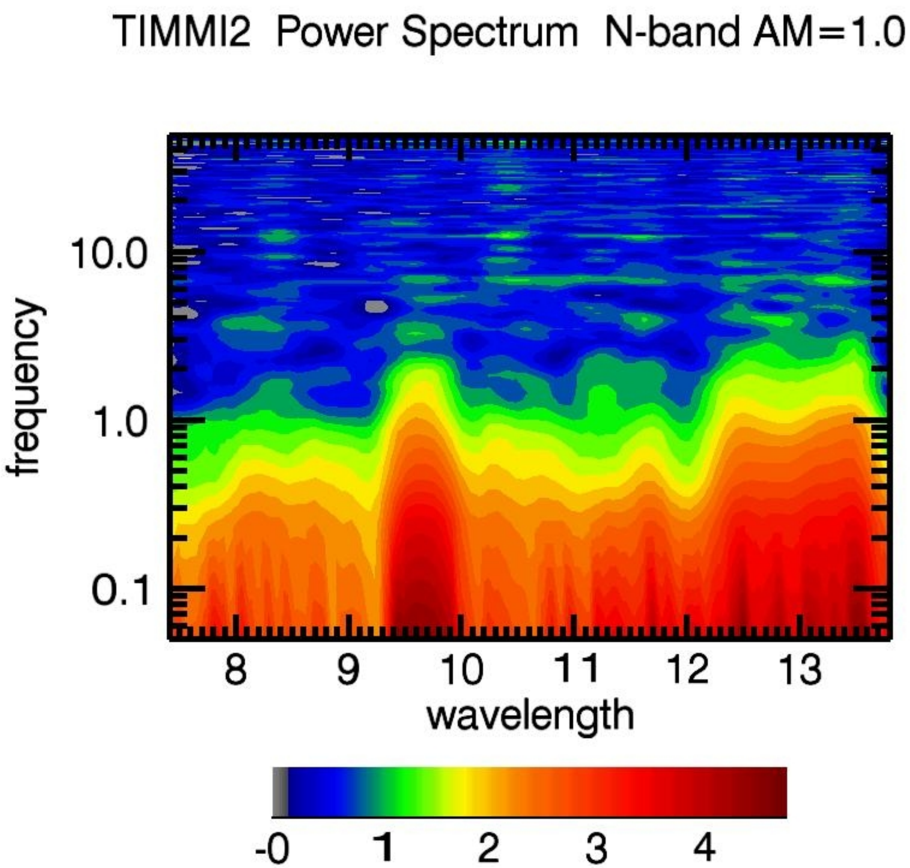
VLTI data reduction and image reconstruction

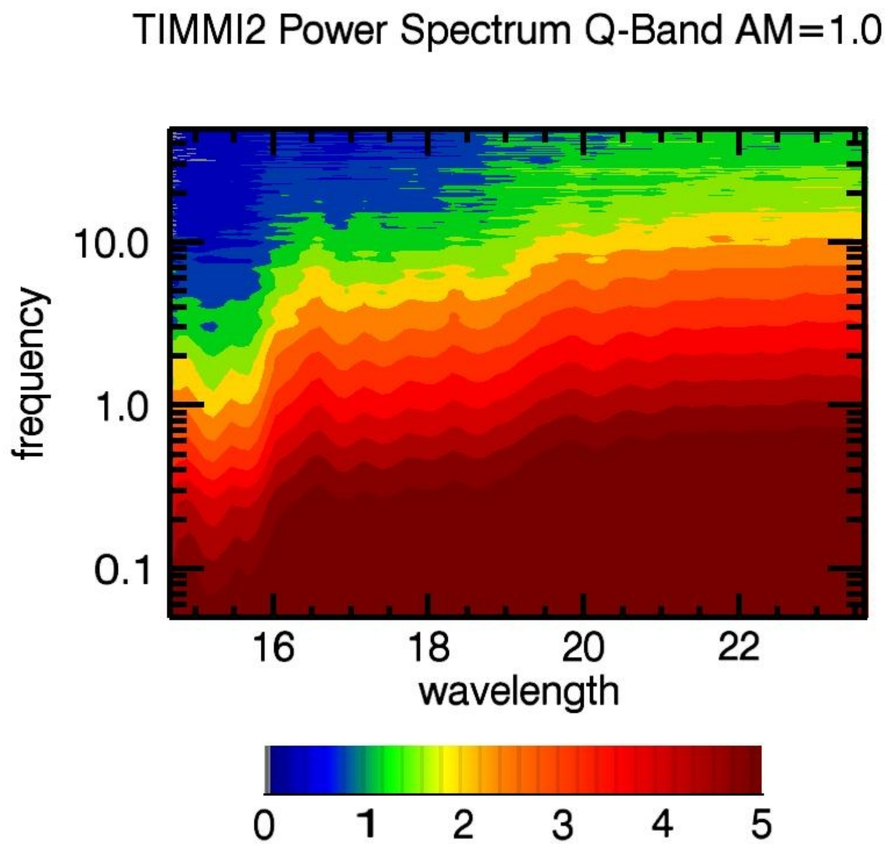
Christian Hummel (ESO)

Overview

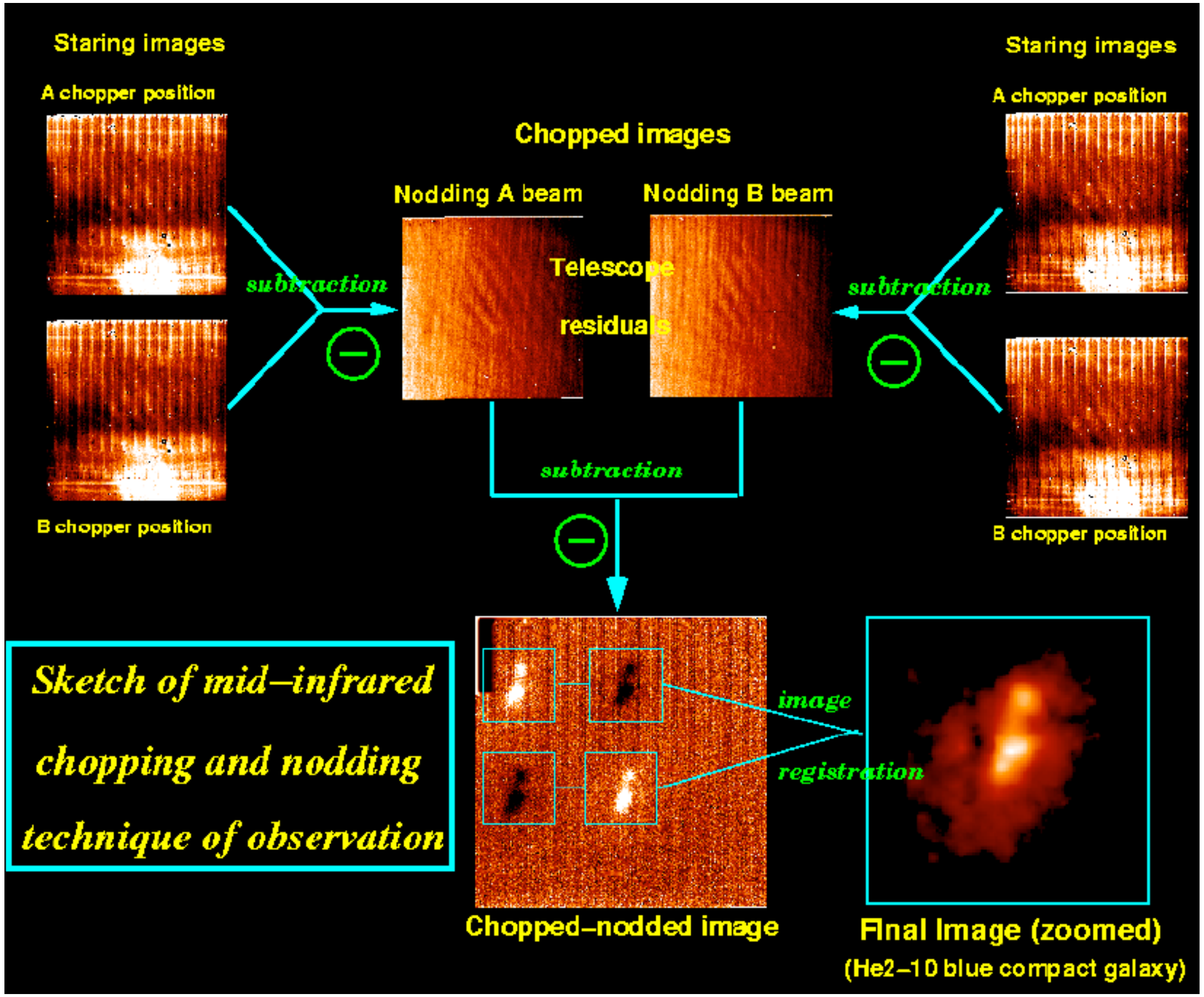
- Mid-infrared: MIDI
- Near-infrared: AMBER
- Imaging

Mid-infrared background

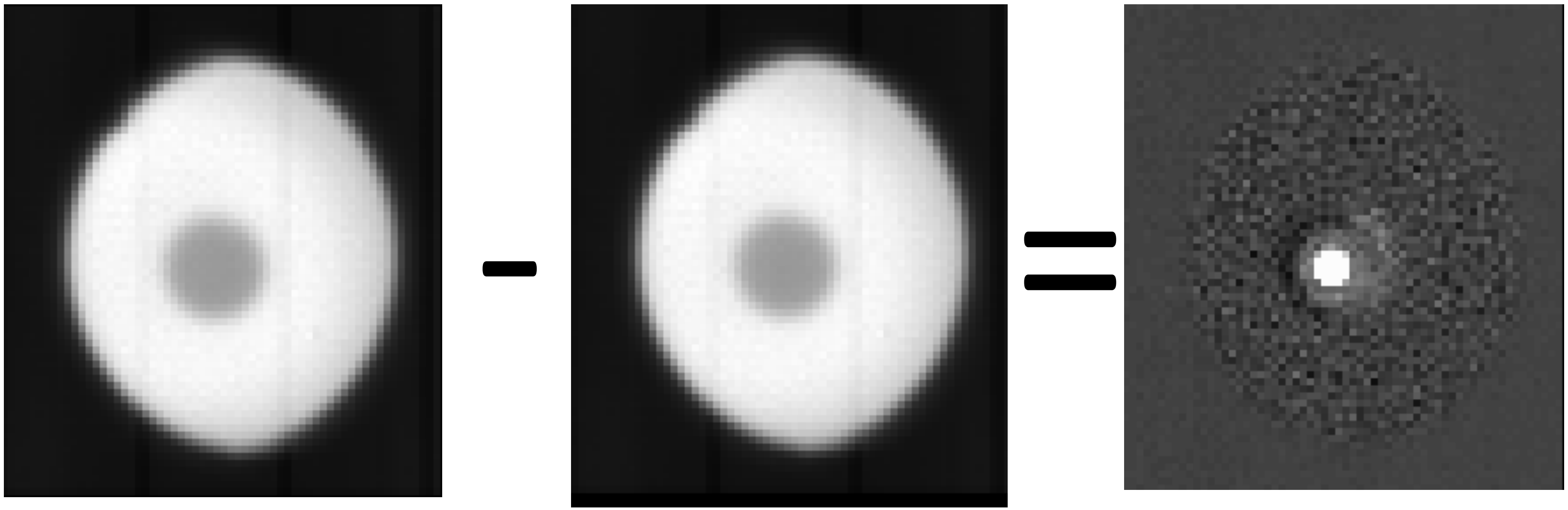




Observing in the mid-infrared

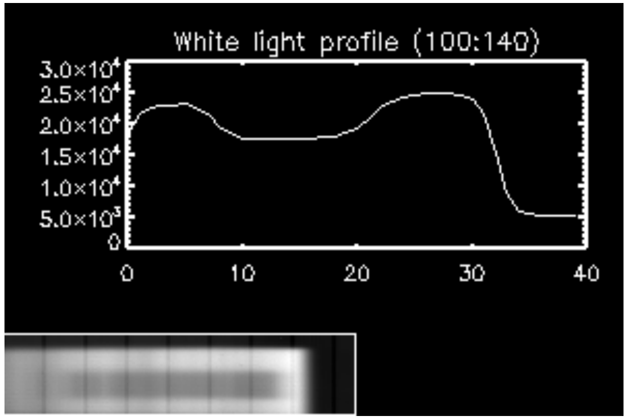


Acquisition



ON **OFF**

Photometry



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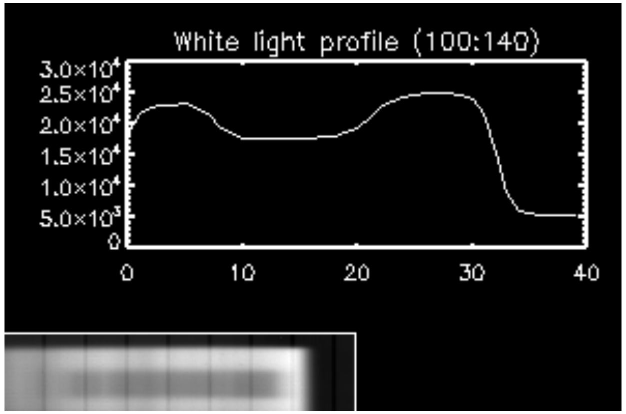
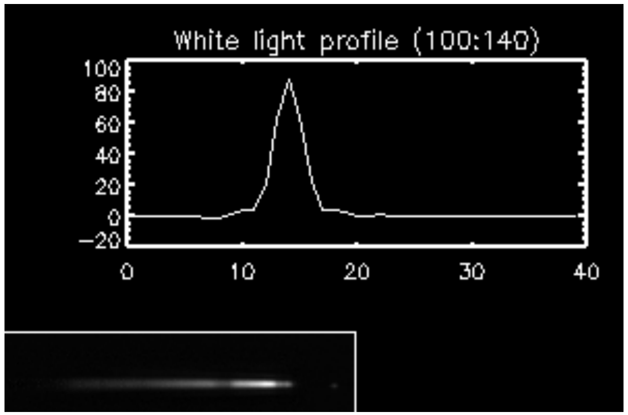


