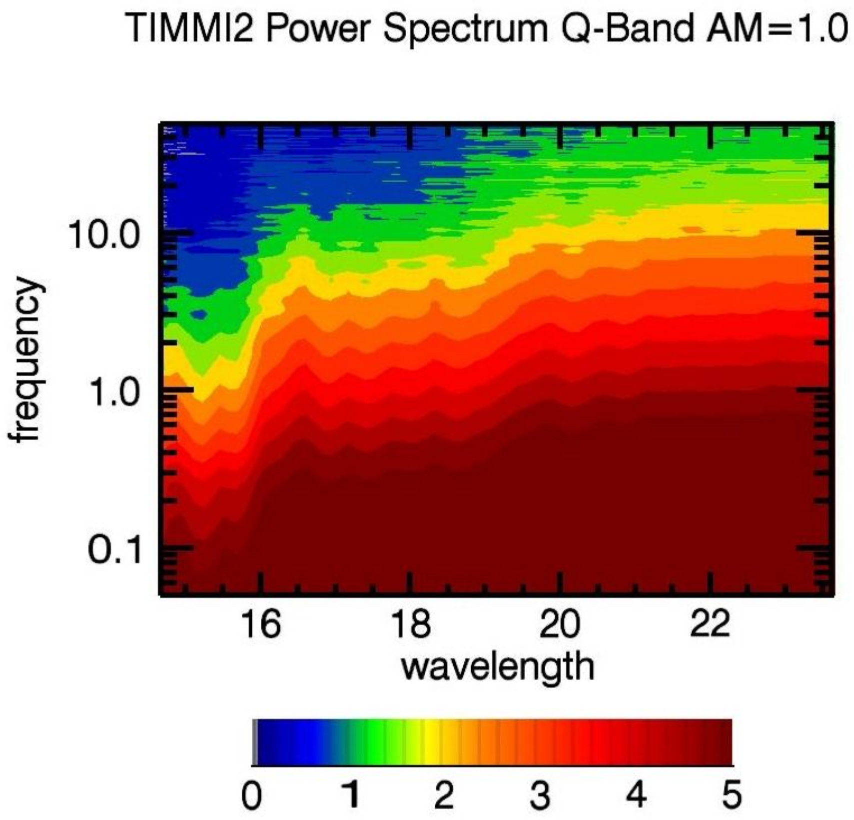
Theory of MIDI and AMBER data reduction

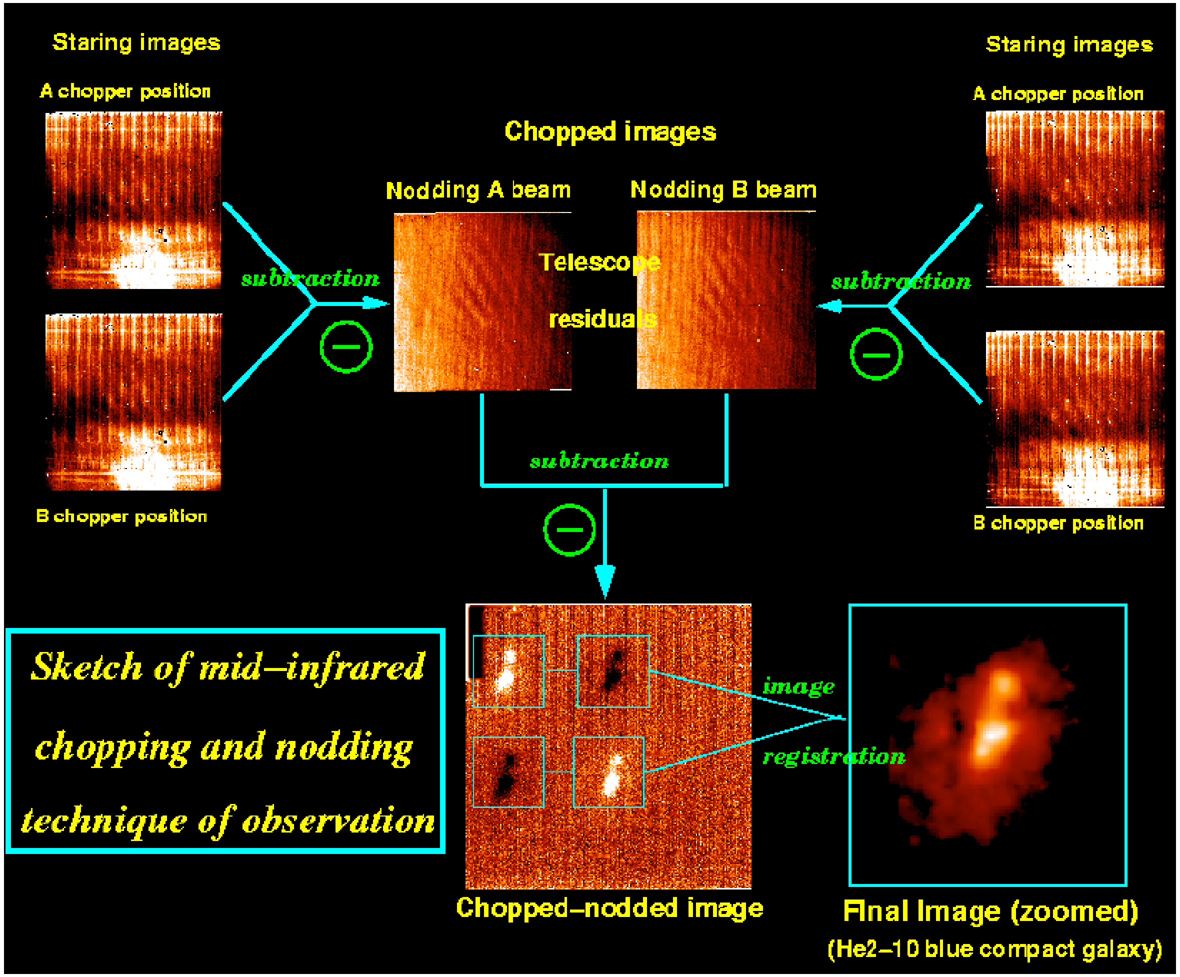
Christian Hummel (ESO)

Mid-infrared background

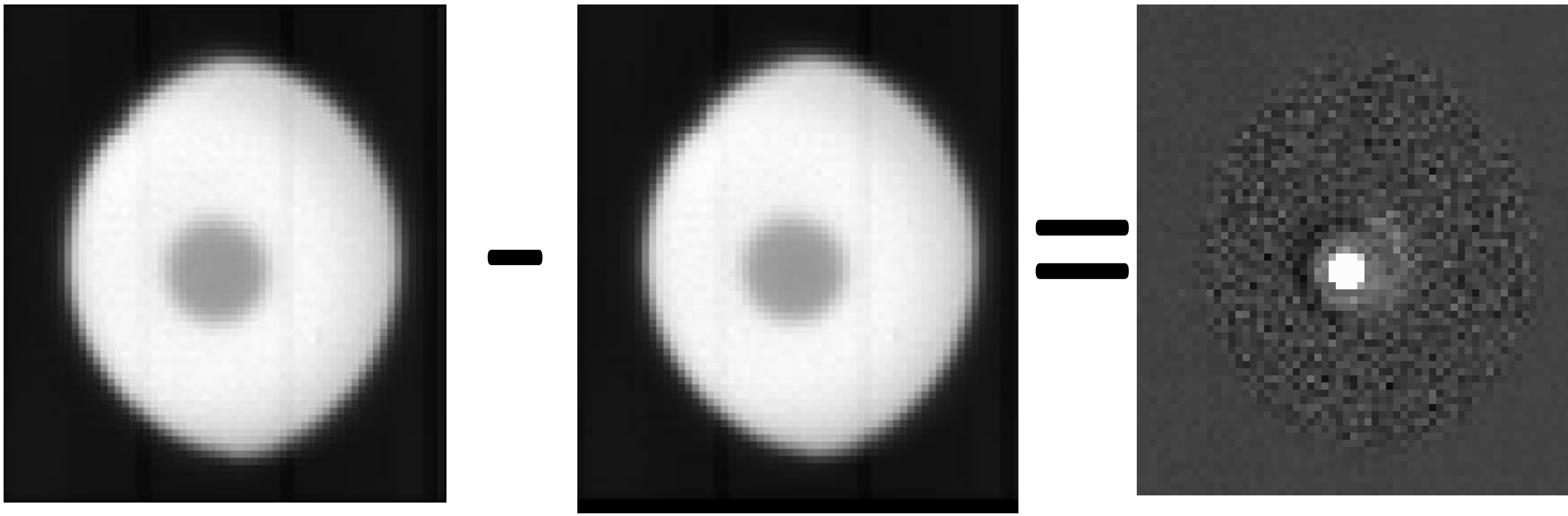




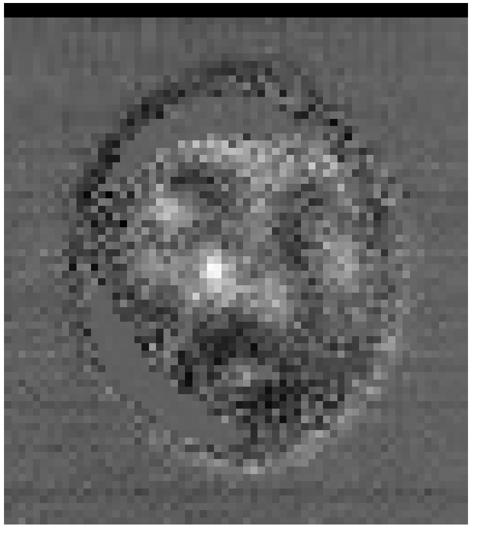
Observing in the mid-infrared



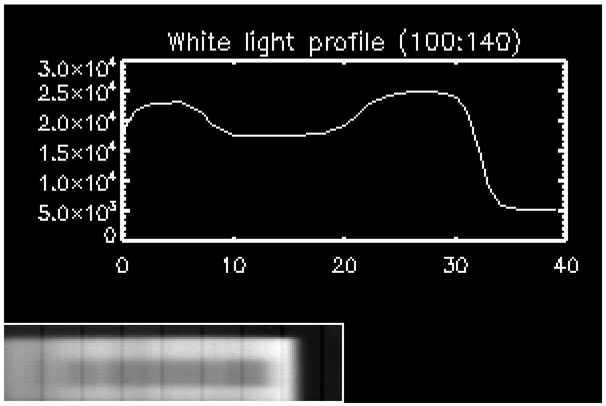
MIDI acquisition



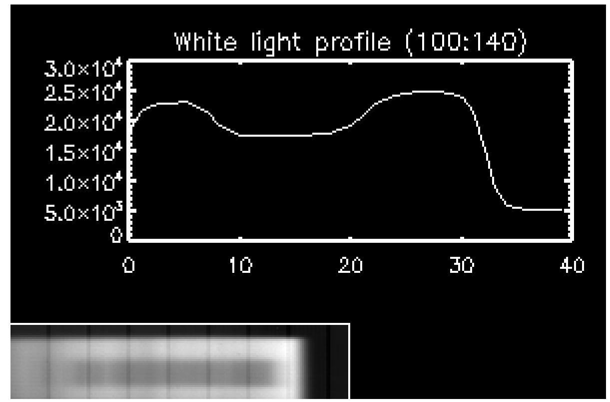
MIDI chopping



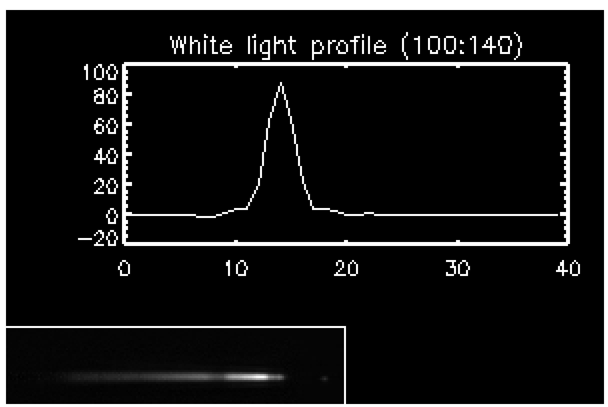
Photometry


White light profile (100:140)
3.0×10^4
2.5×10^4
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
0
0 10 20 30 40

-

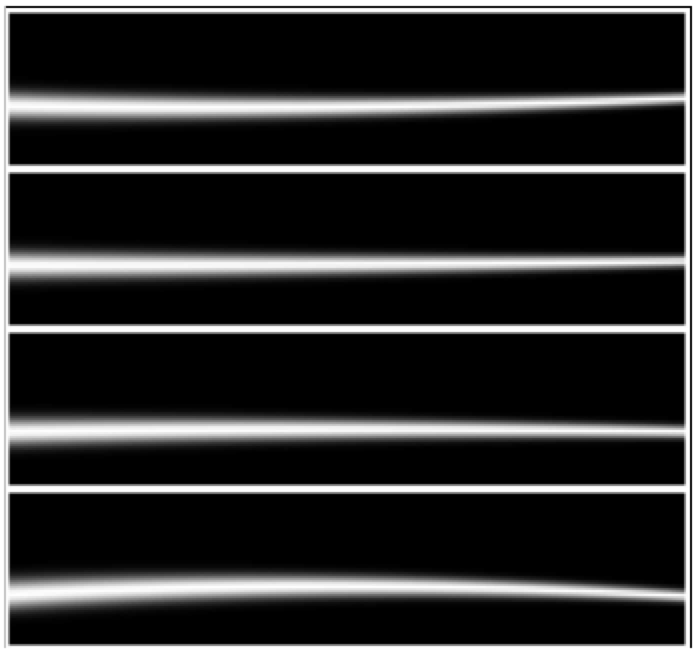

White light profile (100:140)
3.0×10^4
2.5×10^4
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
0
0 10 20 30 40

