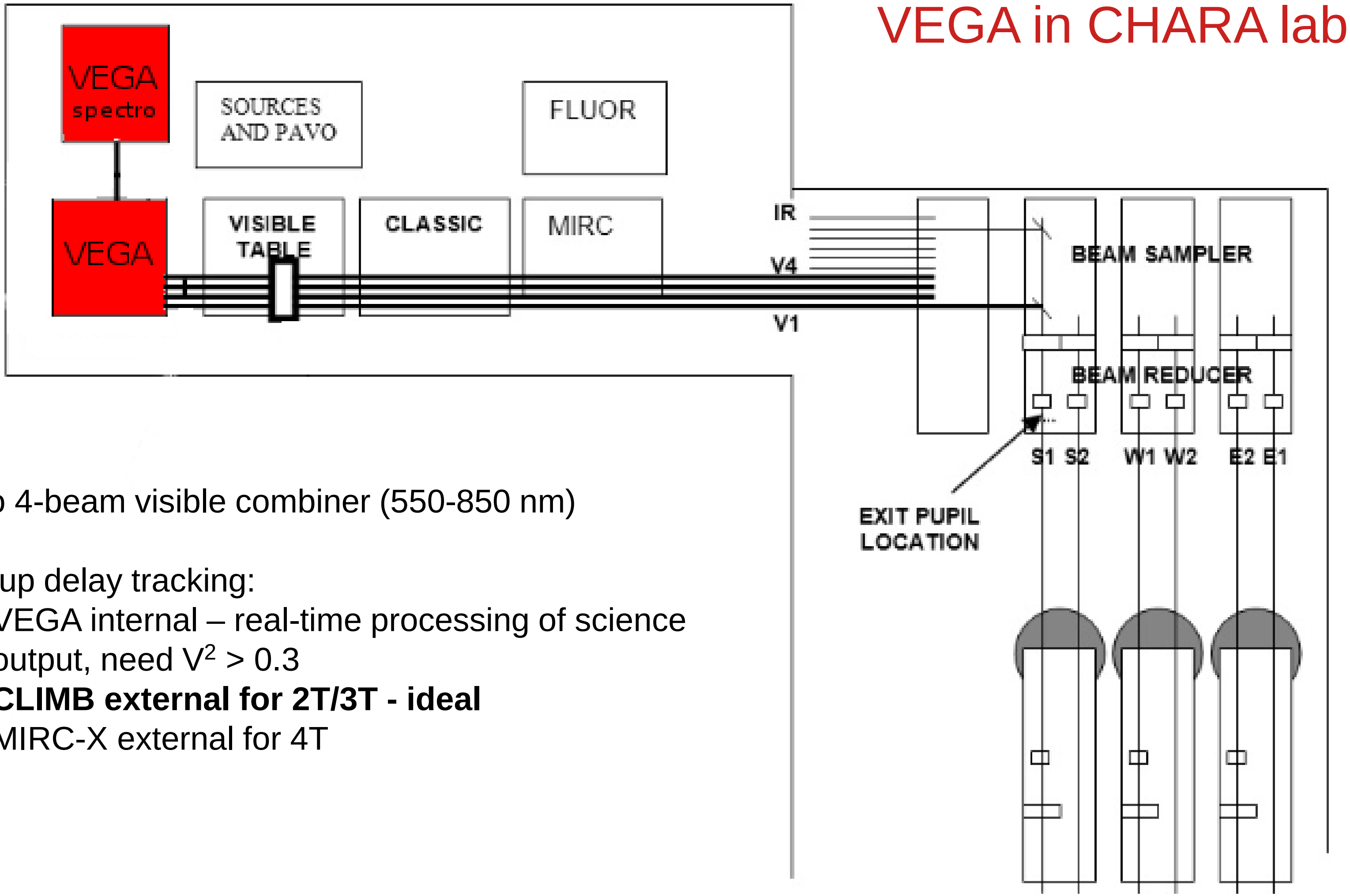
VEGA: Visible spEctroGraph and polArimeter for the CHARA array

- *Visible instruments are much more sensitive to atmospheric conditions, vibrations, etc.!*
- based on GI2T/REGAIN interferometer (Mourard+1994)*;* installed at CHARA in September 2007
- **Will be decommissioned in early 2021! SPICA to be installed in late 2021.**
- main features: **high spatial** (0.3 mas) **and spectral** (up to R=30000) **resolution;** 2-4 telescopes
- records dispersed fringes in multi-speckle regime -> *spectrum*, *squared visibilities* and *differential visibilities and phases* can be extracted. No closure phase capability (in 2T and 3T) due to detector saturation (Mourard et al. 2012).
- Instrument papers:
  - Mourard et al. (2009, 2011) – main instrument papers
  - Mourard et al. (2006, 2008, 2010, 2012) – SPIE technical reports
  - Ligi et al. (2013) – data flow from observation planning to science-ready data
- Science cases:
  - Fundamental stellar parameters – angular diameters (fast rotators, cepheid pulsations), binary stars
  - Circumstellar environments – Be stars, B[e] stars, interacting binaries (β Lyr)

VEGA in CHARA lab

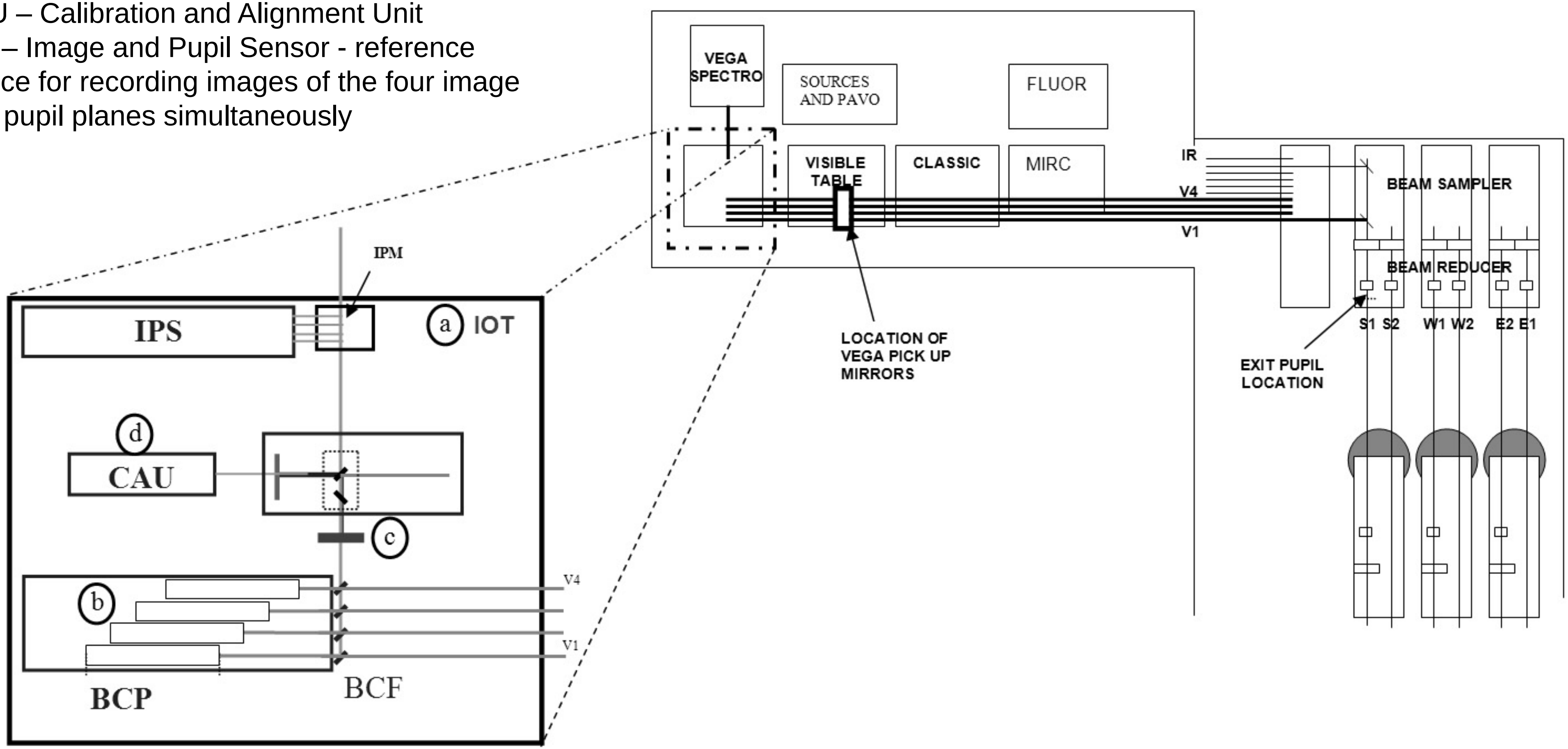


need LDCs in the path when using VEGA+CLIMB or VEGA+MIRC-X

- 2 to 4-beam visible combiner (550-850 nm)
- group delay tracking:
  - VEGA internal – real-time processing of science output, need $V^2 > 0.3$
  - **CLIMB external for 2T/3T - ideal**
  - MIRC-X external for 4T