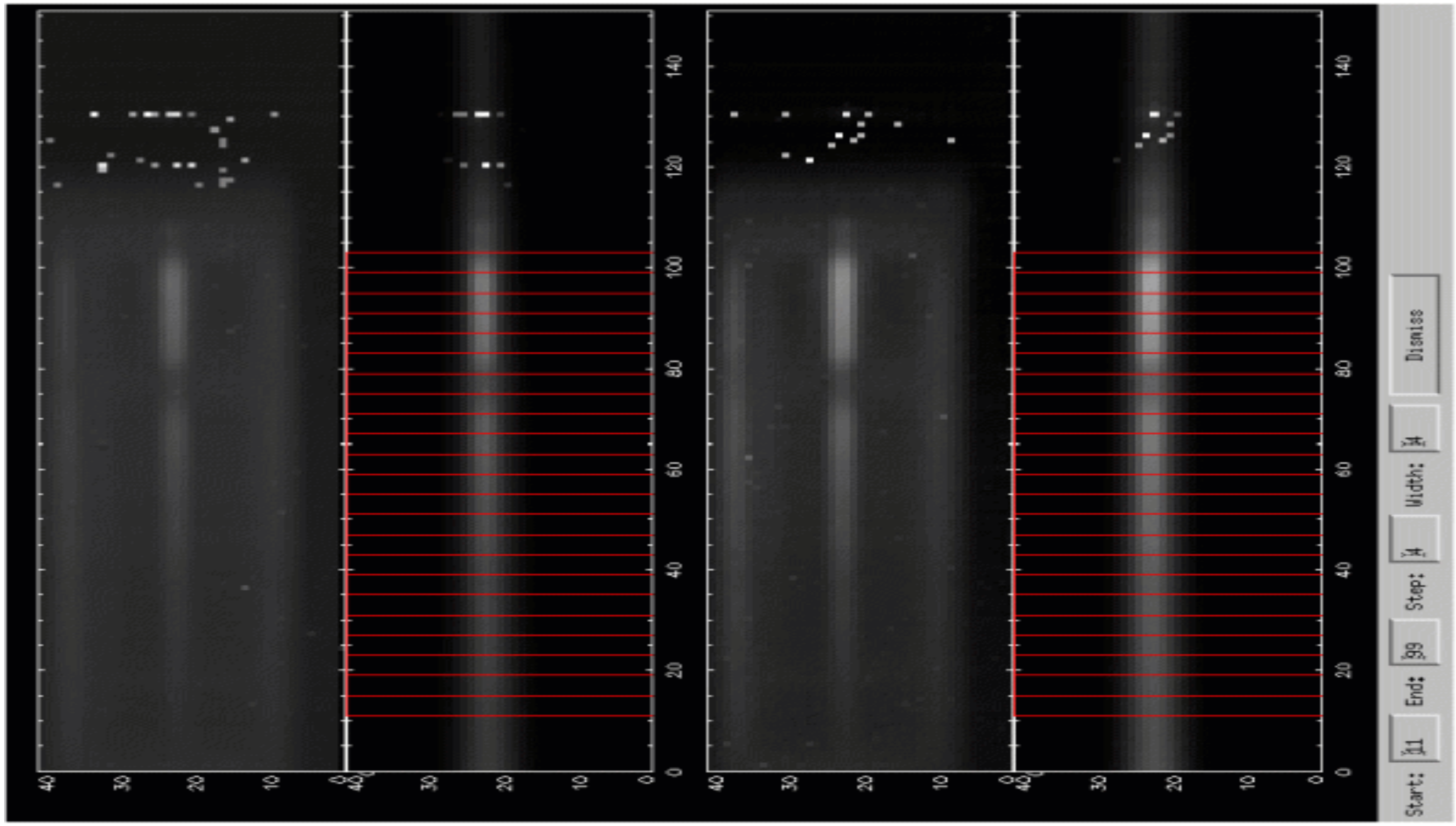
ON

OFF

=

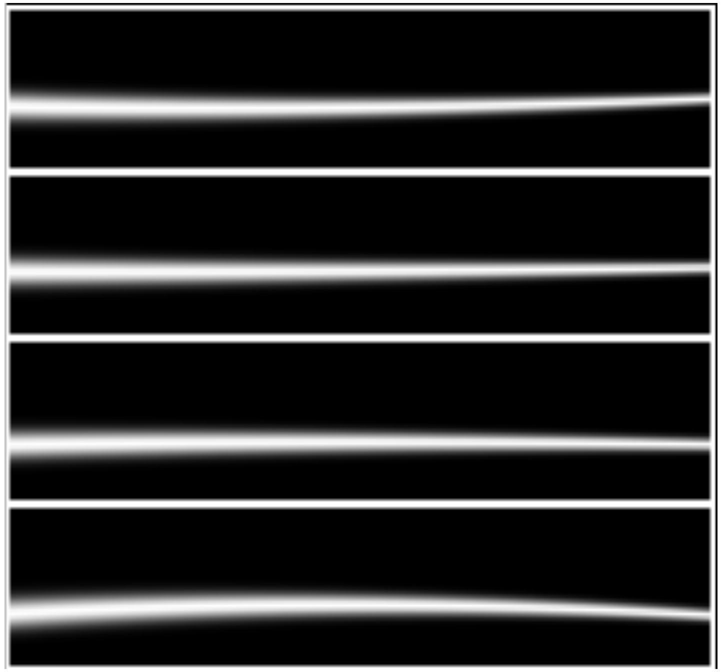


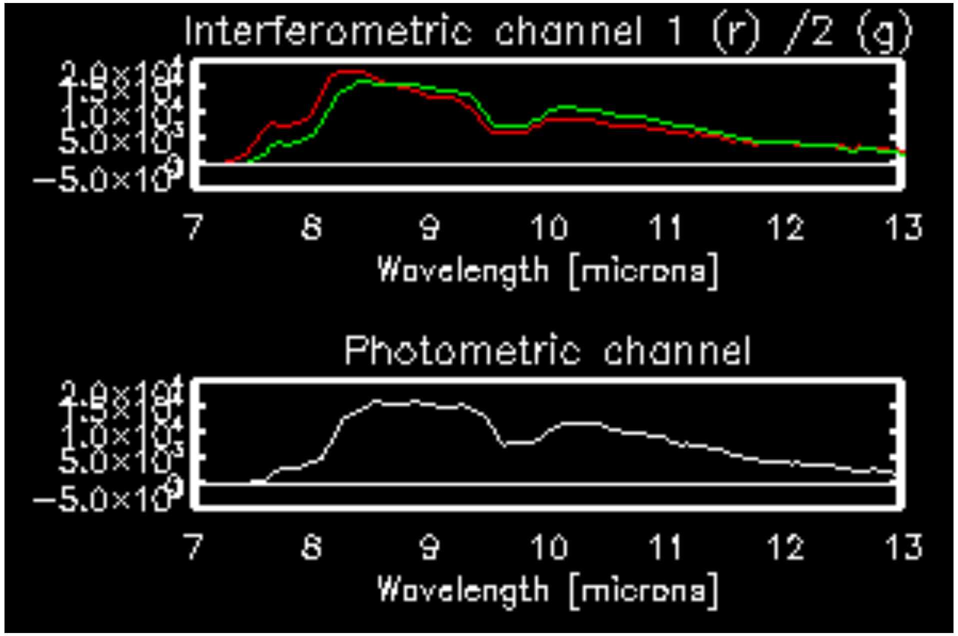
Wavelength binning



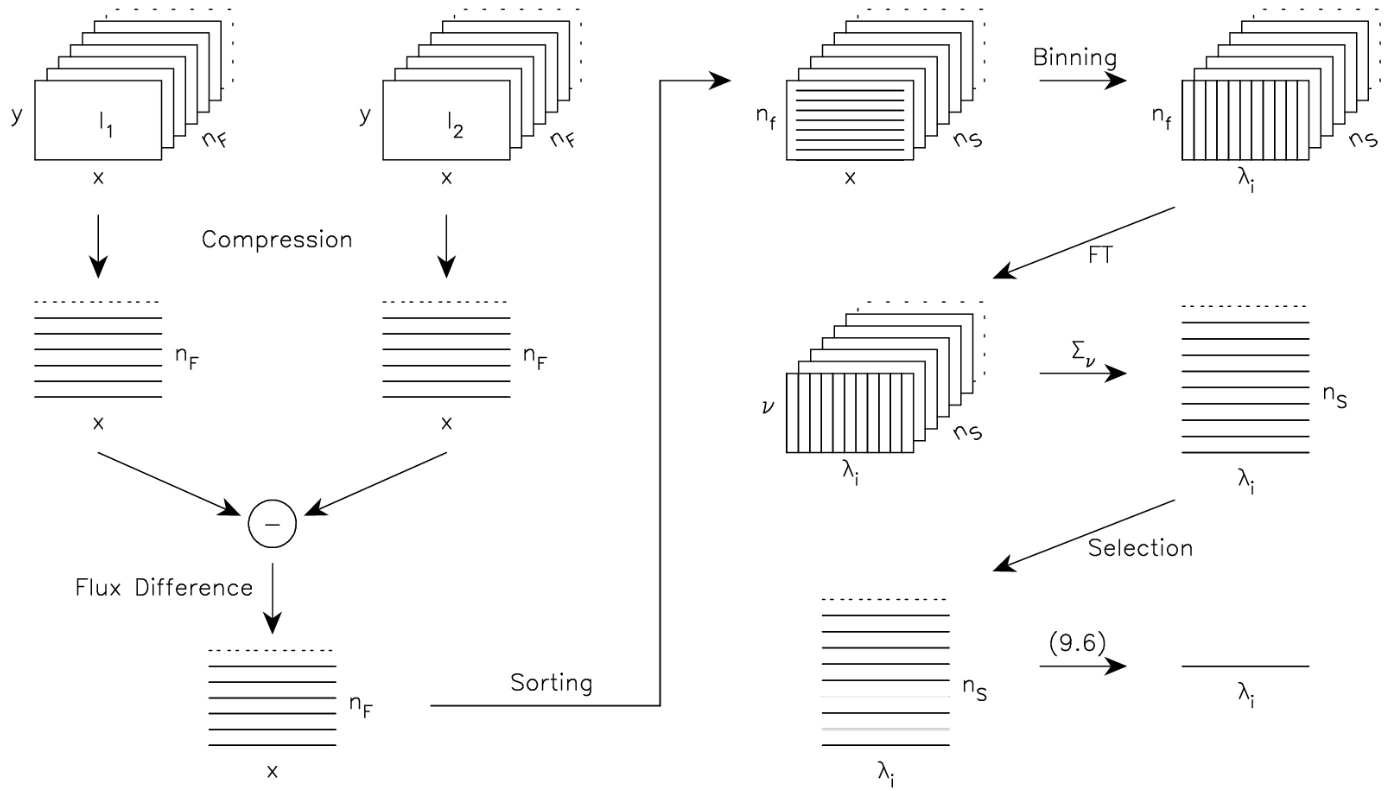
Spectrum extraction

PA
I1
I2
PB



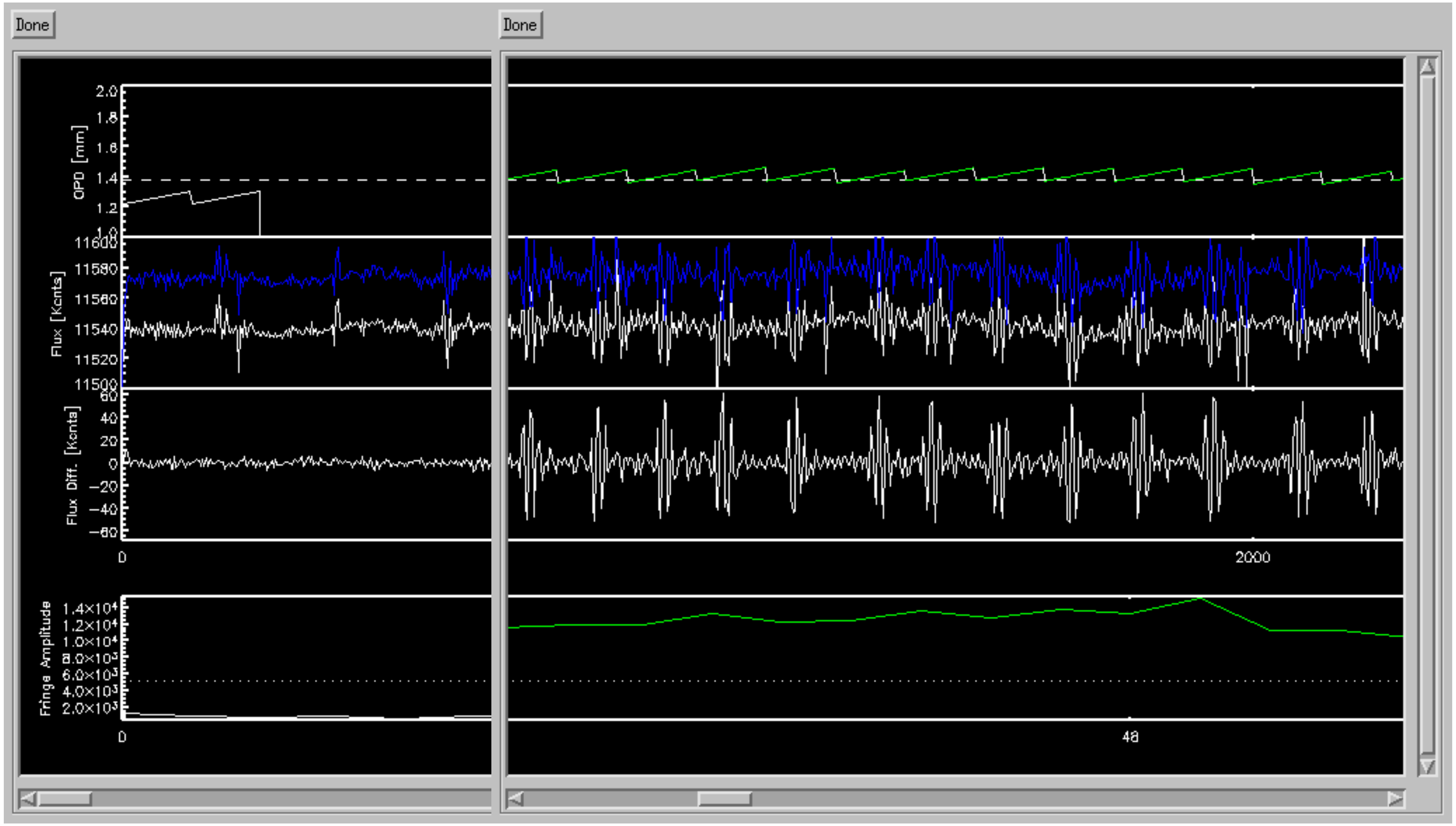


Interferometry

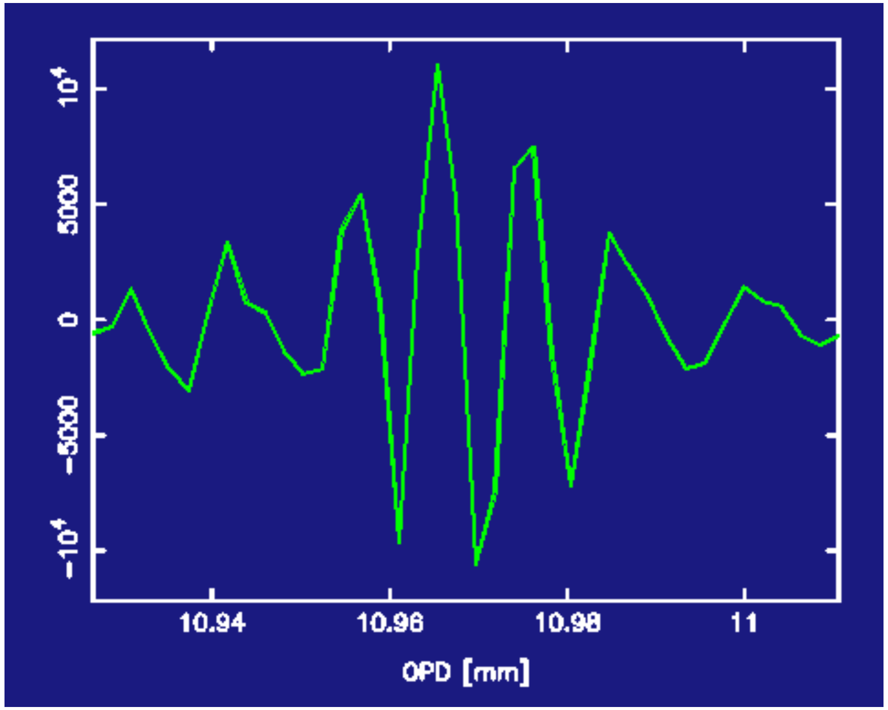


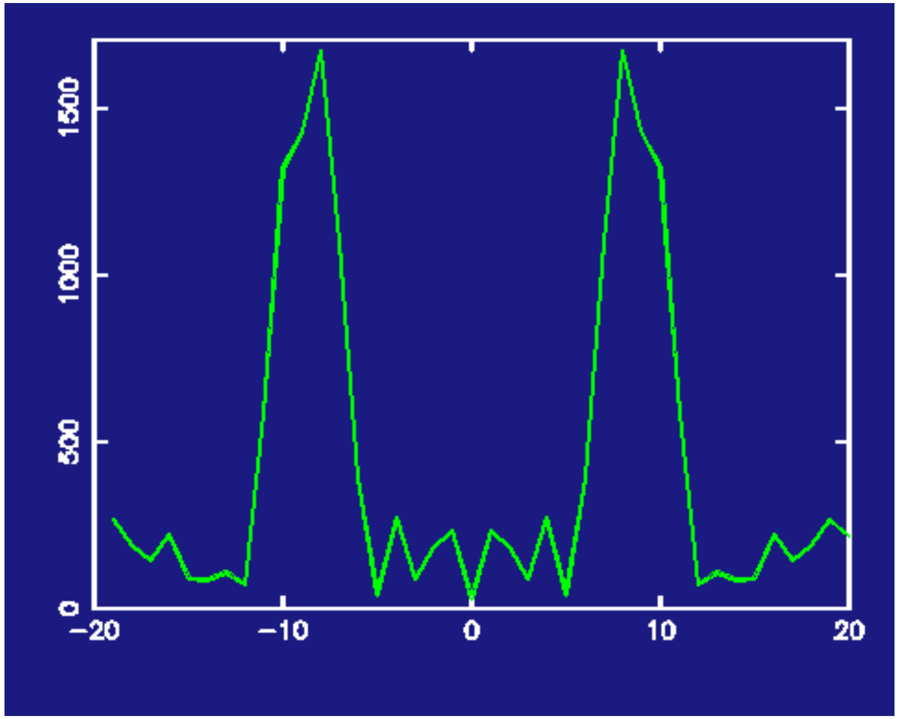
n_F = total number of frames; n_f = number of frames per scan; n_S = number of scans

Interferograms (white light)



Fourier transform

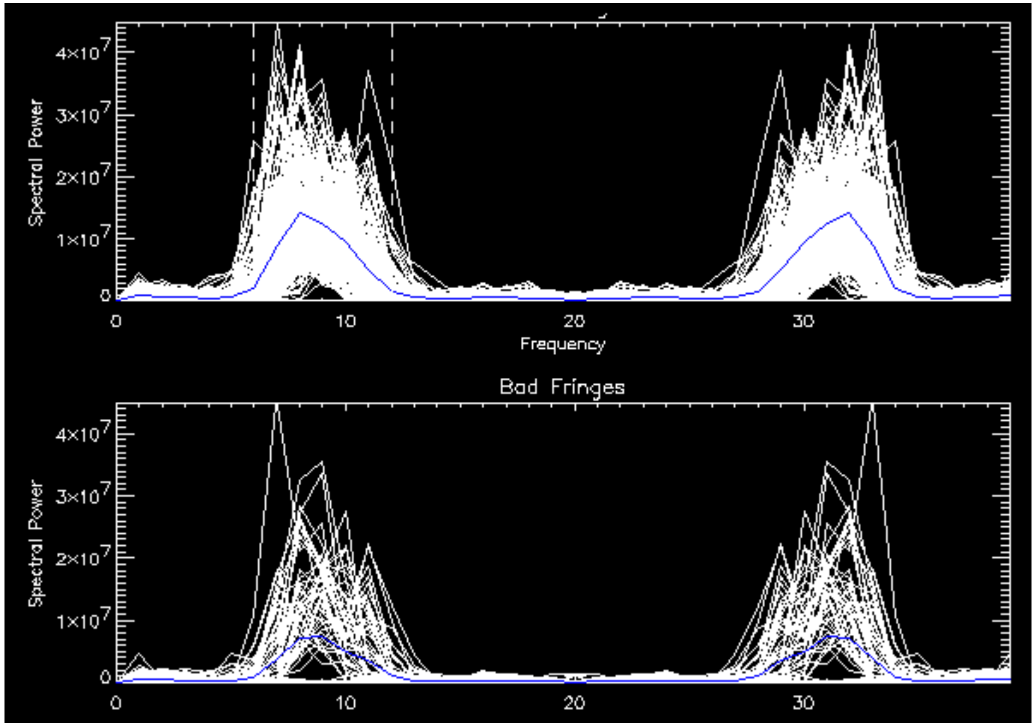


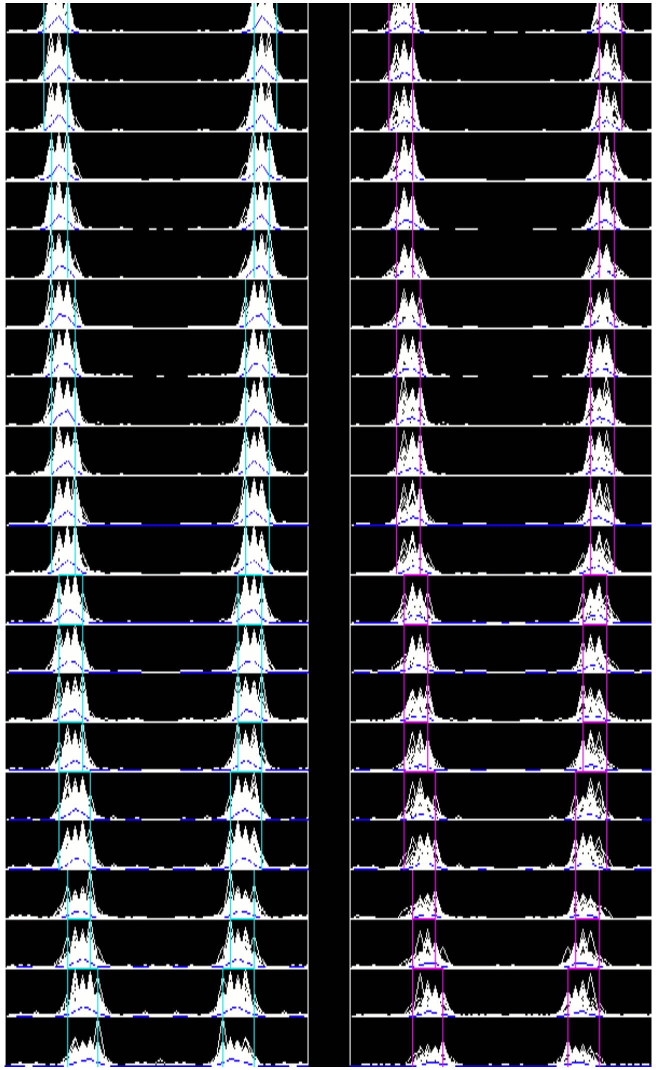


Interferogram = f(OPD)

Powerspectrum = f(v)

Dispersed fringes





Correlated flux normalization

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

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

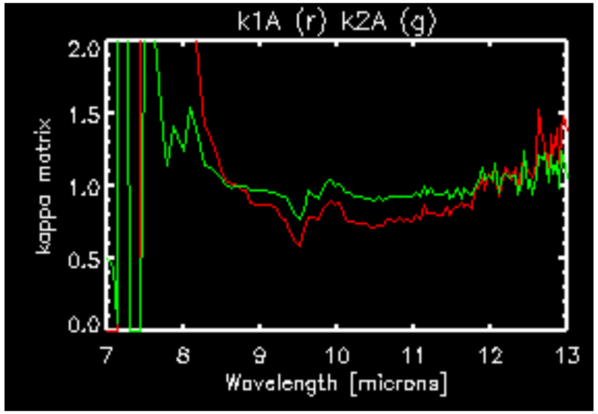
Interferogram in one MIDI channel:

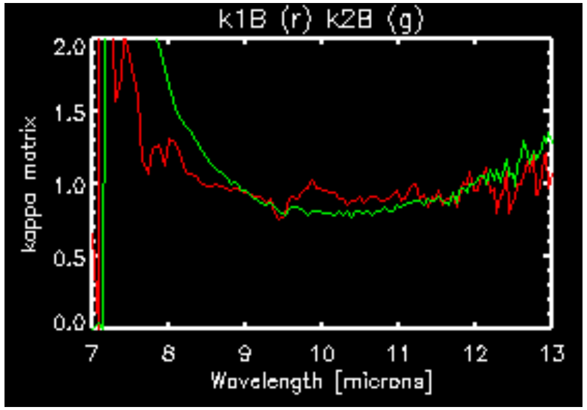
$$I_1 = I_{\mathrm{A},1} + I_{\mathrm{B},1} + (1/2)(I_1^{\mathrm{max}} - I_1^{\mathrm{min}})\sin(2\pi OPD/\lambda)$$