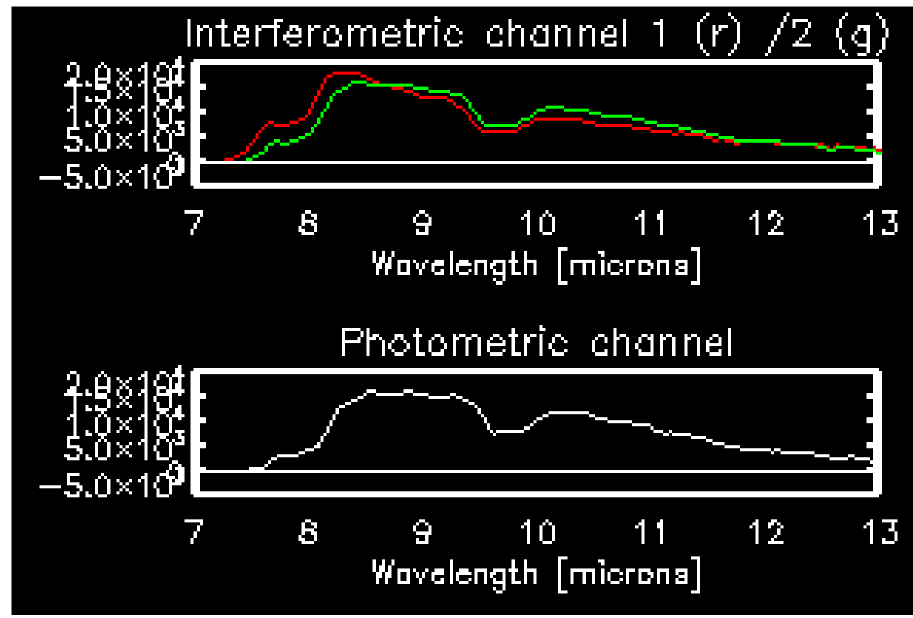
=


White light profile (100:140)
100
80
60
40
20
0
−20
0 10 20 30 40

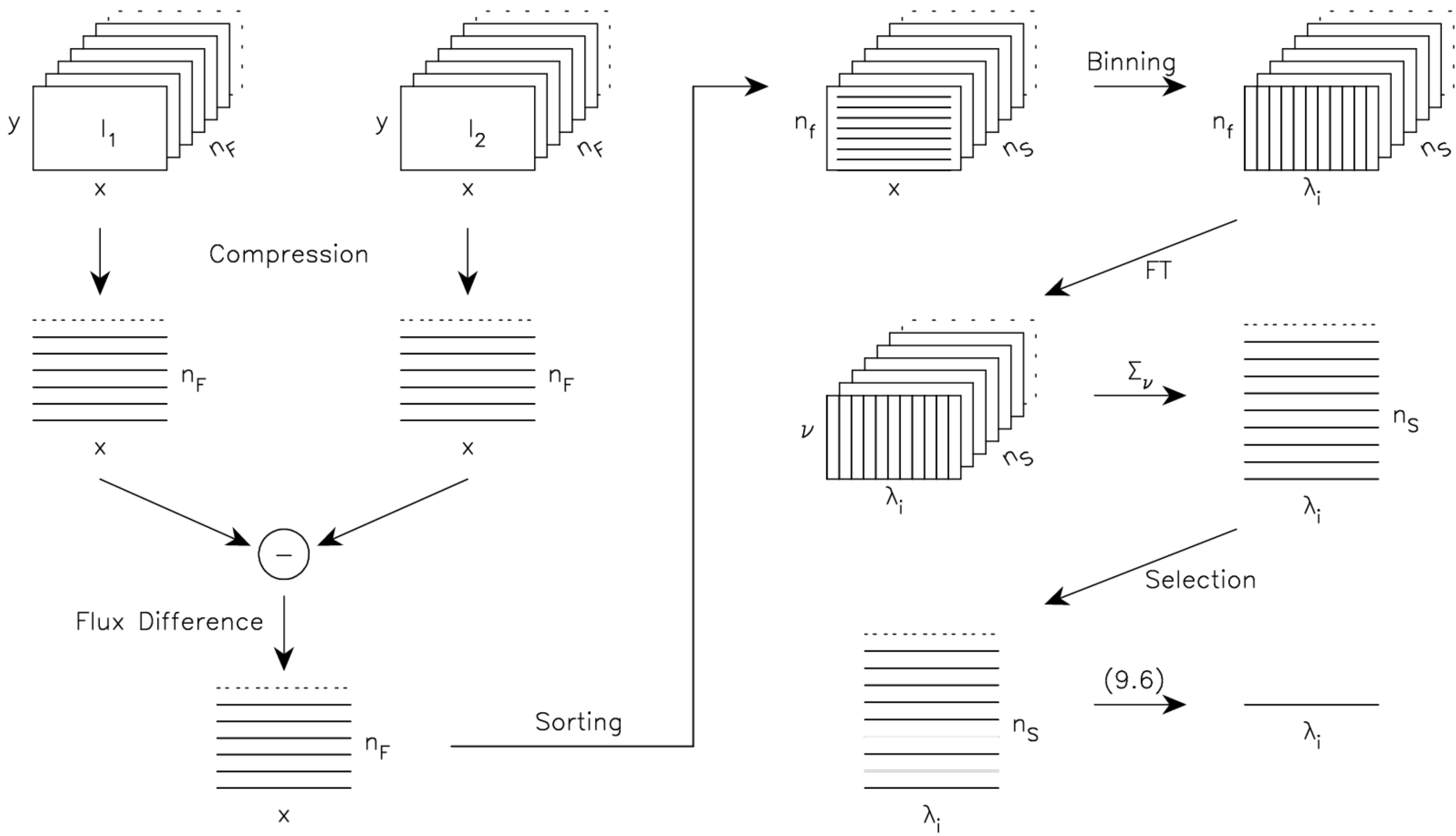
Spectrum extraction

PA
I1
I2
PB

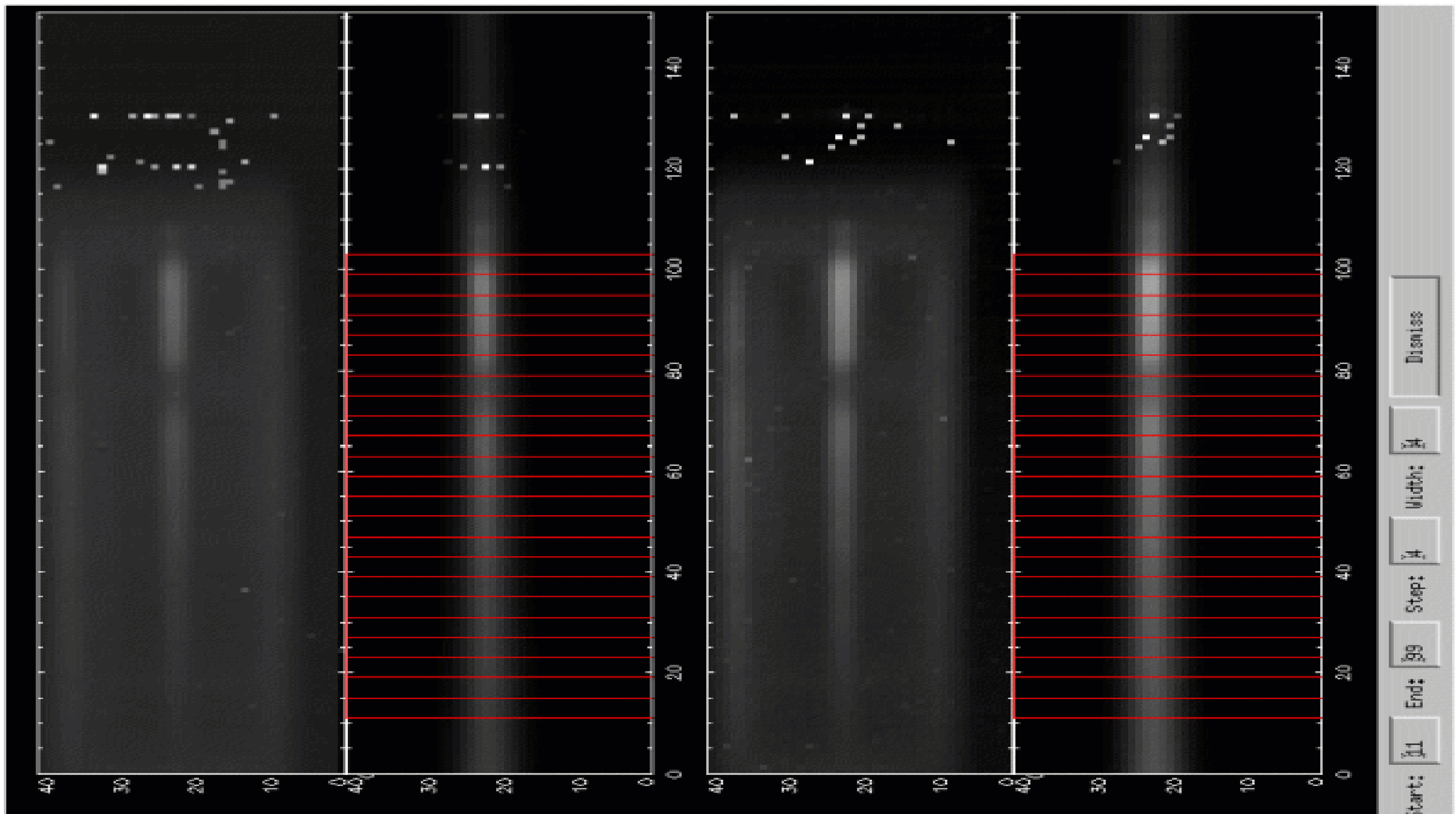




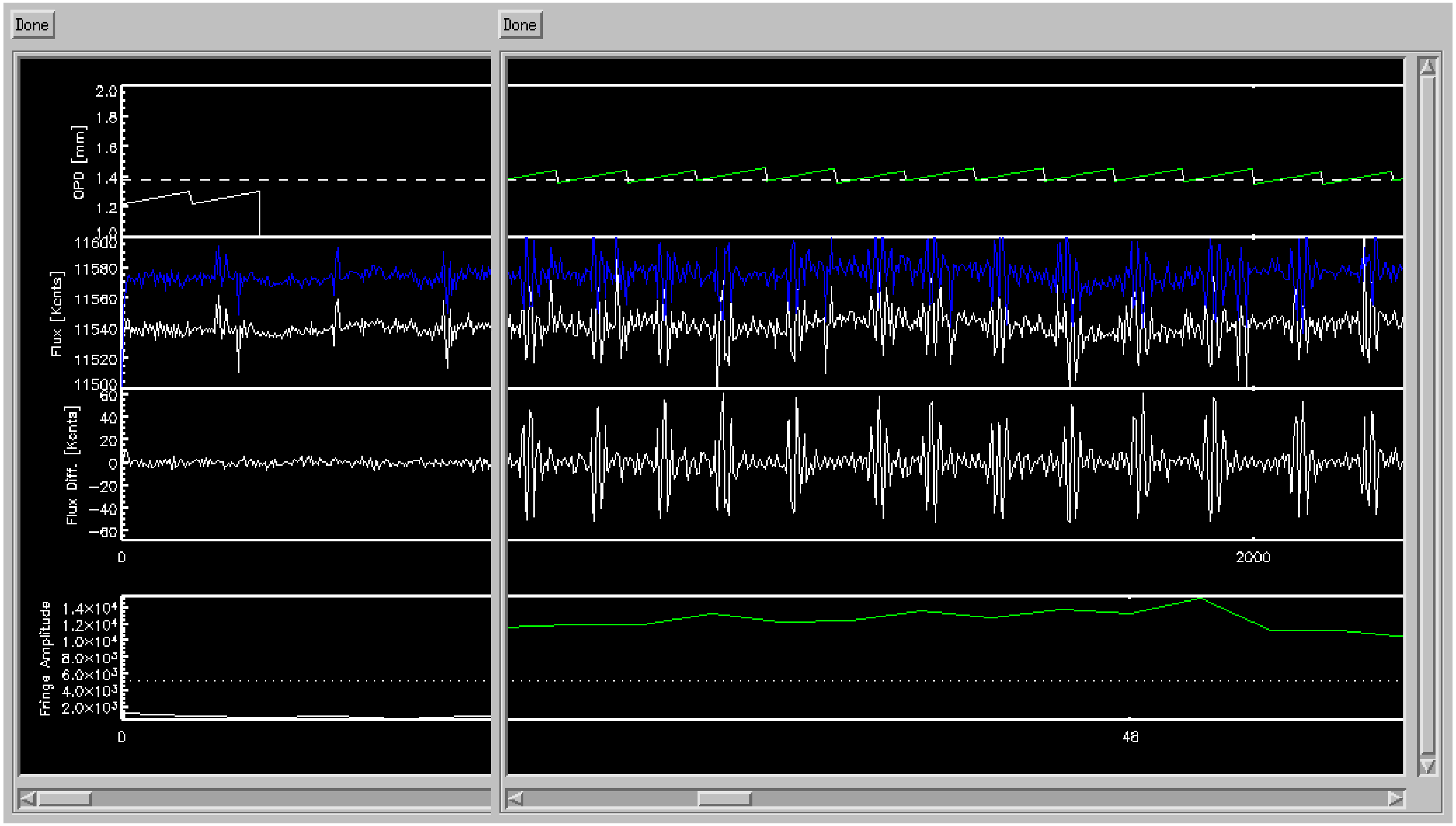
Interferometry



Wavelength binning



HIGH_SENS (high sensitivity)



Background cancellation

- The quality of the initial background cancellation depends on the splitting ratios
- A high-pass filter needs to be used to remove residual background fluctuations

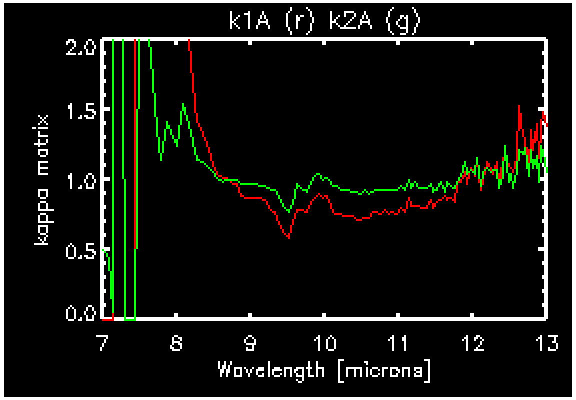
$$P_B = \alpha P_A$$

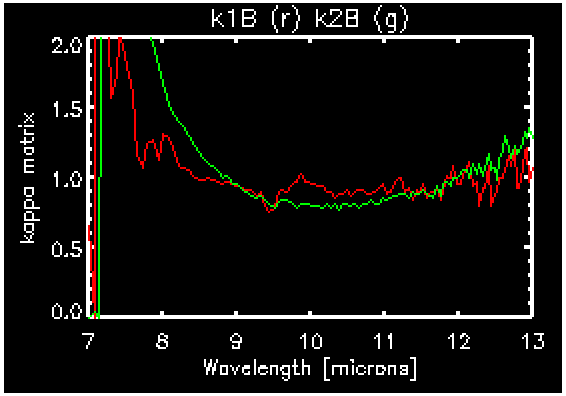
$$I_1 = \kappa_{1,\mathrm{A}} P_A + \alpha \kappa_{1,\mathrm{B}} P_A = P_A(\kappa_{1,\mathrm{A}} + \alpha \kappa_{1,\mathrm{B}})$$

$$I_2 = P_A(\kappa_{2,\mathrm{A}} + \alpha \kappa_{2,\mathrm{B}})$$

$$I_1 - I_2 = P_A[\kappa_{1,\mathrm{A}} - \kappa_{2,\mathrm{A}} + \alpha(\kappa_{1,\mathrm{B}} - \kappa_{2,\mathrm{B}})]$$

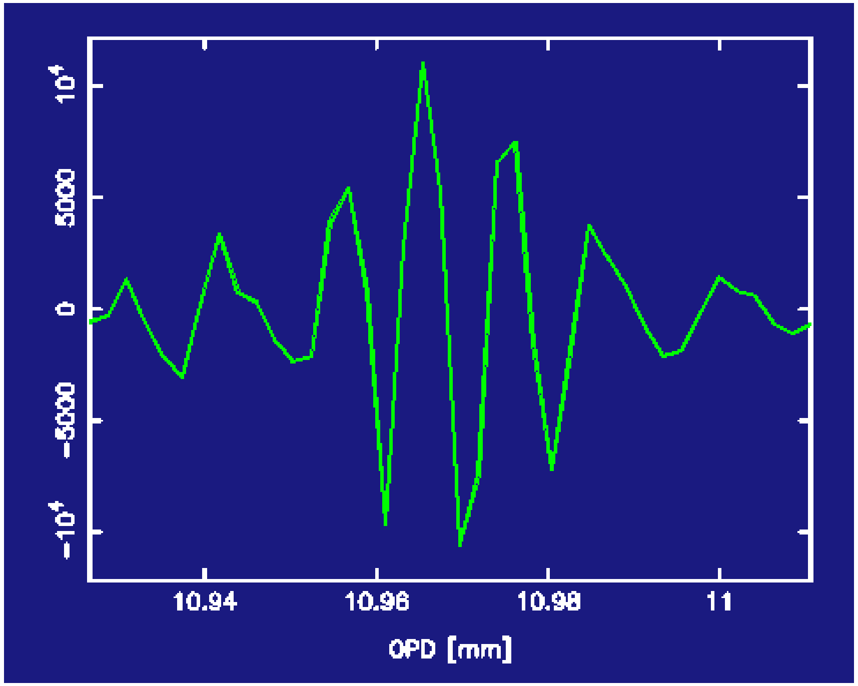
Kappa matrix

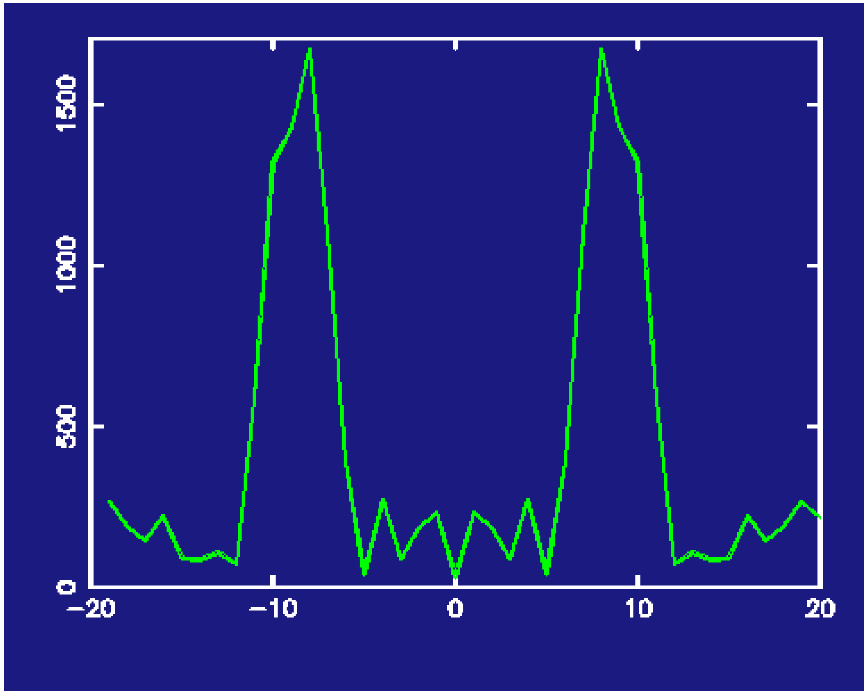




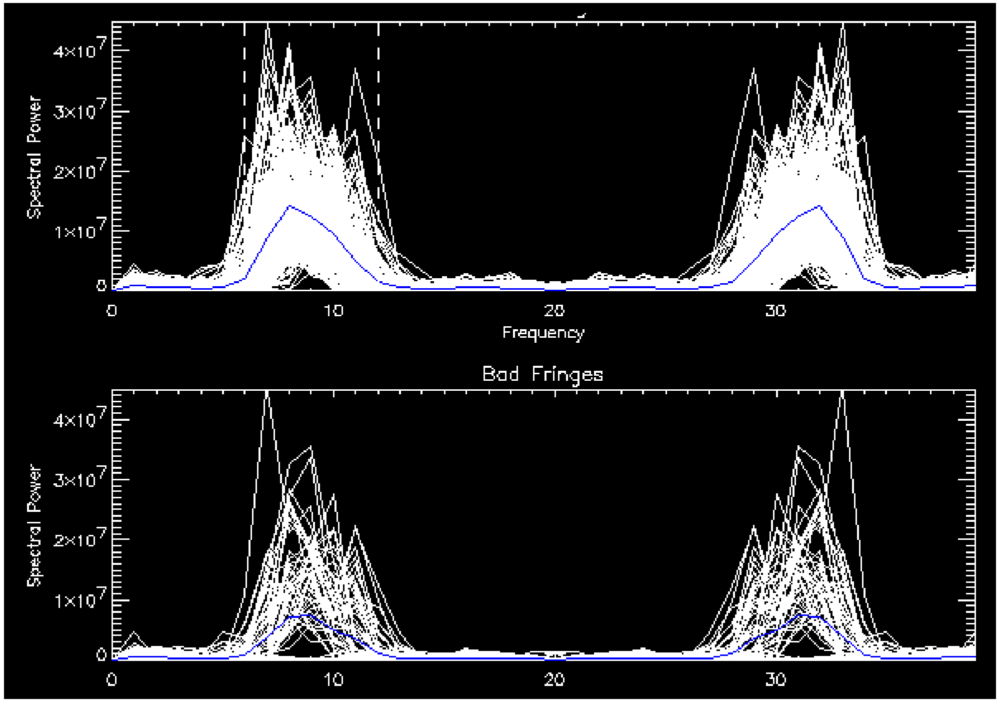
$\kappa_{1,\mathrm{A}} = I_1/(I_1+I_2)$, $\kappa_{2,\mathrm{A}} = I_2/(I_1+I_2)$, and so forth...