VEGA interface table

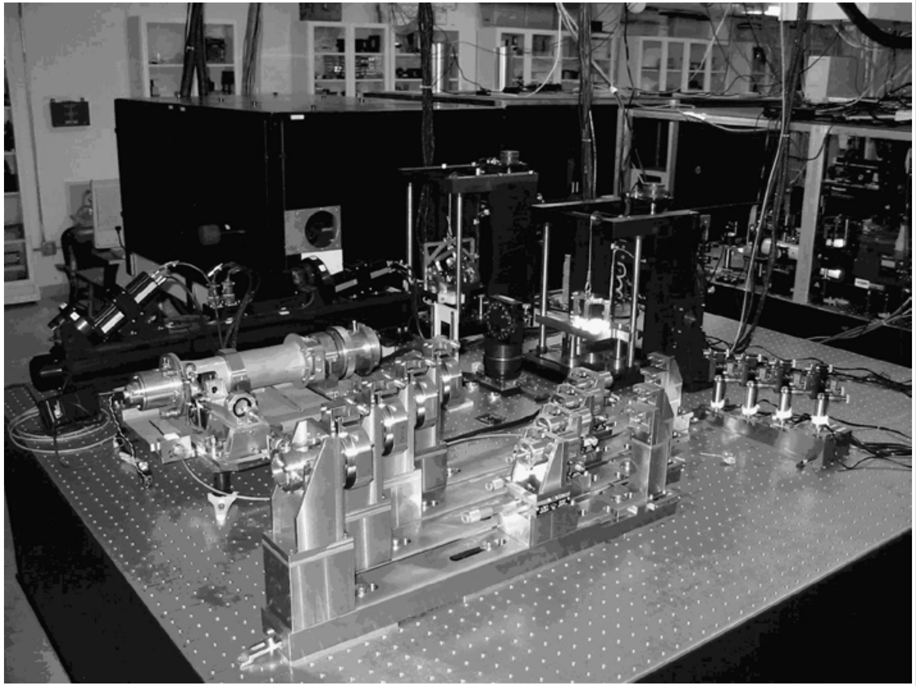
- IOT – Interface Optical Table
- BCP – Beam compressors, also for accurate equalization of internal optical path
- BCF – Beam configuration
- CAU – Calibration and Alignment Unit
- IPS – Image and Pupil Sensor - reference device for recording images of the four image and pupil planes simultaneously

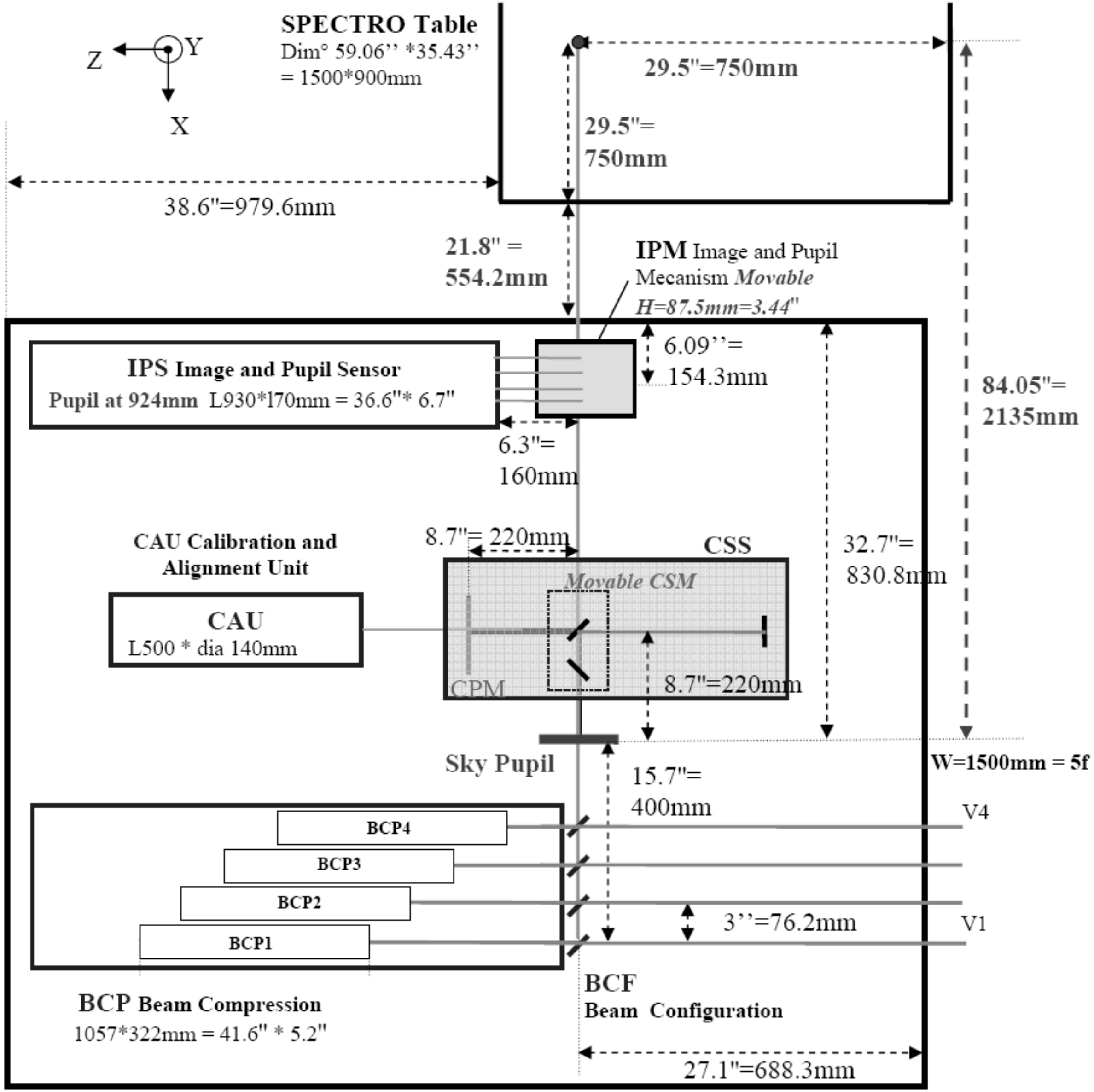


VEGA IOT

IOT functions:

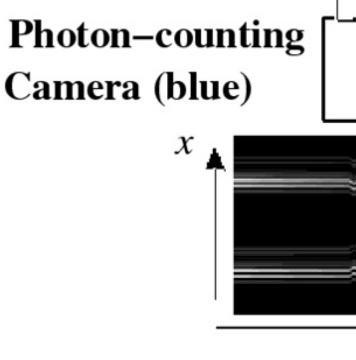
- geometrical adaptation of the beams
- control of the longitudinal position of the CHARA pupils + reimaging on VEGA spectrograph entrance slit
- equalization of the internal optical paths
- alignment and calibrations (Th-Ar)