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

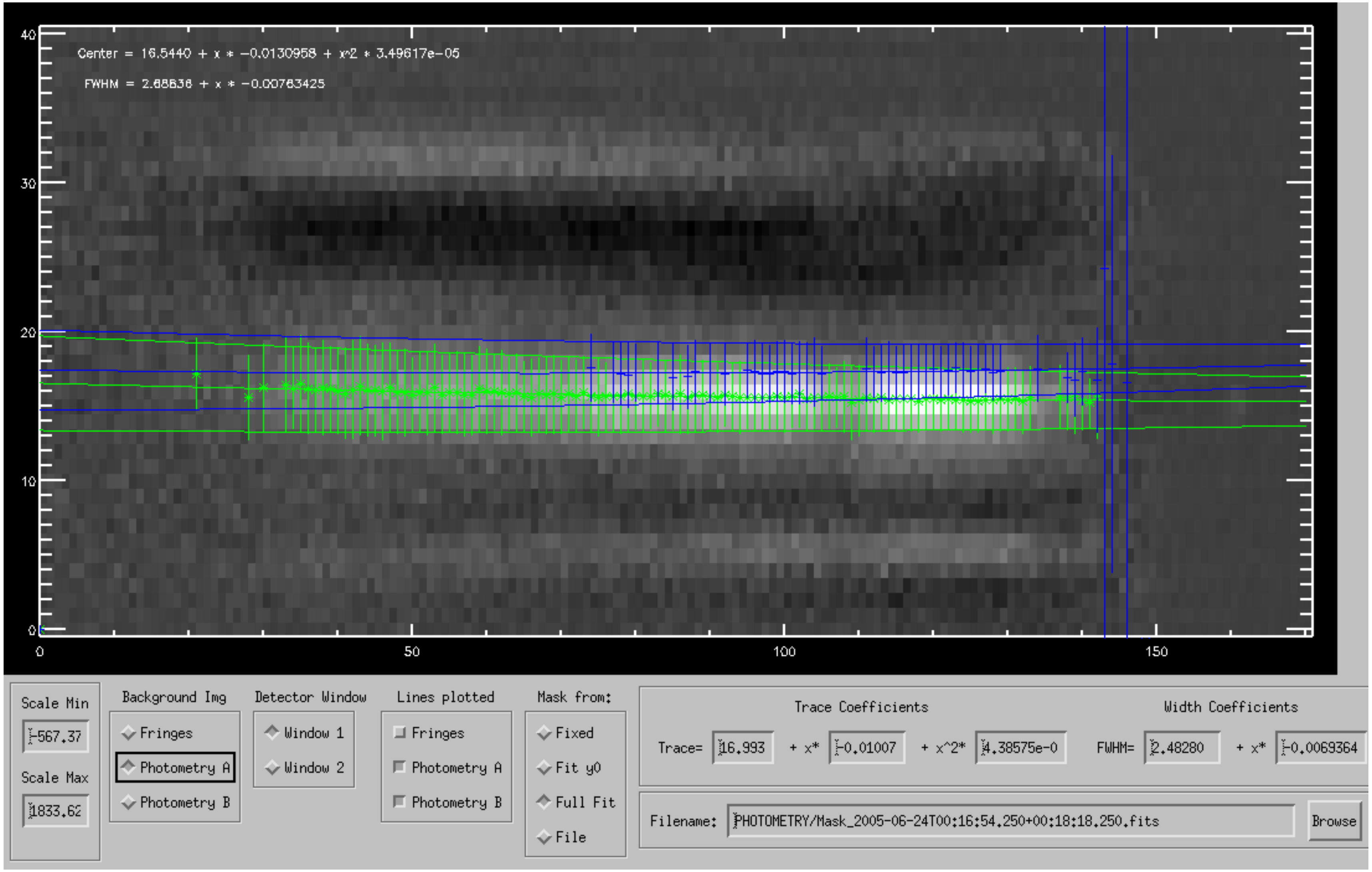
Kappa matrix





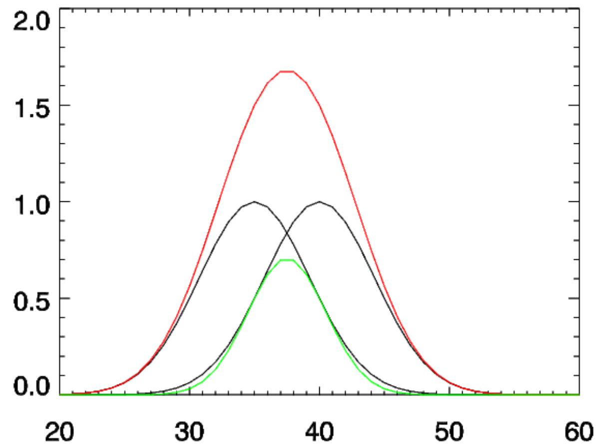
$\kappa_{1,\mathrm{A}} = I_1/(I_1 + I_2),\ \kappa_{2,\mathrm{A}} = I_2/(I_1 + I_2),$ and so forth…

Beam overlap problems



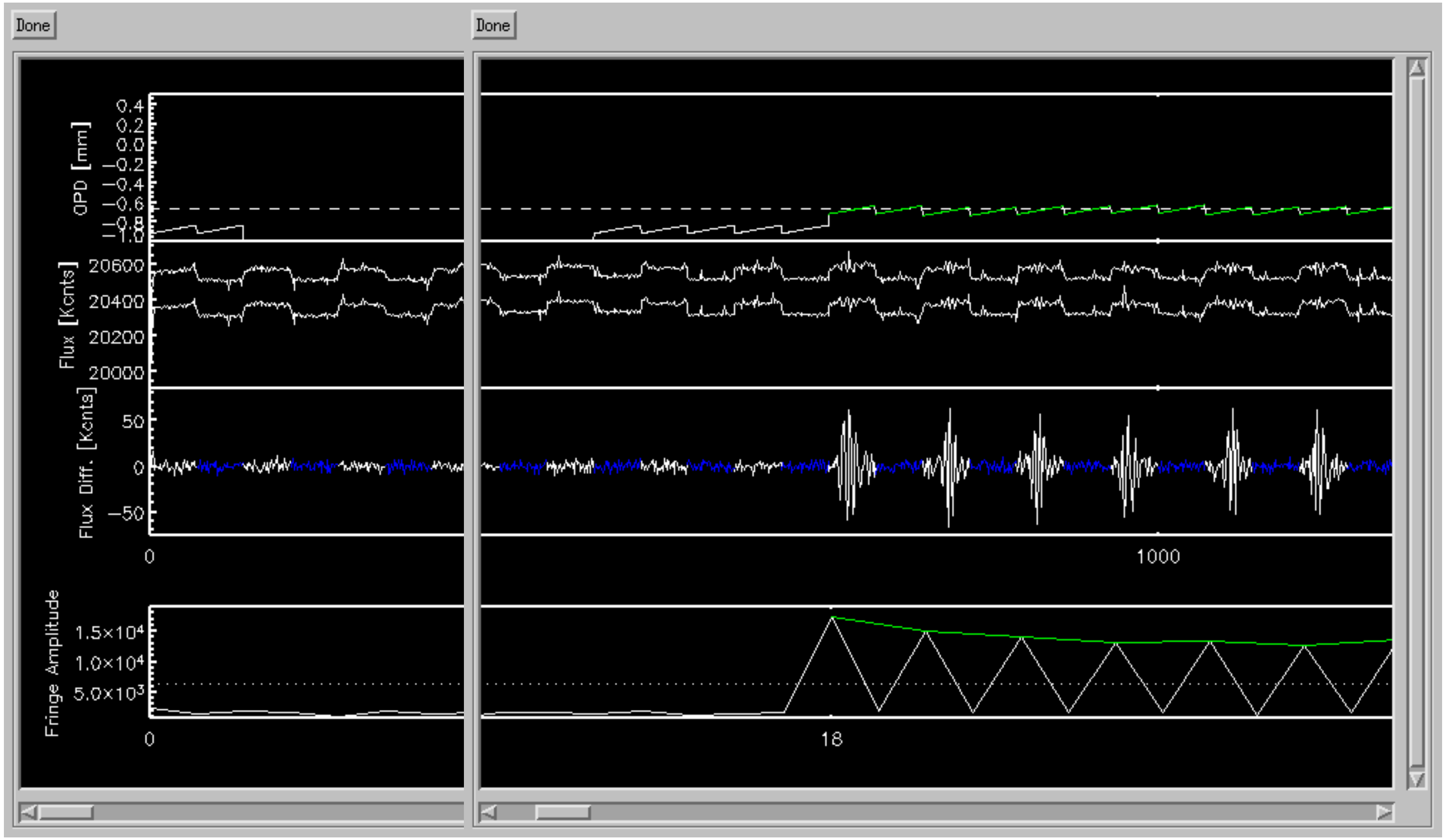
Multiply, then mask…

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



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

SCI_PHOT

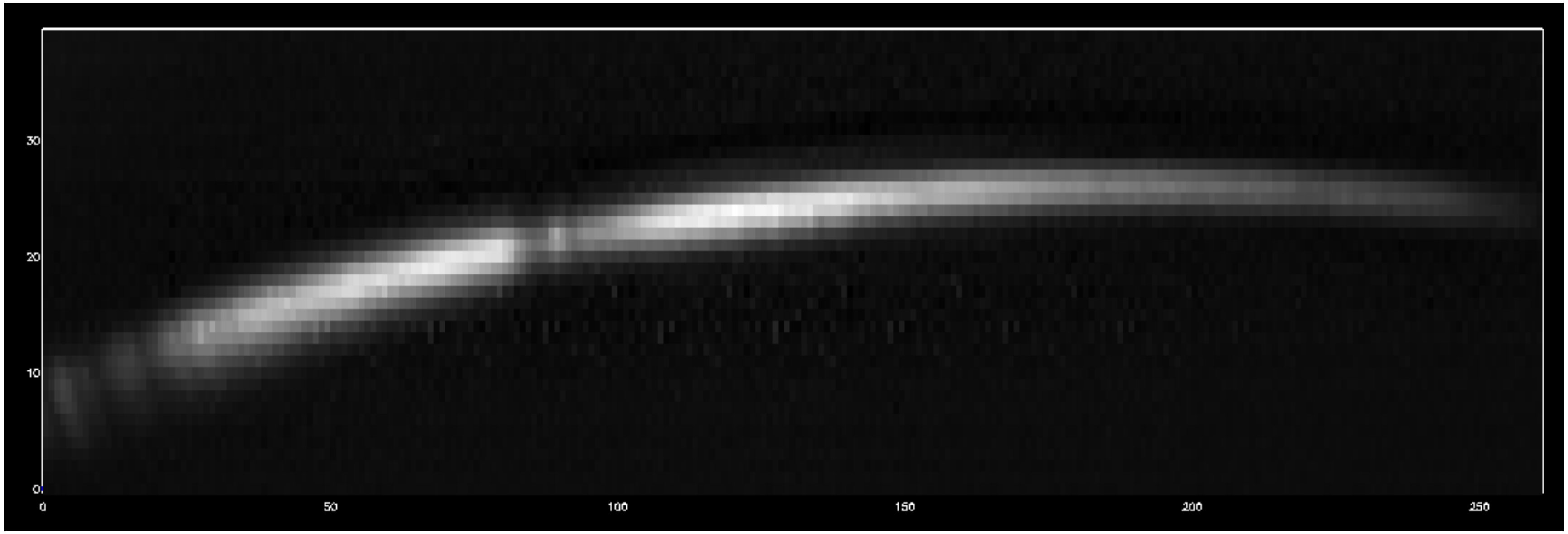

Done
Done
OPD [mm]
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
Flux [Kcnts]
20600
20400
20200
20000
Flux Diff. [Kcnts]
50
0
−50
0
1000
Fringe Amplitude
1.5×10⁴
1.0×10⁴
5.0×10³
0
18

HIGH_SENS versus SCI_PHOT

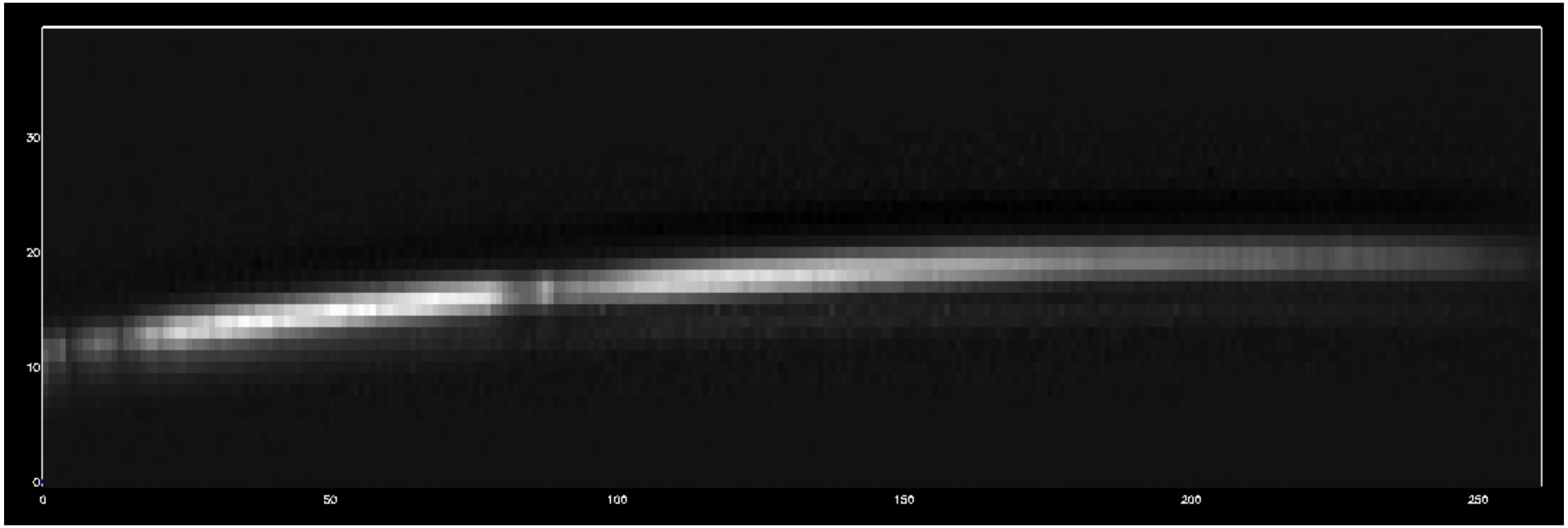
- Photometry recorded simultaneously with the fringe data (must be chopping). Use kappa matrix to convert $P_{A,B}$ into $I_{1,2}$.
- Changes in beam overlap will simultaneously affect all extracted fluxes, thus will divide out.
- Kappa matrix can be determined from A and B photometry (needs only to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

Optical distortion

P_B



I_1



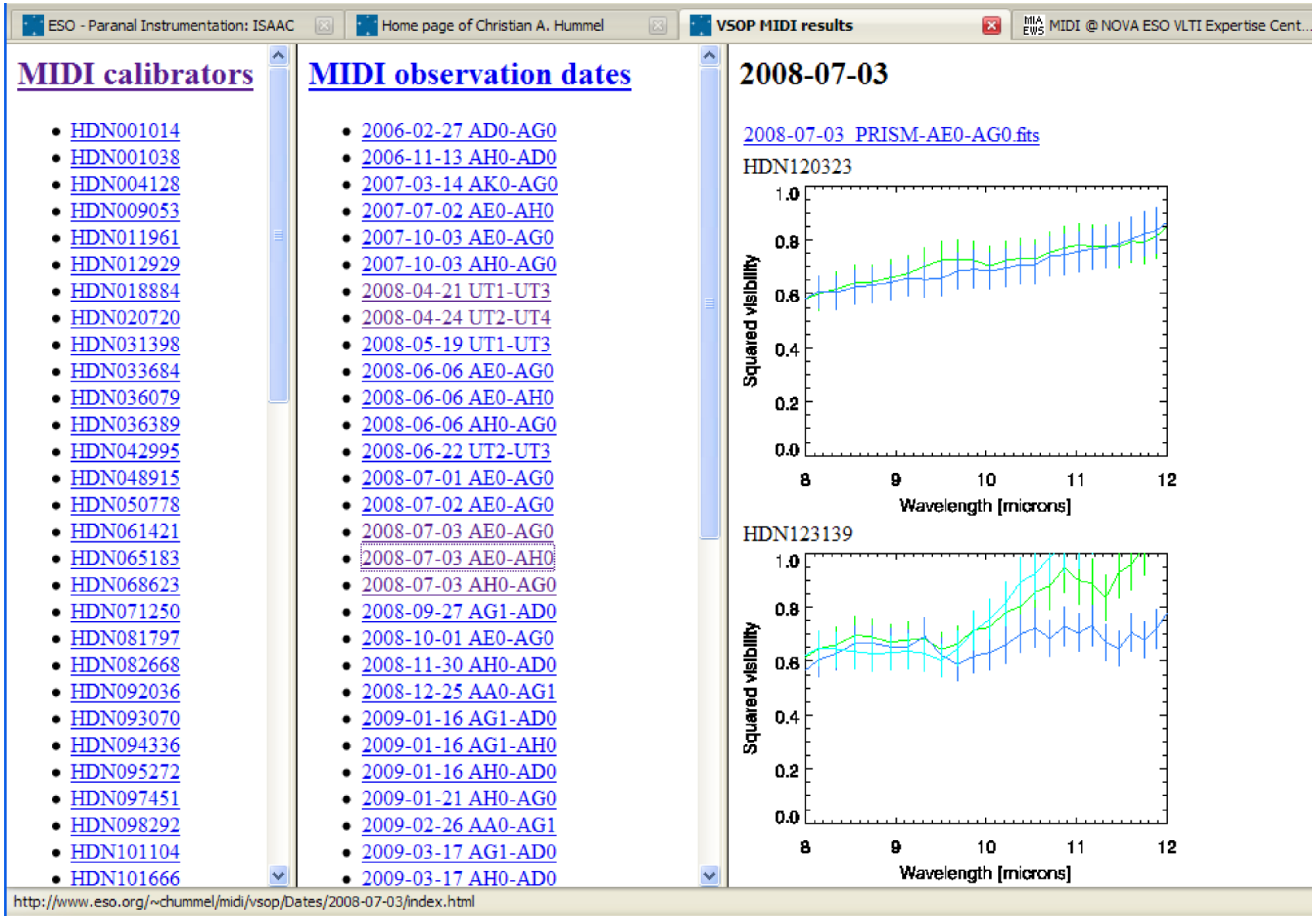
Coherent integration

- 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

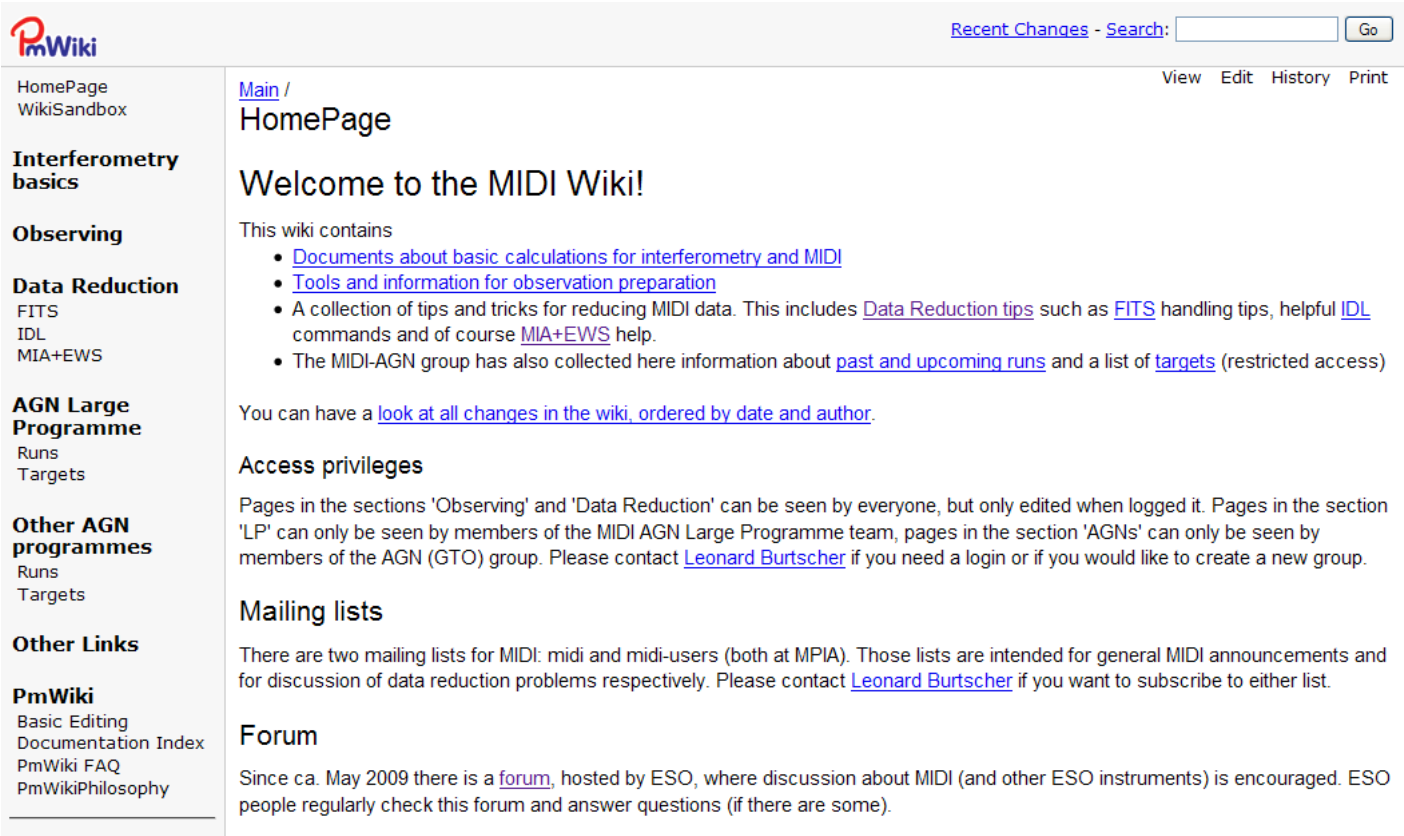
MIDI resources

- MIA+EWS: http://www.strw.leidenuniv.nl/~nevec/MIDI/index.html
- MyMidiGui (IDL front-end for MIA+EWS): http://www.eso.org/~chummel/midi/mymidigui/mymidigui.html
- MIDI Wiki (MPIA): http://www.mpia-hd.mpg.de/MIDISOFT/wiki/
- MIDI data reduction: http://www.eso.org/~chummel/midi/midi.html
- ESO Science Data Products Forum: https://www.eso.org/scienceforum/forums/list.page
- ESO pipelines: http://www.eso.org/sci/data-processing/software/pipelines/

SM/VM calibrator reductions



MIDI Wiki



PmWiki

Recent Changes - Search: Go

HomePage
WikiSandbox

Interferometry basics

Observing

Data Reduction
FITS
IDL
MIA+EWS

AGN Large Programme
Runs
Targets

Other AGN programmes
Runs
Targets

Other Links

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HomePage

Welcome to the MIDI Wiki!