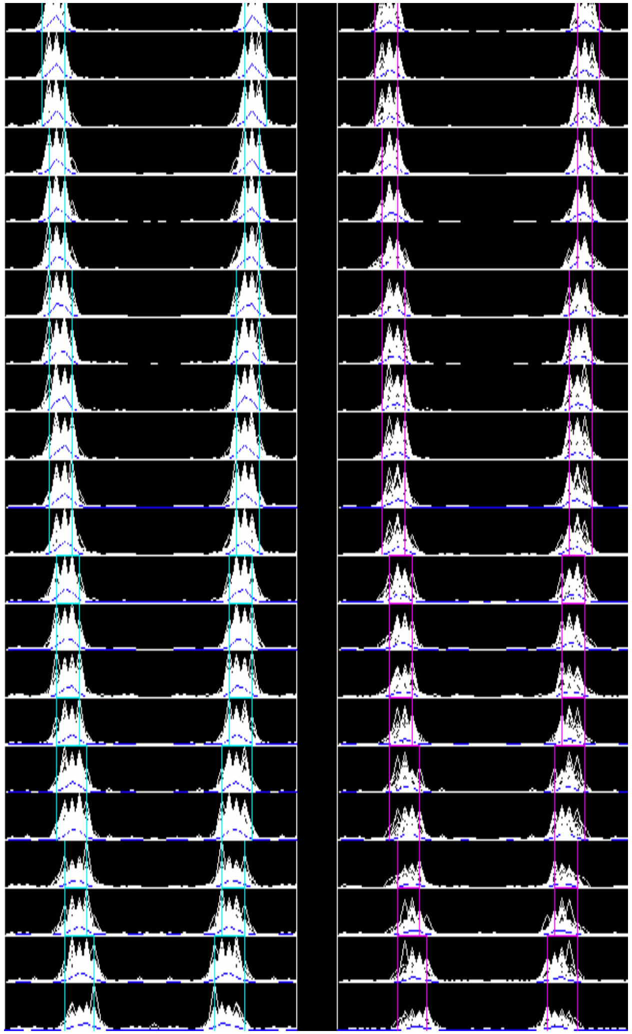
Interferograms and PSDs



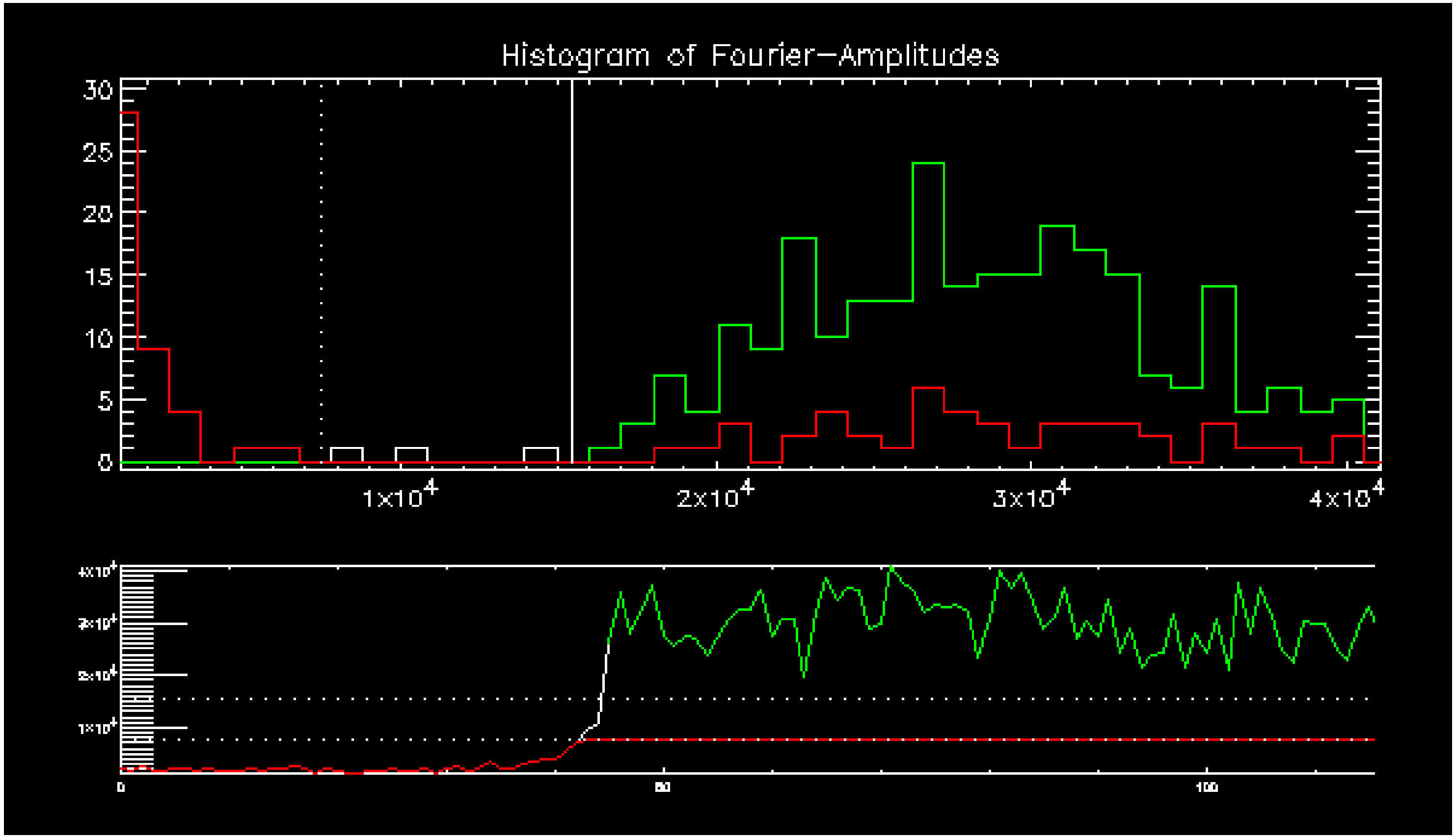


Channel PSDs





Good and bad fringes



Correlated flux normalization

Max. and min. field amplitudes: $A_\mathrm{A} + A_\mathrm{B}$ $A_\mathrm{A} - A_\mathrm{B}$

Max. and min. intensities:

$$I^\mathrm{max} = A_\mathrm{A}^2 + 2A_\mathrm{A}A_\mathrm{B} + A_\mathrm{B}^2 \qquad I^\mathrm{min} = A_\mathrm{A}^2 - 2A_\mathrm{A}A_\mathrm{B} + A_\mathrm{B}^2$$

Visibility amplitude: $V = (I^\mathrm{max} - I^\mathrm{min})/(I^\mathrm{max} + I^\mathrm{min})$

yields: $V^\mathrm{max} = 2\sqrt{I_\mathrm{A} I_\mathrm{B}}/(I_\mathrm{A} + I_\mathrm{B})$

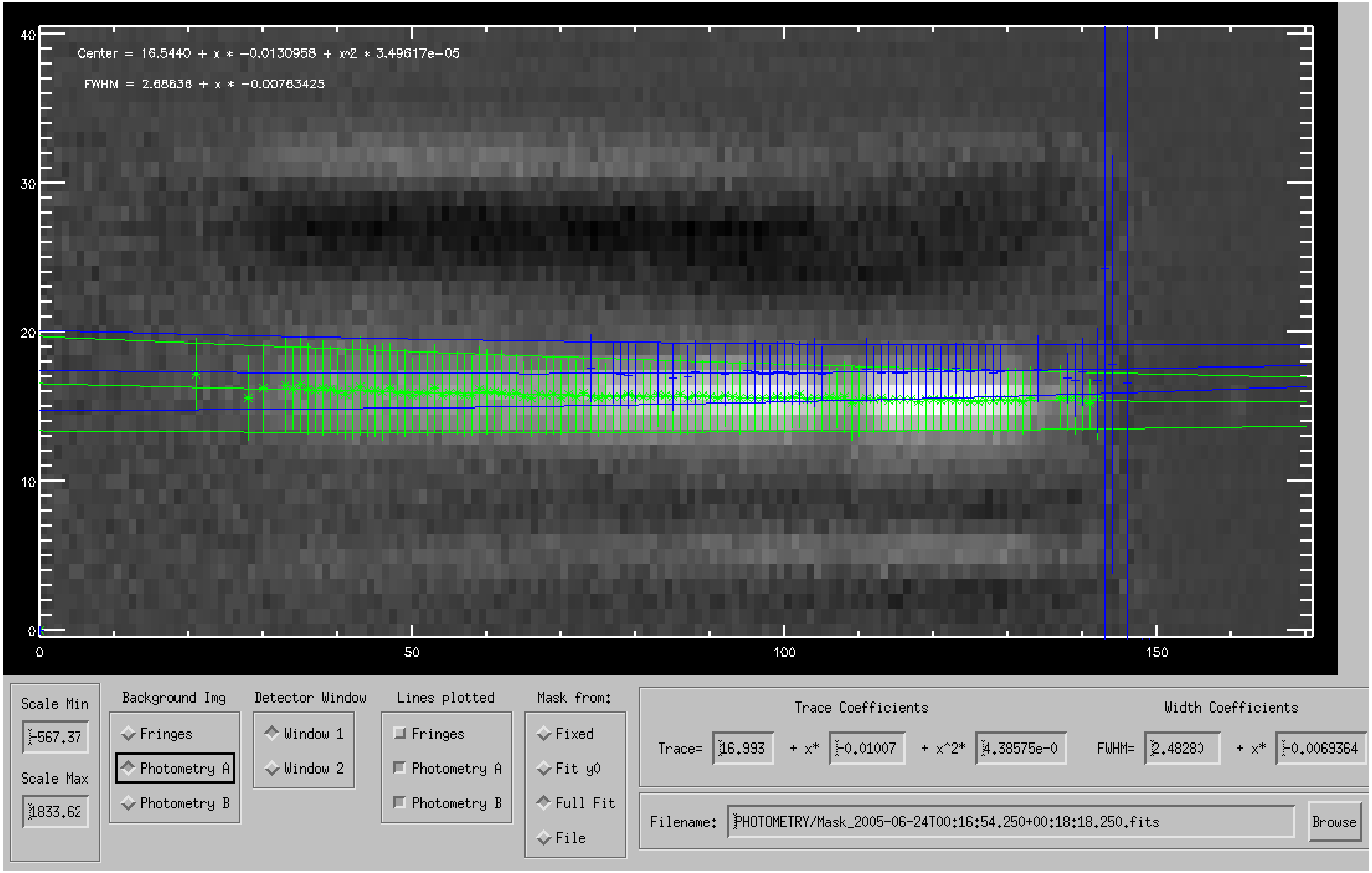
Interferogram in one MIDI channel:

$$I_1 = I_{\mathrm{A},1} + I_{\mathrm{B},1} + (1/2)(I_1^\mathrm{max} - I_1^\mathrm{min}) \sin(2\pi OPD/\lambda)$$

Subtracting the two channels: $2\gamma\sqrt{I_{\mathrm{A},1} I_{\mathrm{B},1}} + 2\gamma\sqrt{I_{\mathrm{A},2} I_{\mathrm{B},2}}$

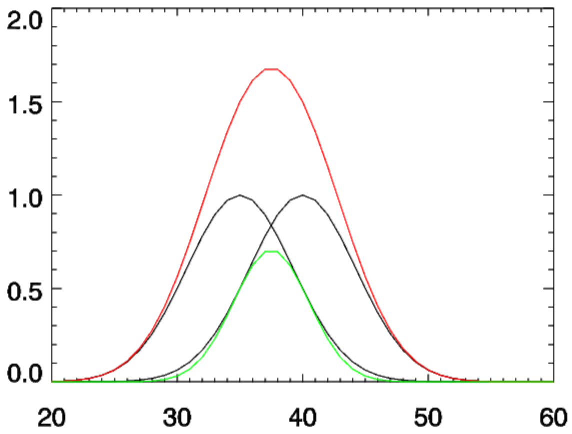
Normalization factor: $\sqrt{I_{\mathrm{A},1} I_{\mathrm{B},1}} + \sqrt{I_{\mathrm{A},2} I_{\mathrm{B},2}}$

Beam overlap problems



Multiply, then mask…

$$\sqrt{I_{\mathrm{A},1} I_{\mathrm{B},1}} + \sqrt{I_{\mathrm{A},2} I_{\mathrm{B},2}}$$

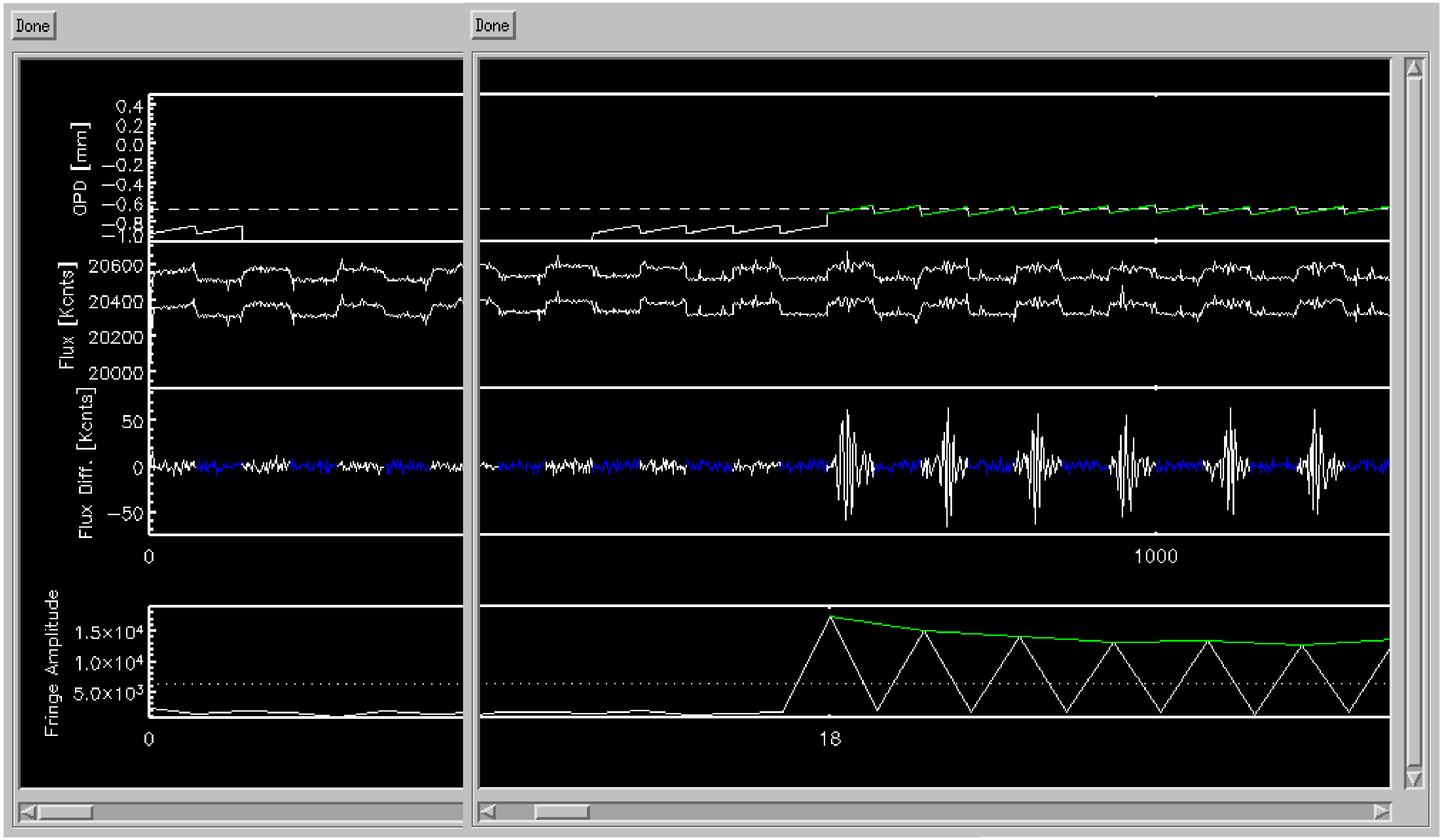


- Only the green overlap area contributes to the correlated flux
- Therefore, multiply detector pixels first, then use common mask (red) to extract

SCI_PHOT (high precision mode)

- Photometry recorded simultaneously with the fringe data (must be chopping). Use kappa matrix to convert $P_{\mathrm{A,B}}$ into $I_{1,2}$.
- Changes in beam overlap will simultaneously affect all extracted fluxes, thus will divide out.
- Kappa matrix can be determined from A and B photometry (needs only to be done once per night on a ***bright*** target).
- Otherwise, same reduction as HIGH_SENS

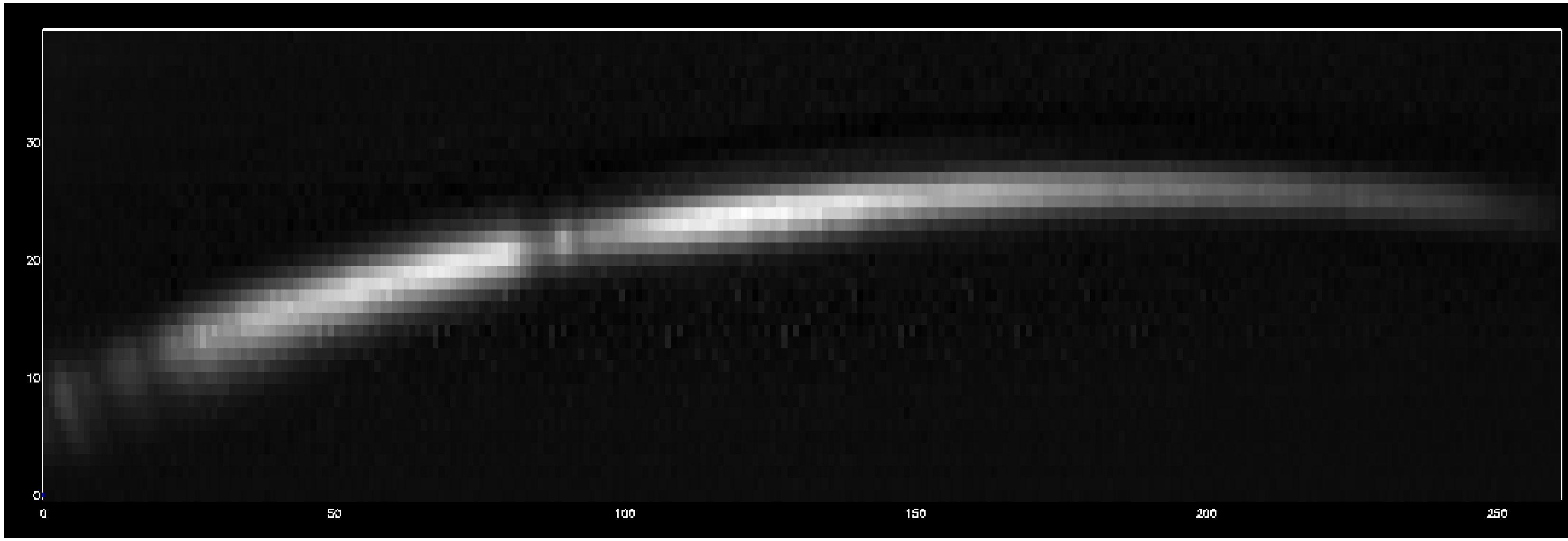
SCI_PHOT



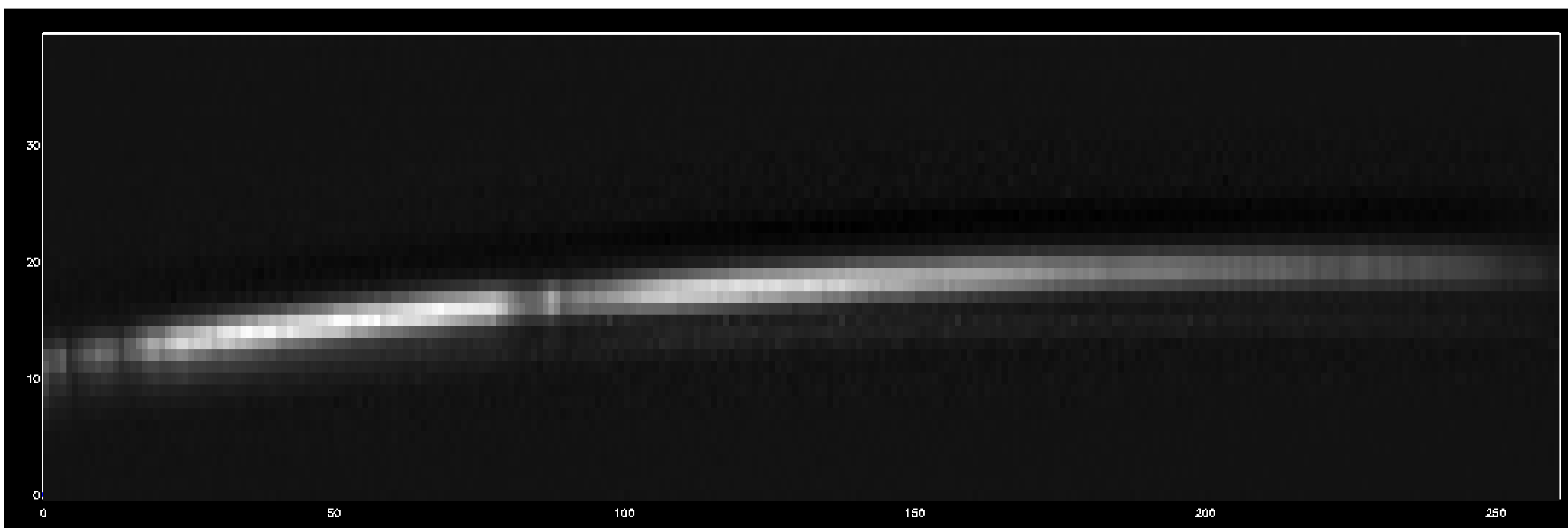
Done
Done
OPD [mm]
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
Flux [Kcnts]
20600
20400
20200
20000
Flux Diff. [Kcnts]
50
0
−50
0
1000
Fringe Amplitude
1.5×10⁴
1.0×10⁴
5.0×10³
0
18