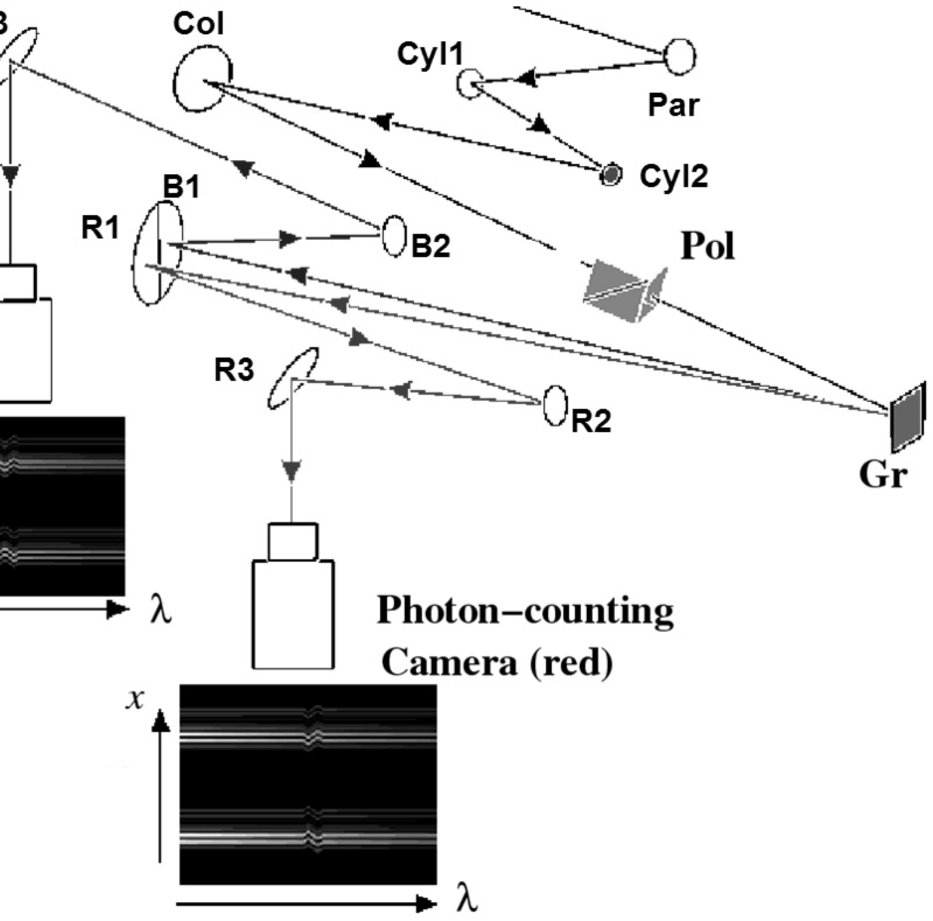


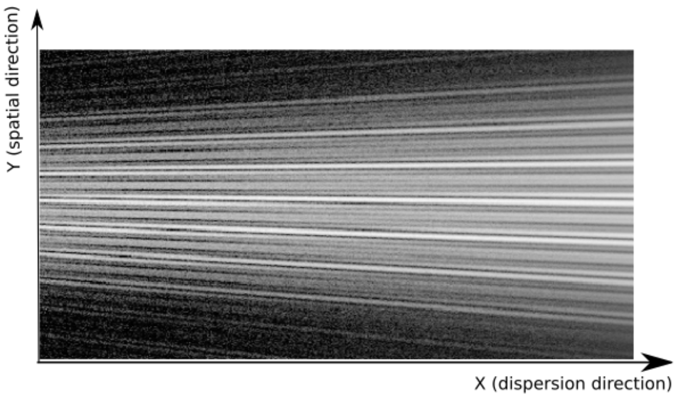


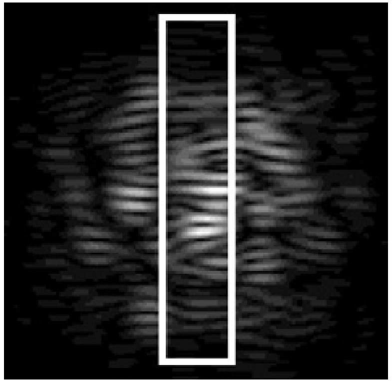
VEGA spectrograph

- fed by vertically aligned CHARA beams (5 mm diameter, 10 mm apart) – **fringes** appear as horizontal lines
- off-axis parabola forms coherent focus at spectrograph entrance slit – wide enough for ~1-2 **speckles**, slit vertical dimension ~4 arcsec on sky
- Cyl1 and Cyl2 mirrors resample horizontal fringes
- Collimator, a grating, and cameras for reimaging the spectrum
- spectral resolution:
  - medium: R = 5000 (60 km/s); $\Delta\lambda$ = 45 nm
  - high: R = 30000 (10 km/s); $\Delta\lambda$ = 8 nm



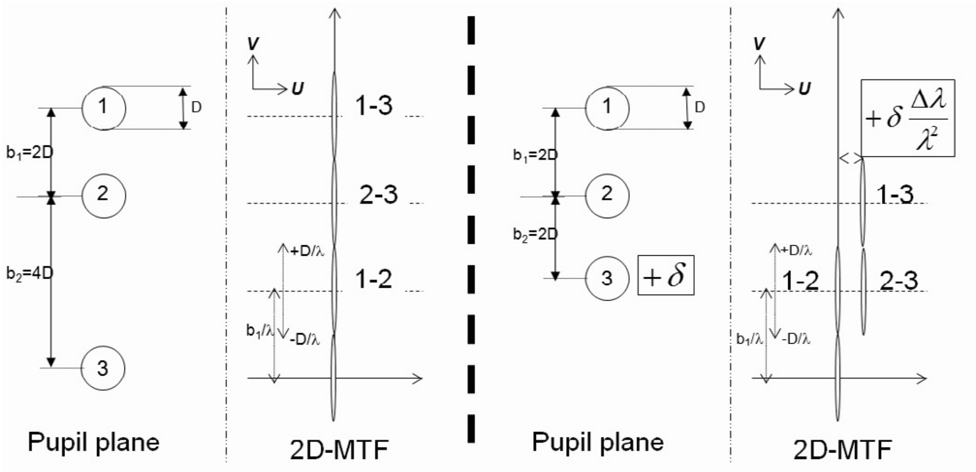


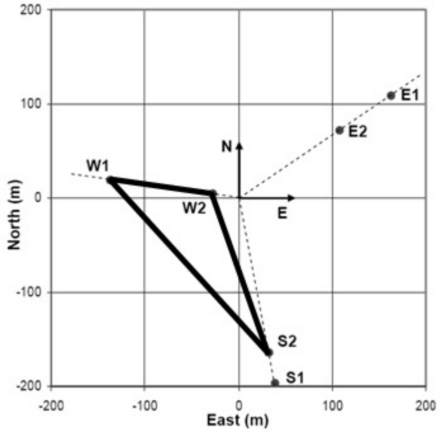


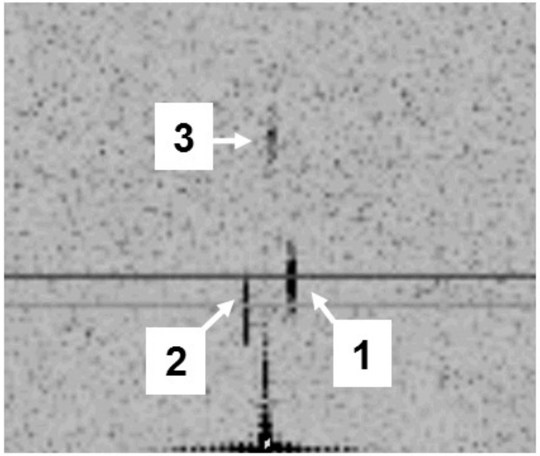


VEGA fringes

- multi-axial beam combination in dispersed fringe mode -> spatio-spectral encoding of fringes in a redundant linear configuration (cf. AMBER, MIRC)
- **spectrum** is extracted by collapsing 2D flux
- the **interferometric observables** are recovered in post-processing using the cros



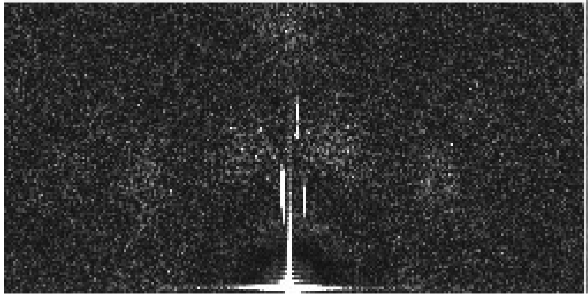




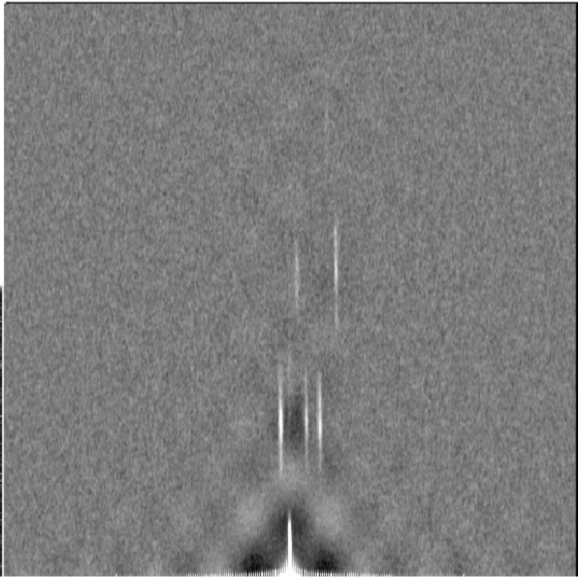
spectral density (power spectrum)

VEGA fringes

- multi-axial beam combination in dispersed fringe mode -> spatio-spectral encoding of fringes in a redundant linear configuration (cf. AMBER, MIRC)
- **spectrum** is extracted by collapsing 2D flux
- the **interferometric observables** are recovered in post-processing using the cross-spectrum method