This wiki contains

- Documents about basic calculations for interferometry and MIDI
- Tools and information for observation preparation
- A collection of tips and tricks for reducing MIDI data. This includes Data Reduction tips such as FITS handling tips, helpful IDL commands and of course MIA+EWS help.
- The MIDI-AGN group has also collected here information about past and upcoming runs and a list of targets (restricted access)

You can have a look at all changes in the wiki, ordered by date and author.

Access privileges

Pages in the sections 'Observing' and 'Data Reduction' can be seen by everyone, but only edited when logged it. Pages in the section 'LP' can only be seen by members of the MIDI AGN Large Programme team, pages in the section 'AGNs' can only be seen by members of the AGN (GTO) group. Please contact Leonard Burtscher if you need a login or if you would like to create a new group.

Mailing lists

There are two mailing lists for MIDI: midi and midi-users (both at MPIA). Those lists are intended for general MIDI announcements and for discussion of data reduction problems respectively. Please contact Leonard Burtscher if you want to subscribe to either list.

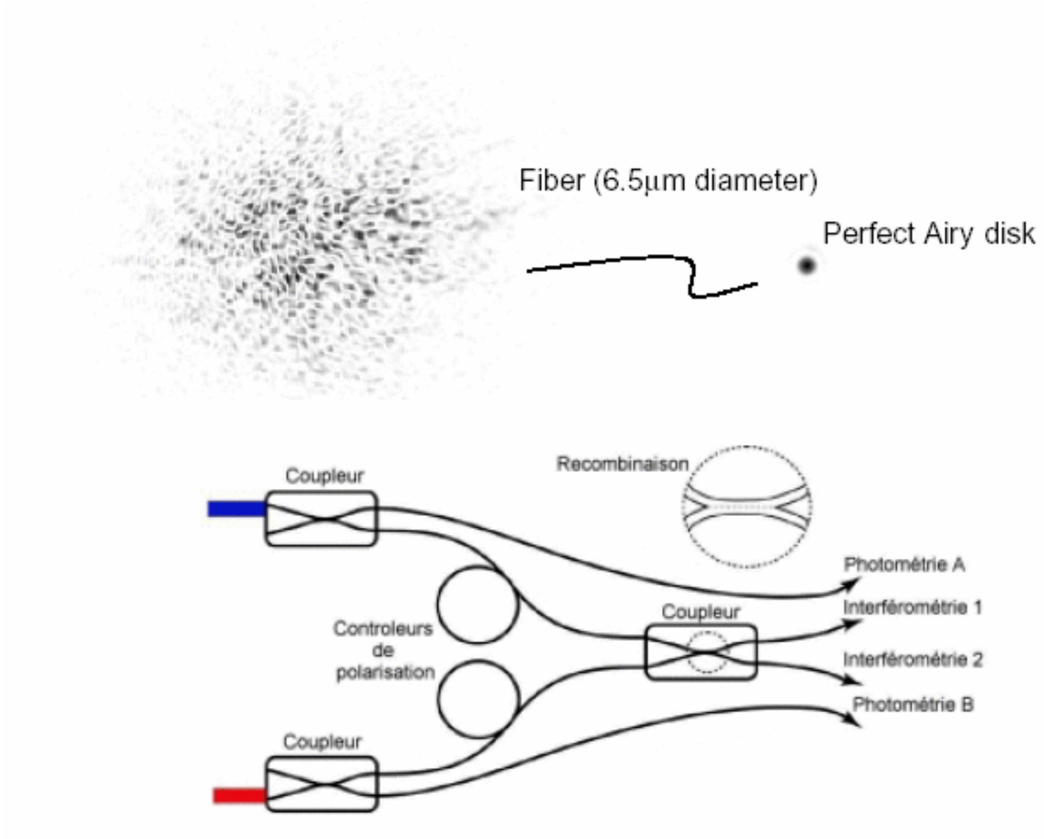
Forum

Since ca. May 2009 there is a forum, hosted by ESO, where discussion about MIDI (and other ESO instruments) is encouraged. ESO people regularly check this forum and answer questions (if there are some).

Principles of AMBER

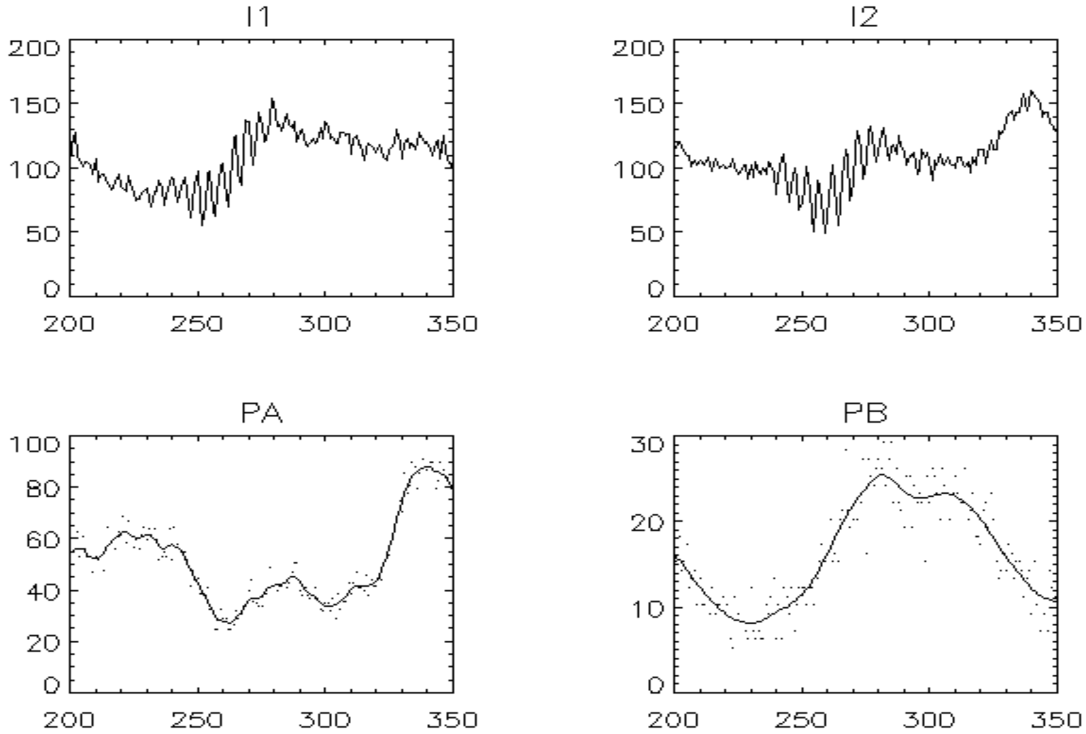
- Single-mode fiber wave front cleaning
- No OPD modulation
- Three baselines encoded at different spatial frequencies on the detector
- Relies on external fringe tracker such as FINITO

Single-mode fiber beam combination



$$I_1 = \kappa_{1,A} P_A + \kappa_{1,B} P_B$$
$$I_2 = \kappa_{2,A} P_A + \kappa_{2,B} P_B.$$

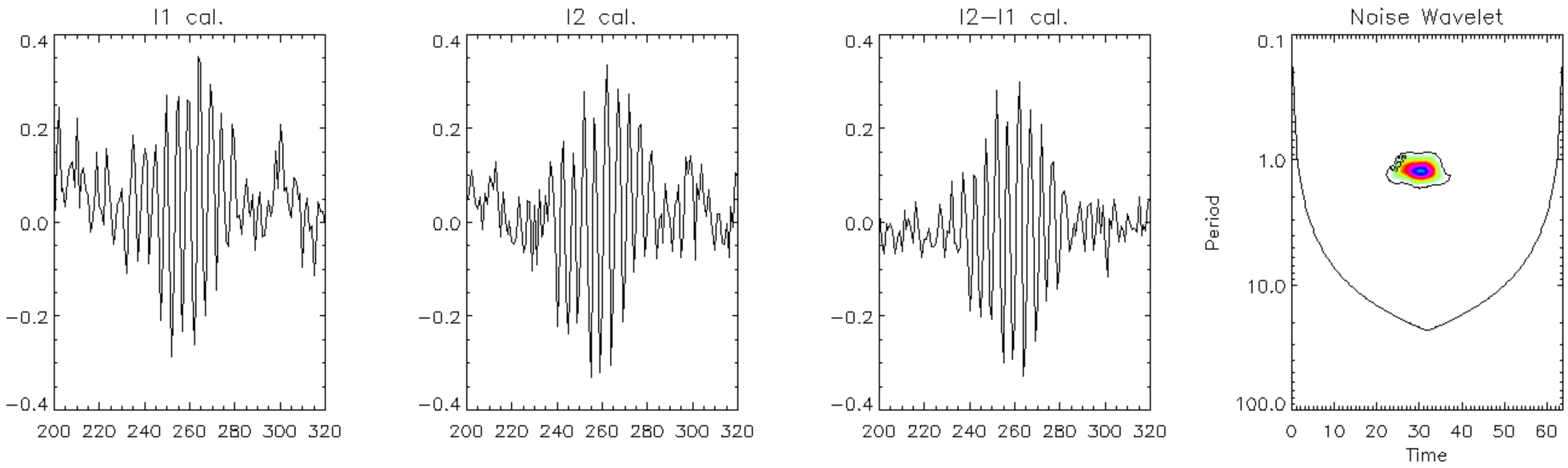
Interferometric signal (VINCI)



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

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

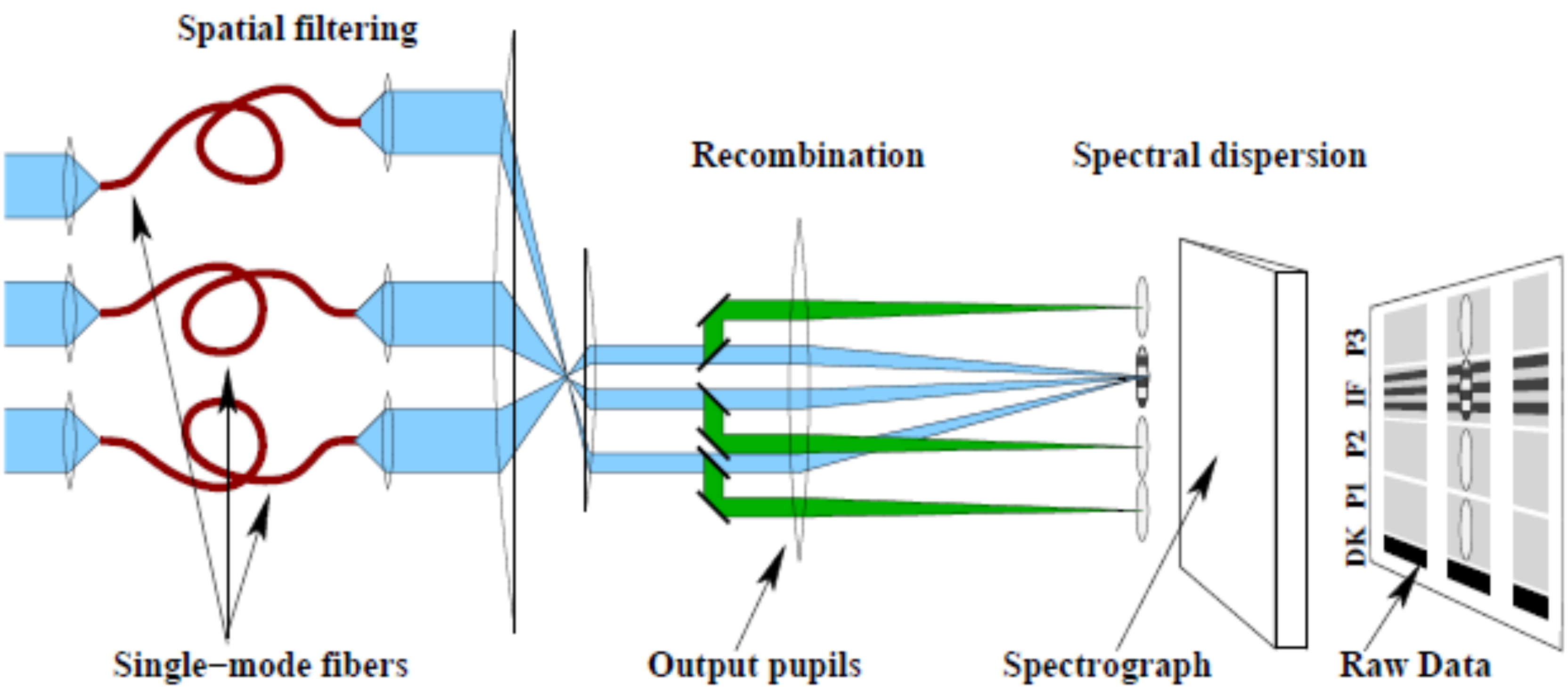
Signal calibration (VINCI)



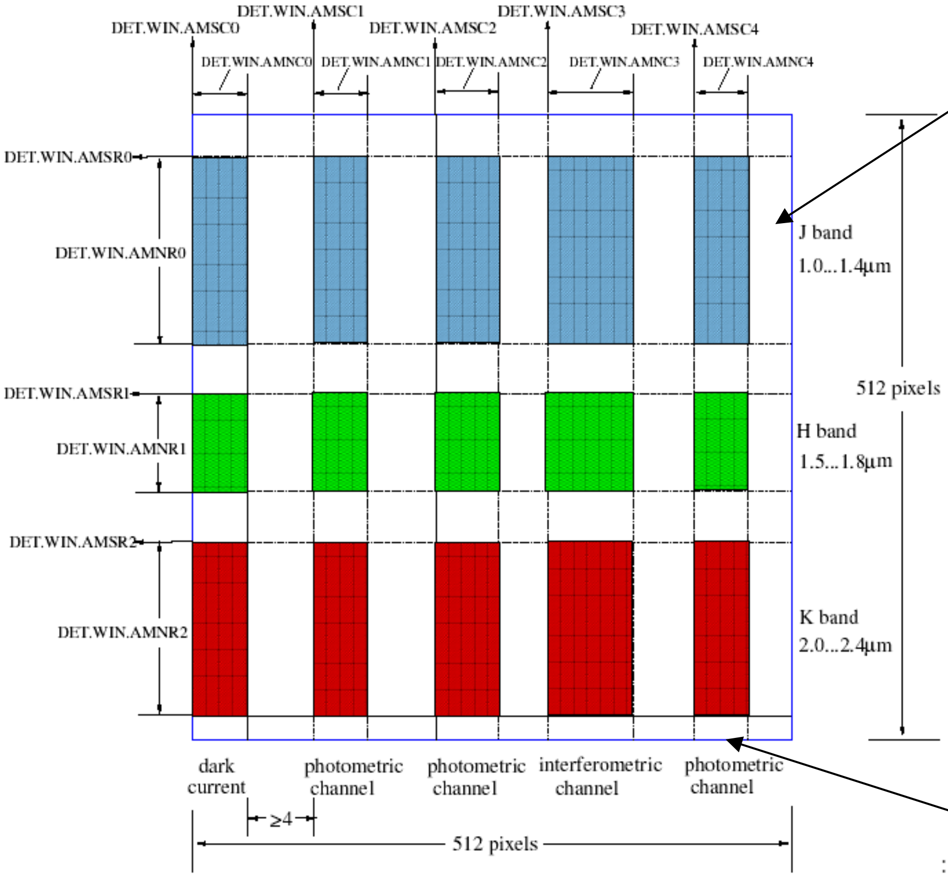
$$I_{1\,\mathrm{cal}} = \frac{1}{2\sqrt{\kappa_{1,\mathrm{A}}\ \kappa_{1,\mathrm{B}}}} \frac{I_1 - \kappa_{1,\mathrm{A}} P_\mathrm{A} - \kappa_{1,\mathrm{B}} P_\mathrm{B}}{[\sqrt{P_\mathrm{A}\ P_\mathrm{B}}]_{\mathrm{Wiener}}}$$

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

AMBER instrument



•... on an infrared Hawaii Camera:

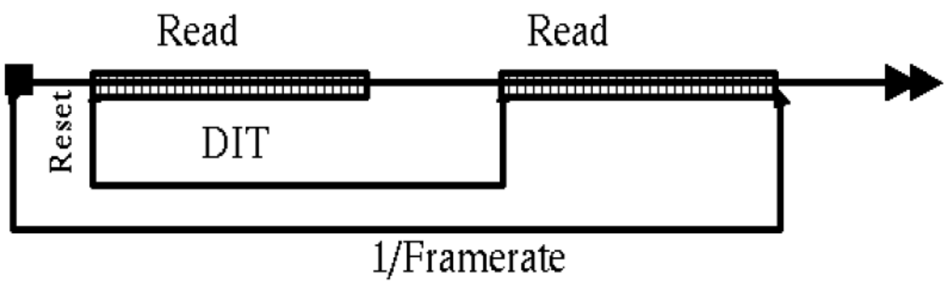


« row »

« 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]