Optical distortion

P_B



I_1



Reductions

3. Calculate I1/I2 "photometry" images based on the flux in the PA/PB channels. This uses the IDL routine sci2Hi and is quite complicated:

   A: From the PA/PB channels estimate the shift in actual pointing between the target and the photcalibrator.

   B: From this shift and the calibrator PSF calculate "sky background" regions in the PA/PB channels and remove sky background

   C: wavelength channel by channel in PA and PB, fit the calibrator psf in this channel to the measured target signal in order to estimate the flux.

   D: Transfer this flux to the I1 or I2 channels:
      i) Multiply by the appropriate kappa coefficient
      ii) shift in wavelength to correct for differences in PA/I1 wavelength scale (etc.)
      iii) Multiply by I1 or I2 y-PSF for photcalibrator. Note that this produces a much sharper image in I1 or I2 than my old procedure of correcting PA/PB images for the y-curvature. That procedure erred greviously in calculating the overlap.
      iv) Calculate the geometric mean images SQRT(I1_A*I1_B) etc., where I1_A is the image predicted in I1 from the data in PA.
      v) Also calculate predicted I1_A + I2_B images, which should approximate the data in targ.ABchop.fits. This is useful for estimating the photometric flux later.
      vi) Optionally: correct for lost fine spectral structure data. The poor optics of the PA/PB channels results in poor spectral resolution in the corners of the image. Essentially I measure the photometry in the I1/I2 channels where the optics is good by using the predicted A+B images from step (v). Then I correct the SQRT(A*B) images so that the fine structure looks like the photometry in the I1/I2 channels, but the smooth overall flux variation looks like that predicted from the PA/PB channels.

5. Now the grand finale in routine spVis: Channel by channel, pixel by pixel, for I1 and I2 separately, fit the estimated SQRT(A*B) (targ.geo.fits or targ.geo2.fits) to the estimated correlated signal (targ.RMS1/2.fits). In otherwords find the number which when multiplied by the geo y-profile for a specific channel, best fits the correlated signal profile in the same channel (with allowance for a linear background in the geo signal). This number is the instrumental visibility for this channel. Average the I1 and I2 results, and produce:

   targ.insvis.fits

Coherent integration

- Integration by co-adding interferograms
- Requires off-line fringe tracking (post processing)
- Maintains visibility phase (second derivative)
- Implemented by EWS package (W. Jaffe)
- Results have been tested to be consistent with MIA

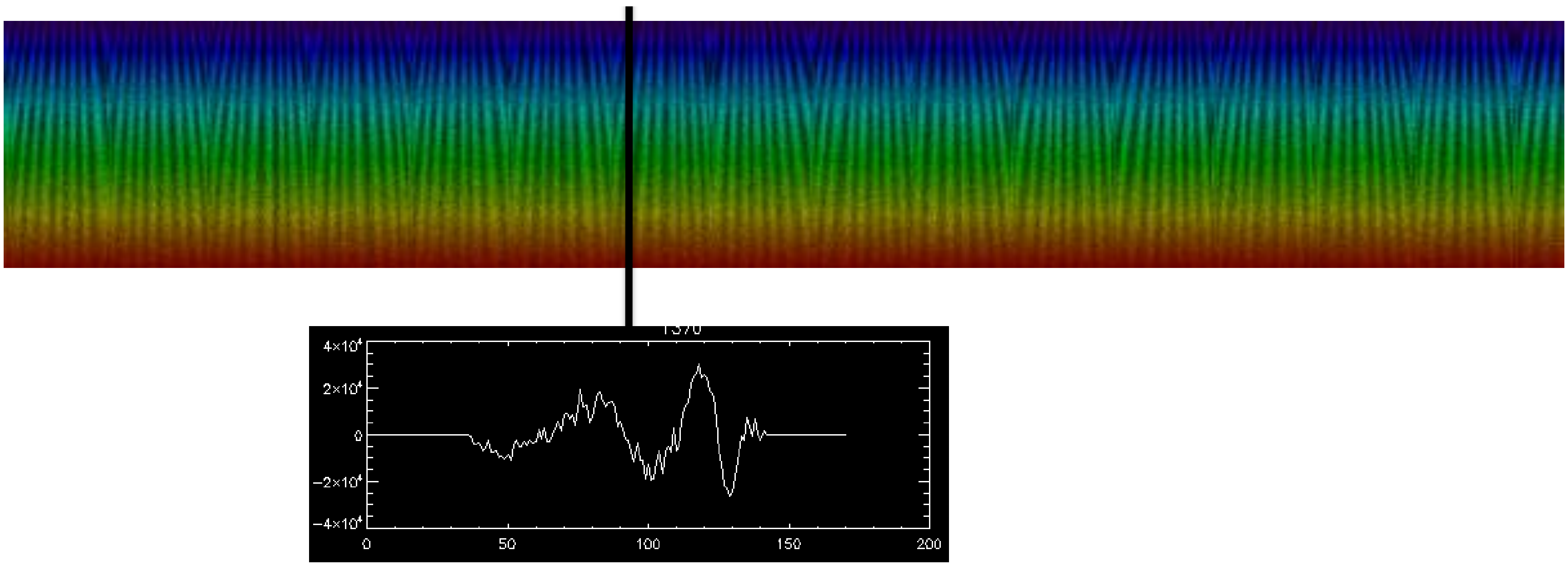
EWS processing steps

- Compress (extract) spectra for each frame
- Difference BC outputs and apply high-pass
- Multiply by $e^{i2\pi d/\lambda}$ and sum over scan
- Fourier transform complex visibility as a function of wave number into delay space
- Average several scans and find peak
- Apply both instrumental OPD and group delay to align phasors before coherent integration

Polychromatic fringes

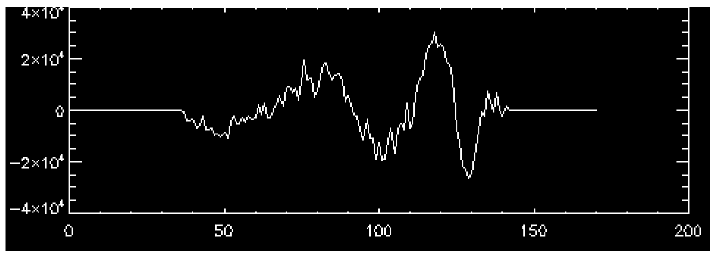
- Compressed spectra (vertical, with color coding) as a function of time (OPD). The pattern repeats after each scan.

$$S = \text{GARBAGE} + F \times V \times \cos(k \times D + \Phi)$$



Group delay analysis

$$G(D') \quad = \quad \int S(k,D)\exp(i\ kD')dk$$

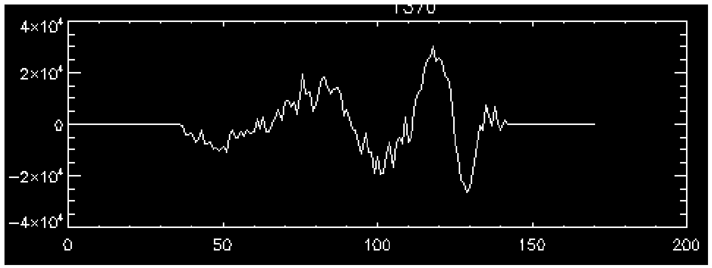


$D = D_{ins} + D_{atm}$

With $\quad \cos(kD) \quad \equiv \quad (\exp(i\ kD)\ + \exp(-i\ kD))/2$

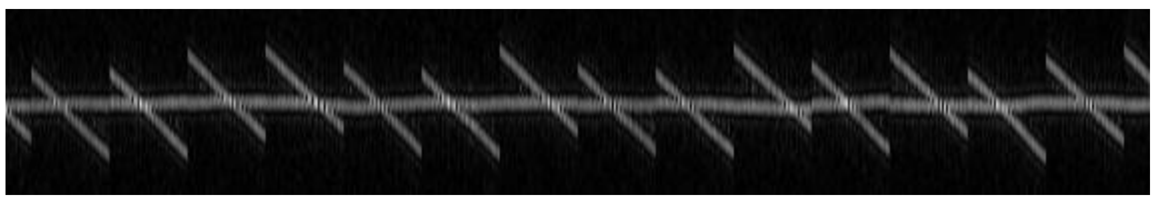
$$G(D') \quad \simeq \quad (\delta(D'-D)\ +\ \delta(D'+D))/2$$

Demodulation

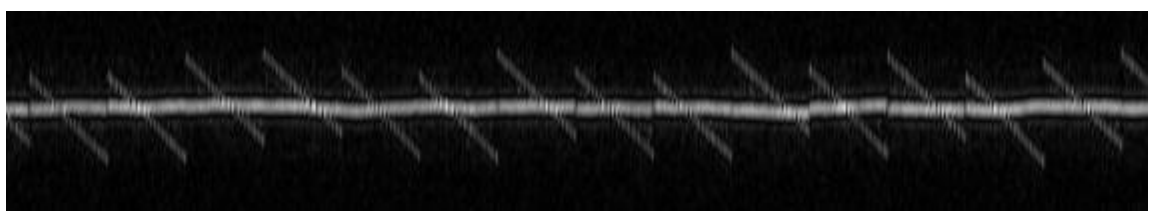


$$* \, e^{i2\pi D_\mathrm{i} / \lambda}$$

$$G(D') \rightarrow \quad (\delta(D' - D_a) \; + \; \delta(D' + D_a + 2D_i))/2$$

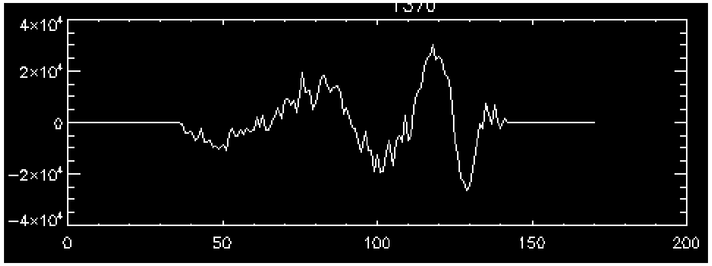


0.4s smoothing

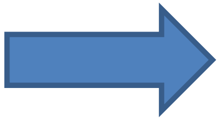


0.8s smoothing

EWS product: amplitude and "phase"



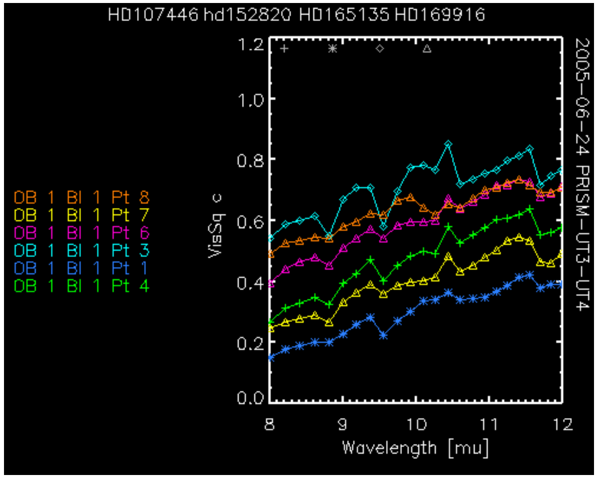
$$* \; e^{i2\pi D_\mathrm{i}/\lambda} \quad * \; e^{i2\pi D_\mathrm{a}/\lambda}$$

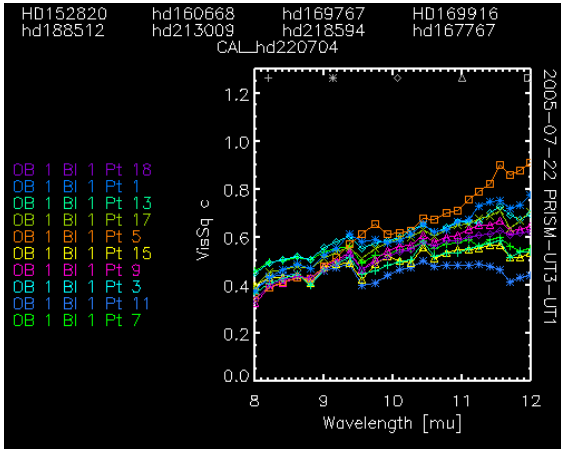


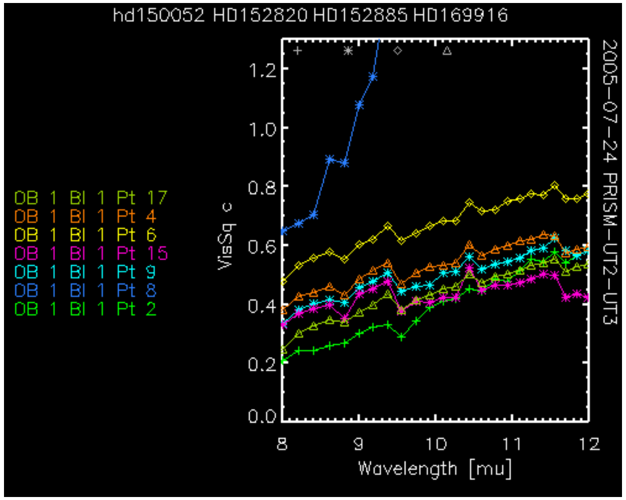
$$S'(k) \quad = \quad F(k)V(k)\exp(i\phi(k))$$

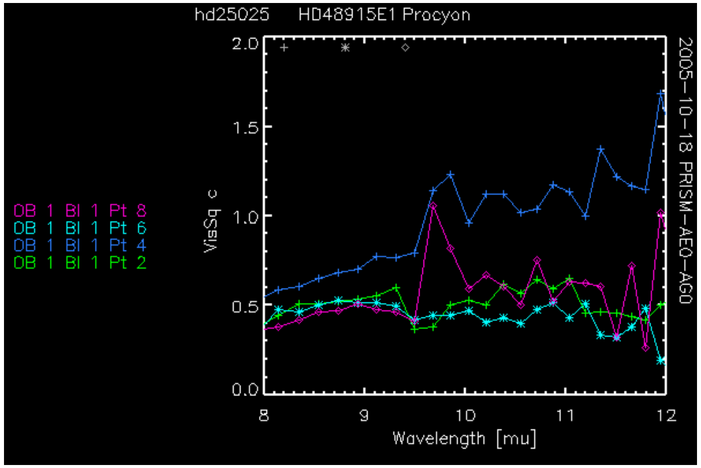
This complex quantity can now be coherently integrated

Calibrator visibility (TF)