3T mode



4T mode

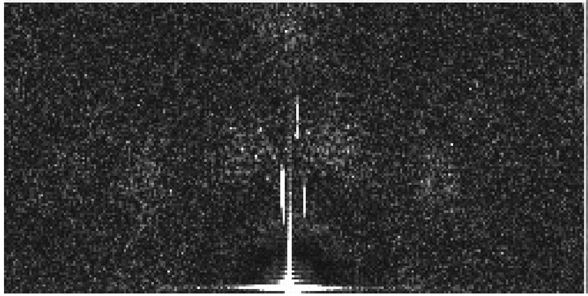
VEGA fringes

- multi-axial beam combination in dispersed fringe mode -> spatio-spectral encoding of fringes in a redundant linear configuration (cf. AMBER, MIRC)

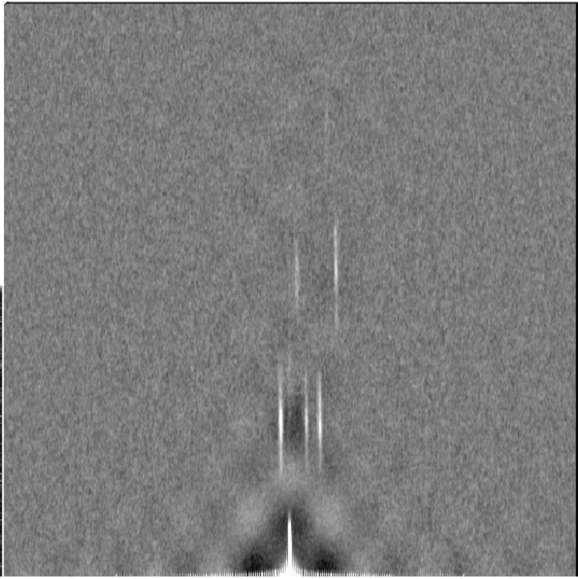
- **spectrum** is extracted by collapsing 2D flux

- the **interferometric observables** are recovered in post-processing using the cross-spectrum method

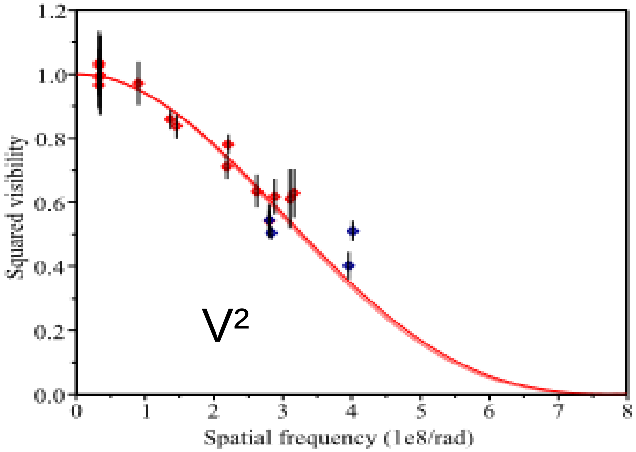
- **auto-correlation** -> V^2
  - V^2 estimated from the energy of high frequencies in the power-spectrum
  - need to calibrate for absolute visibility scale
  - useful for stellar diameters - ideal range 0.4 – 1.0 arcsec (minimum ~0.15 mas)



3T mode

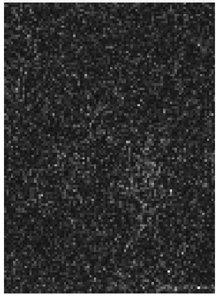


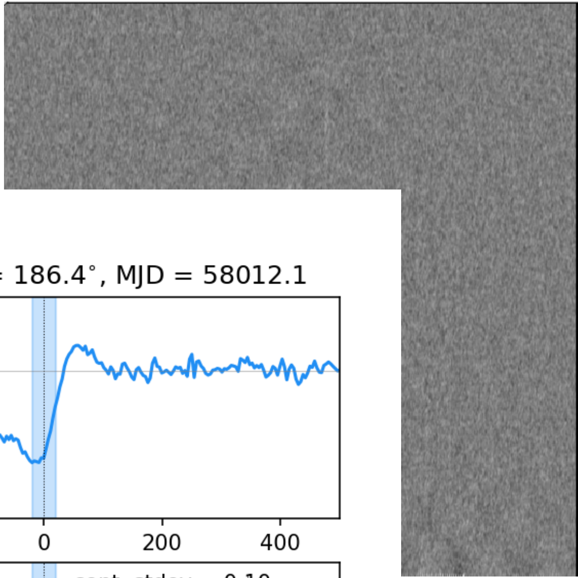
4T mode

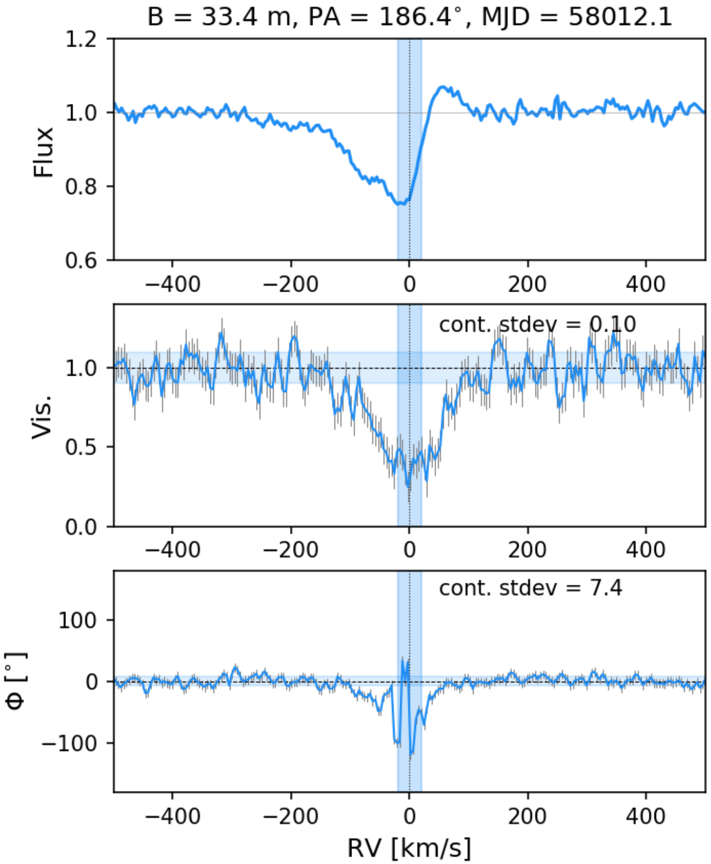


VEGA fringes

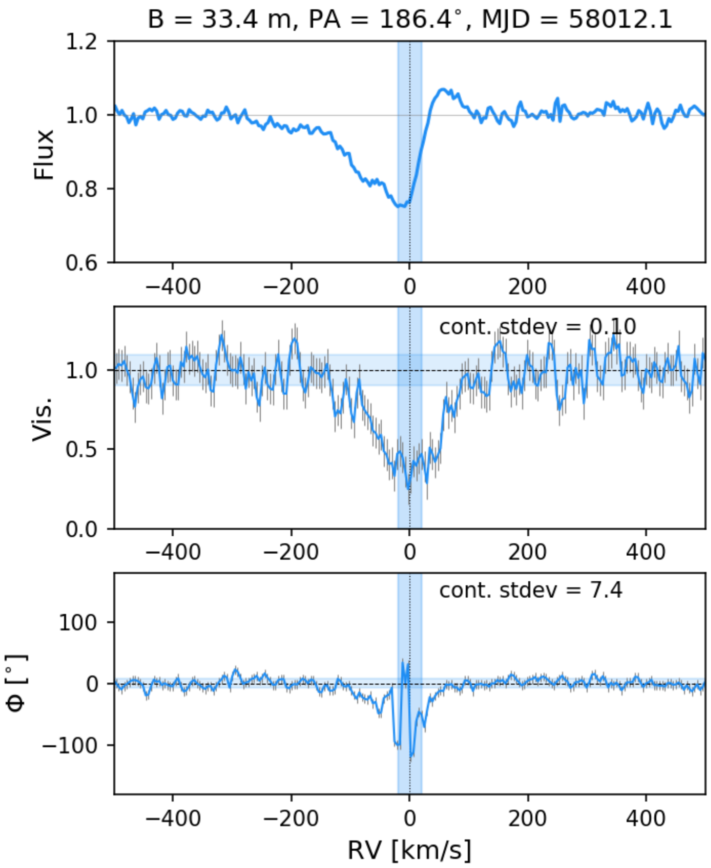
- dispersed fringe mode -> spatio-spectral encoding of fringes in a redundant linear configuration (cf. AMBER, MIRC)
- **spectrum** is extracted by collapsing 2D flux
- the **interferometric observables** are recovered in post-processing using the cross-spectrum method
- **inter-correlation** – differential data – V(λ) and φ(λ)
  - spectral resolution recovered by computing cross-spectrum between a narrow sliding spectral channel and the whole spectral band
  - **V(λ)** – size of line-emitting region for each λ bin
  - **φ(λ)** – photocenter displacement for each λ bin
  - useful for emission lines – circumstellar structure and kinematics