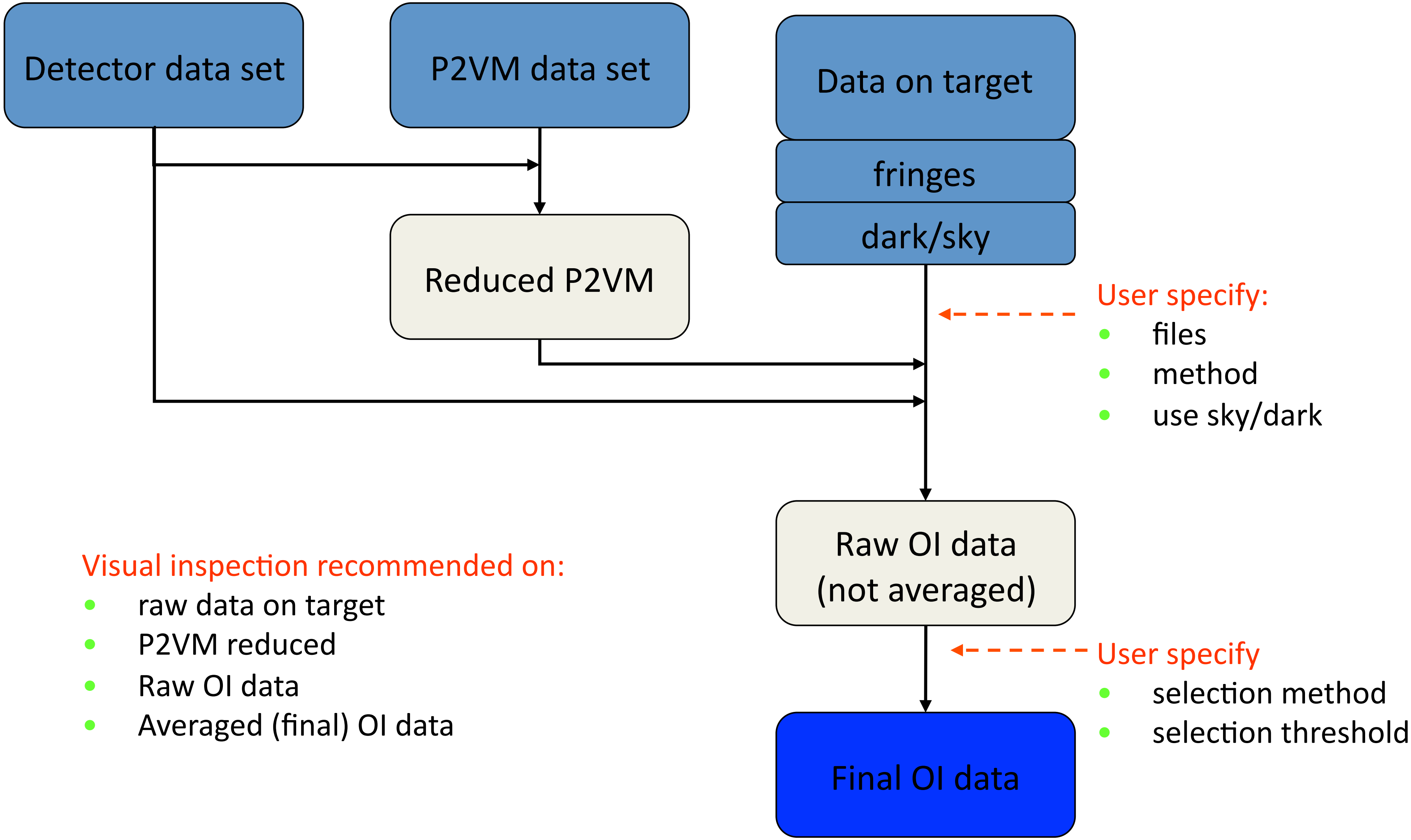


The READOUT mode used is DOUBLE-CORRELATED

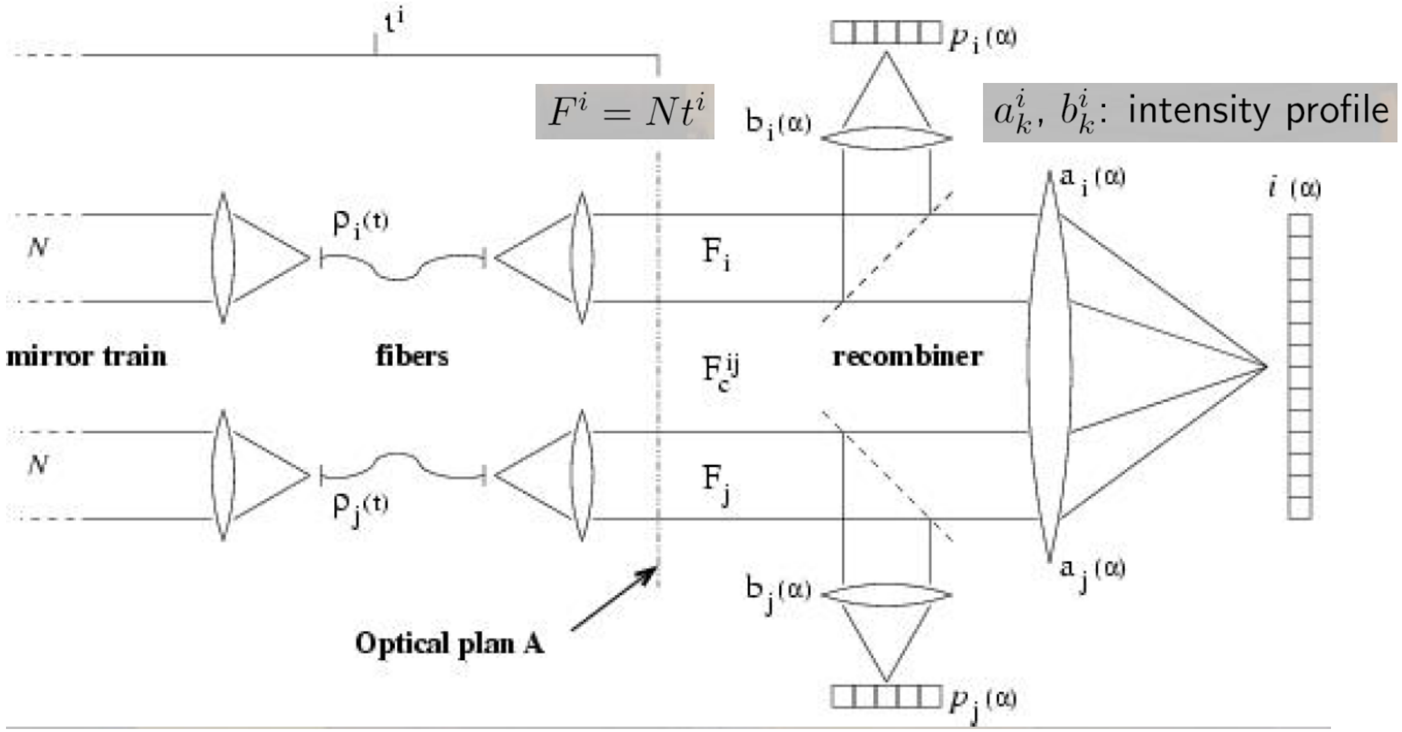
Data reduction overview

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

Data reduction work-flow



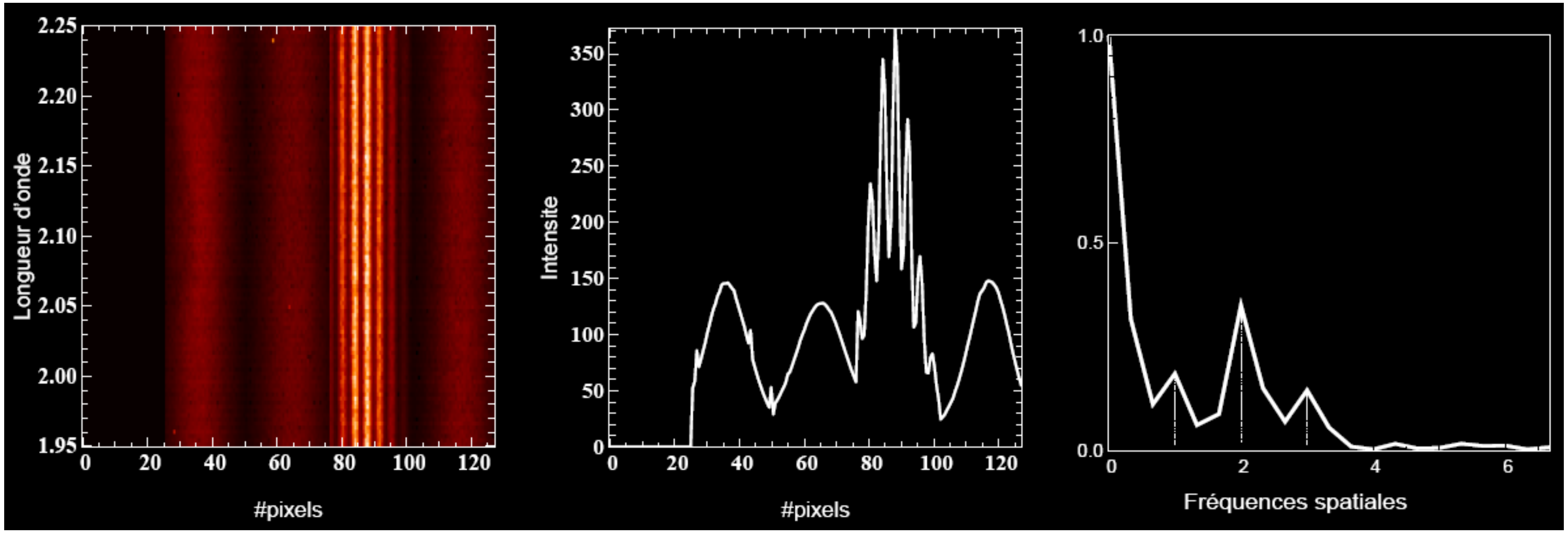
Definitions



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



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

Modeling the interferogram

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

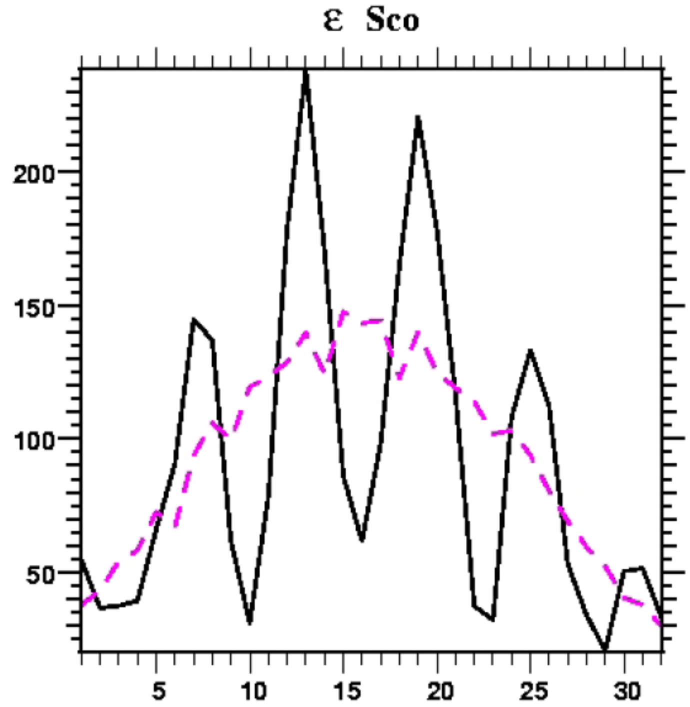
with

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

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

and

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

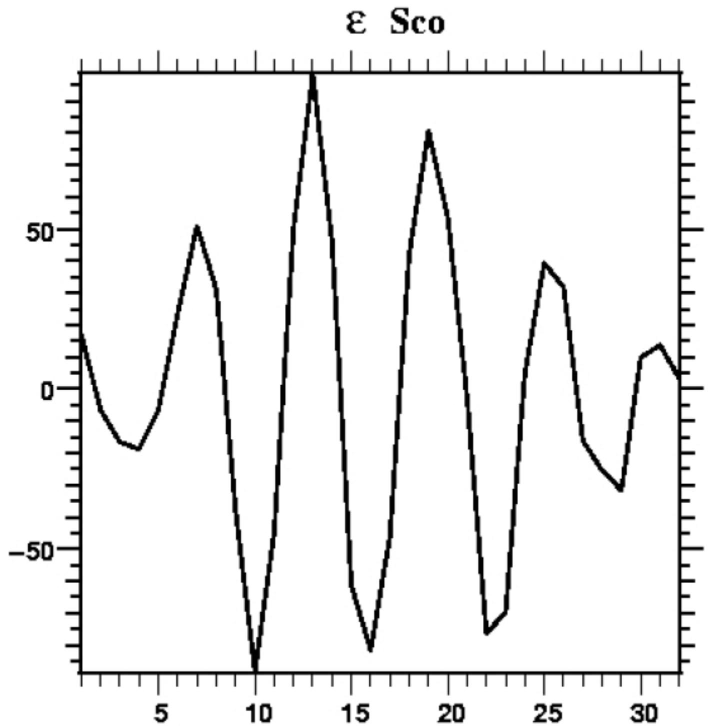


DC corrected interferogram

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

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

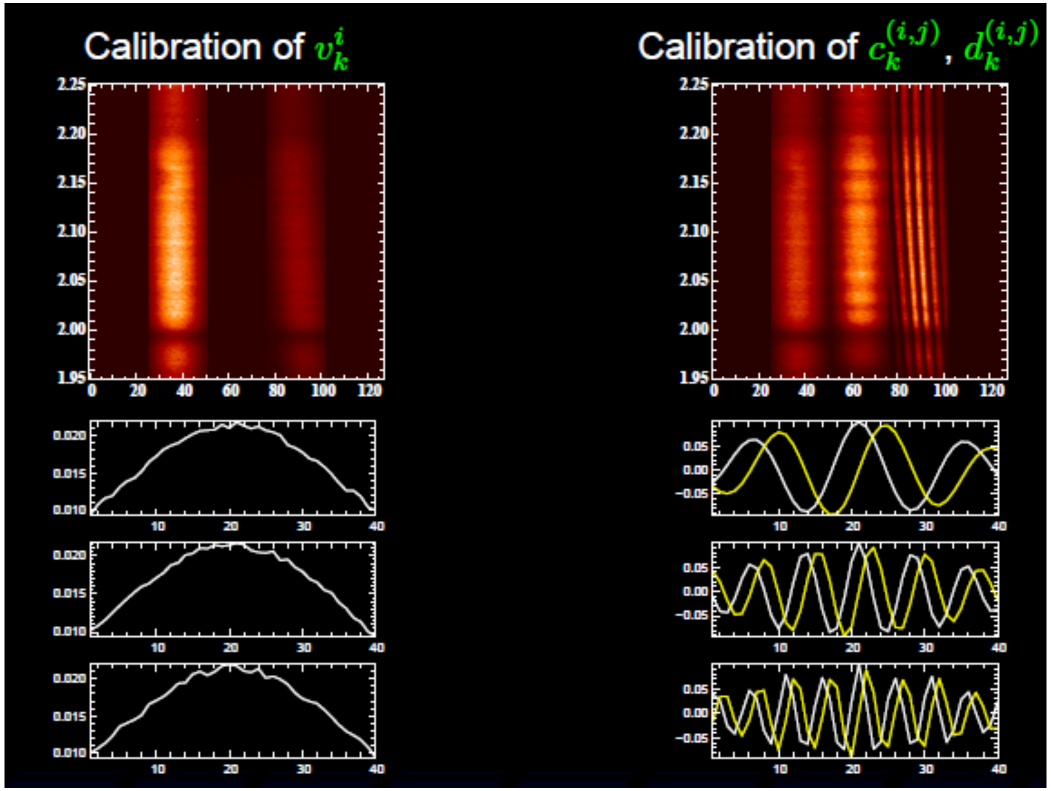
$$i_k = \sum_{i}^{N_{\rm tel}} a_k^i F^i + \sum_{i<j}^{N_{\rm tel}} \left[c_k^{ij} R^{ij} + d_k^{ij} I^{ij} \right]$$

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

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

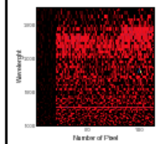
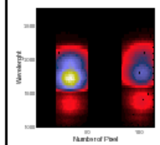
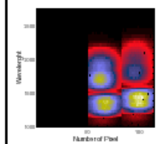
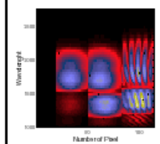
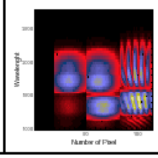
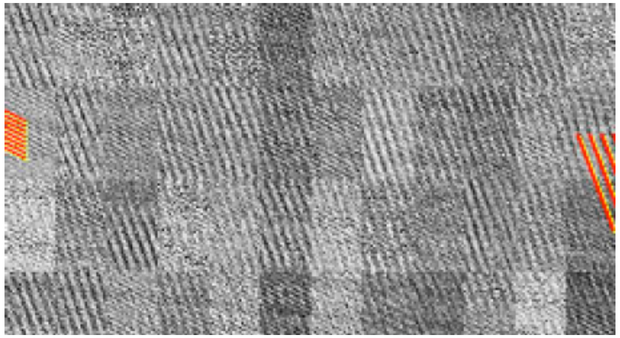
Shutter 1	Shutter 2	Shutter 3	Delaying plate	file Name	figure
Close	Close	Close	No Delay	AMBER_3TSTD_CAL_0001.fits	
Open	Close	Close	No Delay	AMBER_3TSTD_CAL_0002.fits	
Close	Open	Close	No Delay	AMBER_3TSTD_CAL_0003.fits	
Open	Open	Close	No Delay	AMBER_3TSTD_CAL_0004.fits	
Open	Open	Close	1/2 Delayed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

Figure 3. Complete calibration sequence for 2 telescopes

AMBER detector cosmetics

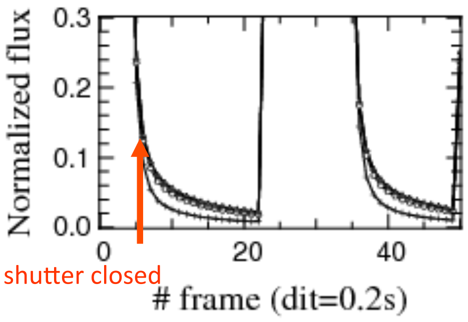
- Classical issues of IR-detector:
  - flat-field map
  - bad pixel map
- Other issues are exacerbated due to fast read-out:
  - noise structure
  - detector remanents
  - synchronizations…

Dark exposures

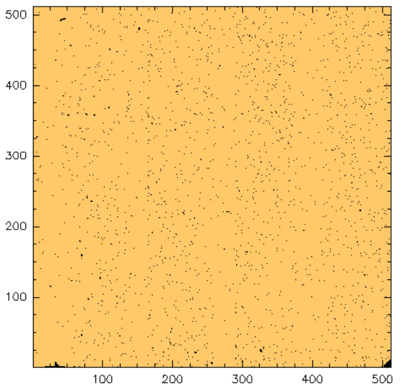


Detector fringes due to electro-magnetic interferences (Li Causi, 2007).

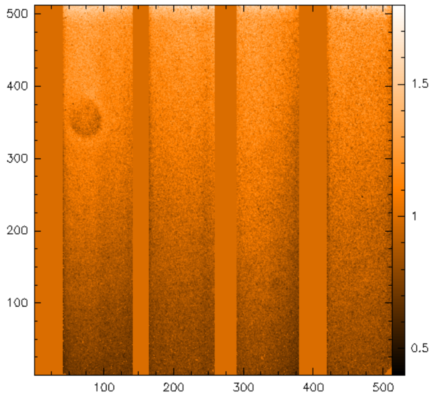
Detector remanent



Bad pixels map



Flat field map



Fringe fitting and estimation

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

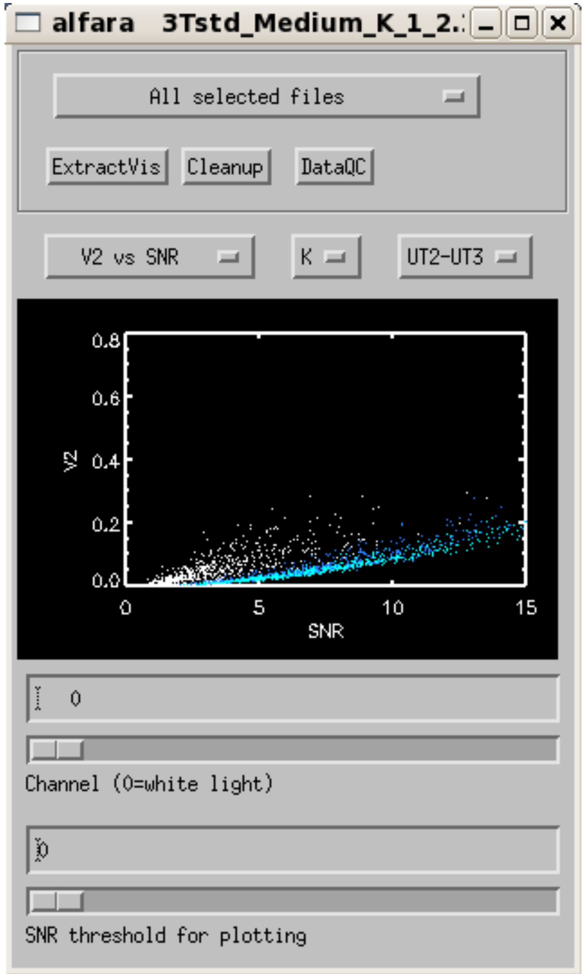
where

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

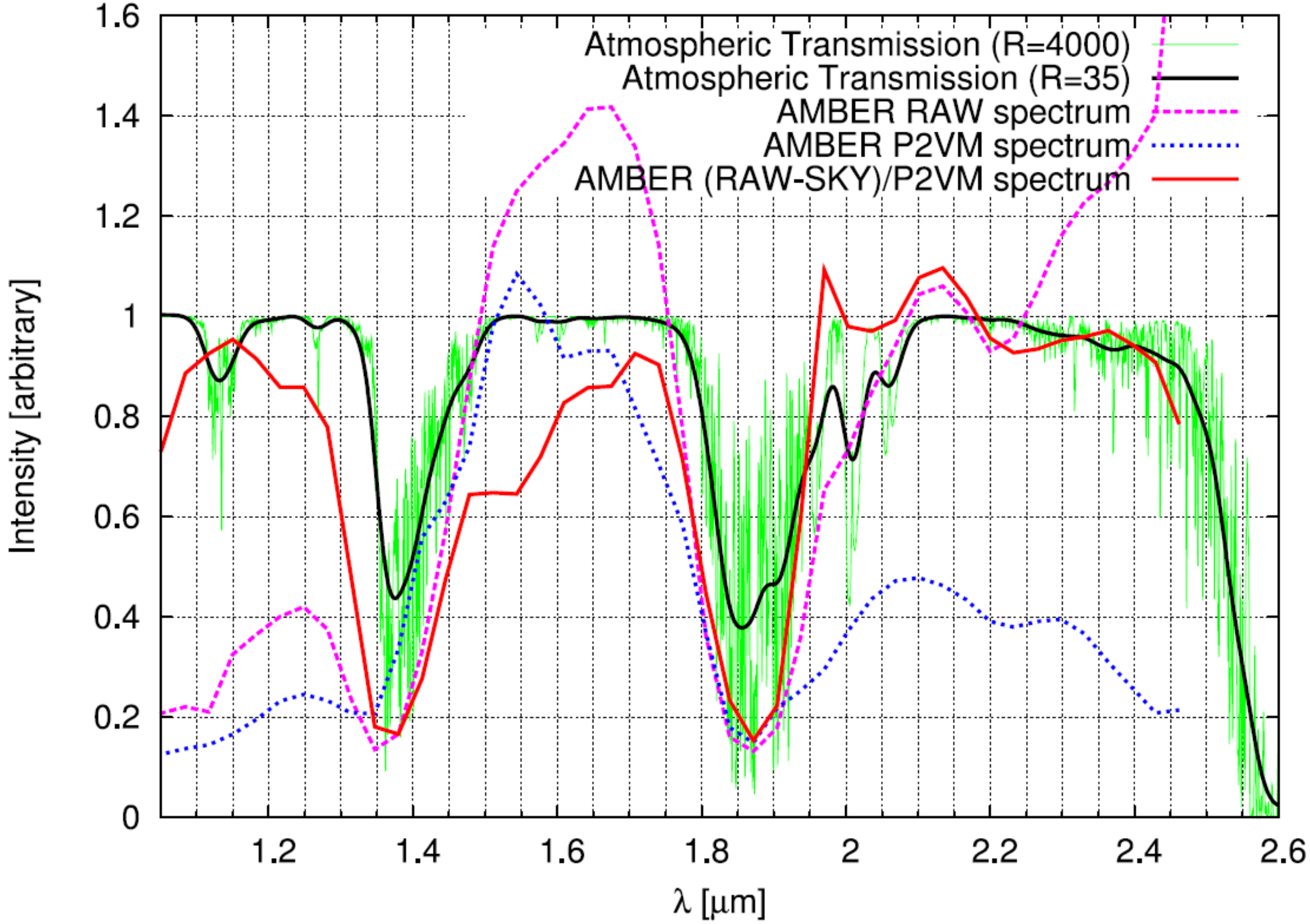
$$\frac{\widetilde{|V^{ij}|^2}}{{V_c^{ij}}^2} = \frac{\left\langle {R^{ij}}^2 + {I^{ij}}^2 \right\rangle - \ \mathrm{Bias}\{{R^{ij}}^2 + {I^{ij}}^2\}}{4 \left\langle P^i P^j \right\rangle \sum_k v_k^i v_k^j}$$