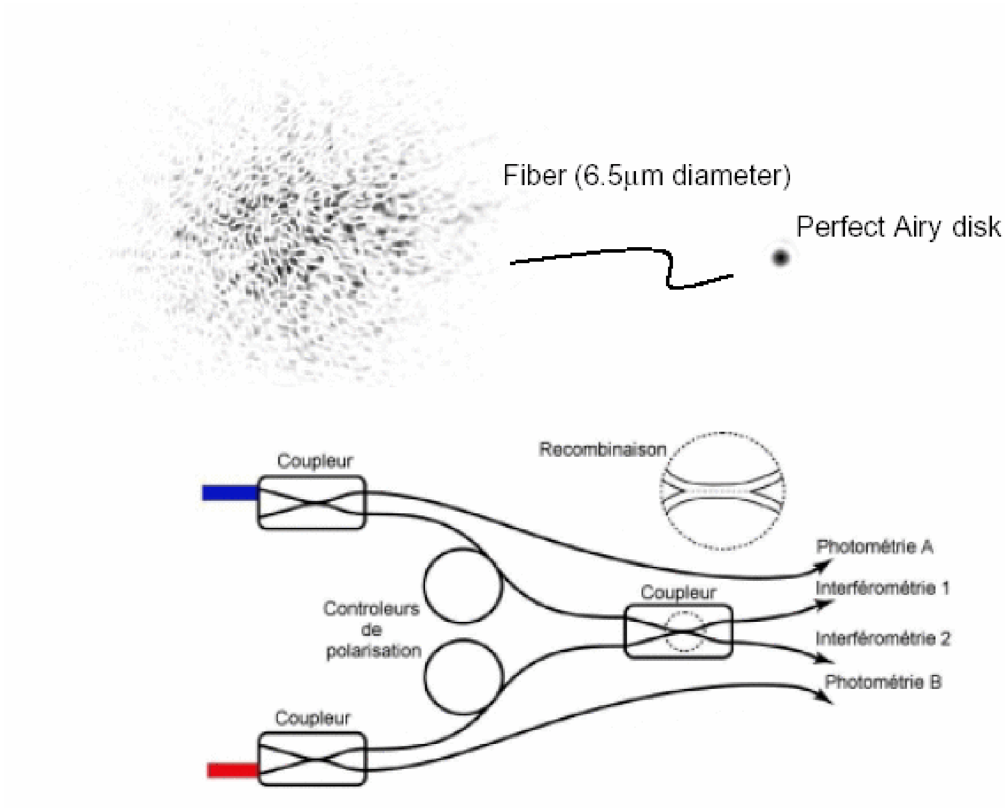


A short break…

Principles of AMBER

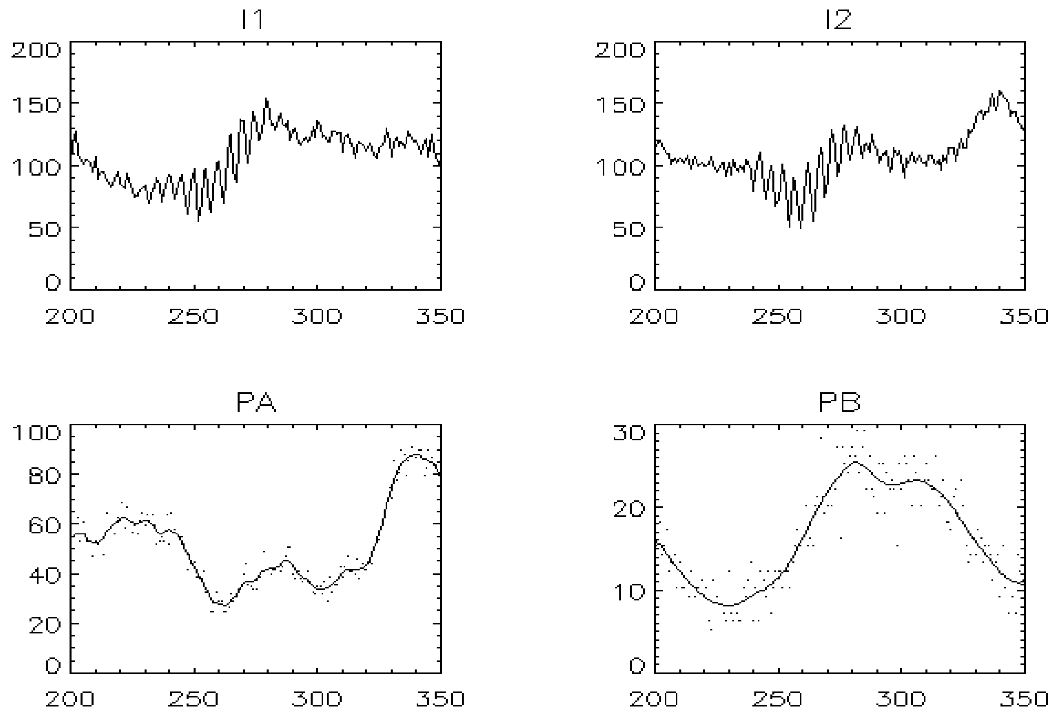
- Single-mode fiber wave front cleaning
- No OPD modulation
- Three baselines encoded at different spatial frequencies on the detector
- Relies on external fringe tracker such as FINITO

Single-mode fiber beam combination



$$I_1 = \kappa_{1,\mathrm{A}} P_\mathrm{A} + \kappa_{1,\mathrm{B}} P_\mathrm{B}$$
$$I_2 = \kappa_{2,\mathrm{A}} P_\mathrm{A} + \kappa_{2,\mathrm{B}} P_\mathrm{B}.$$

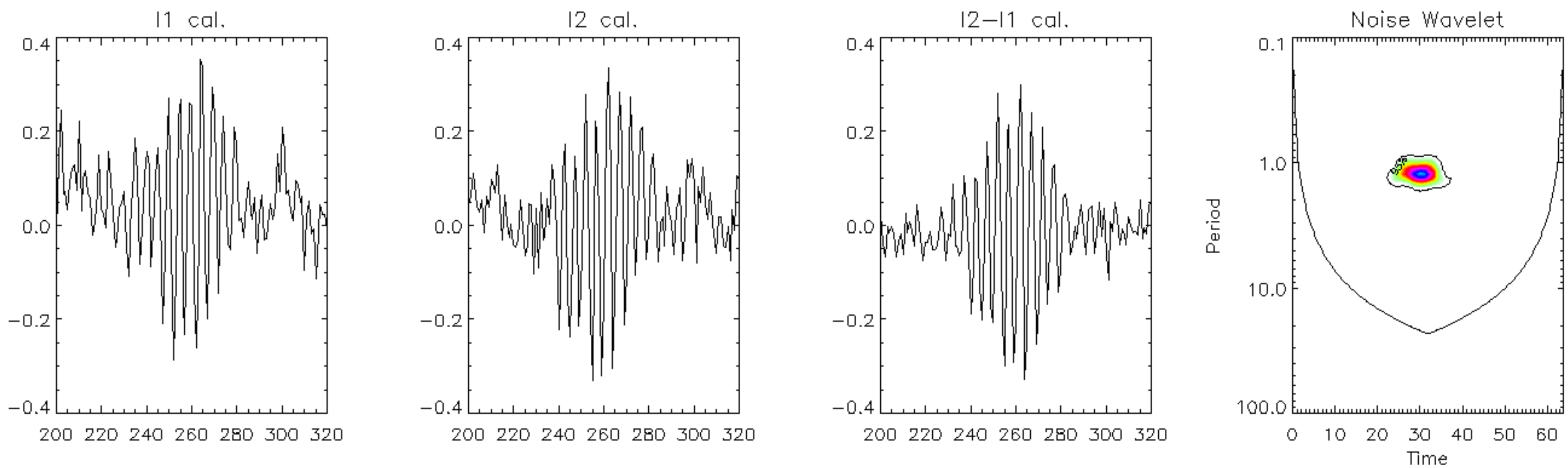
Interferometric signal (VINCI)



$$I_1 = \kappa_{1,\mathrm{A}} P_A + \kappa_{1,\mathrm{B}} P_B + \frac{1}{2}(I_{\max} - I_{\min}) \cos\left(\frac{OPD}{2\pi\lambda}\right)$$

$$\frac{1}{2}(I_{\max} - I_{\min}) = 2\sqrt{\kappa_{1,\mathrm{A}} P_A \kappa_{1,\mathrm{B}} P_B} V(OPD)$$

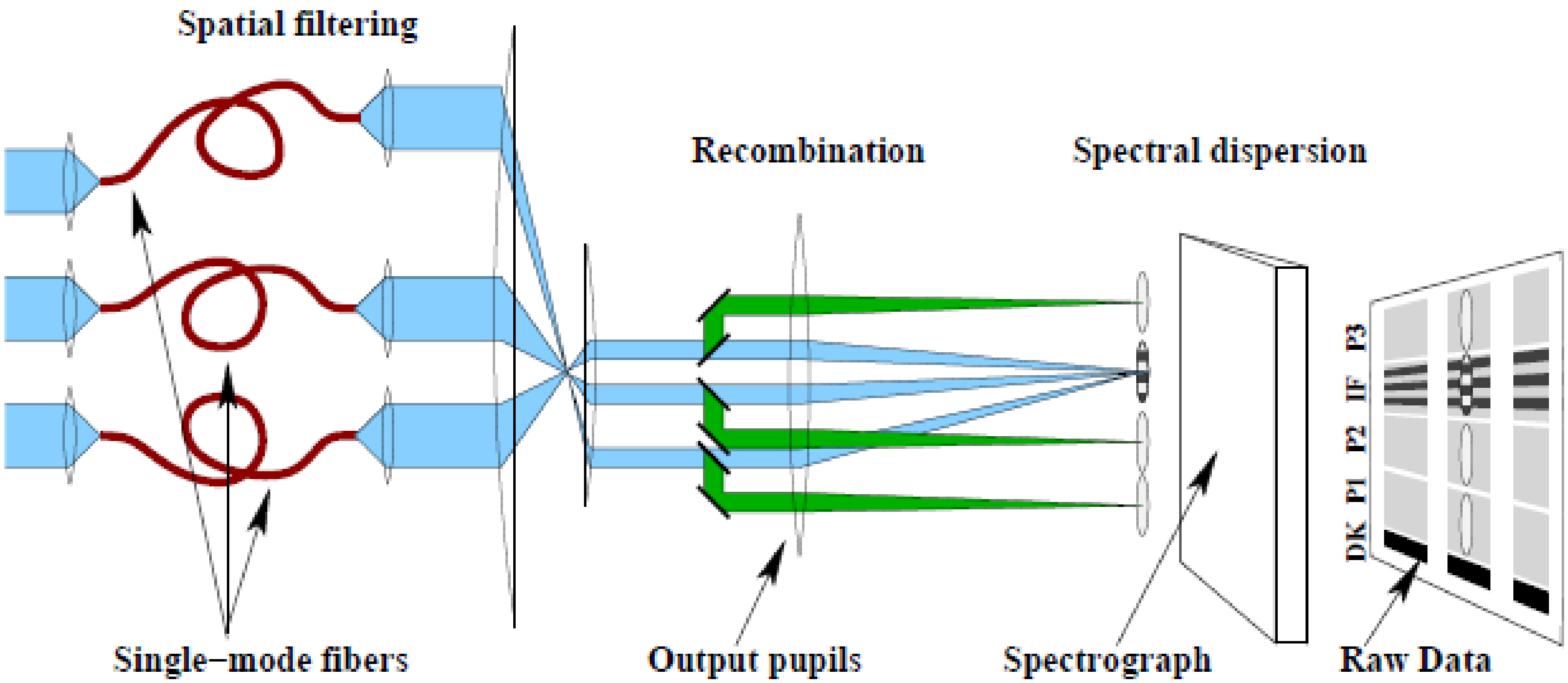
Signal calibration (VINCI)



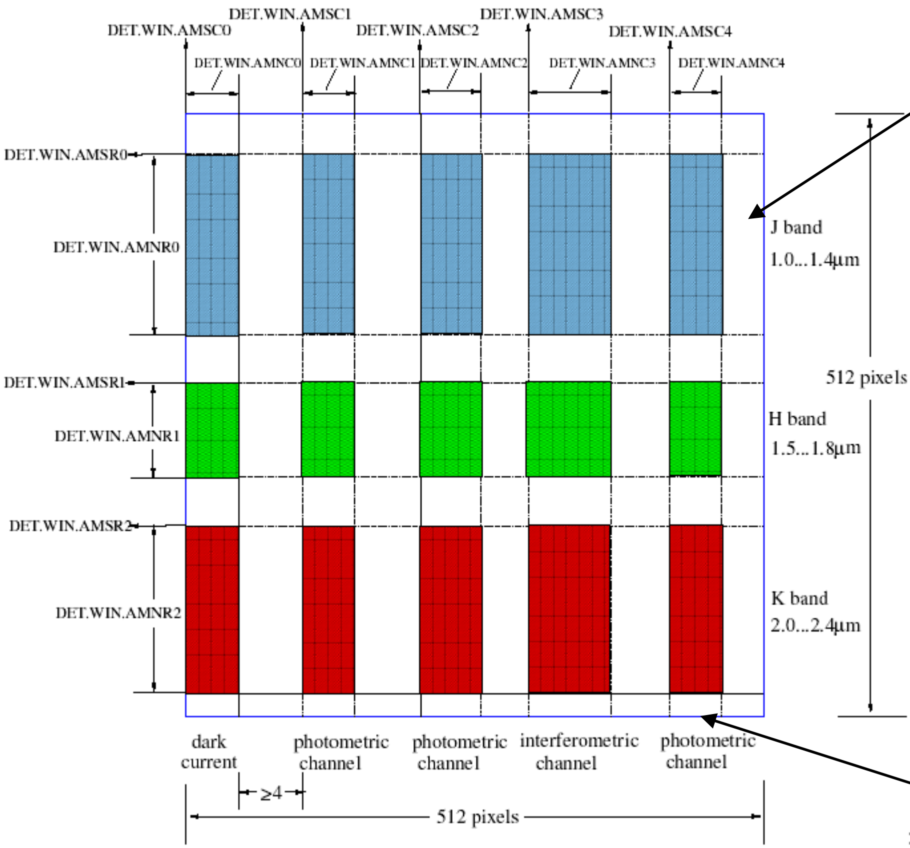
$$I_{1\,\mathrm{cal}} = \frac{1}{2\sqrt{\kappa_{1,\mathrm{A}}\ \kappa_{1,\mathrm{B}}}} \frac{I_1 - \kappa_{1,\mathrm{A}} P_\mathrm{A} - \kappa_{1,\mathrm{B}} P_\mathrm{B}}{[\sqrt{P_\mathrm{A}\ P_\mathrm{B}}]_\mathrm{Wiener}}$$

$$I_{2\,\mathrm{cal}} = \frac{1}{2\sqrt{\kappa_{2,\mathrm{A}}\ \kappa_{2,\mathrm{B}}}} \frac{I_2 - \kappa_{2,\mathrm{A}} P_\mathrm{A} - \kappa_{2,\mathrm{B}} P_\mathrm{B}}{[\sqrt{P_\mathrm{A}\ P_\mathrm{B}}]_\mathrm{Wiener}}.$$

AMBER instrument



• ... on an infrared Hawaii Camera:

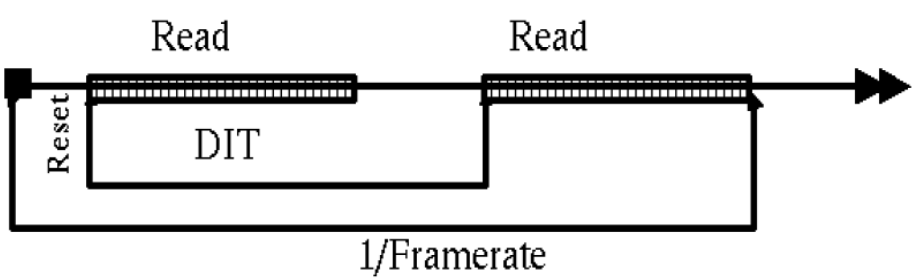


« row »

« channel »

The camera is ALWAYS illuminated (NO shutter)

The camera is divided in (max 3) ROWS of (4 or 5) , regions: Dark, P1 , P2, I [, P3]

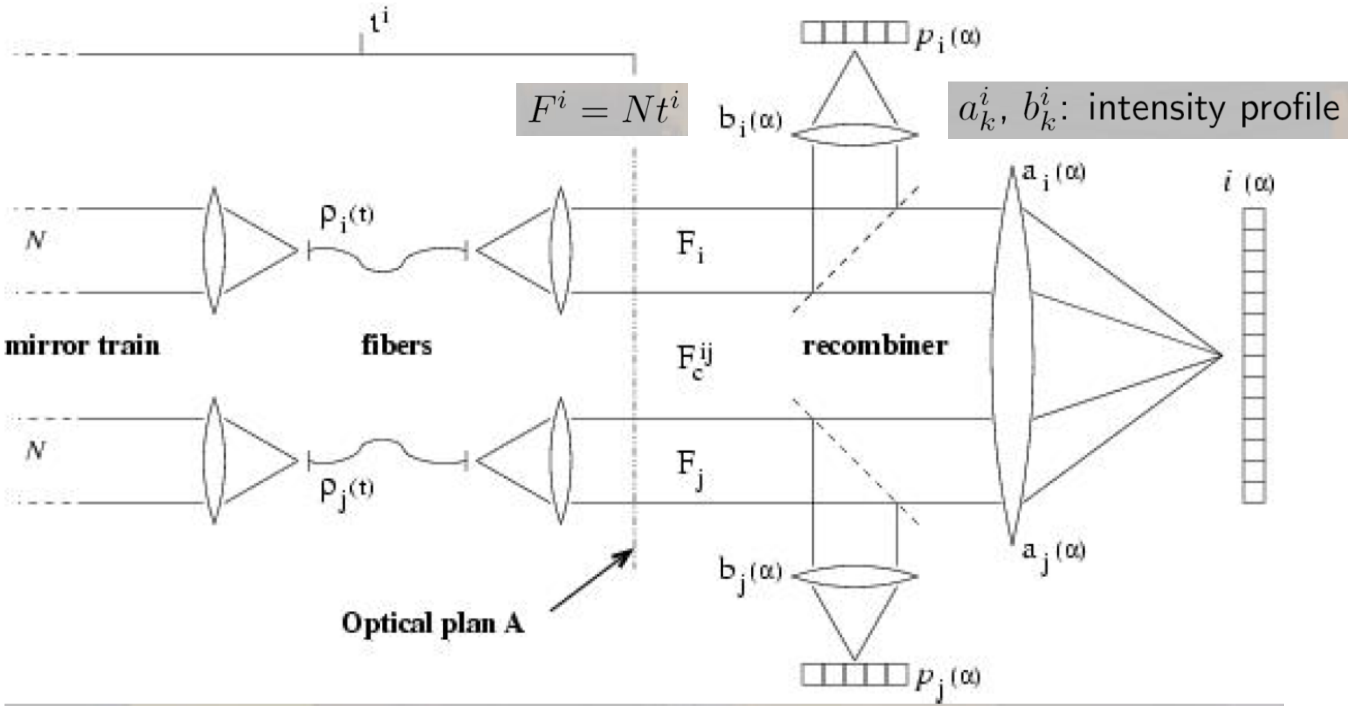


The READOUT mode used is DOUBLE-CORRELATED

Data reduction overview

- Spatially coded fringes
  - cosmetic corrections needed
  - coding calibration needed (P2VM matrix)
- Spectrally dispersed fringes
  - wavelength calibration
- Bandwidth smearing
  - piston bias correction
- Frame selection