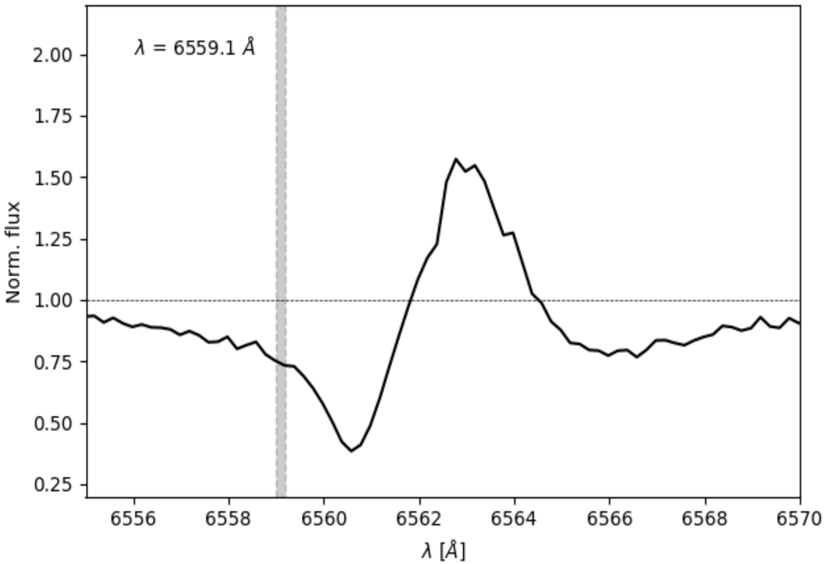




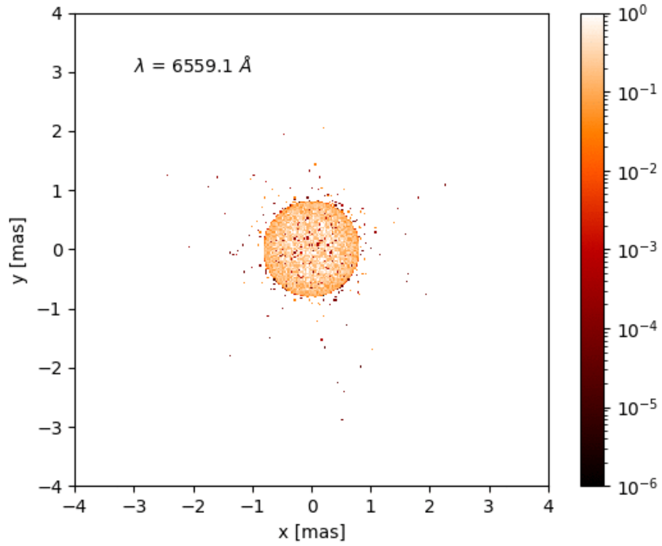


data


B = 33.4 m, PA = 186.4°, MJD = 58012.1
Flux
cont. stdev = 0.10
Vis.
cont. stdev = 7.4
Φ [°]
RV [km/s]


λ = 6559.1 Å
Norm. flux
λ [Å]

model


λ = 6559.1 Å
y [mas]
x [mas]

VEGA limitations

- Limitations set by detector (iCCD) saturation and multi-speckle approach
  - Saturation – need to use neutral density filters for bright stars – prevents from acquiring sufficient SNR to measure closure phases in 3T/4T mode
  - Speckle mode – need good seeing conditions – ideally > 1 photon/speckle/exposure
  -
- spectrum recovered from VEGA is unreliable due to detector saturation and not fully understood spectral PSF – might be influencing visibilities for objects with very strong line emission (Tallon et al. 2014, SPIE)

- limiting magnitudes – Sect. 4.4 of Mourard et al. (2009) – depend strongly on conditions, the object itself, and the spectral resolution (for differential measurements)

- the calibrator problem - need for calibrators <0.15 mas (for 300 m baselines) to get V^2 > 0.8

- portion of visible light has to be separated and used for tiptilt/AO

Resolution	R	Typical lim. magnitude	Best perf.
Low	1700	6.8	7.5
Medium	6000	6.5	7.5
High	30 000	4.2	5.5

These values are presented for the median value of r_0 at Mount Wilson i.e. 8 cm. We also indicate the best performances assuming an r_0 of 15 cm.

Science with VEGA

https://lagrange.oca.eu/fr/publications-vega

Publications with VEGA (refereed)

2020

P46: "Benchmarking the fundamental parameters of Ap stars with optical long-baseline interferometric measurements", K. Perraut, M. Cunha, A. Romanovskaya et al., A&A submitted

P45: "Calibrating the Surface-Brightness-color relation for late type red giant stars in the visible domain using VEGA/CHARA interferometric measurements', N. Nardetto, A. Salsi, D. Mourard et al., A&A (accepted pdf)

P44: "Precise calibration of the colour- and class-dependence of surfacePrecise calibration of the colour- and class-dependence of surfacebrightness-colour relations for late-type stars", A. Salsi, N. Nardetto, D. Mourard et al., A&A (accepted pdf)

P43: "Optical interferometry and Gaia measurement uncertainties revealOptical interferometry and Gaia measurement uncertainties revealthe physics of asymptotic giant branch stars", A. Chiavassa, K. Kravchenko, F. Millour et al. (mainly MIRCx)., A&A (accepted pdf)

Planning observations

- Do you want differential data, calibrated V^2, or both?
  - differential only – consider using high spectral resolution for very bright targets
  - calibrated + differential – need to use medium spectral resolution and calibrators

- adapt baselines to the observed target – if the object is highly resolved in continuum, VEGA will have trouble

- one VEGA observation takes 10-15 minutes – calibrated bracket 30-45 minutes

- **Measurement of differential vis. and phase data** is highly sensitive to seeing and atmospheric piston on long baselines – in practice mostly 2T mode on the inner pairs

- **Measuring of V^2 data** is easier - 3T mode is routinely used

Planning observations

- VEGA observations are scheduled in ~week-long runs and performed on-site or remotely by the VEGA team (Nice, France)

- if your program is considered for the run -> prepare .asprox file and describe priorities and observing strategy

- The observations are ordered in a queue based on priority and conditions – ‘service mode’ – you don’t have to do anything

- It is up to the PI to reduce the data using the VEGA pipeline (idl)

Observing with VEGA

- 3 offsets: carts, BC1 (CLIMB table), VEGA internal offset
- scanning for CLIMB fringes with carts -> BC1 moved to find fringes on VEGA
- target has to be bright enough for VEGA and CLIMB with LDCs!!!
- VEGA internal offset – VEGA can operate without CLIMB, but performance is much worse