Frame selection

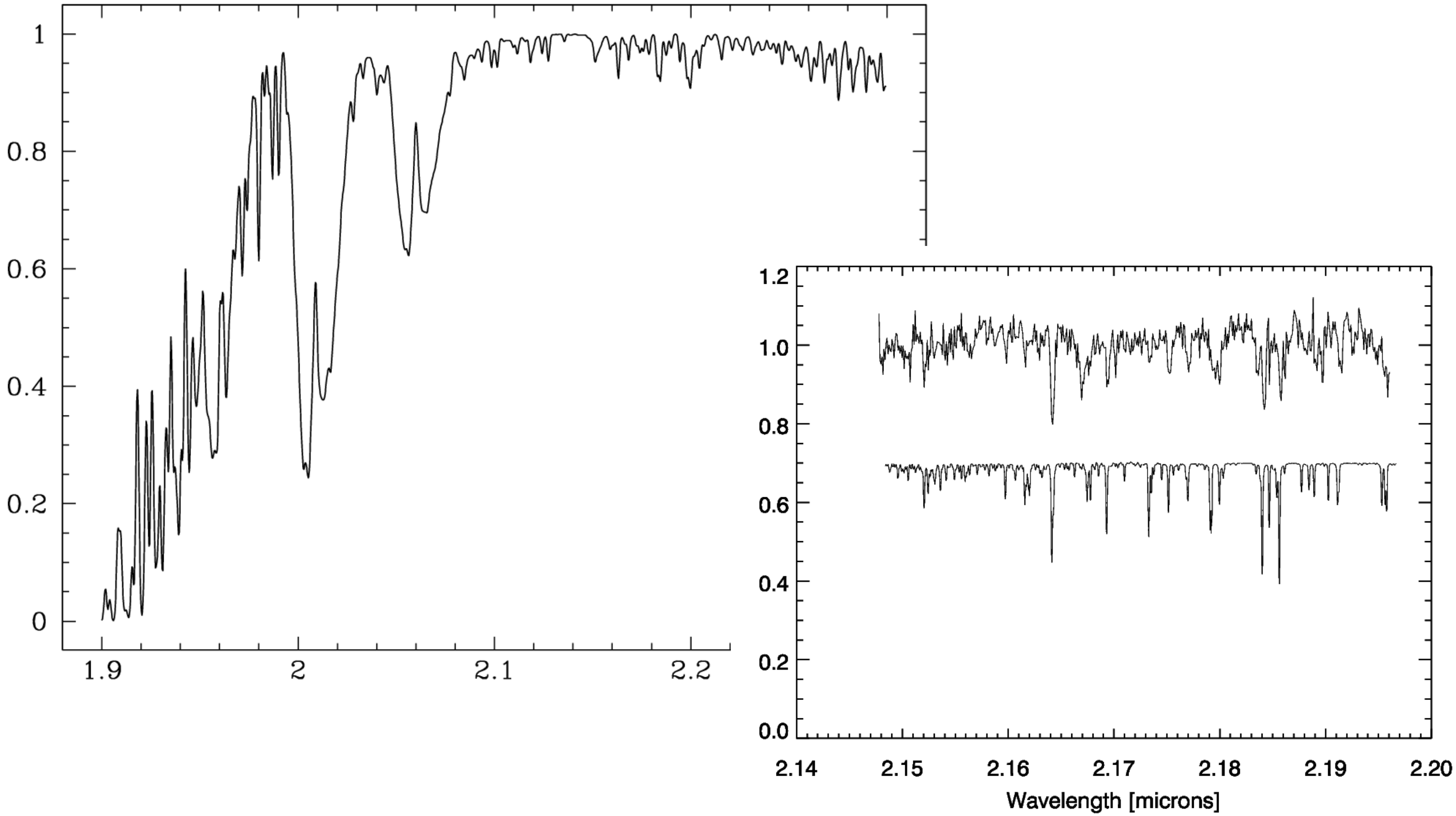
- With UTs:
  - select best 20% of SNR for amplitudes
  - Select all frames for closure phases
- With ATs:
  - Select 50% - 80% SNR
  - All frames for closure phases
- Without FINITO:
  - no more than 8 micron piston



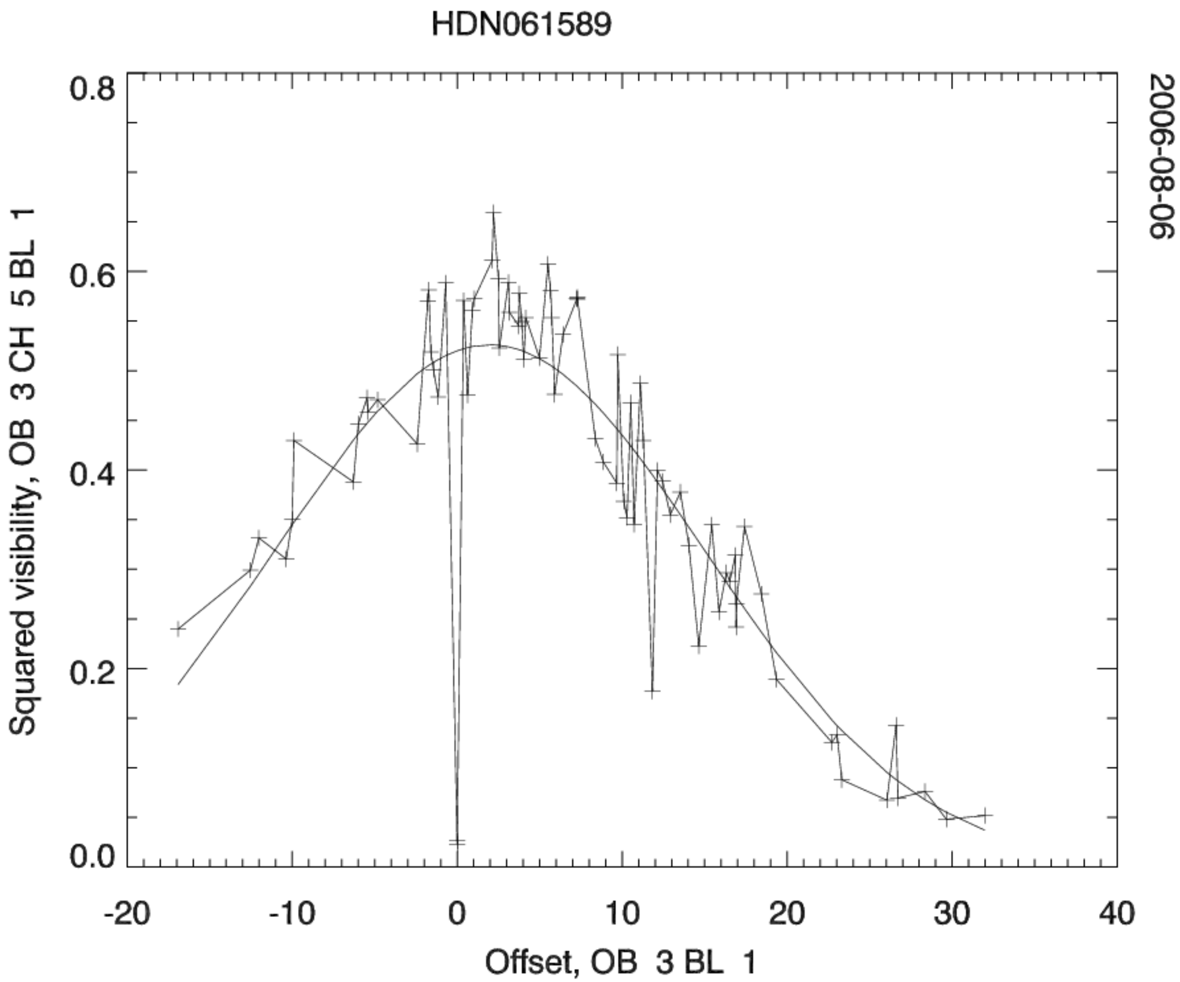
LR wavelength calibration

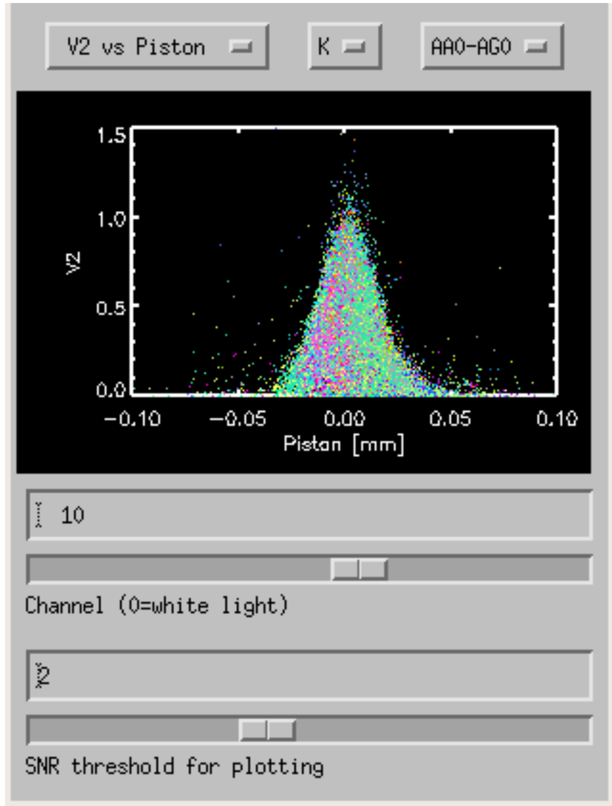


MR/HR wavelength calibration



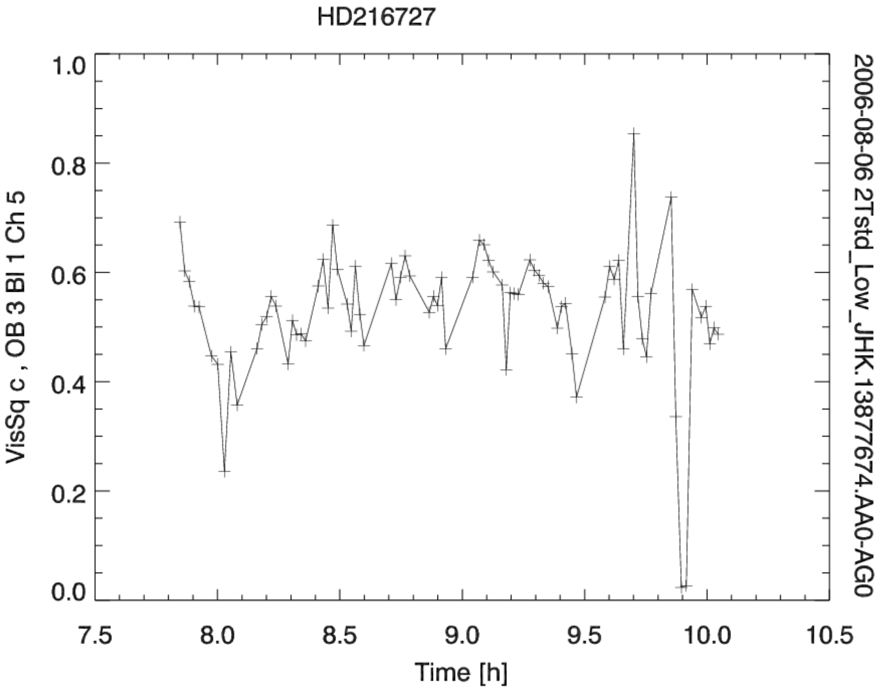
Piston bias (LR, no FINITO)



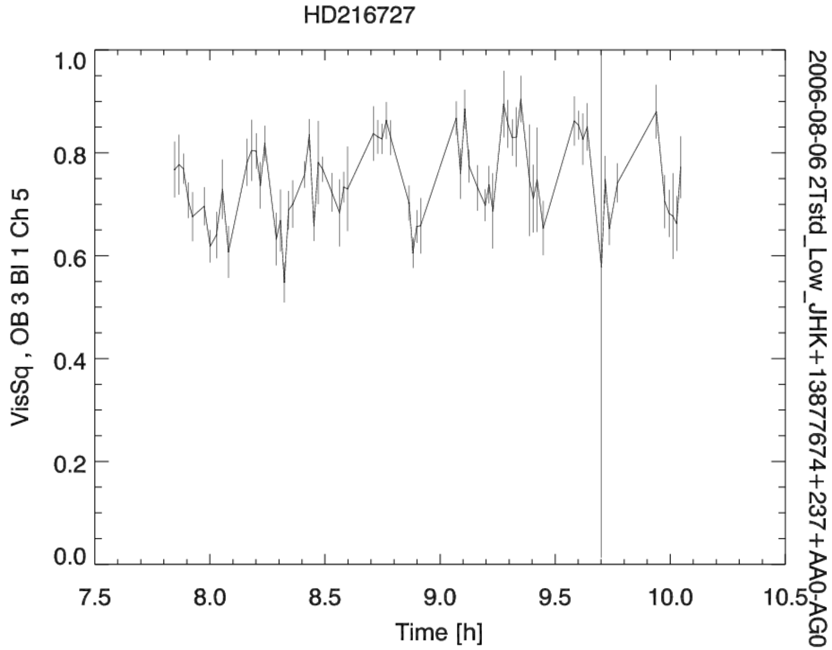


Piston bias correction

Using Gaussian fit



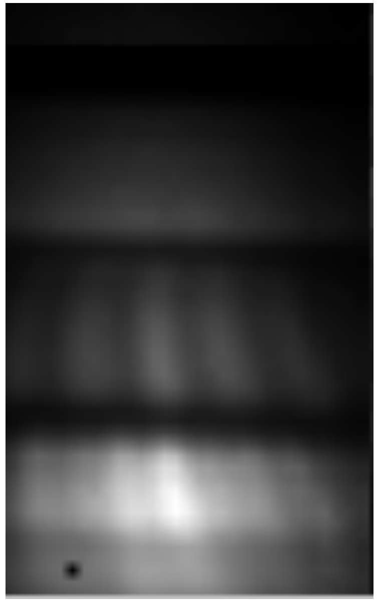
Using only piston < 8 micron



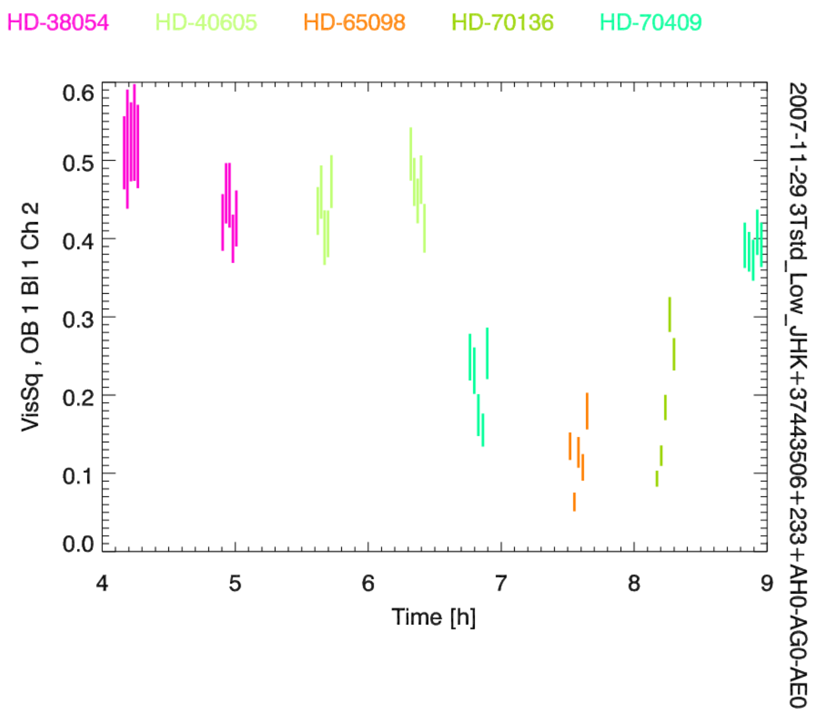
FINITO fringe tracker

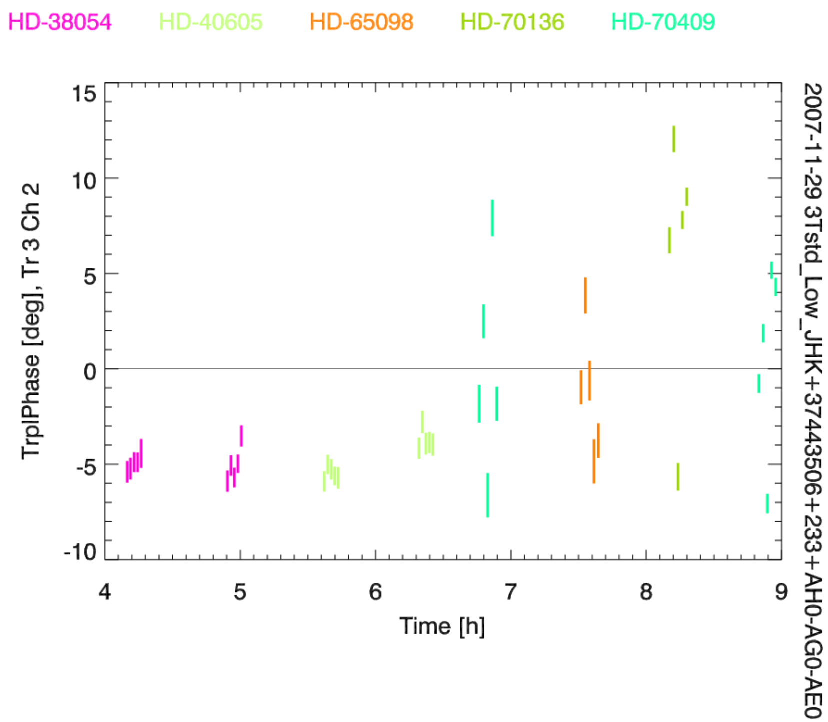
- Stabilizes fringe for on-chip integration for up to 12 s
- Example: 50 s (!) integration time