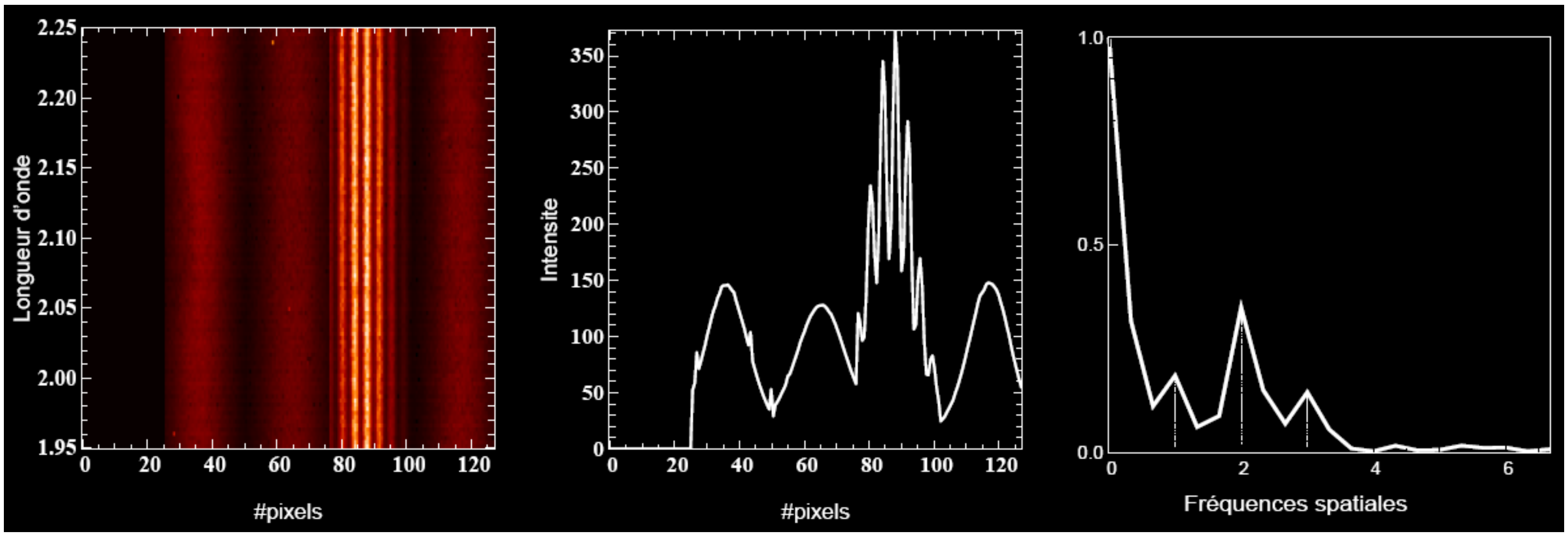
Definitions



Interferometric channel: $i_k = F^i a^i_k$
Photometric channel: $p^i_k = F^i b^i_k$

k in index: pixel coordinate
i, j in exponent: telescope(s)number(s)

AMBER fringes



$$i_k = \sum_{i}^{N_{\mathrm{tel}}} a_k^i F^i + \sum_{i<j}^{N_{\mathrm{tel}}} \sqrt{a_k^i a_k^j} C_{\mathrm{B}}^{ij} \mathrm{Re}\left[F_{\mathrm{c}}^{ij} \mathrm{e}^{i\left(2\pi\alpha_k f^{ij} + \phi_{\mathrm{s}}^{ij} + \Phi_{\mathrm{B}}^{ij}\right)} \right]$$

Modeling the interferogram

$$i_k = \sum_{i}^{N_{\rm tel}} a_k^i F^i + \sum_{i<j}^{N_{\rm tel}} \left[c_k^{ij} R^{ij} + d_k^{ij} I^{ij} \right]$$

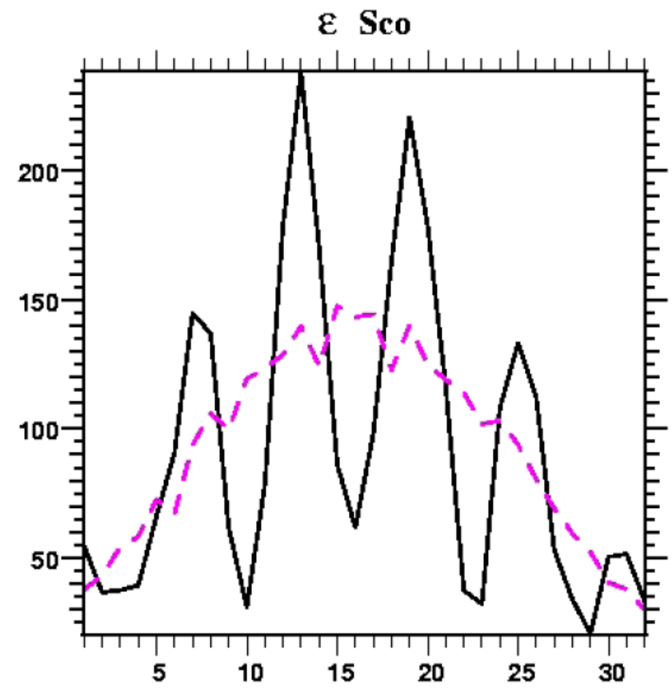
with

$$c_k^{ij} = C_{\rm B}^{ij} \frac{\sqrt{a_k^i a_k^j}}{\sqrt{\sum_k a_k^i a_k^j}} \cos\left(2\pi\alpha_k f^{ij} + \phi_{\rm s}^{ij} + \Phi_{\rm B}^{ij}\right),$$

$$d_k^{ij} = C_{\rm B}^{ij} \frac{\sqrt{a_k^i a_k^j}}{\sqrt{\sum_k a_k^i a_k^j}} \sin\left(2\pi\alpha_k f^{ij} + \phi_{\rm s}^{ij} + \Phi_{\rm B}^{ij}\right),$$

and

$$R^{ij} = \sqrt{\sum_k a_k^i a_k^j} {\rm Re}\left[F_{\rm c}^{ij}\right], \quad I^{ij} = \sqrt{\sum_k a_k^i a_k^j} {\rm Im}\left[F_{\rm c}^{ij}\right]$$

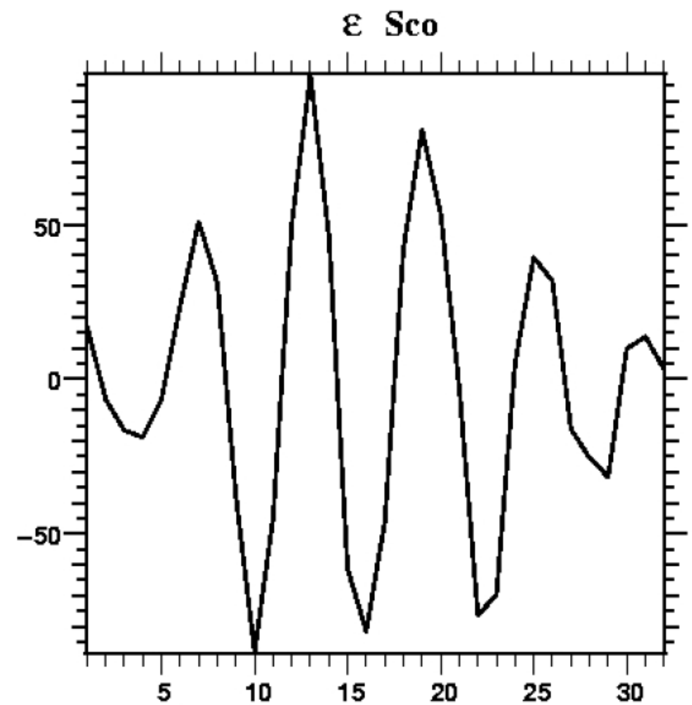


DC corrected interferogram

$$m_k = i_k - \sum_{i=1}^{N_{\rm tel}} P^i v_k^i$$

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

with $$P^i = F^i \sum_k b_k^i$$



The Visibility-to-Pixel Matrix

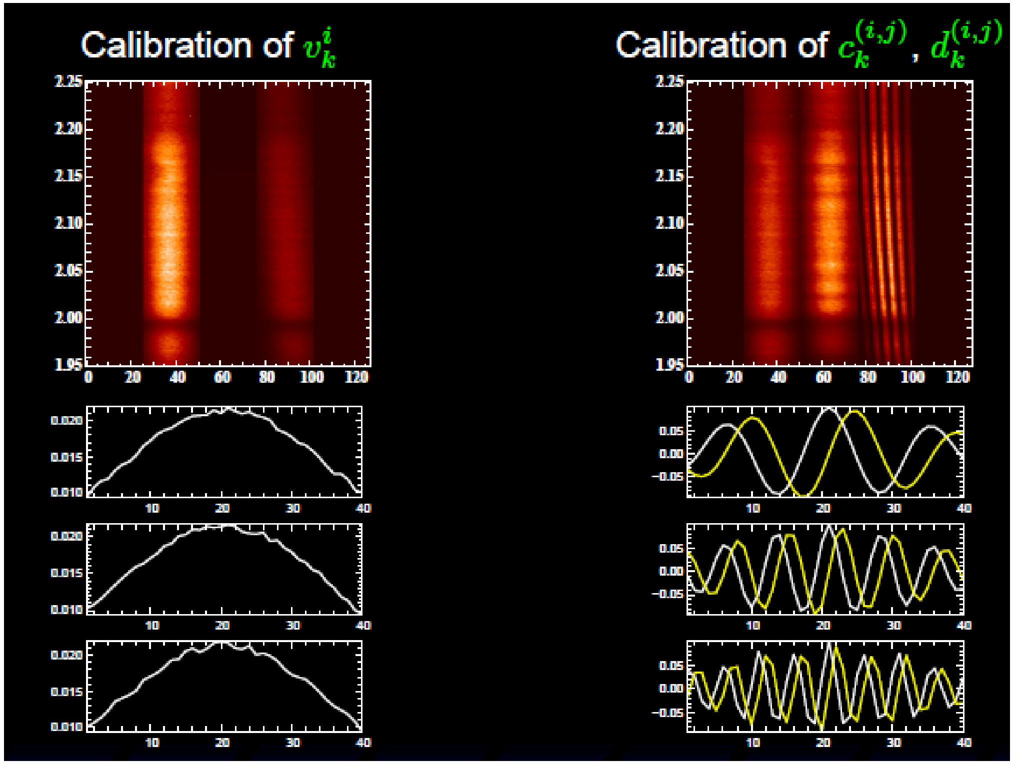
$$i_k = \sum_{i}^{N_{\rm tel}} a_k^i F^i + \sum_{i<j}^{N_{\rm tel}} \left[c_k^{ij} R^{ij} + d_k^{ij} I^{ij} \right]$$

$$\begin{pmatrix} m_1 \\ | \\ m_{N_{\rm pix}} \end{pmatrix} = \begin{pmatrix} \overbrace{\begin{matrix} .. & c_1^{ij} & .. \\ | & \vdots & | \\ .. & c_{N_{\rm pix}}^{ij} & .. \end{matrix}}^{N_{\rm b}} & \overbrace{\begin{matrix} .. & d_1^{ij} & .. \\ | & \vdots & | \\ .. & d_{N_{\rm pix}}^{ij} & .. \end{matrix}}^{N_{\rm b}} \end{pmatrix} \begin{pmatrix} \vdots \\ R^{ij} \\ \vdots \\ I^{ij} \\ \vdots \end{pmatrix} = \mathrm{V2PM} \begin{pmatrix} \vdots \\ R^{ij} \\ \vdots \\ I^{ij} \\ \vdots \end{pmatrix}$$

Internal calibration (P2VM)

- Need for a internal calibration:
  - relative flux in the photometric and interferometric beams
  - relative transmission in λ
  - wavelength table
  - disentangle the 3 fringe patterns by a fringe fitting technique
- Internal calibration depends
  - on setup (LR, MR…)
  - on time (unstable)
- Calibration sequence:
  - wavelength calibration
  - one beam at a time (1)
  - one pair at a time (2)

(1) (2)



Measuring the V2PM

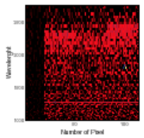
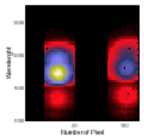
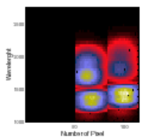
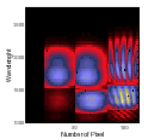
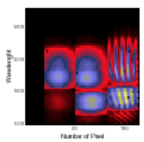
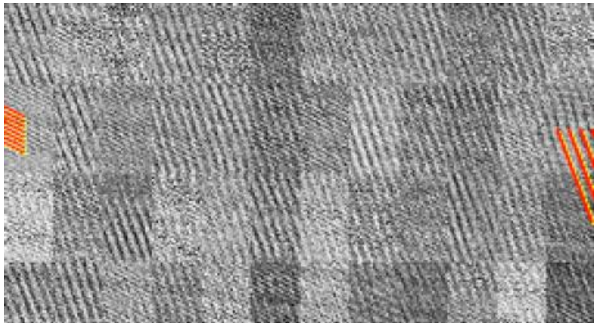
Shutter 1	Shutter 2	Shutter 3	Delaying plate	file Name	figure
Close	Close	Close	No Delay	AMBER_3TSTD_CAL_0001.fits	
Open	Close	Close	No Delay	AMBER_3TSTD_CAL_0002.fits	
Close	Open	Close	No Delay	AMBER_3TSTD_CAL_0003.fits	
Open	Open	Close	No Delay	AMBER_3TSTD_CAL_0004.fits	
Open	Open	Close	1/2 Delayed	AMBER_3TSTD_CAL_0005.fits	

Figure 3. Complete calibration sequence for 2 telescopes

AMBER detector issues

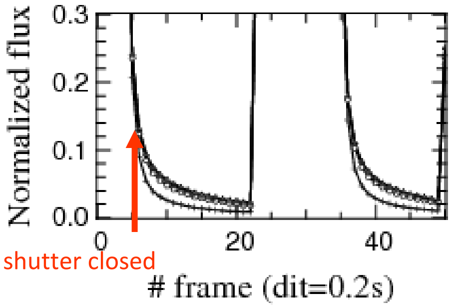
- Classical issues of IR-detector:
  - flat-field map
  - bad pixel map
- Other issues are exacerbated due to fast read-out:
  - noise structure
  - detector remanents
  - synchronizations…

Dark exposures

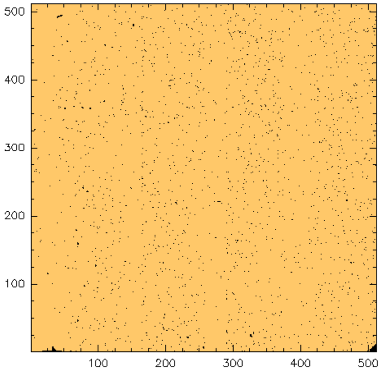


Detector fringes due to electro-magnetic interferences (Li Causi, 2007).

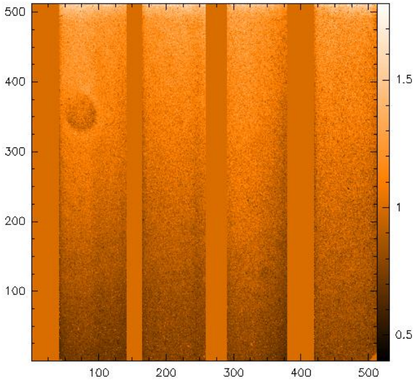
Detector remanent



Bad pixels map



Flat field map



Fringe fitting and estimation

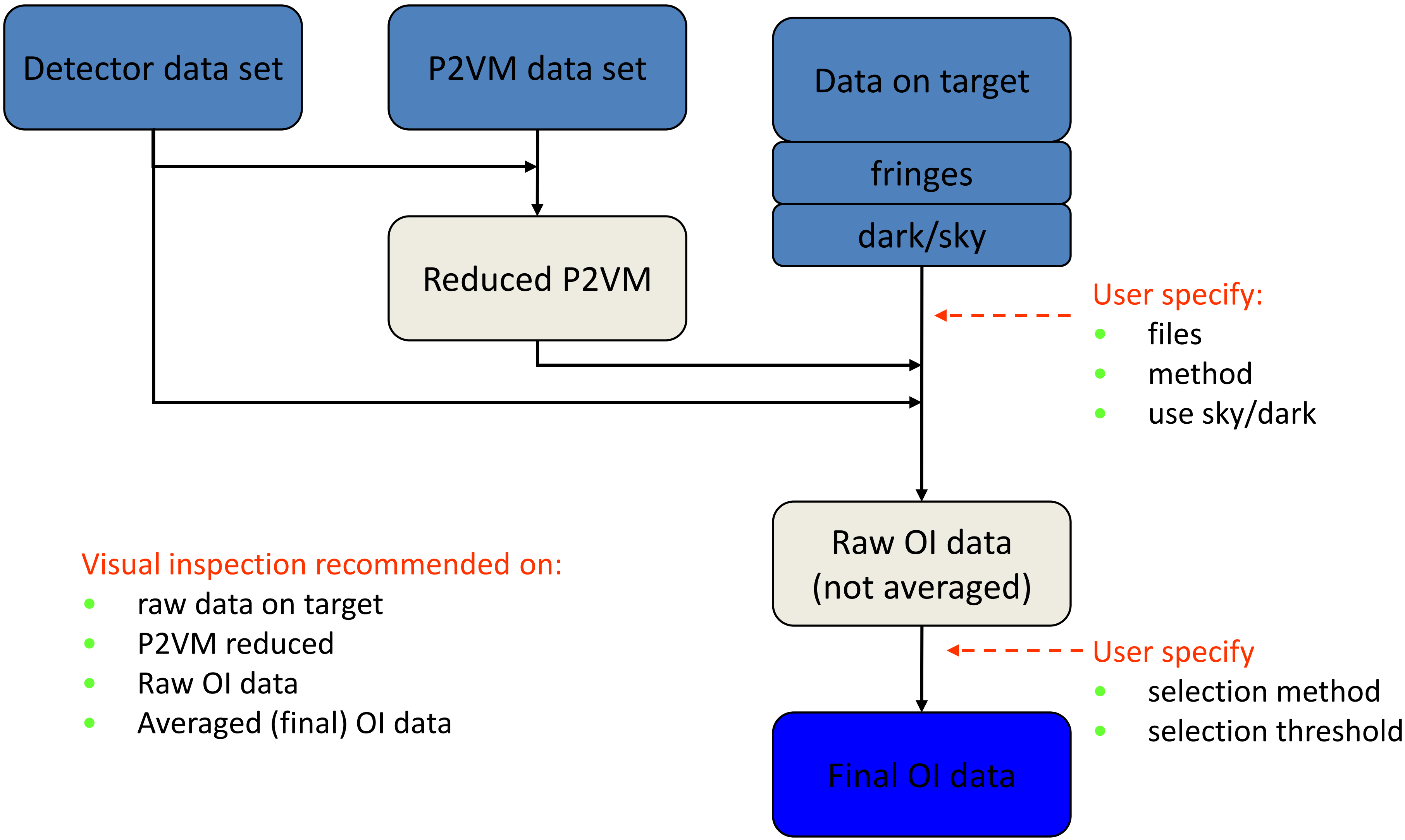
$$[\widetilde{R}^{ij}, \widetilde{I}^{ij}] = \mathrm{P2VM}[m_k]$$

where

$$\mathrm{P2VM} = [\mathrm{V2PM}^T C_M^{-1} \mathrm{V2PM}]^{-1} \mathrm{V2PM}^T C_M^{-1}$$