Processing your data

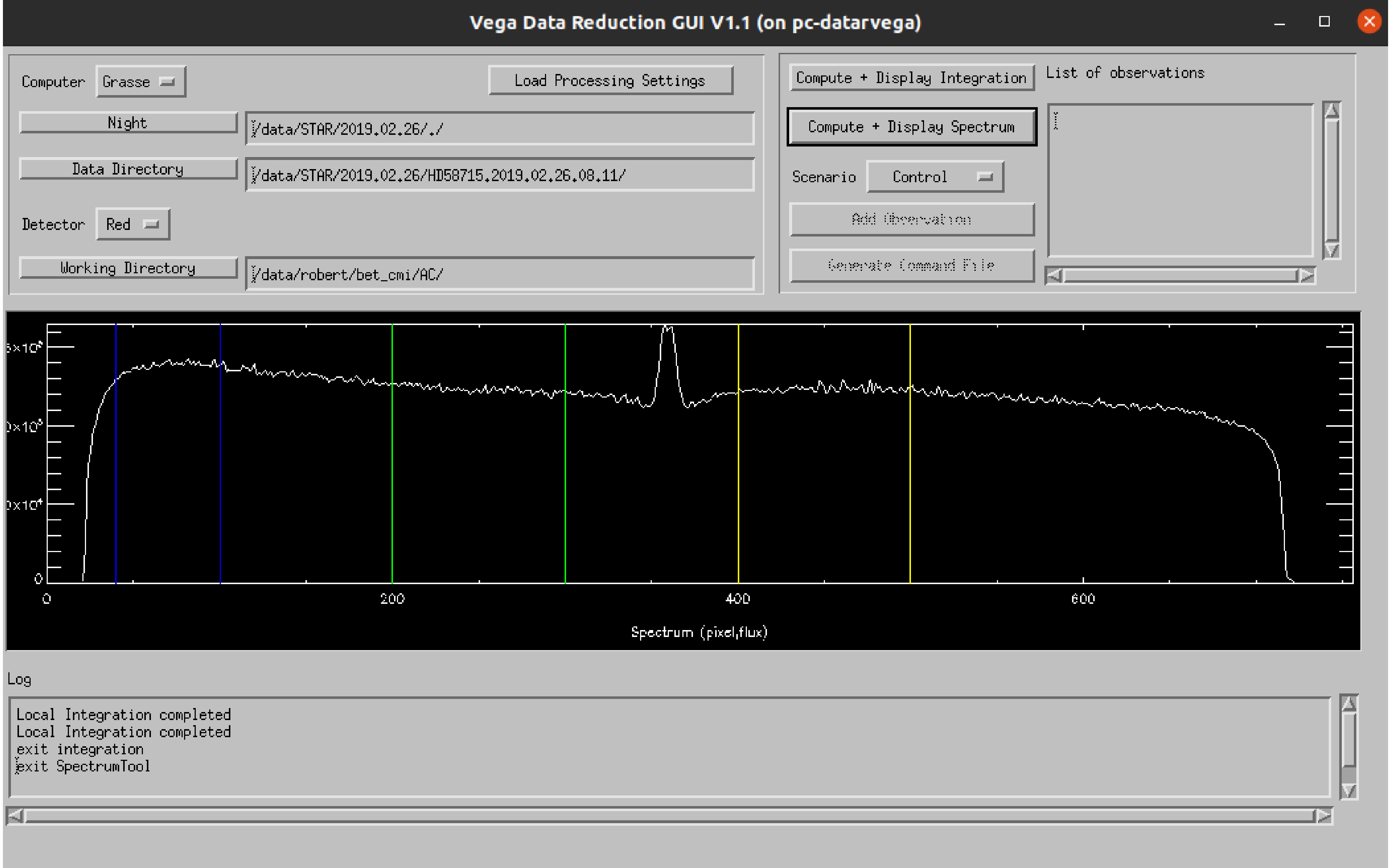
1) learn French (some manuals, obs. logs, and communications are in French only)
2) check the observing log - https://lagrange.oca.eu/fr/news-vega
3) ask D. Mourard to set up an account on *pc-datarvega* (Mount Wilson)
4) on pc-datarvega run *idl* -> *vegadrs* (VEGA data reduction system)
5) follow steps to reduce data in auto-correlation and/or inter-correlation mode
6) (calibrate V^2 data with calibrator observations)

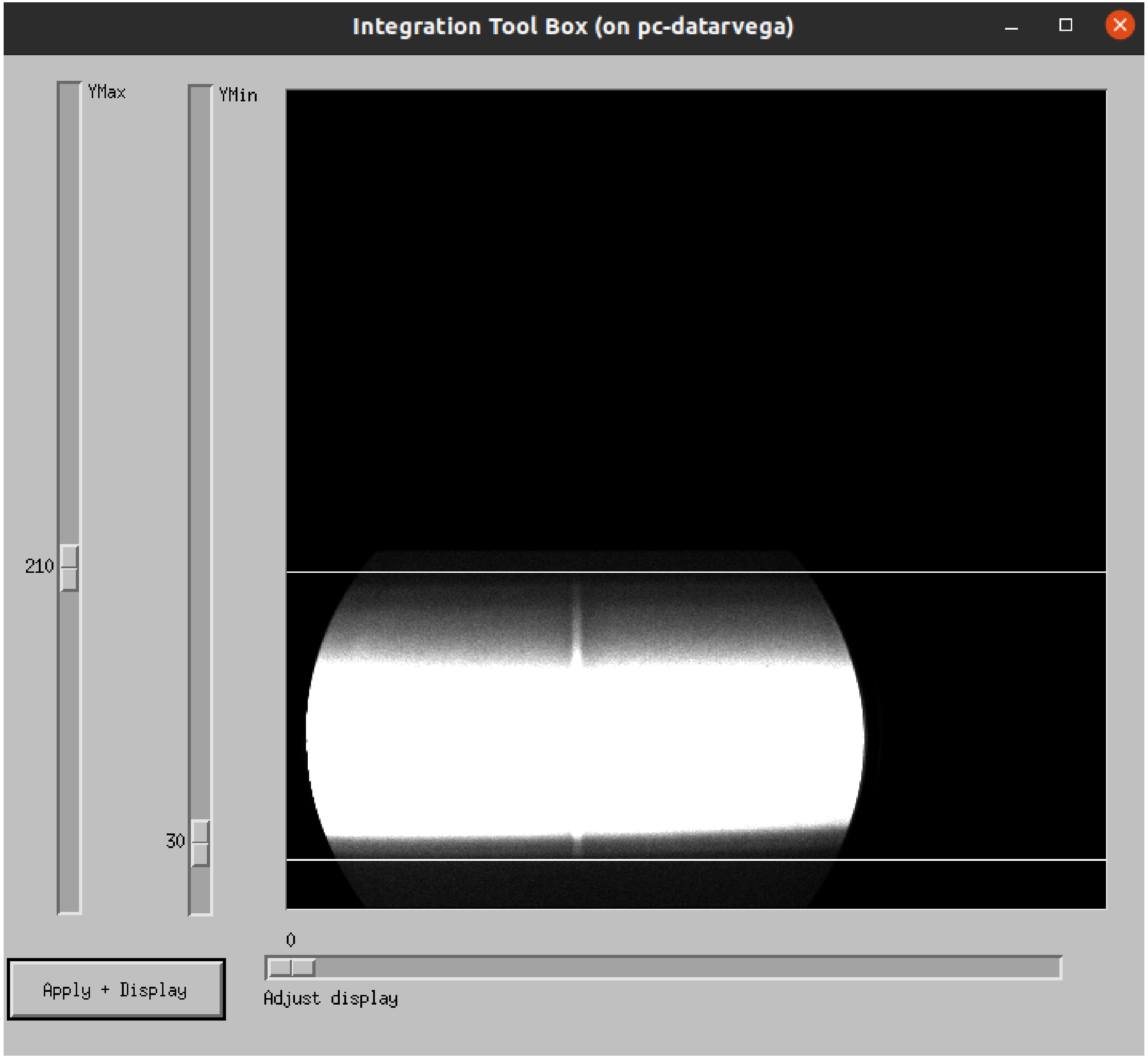
E2 POP1 B1 – E2 POP2 B2 - W1 POP1 B3
V70 (R. Klement) – P Cyg
OPD offset: +150μm (left)