FINITO

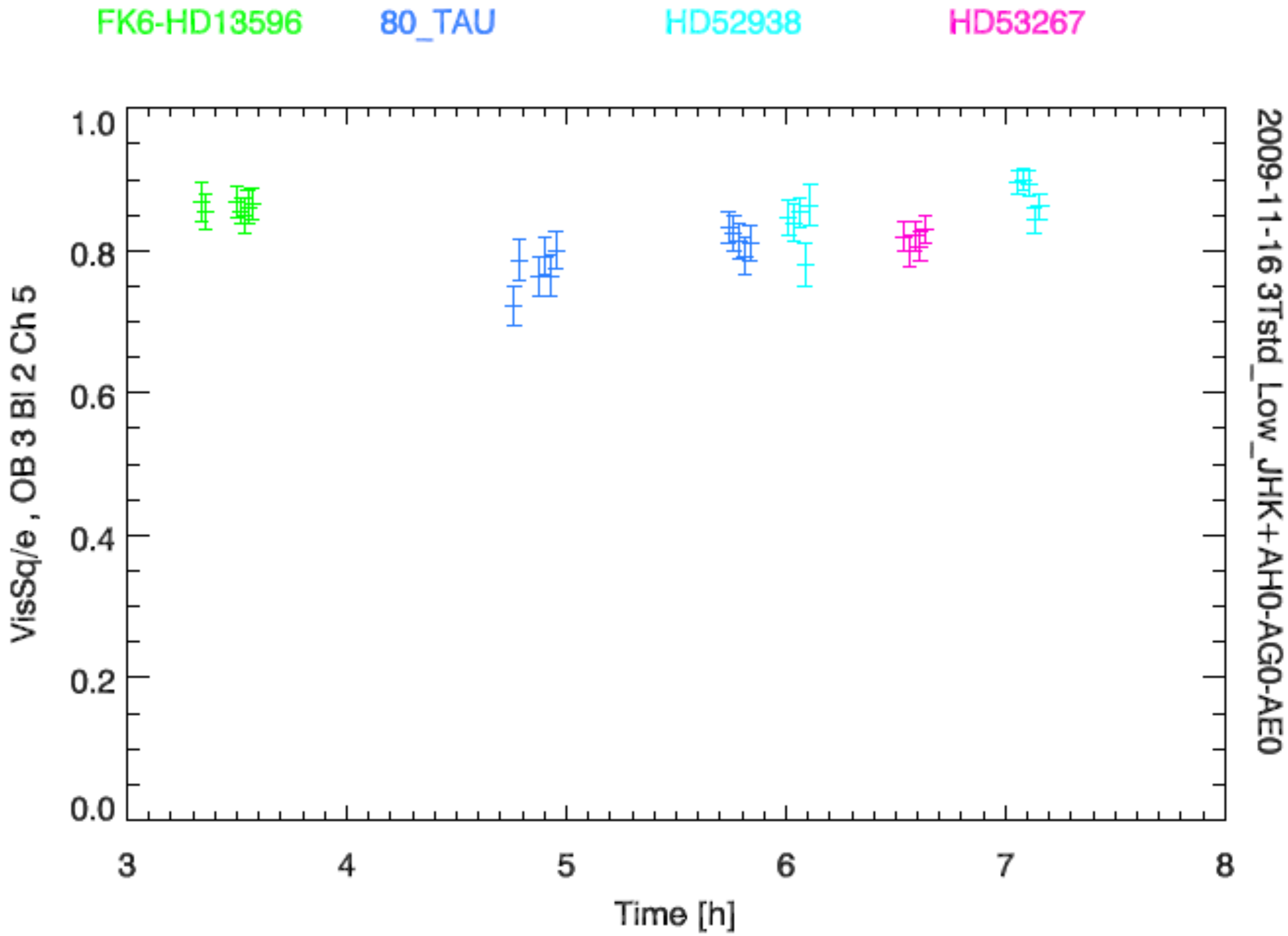


Amplitudes and phases with FINITO

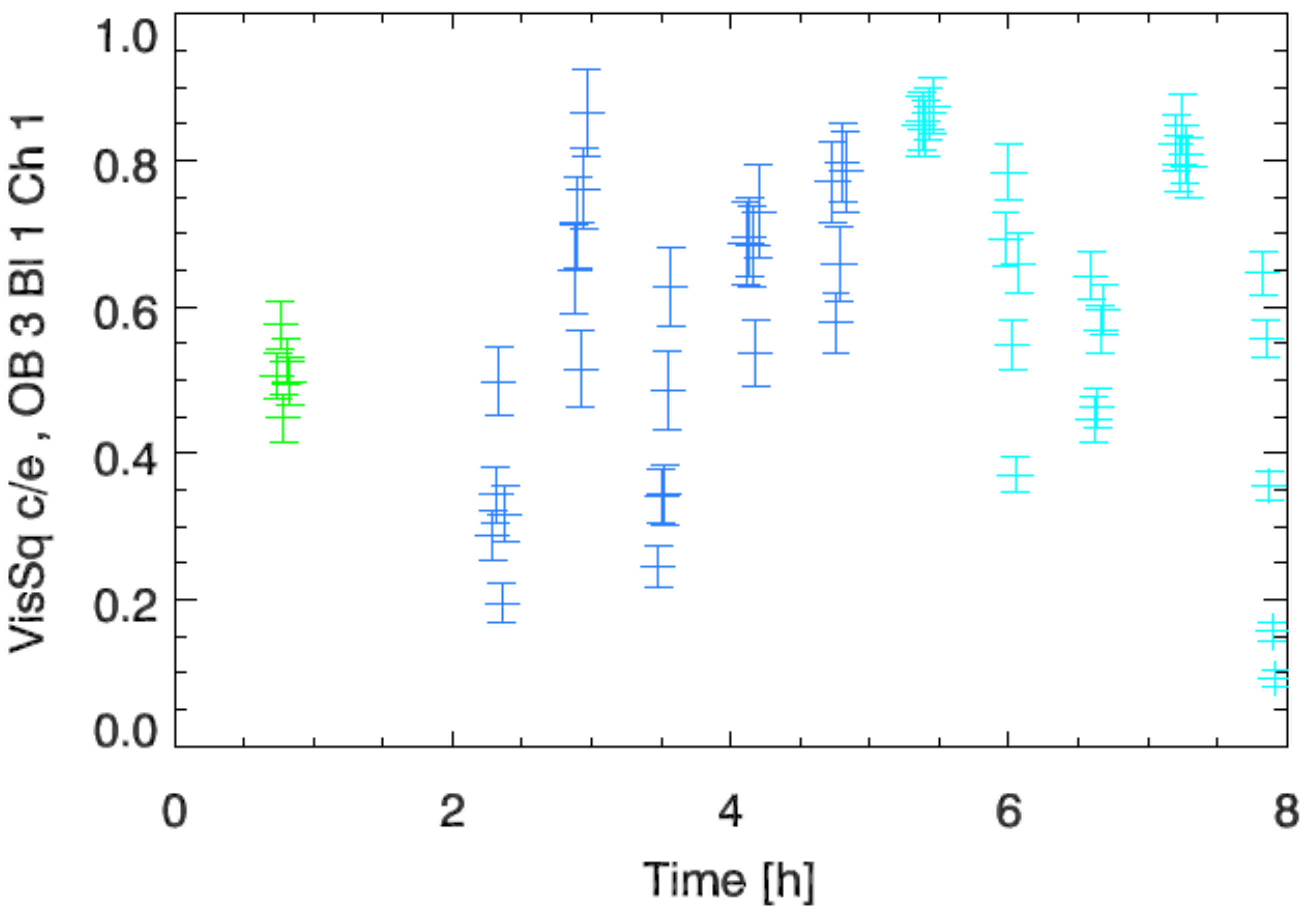




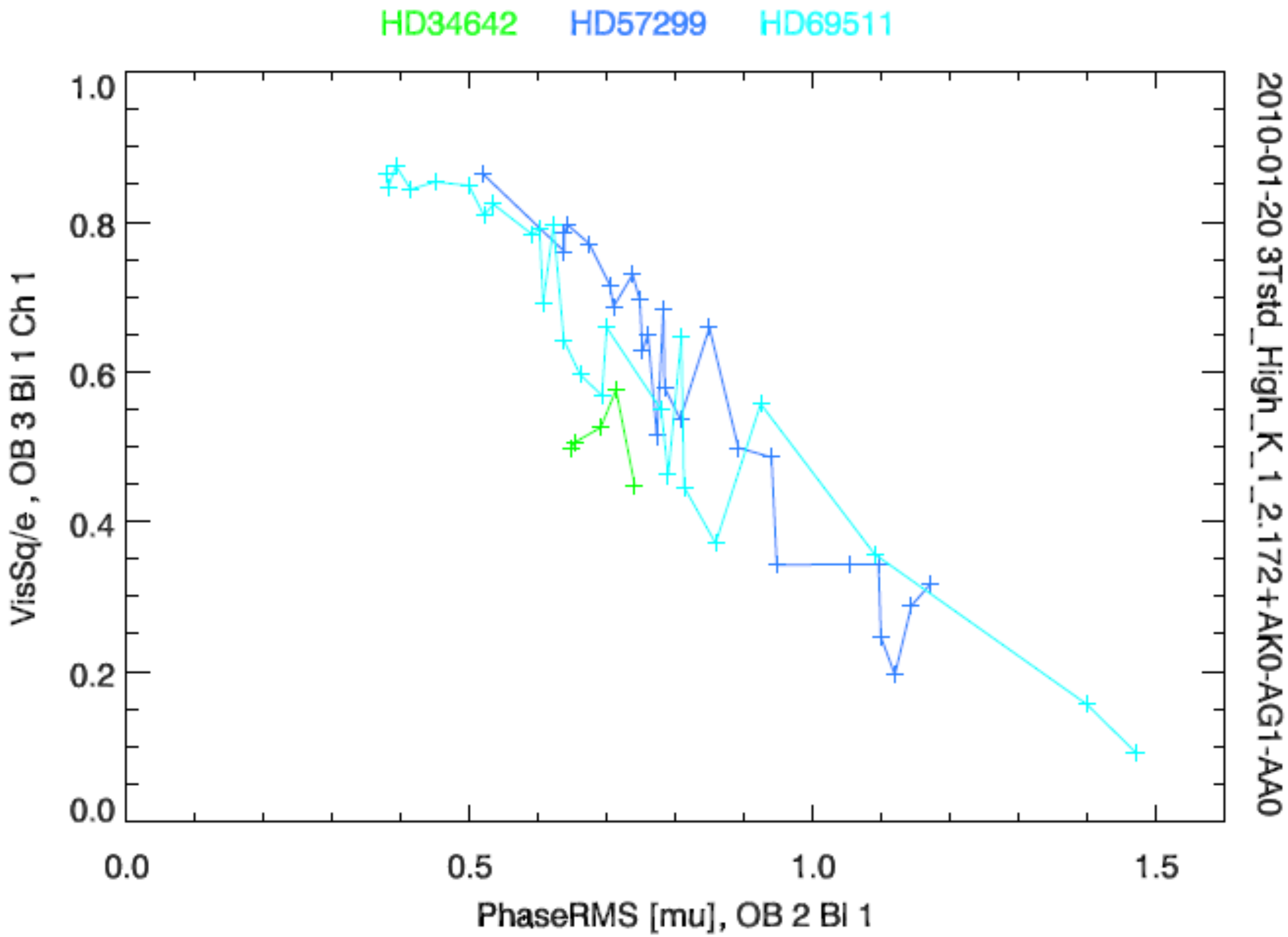
LR TF stability: 2% - 4%



MR transfer function

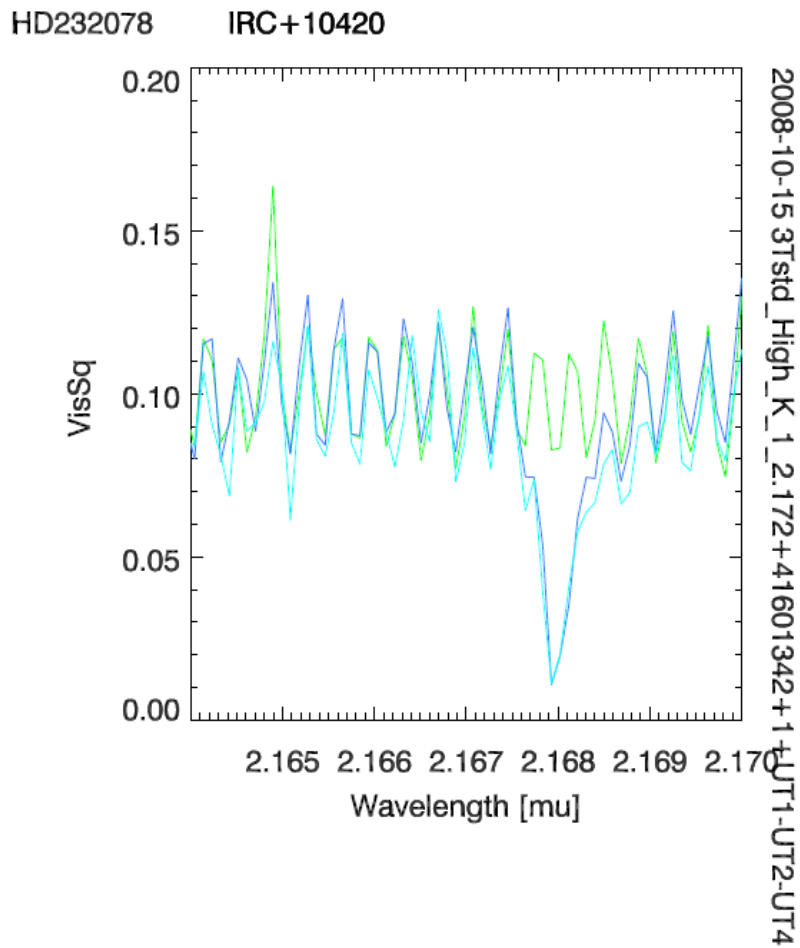


Correlations of MR TF



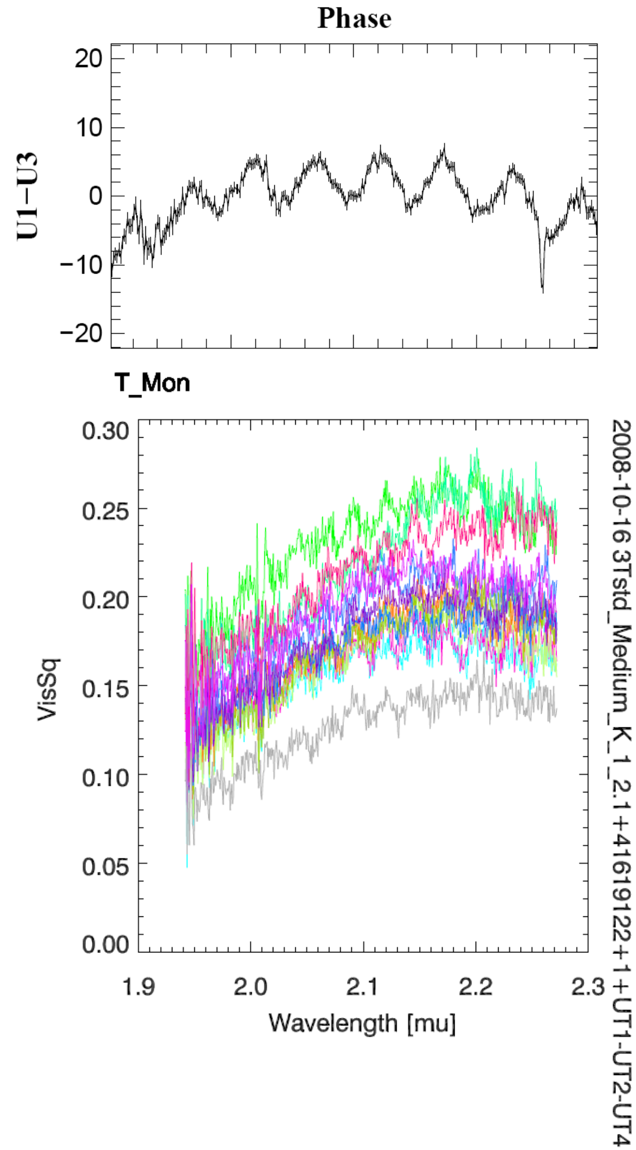
HR “Fringing”

- Fringes: in HR until end of 2009, due to IRIS dichroic
- Remove by binning



MR “Socks”

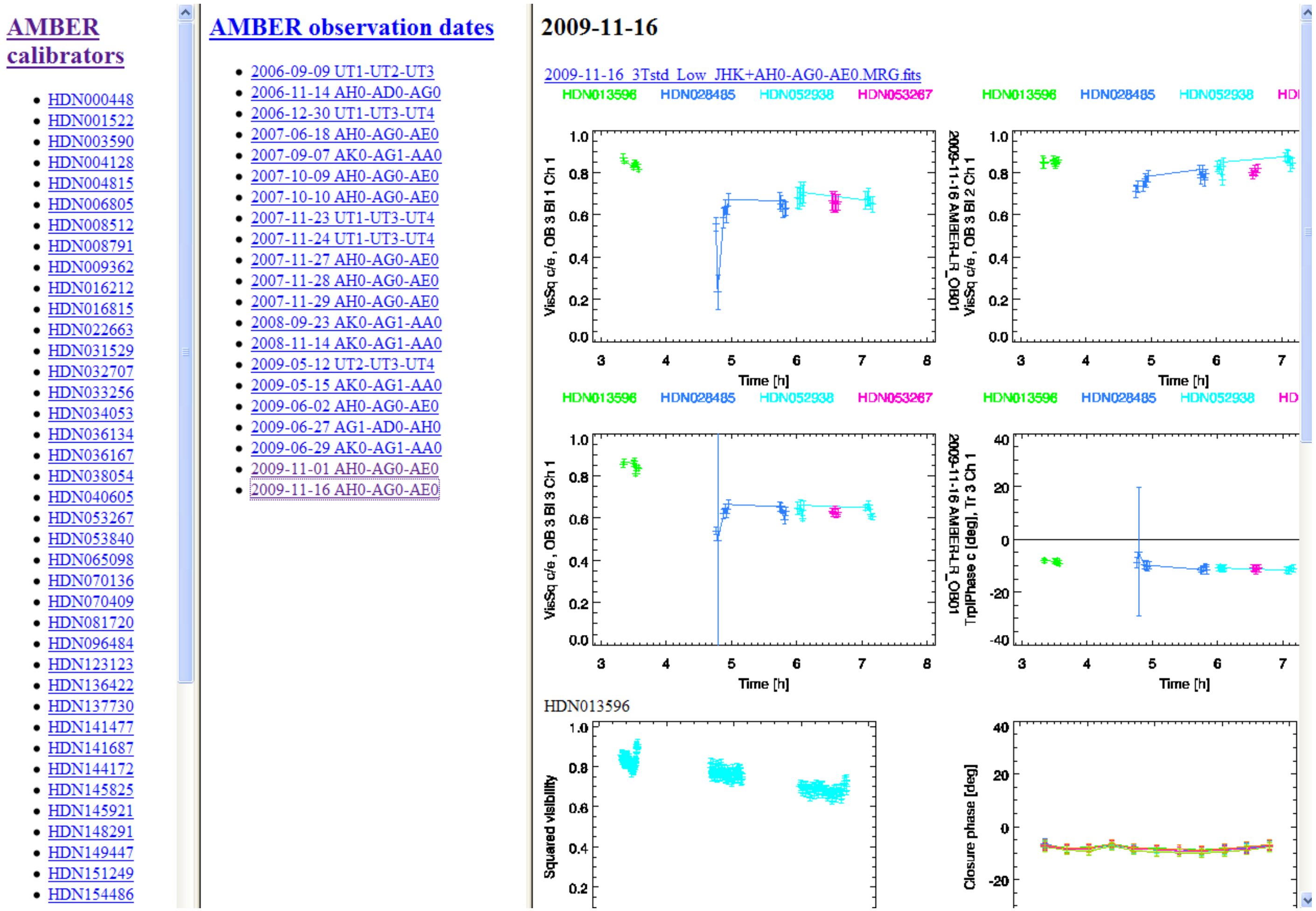
- Socks: in MR until December 2008, due to polarizer
- Removed by high-pass filter



AMBER resources

- JMMC: http://www.jmmc.fr/data_processing_amber.htm
- AMBER data reduction:
  http://www.eso.org/~chummel/amber/amber.html
- Telluric spectra:
  http://www.eso.org/sci/facilities/paranal/instruments/isaac/tools/spectroscopic_standards.html#Telluric
- ESO pipelines:
  http://www.eso.org/sci/data-processing/software/pipelines/

SM/VM calibrator reductions



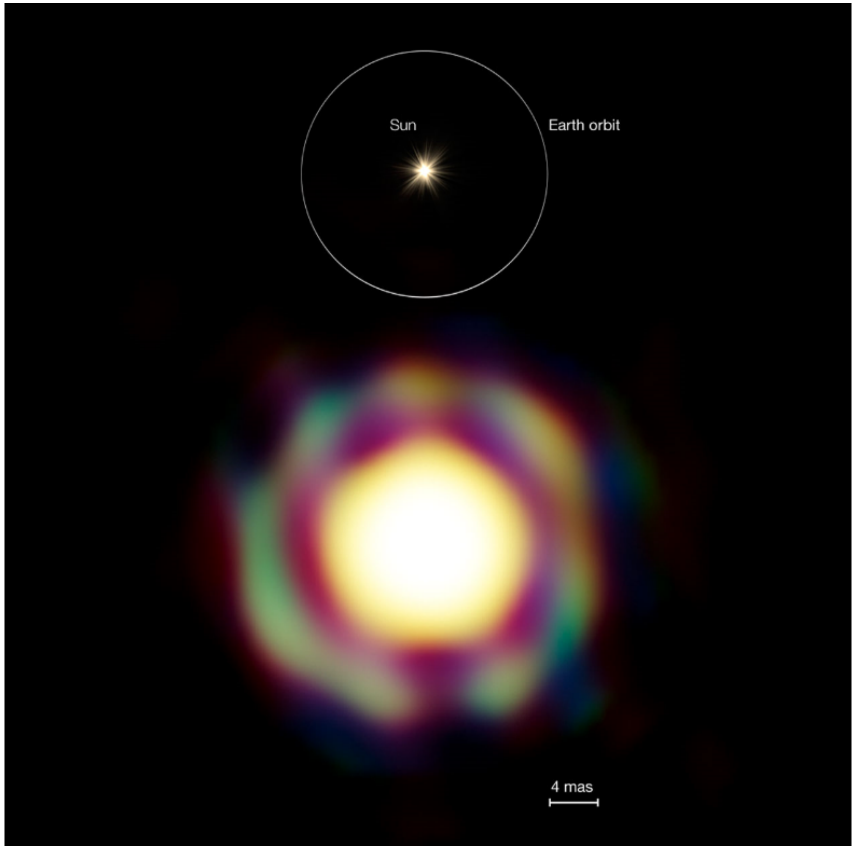
Data reduction software

- Amdlib: C-library from JMMC
- Yorick plugins, to be used with amdlib: http://florentin.millour.free.fr/amdlibPipeline/formulaire.html
- MyAmberGui (IDL front-end for amdlib): http://www.eso.org/~chummel/amber/myambergui/myambergui.html