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

AMBER reduction work-flow



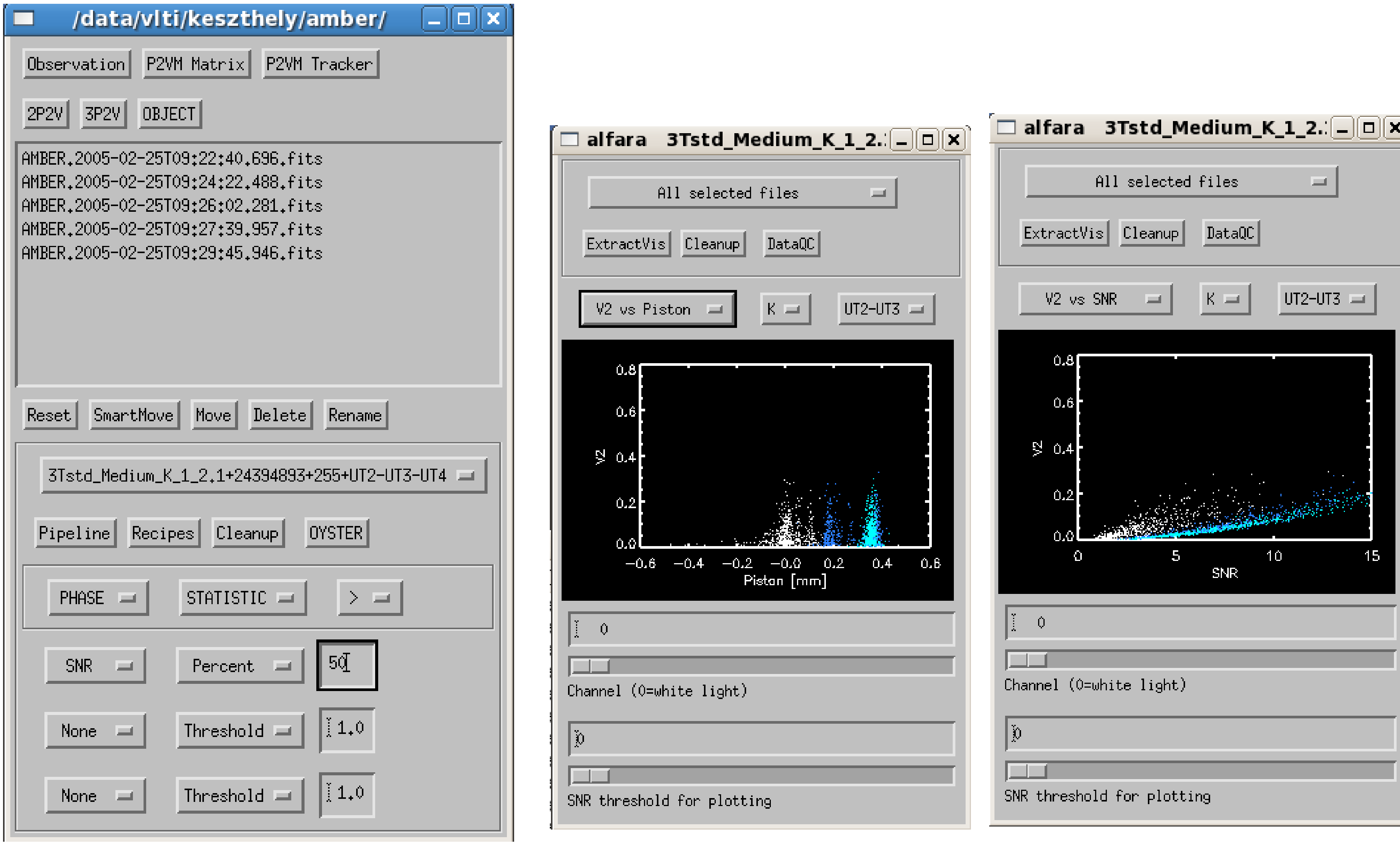
Visual inspection recommended on:

- raw data on target
- P2VM reduced
- Raw OI data
- Averaged (final) OI data

AMBER reduction with myambergui

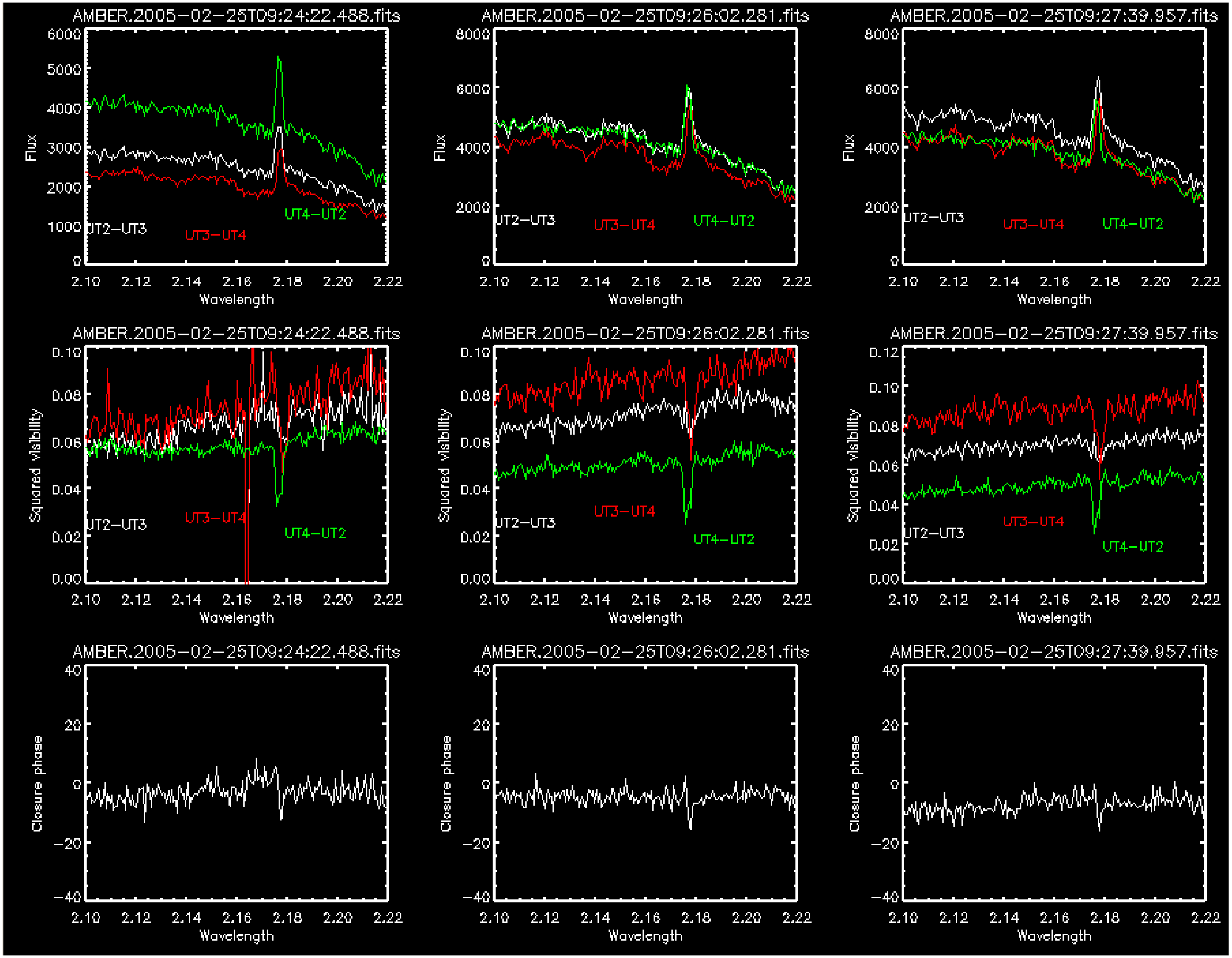
- IDL –based front-end for amdlib
- Integrated into OYSTER for pipeline processing, plotting, and modeling
- Similar to mymidigui in design and philosphy

MyAmberGui

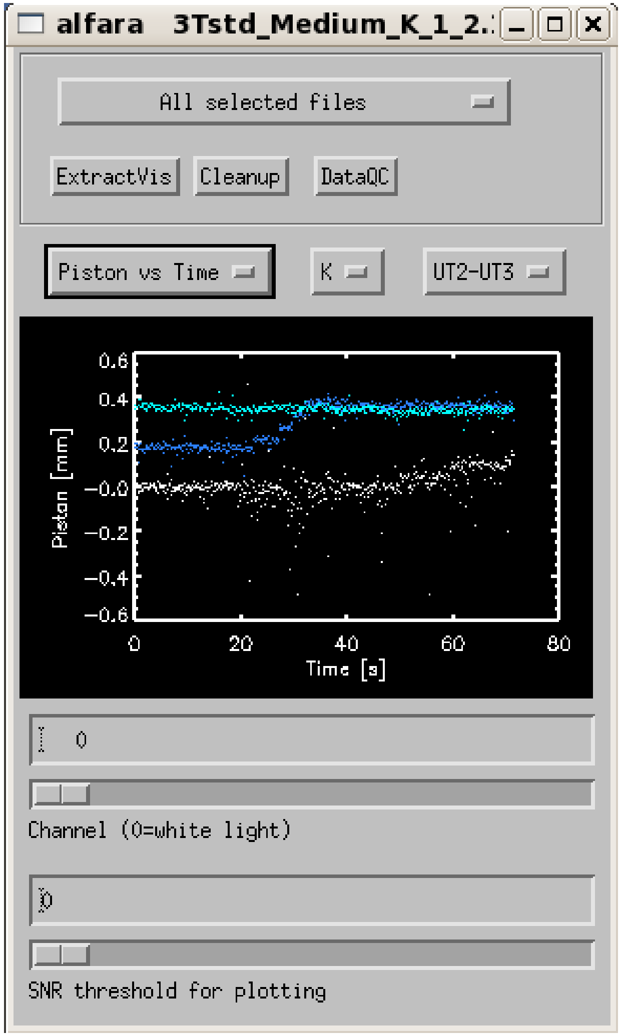


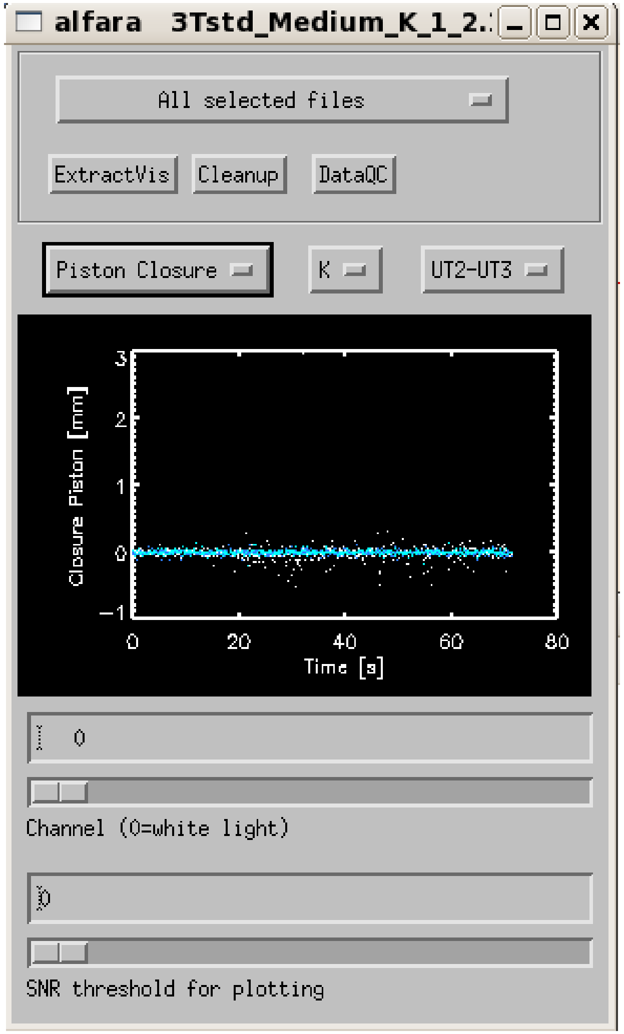
/data/vlti/keszthely/amber/
Observation
P2VM Matrix
P2VM Tracker
2P2V
3P2V
OBJECT
AMBER.2005-02-25T09:22:40.696.fits
AMBER.2005-02-25T09:24:22.488.fits
AMBER.2005-02-25T09:26:02.281.fits
AMBER.2005-02-25T09:27:39.957.fits
AMBER.2005-02-25T09:29:45.946.fits
Reset
SmartMove
Move
Delete
Rename
3Tstd_Medium_K_1_2.1+24394893+255+UT2-UT3-UT4
Pipeline
Recipes
Cleanup
OYSTER
PHASE
STATISTIC
SNR
Percent
50
None
Threshold
1.0
None
Threshold
1.0
alfara 3Tstd_Medium_K_1_2.
All selected files
ExtractVis
Cleanup
DataQC
V2 vs Piston
K
UT2-UT3
V2
Piston [mm]
0
Channel (0=white light)
0
SNR threshold for plotting
alfara 3Tstd_Medium_K_1_2.
All selected files
ExtractVis
Cleanup
DataQC
V2 vs SNR
K
UT2-UT3
V2
SNR
0
Channel (0=white light)
0
SNR threshold for plotting