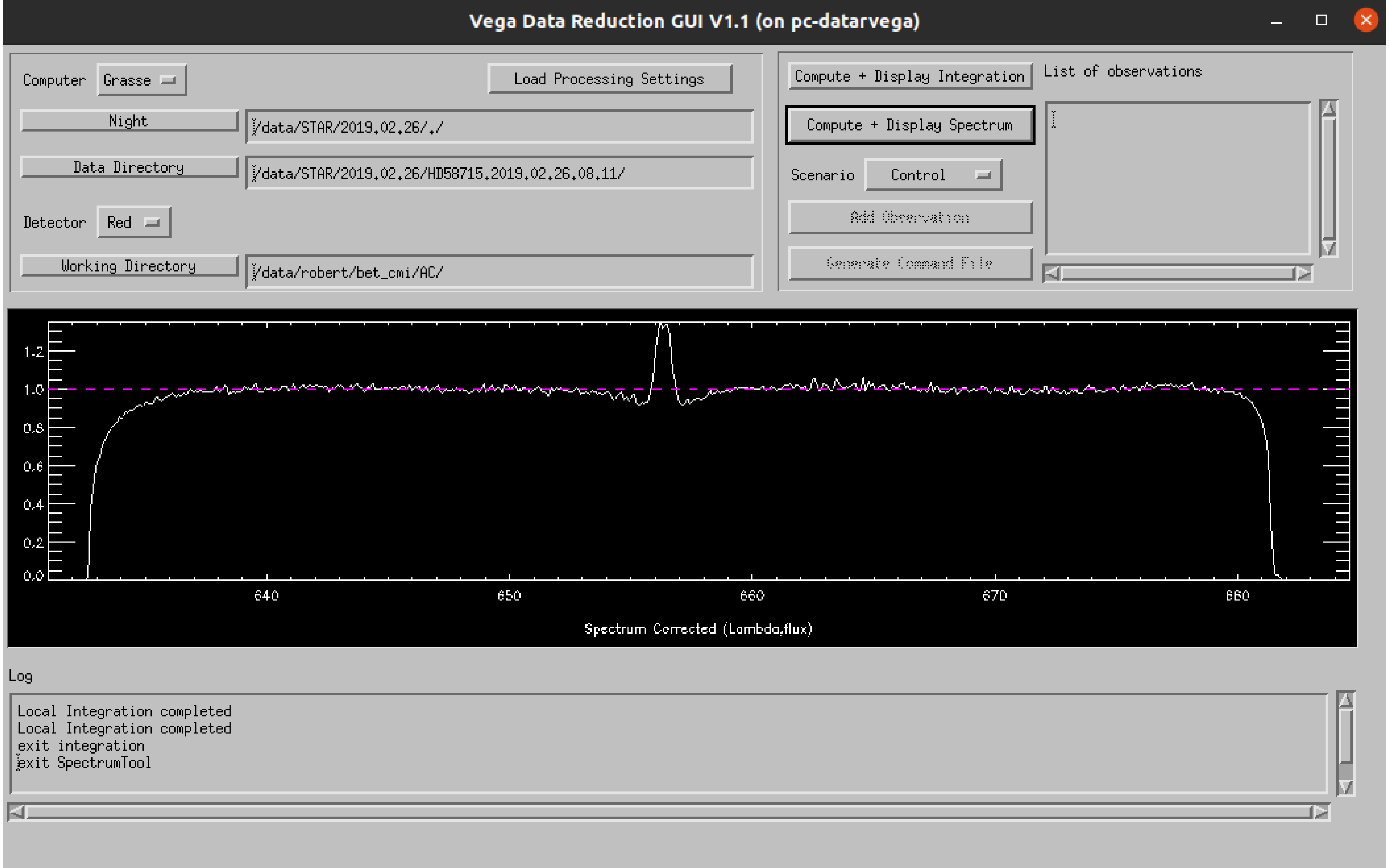
Target HD193237
Cal1 = HD191243
Cal2 = HD197392
Check = Target

06:08: Slewing to the target as a check star
06:25: E2 cart stuck. Rehoming
06:39: E2 is back.
06:52: NIRO Aligned.
06:56: Fringes found by CLIMB, a bit shaky but bright at least.

HD193237.2020.06.12.06.59
E1: 3040
CLIMB_B1= 6.02
CLIMB_B2= 4.91
20 blocks
07:00: Nice fringes on VEGA.
07:09: Gong to Cal1.
r_0~6.5cm


Vega Data Reduction GUI V1.1 (on pc-datarvega)
Computer
Grasse
Load Processing Settings
Night
/data/STAR/2019.02.26/./
Data Directory
/data/STAR/2019.02.26/HD58715.2019.02.26.08.11/
Detector
Red
Working Directory
/data/robert/bet_cmi/AC/
Compute + Display Integration
List of observations
Compute + Display Spectrum
Scenario
Control
Add Observation
Generate Command File
0
200
400
600
Spectrum (pixel,flux)
Log
Local Integration completed
Local Integration completed
exit integration
exit SpectrumTool


Integration Tool Box (on pc-datarvega)
YMax
YMin
210
30
0
Apply + Display
Adjust display


Vega Data Reduction GUI V1.1 (on pc-datarvega)
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Night
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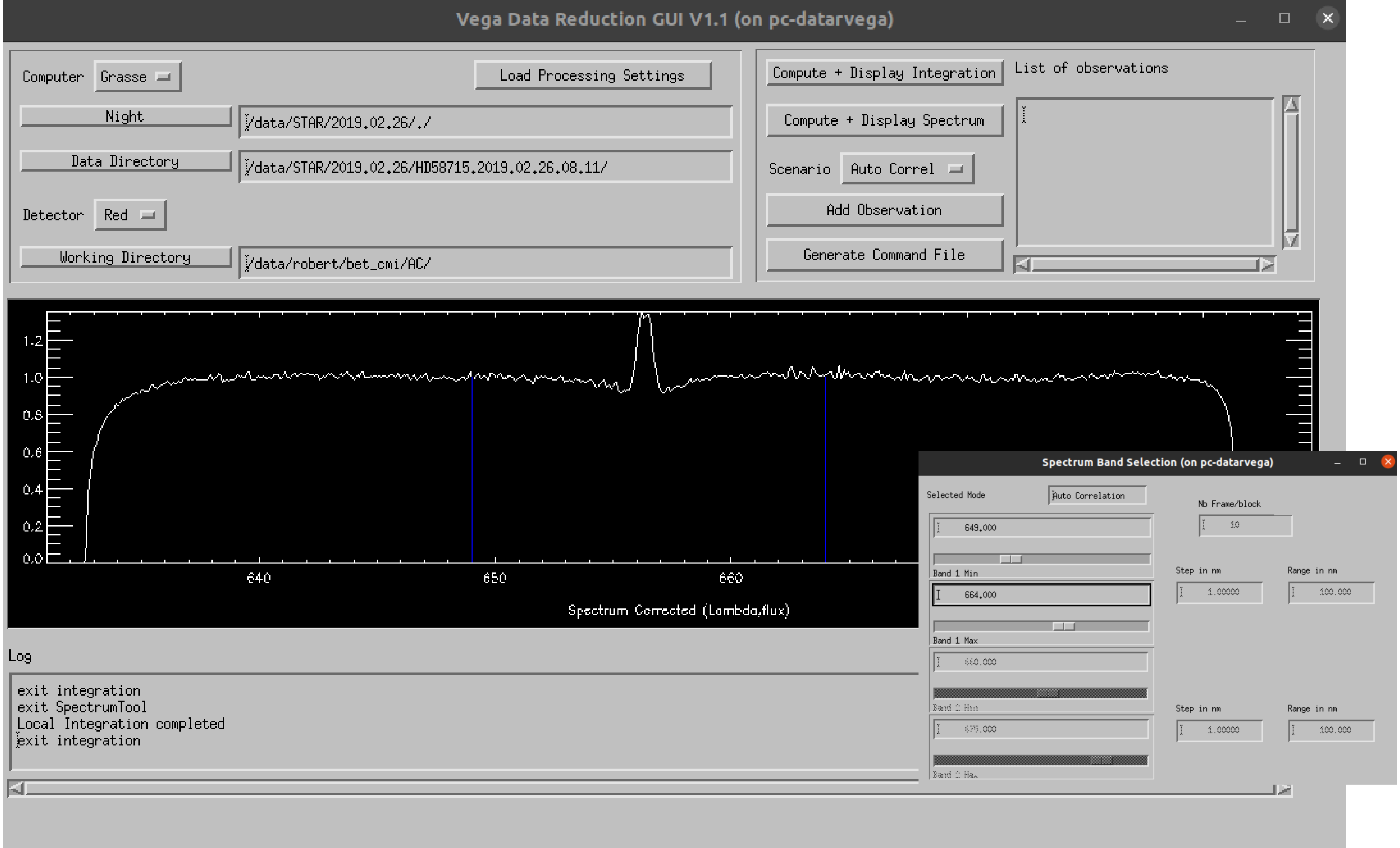
Data Directory
/data/STAR/2019.02.26/HD58715.2019.02.26.08.11/
Detector
Red
Working Directory
/data/robert/bet_cmi/AC/
Compute + Display Integration
Compute + Display Spectrum
Scenario
Control
Add Observation
Generate Command File
List of observations
1.2
1.0
0.8
0.6
0.4
0.2
0.0
640
650
660
670
680
Spectrum Corrected (Lambda,flux)
Log
Local Integration completed
Local Integration completed
exit integration
exit SpectrumTool