Imaging

- No a priori constraints, except positivity
- Needs a lot more data than modeling
- Needs high-quality data
- Similar to radio imaging
  - Closure phases instead of complex visibilities
  - Squared visibilities
  - Wide bandwidths

T Leporis with AMBER



Le Bouquin et al. 2009

Basic principles

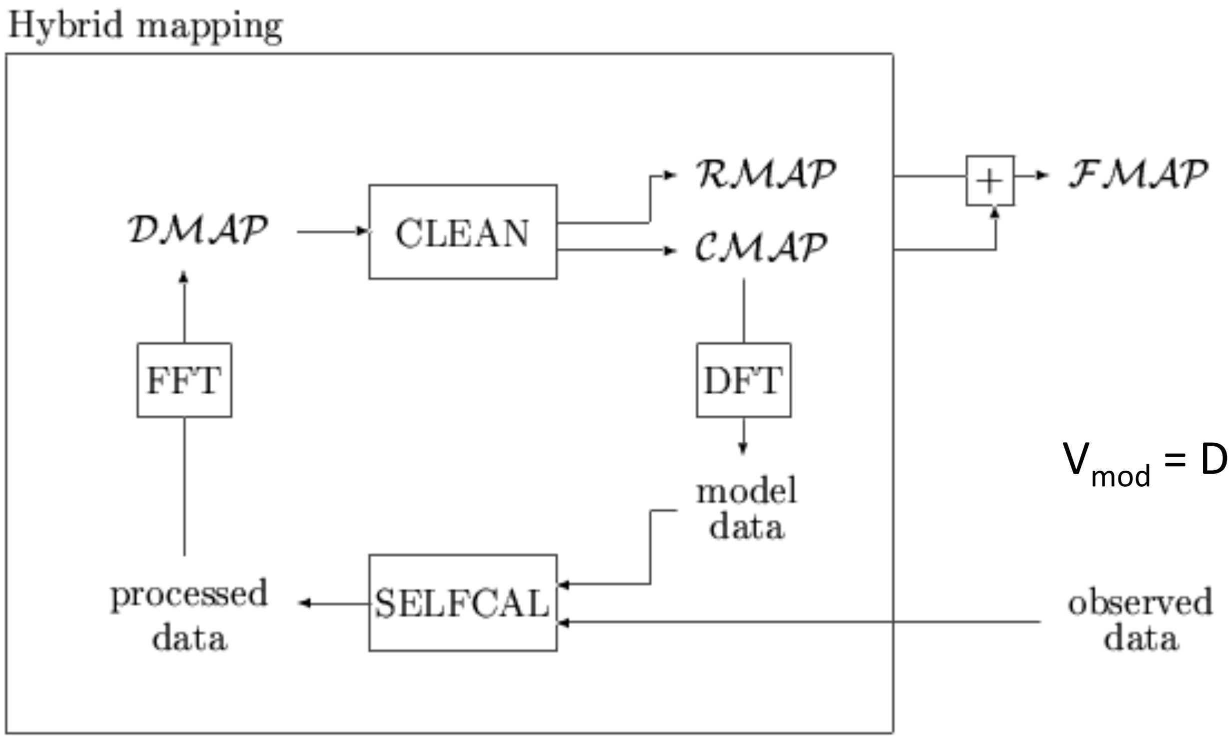
- Sparse aperture coverage
  - Deconvolution, CLEANing, maximum entropy
- Phases corrupted, but not closure phases
  - Missing data needs to be replaced by model
- Complexity of source structure
  - Convergence only with simple structures
- Range of baselines
  - Determines field of view and resolution

Classics: Self-cal and CLEAN

DMAP = dirty map
DMAP = FFT(V_{obs})

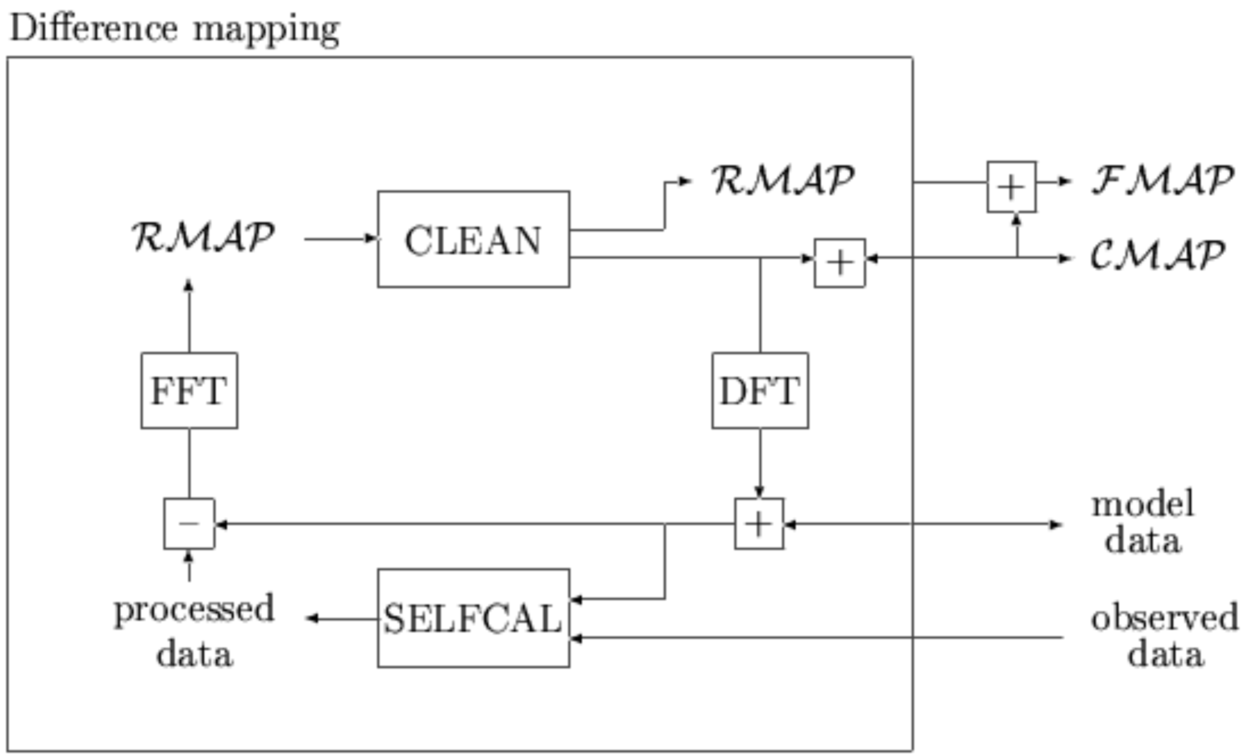
RMAP = residual map
CMAP = clean map

FMAP = final map
FMAP = RMAP + CMAP

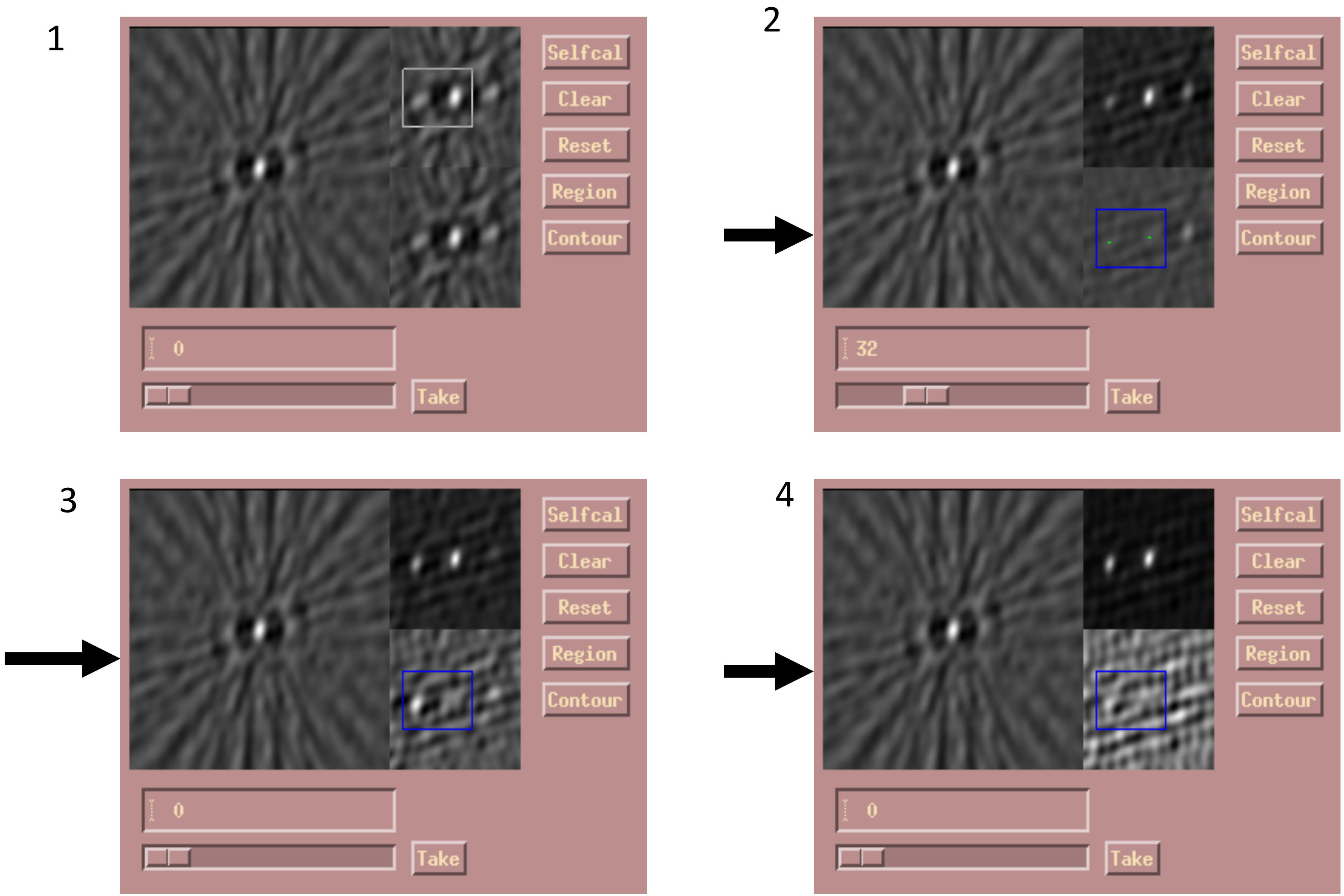


V_{mod} = DFT(CMAP)

Modification: Difference mapping



Difference mapping (pearl)



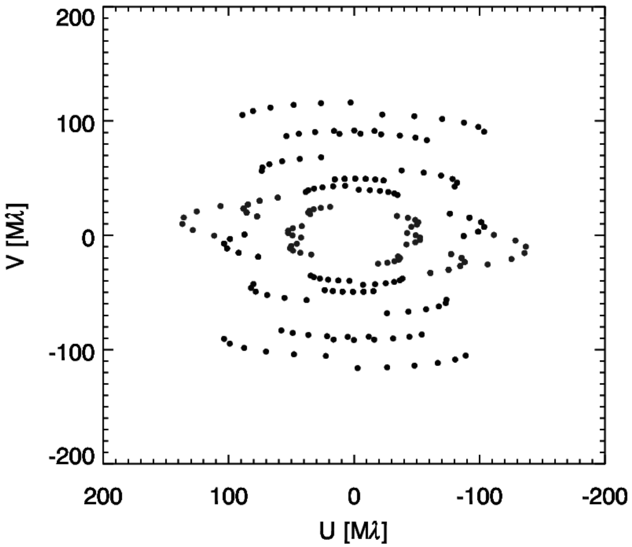
Alternative algorithms

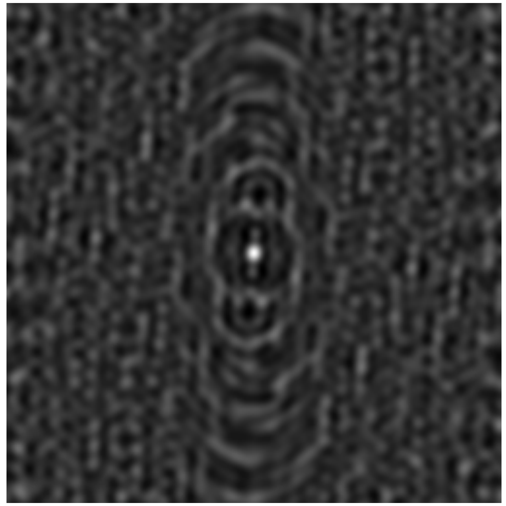
- Maximum entropy
- Markov-chains
- Building-blocks
- Linear pixel fitting

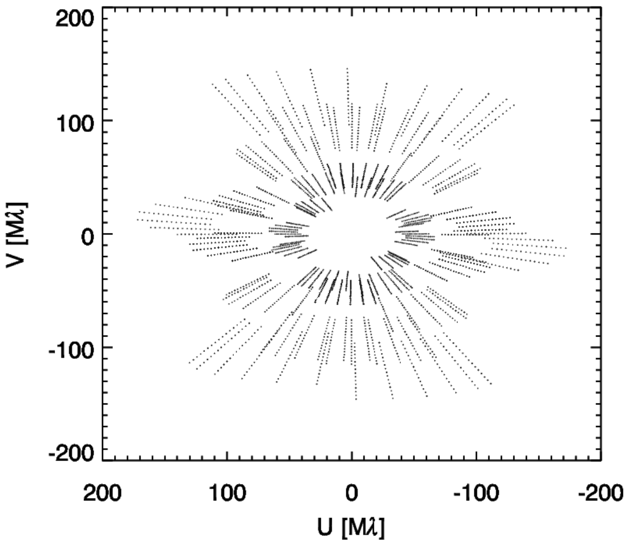
Resources (all codes public!)

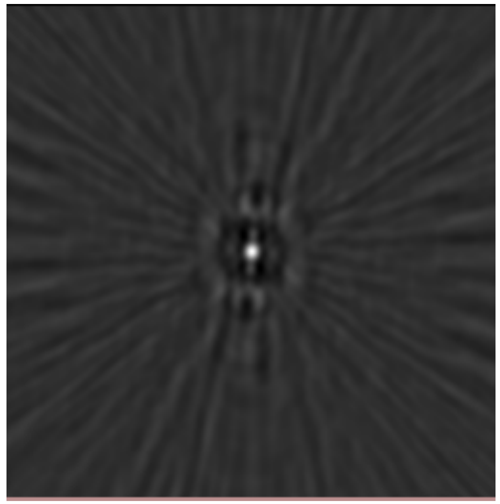
- BSMEM: http://www.mrao.cam.ac.uk/research/OAS/bsmem.html
- MIRA: http://www-obs.univ-lyon1.fr/labo/perso/eric.thiebaut/mira.html
- MACIM: http://www.physics.usyd.edu.au/~mireland/MACIM/
- WISARD: http://www.onera.fr/dota-en/wisard/index.php, http://eii-jra4.ujf-grenoble.fr/wizard.html

Interferometric PSF



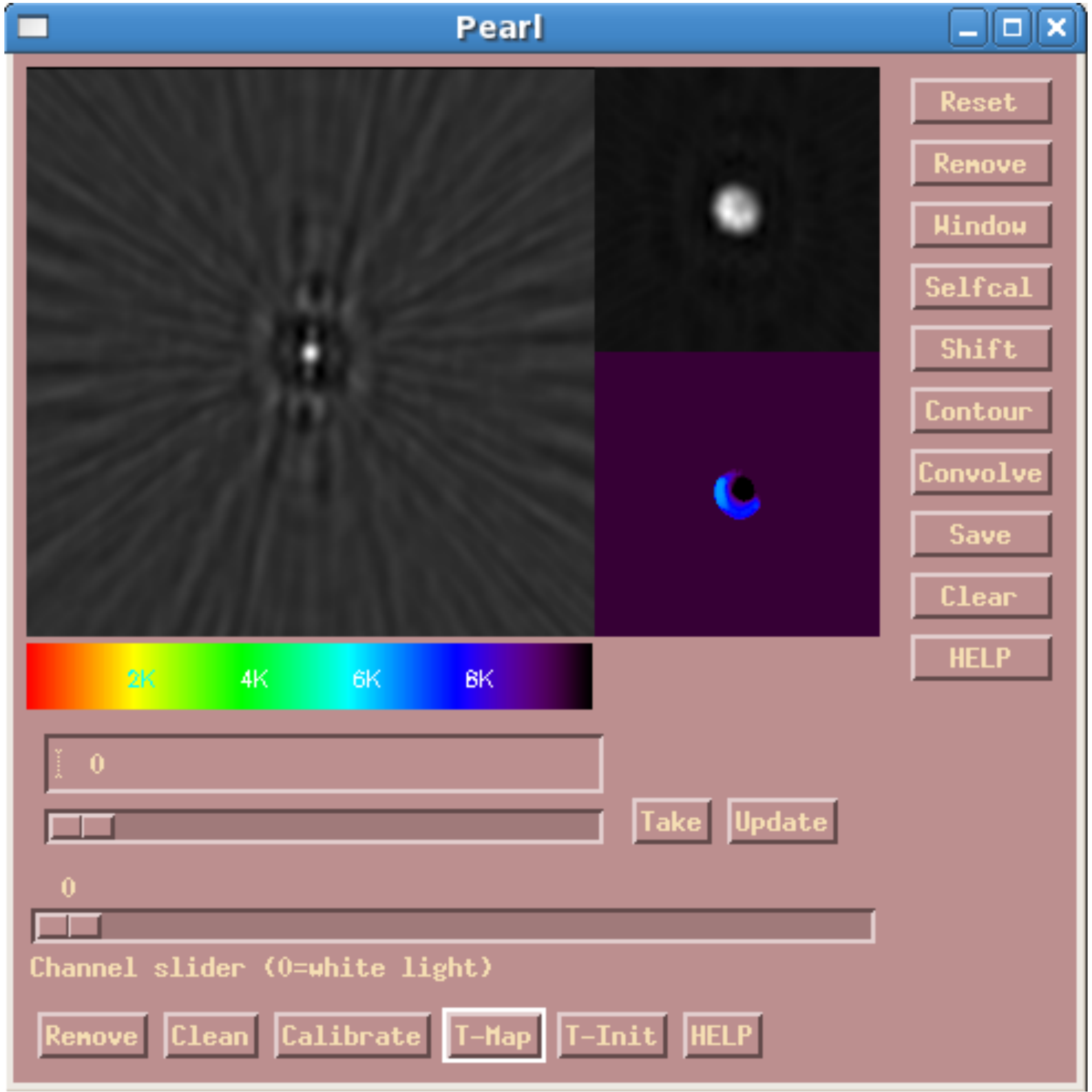






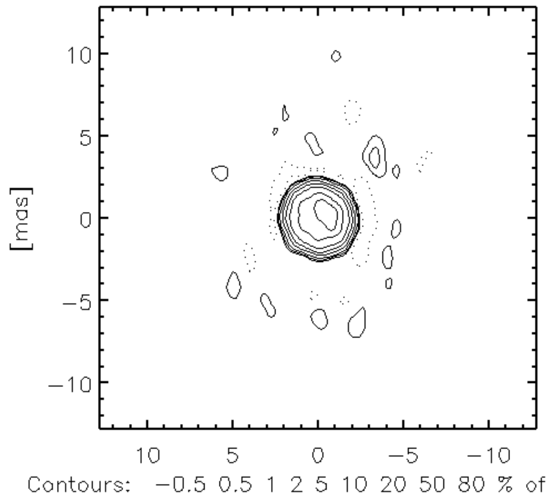
Implementation

- Assign eff. T to CLEAN components
- Combine all channels but compute PSF for each one
- Use spectrum for T calibration



Images of a rotating star

Uniform T: brightness



Cal. T-map: number density of CLEAN components