Quick-look data QC

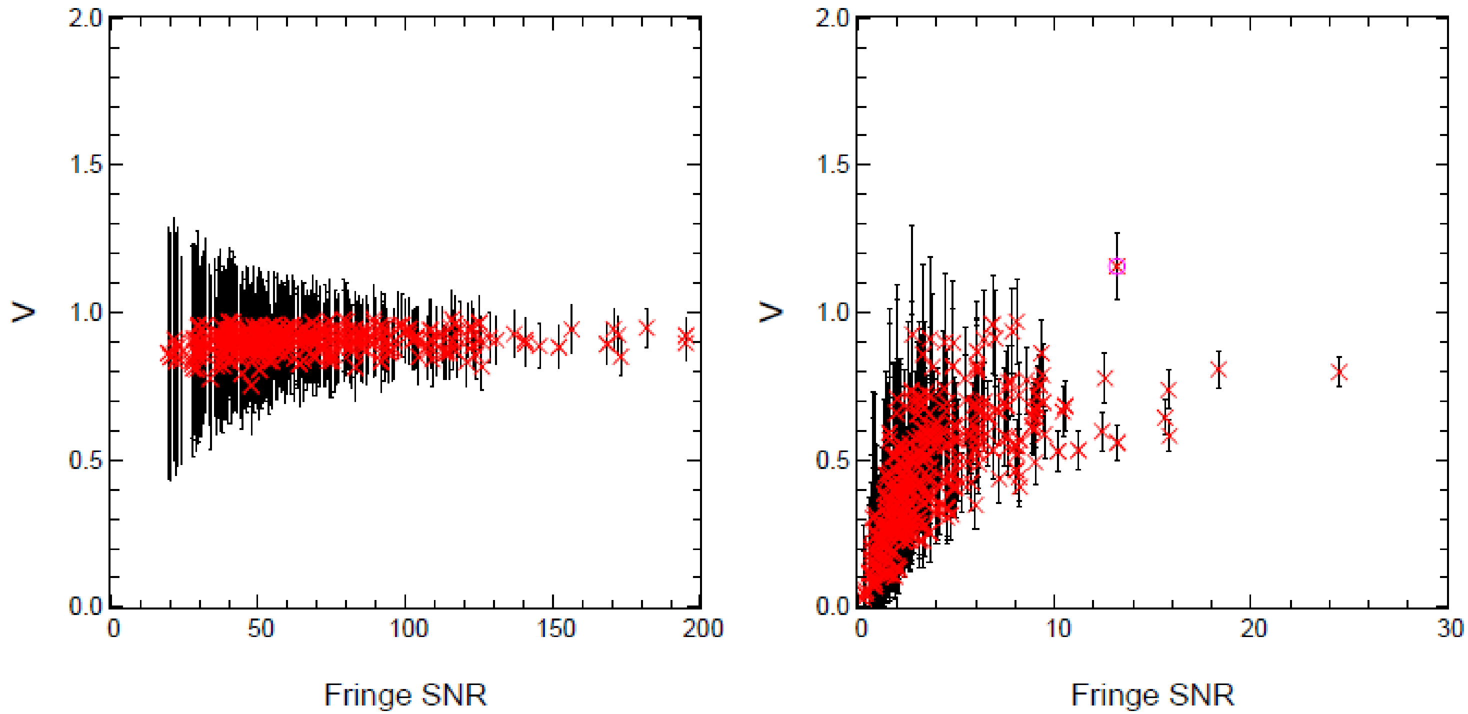


More frame result statistics…



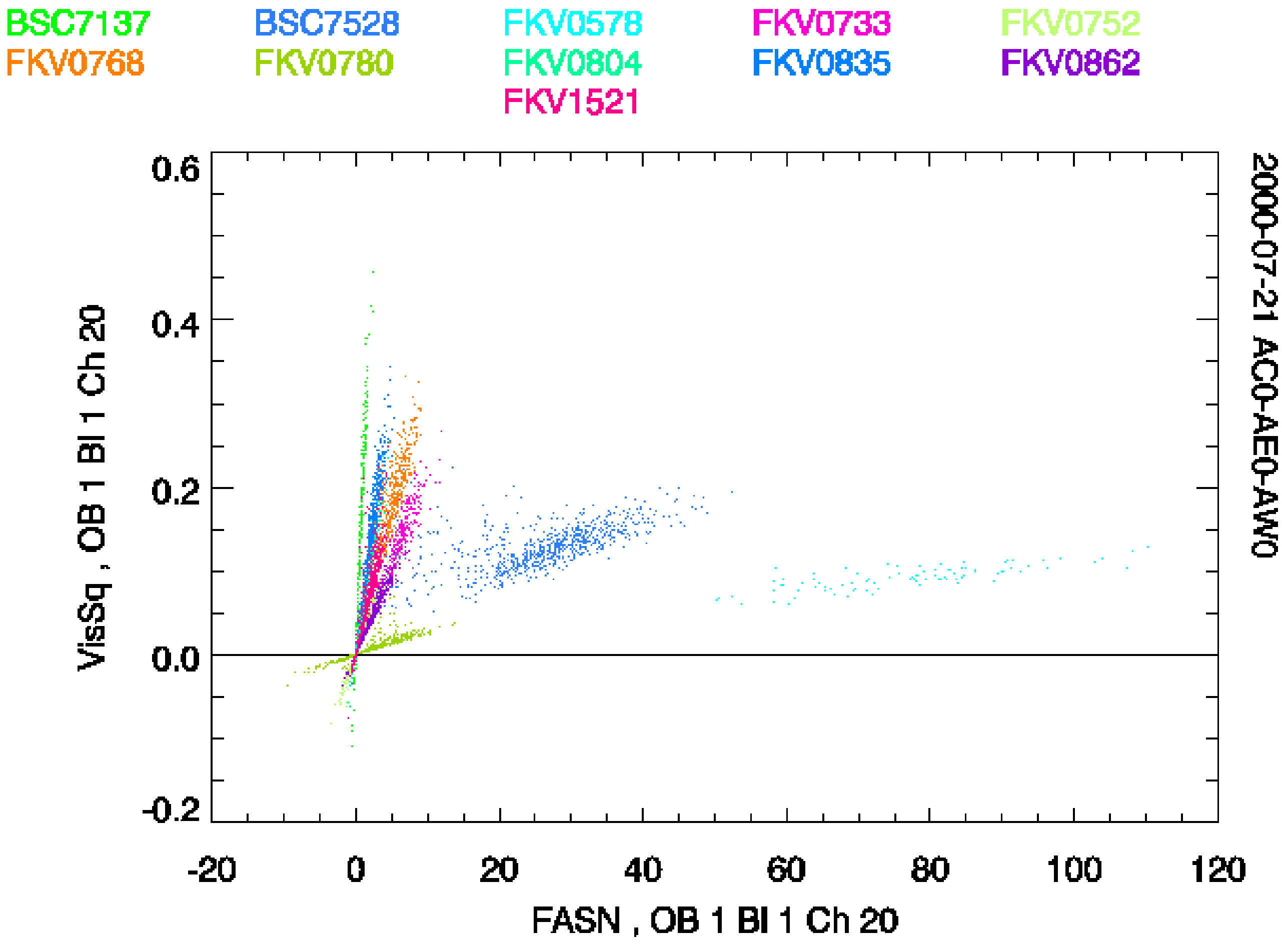


Fringe SNR

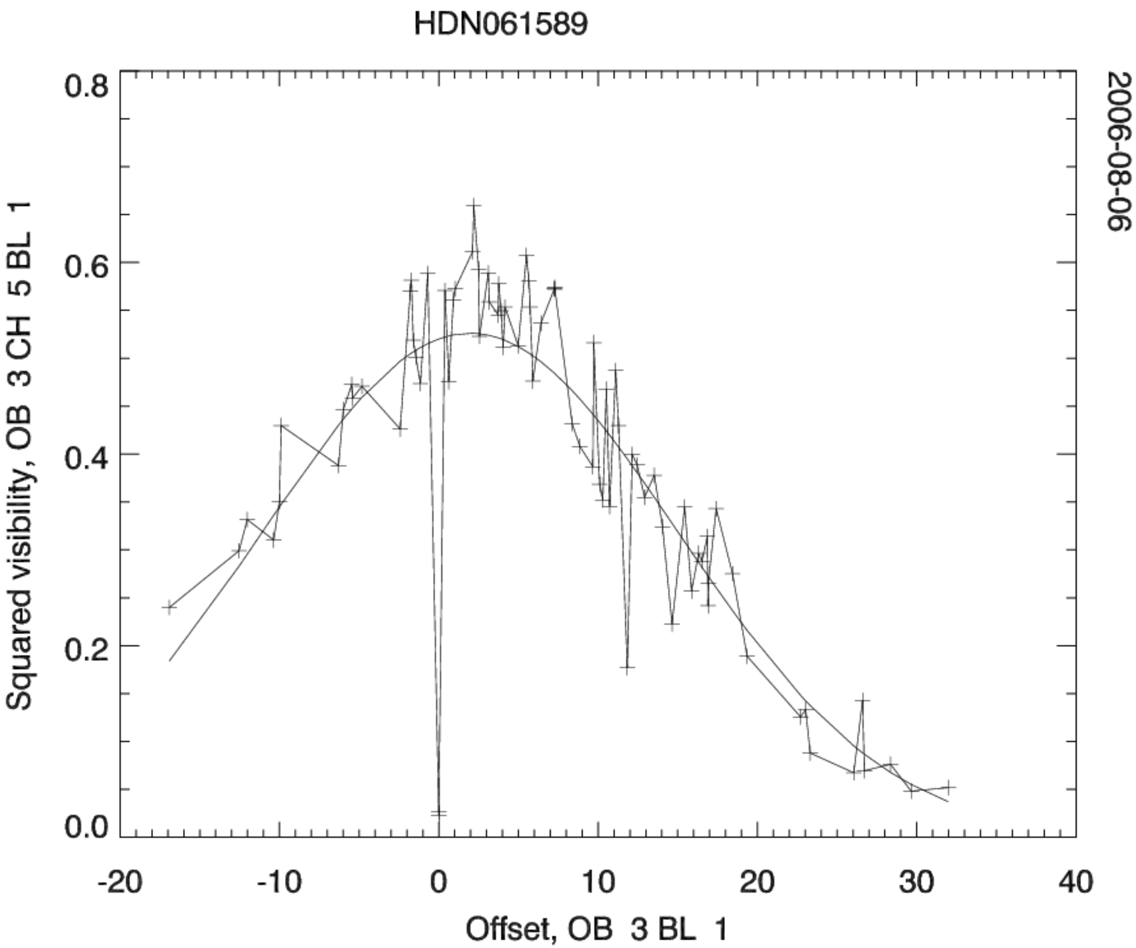


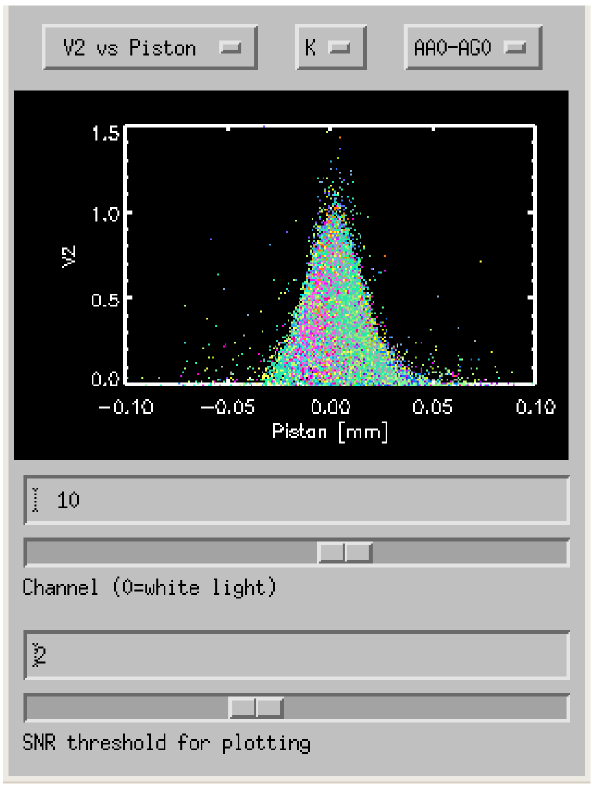
$$\mathrm{SNR}^2(t) = \frac{1}{N_b}\frac{1}{N_l}\sum_{b}^{N_b}\sum_{l}^{N_l}\left[\left(\frac{R^{b^2}(l,t)}{\sigma^2_{R^b}} - 1\right) + \left(\frac{I^{b^2}(l,t)}{\sigma^2_{I^b}} - 1\right)\right]$$

NPOI fringe SNR



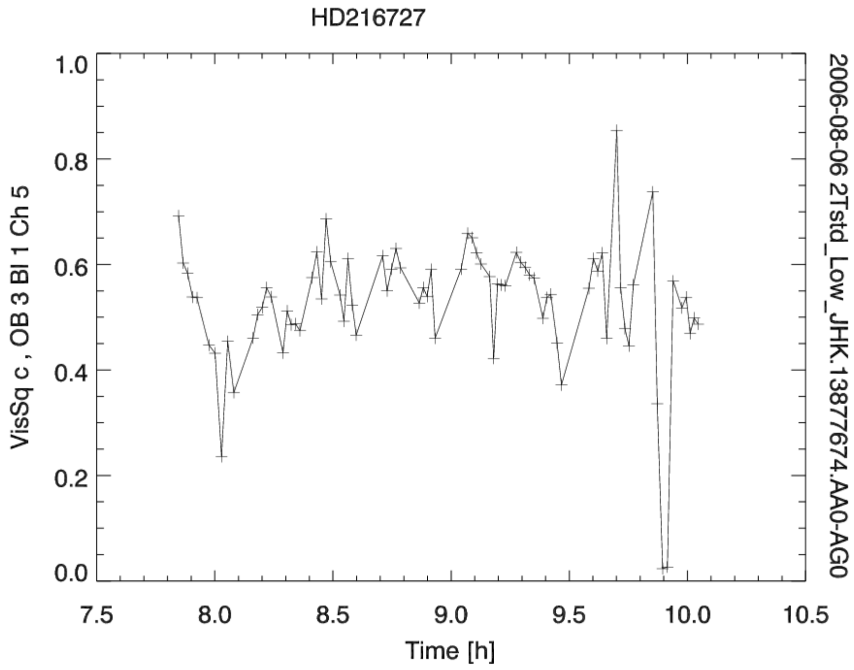
Piston bias


HDN061589
2006-08-06
Squared visibility, OB 3 CH 5 BL 1
Offset, OB 3 BL 1
0.8
0.6
0.4
0.2
0.0
-20
-10
0
10
20
30
40

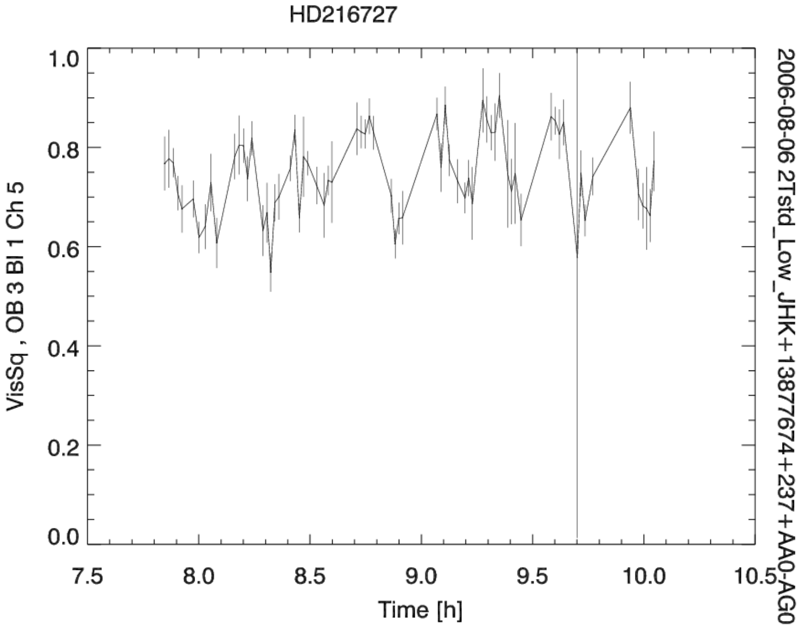

V2 vs Piston
K
AA0-AG0
1.5
1.0
0.5
0.0
V2
−0.10
−0.05
0.00
0.05
0.10
Piston [mm]
10
Channel (0=white light)
2
SNR threshold for plotting

Piston bias correction

Using Gaussian fit

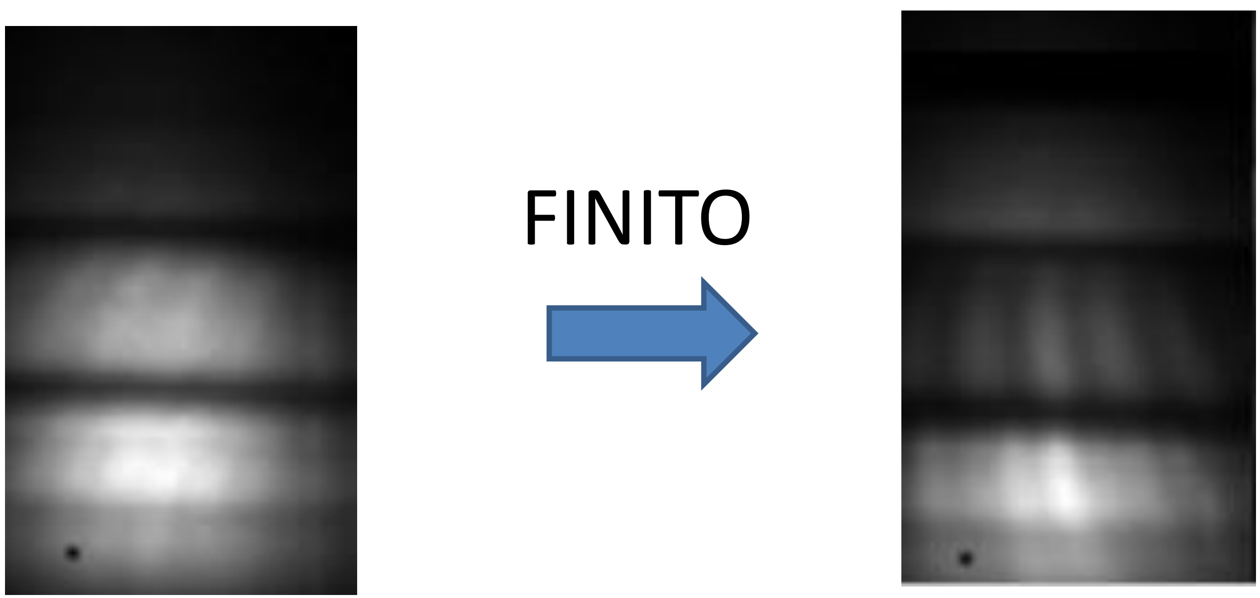


Using only piston < 8 micron

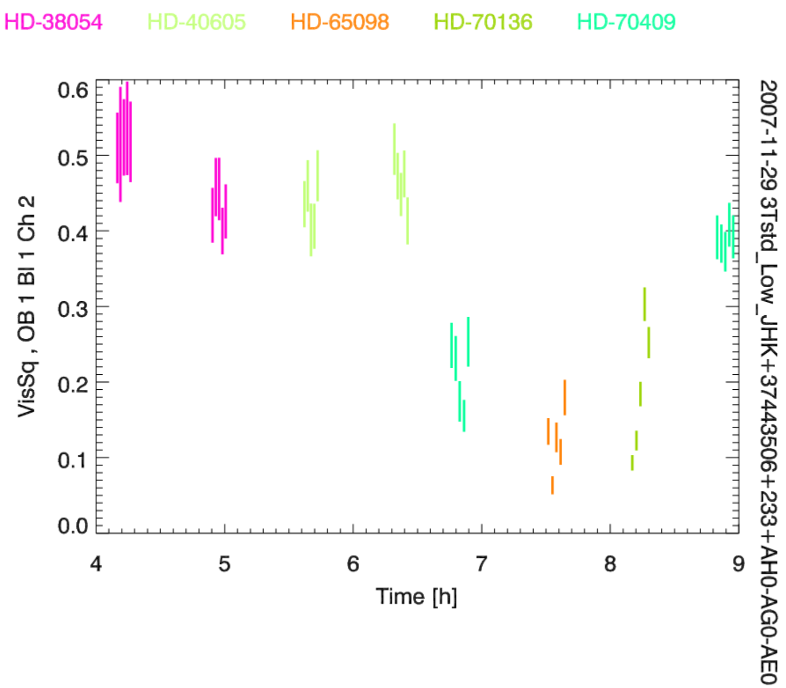


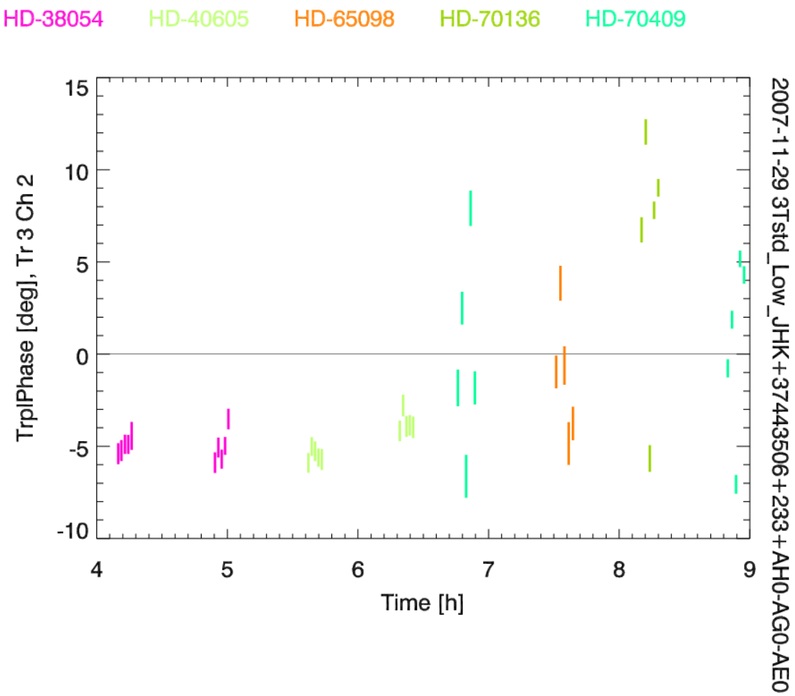
FINITO fringe tracker

- Stabilizes fringe for on-chip integration for up to 12 s
- Example: 50 s (!) integration time



Amplitudes and phases with FINITO





Summary

- For AMBER, a bit still to be done
  - e.g. LR visibility reduction due to piston
- FINITO can stabilize AMBER visibilities
  - longer integration times, full frame read-out
- Not discussed: internal dispersion and differential phase issues
  - important for astrometry