Vega Data Reduction GUI V1.1 (on pc-datarvega)
Computer
Grasse
Load Processing Settings
Night
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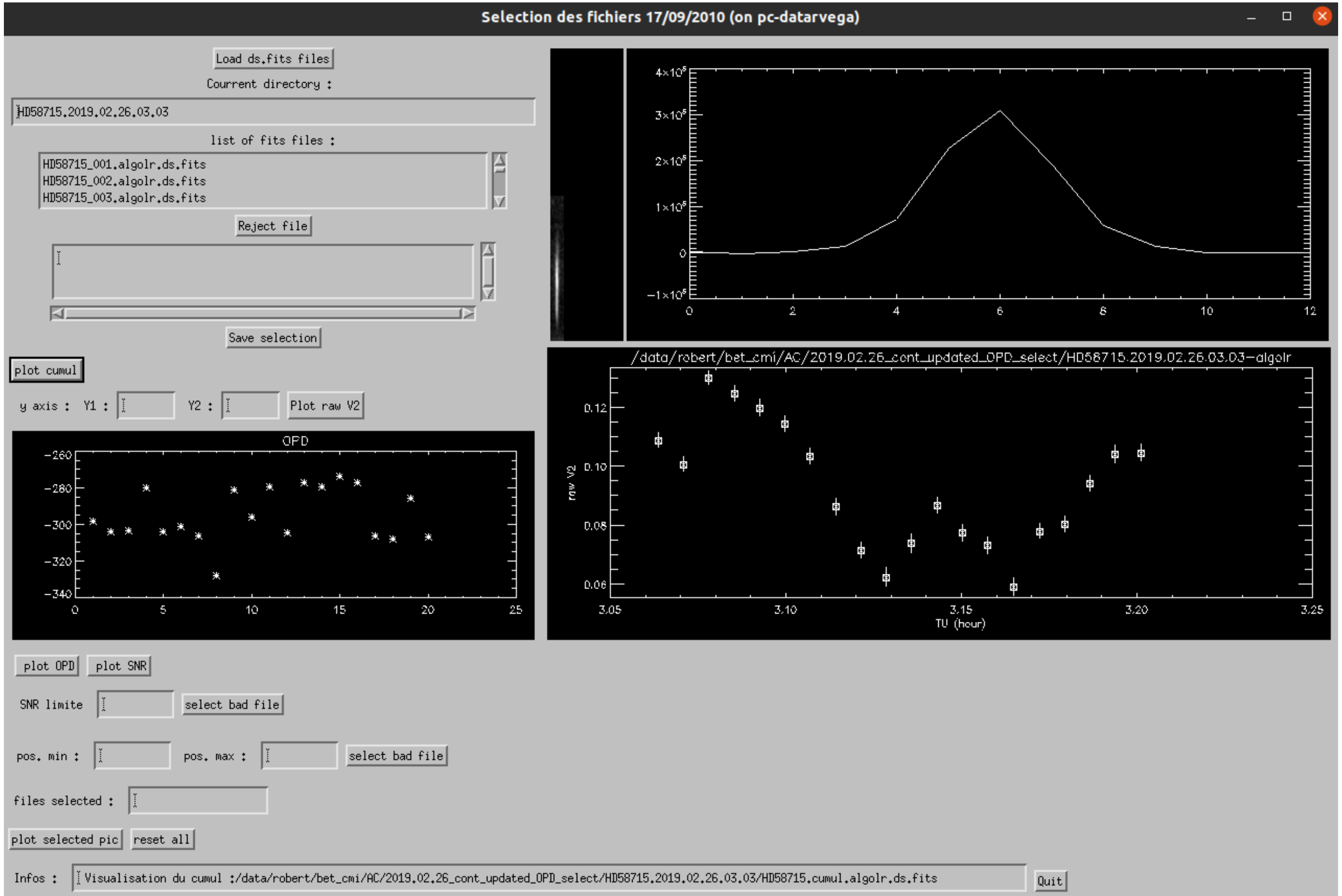
Data Directory
/data/STAR/2019.02.26/HD58715.2019.02.26.08.11/
Detector
Red
Working Directory
/data/robert/bet_cmi/AC/
Compute + Display Integration
Compute + Display Spectrum
Scenario
Auto Correl
Add Observation
Generate Command File
List of observations
Spectrum Corrected (Lambda,flux)
Log
exit integration
exit SpectrumTool
Local Integration completed
exit integration
Spectrum Band Selection (on pc-datarvega)
Selected Mode
Auto Correlation
Nb Frame/block
10
649.000
Band 1 Min
664.000
Band 1 Max
Step in nm
1.00000
Range in nm
100.000
660.000
675.000
Step in nm
1.00000
Range in nm
100.000

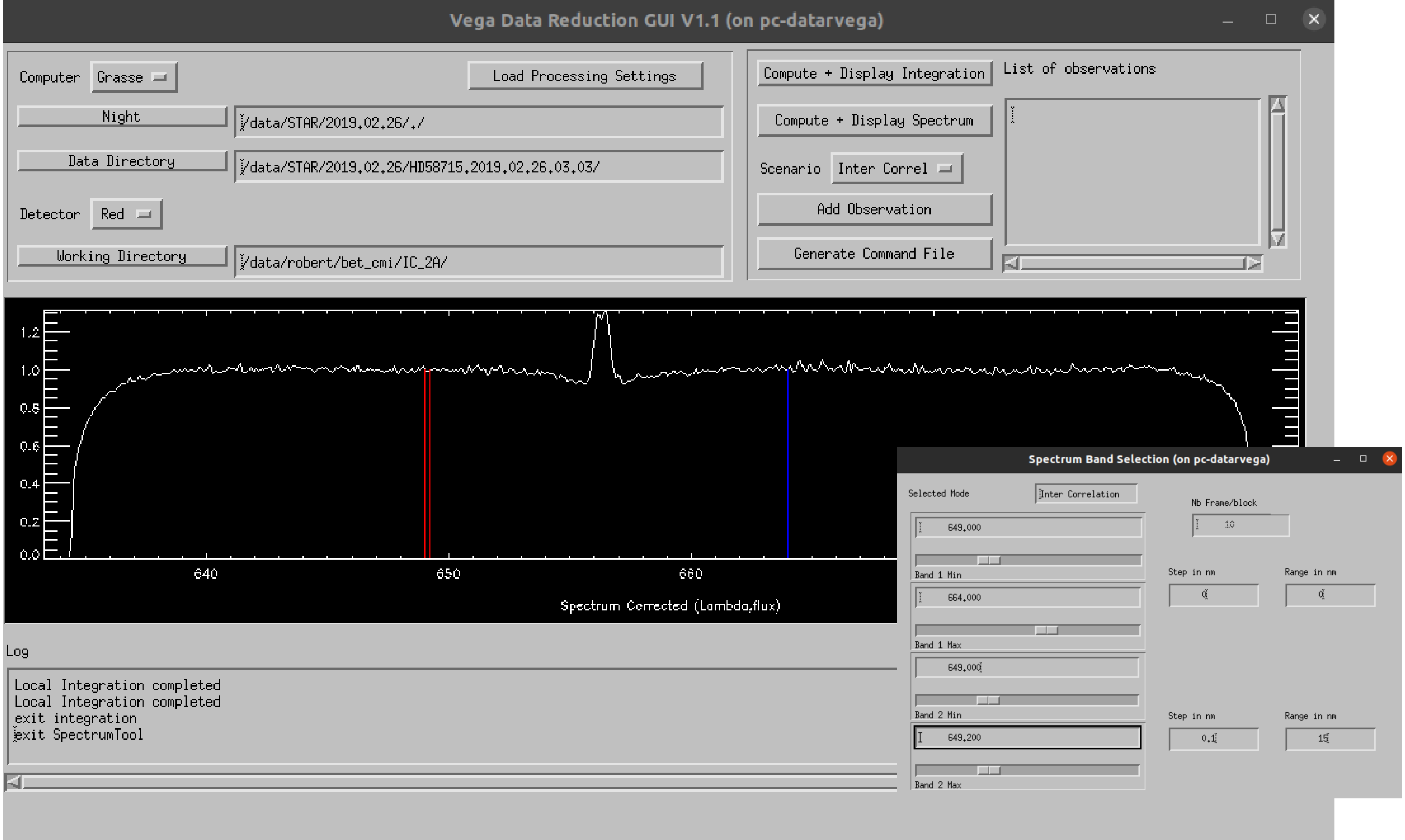
```
WORKINGDIR      /data/robert/bet_cmi/AC/.
NIGHT   2019.12.10
CAMERA  algolr
SCENARIO        AC_INDIV
LMIN0       6490.00
LMAX0       6640.00
YMAX           420
YMIN            60
POLDEG  3
NBCONT  3
CONTMIN3            503
CONTMAX3            654
CONTMIN2            208
CONTMAX2            308
CONTMIN1             91
CONTMAX1            420
NBOBS          4
OBS1    HD58187.2019.12.10.10.58
OBS2    HD58187.2019.12.10.11.50
OBS3    HD58187.2019.12.10.12.45
OBS4    HD58187.2019.12.10.13.31
OPD1 -300
```

- vega_gen_conf_file 2019-02-26_SCI.cmd
- csh lance_ac_2019.02.26.csh – takes some time to run

to inspect individual blocks, run idl -> vega_select_file – blocks with low SNR or wrong OPD should be discarded



- repeat for CALs
- calibrate V^2 of SCI using known diameters of CALs
- idl -> vega_post_ac_raw -> vega_post_ac_cal



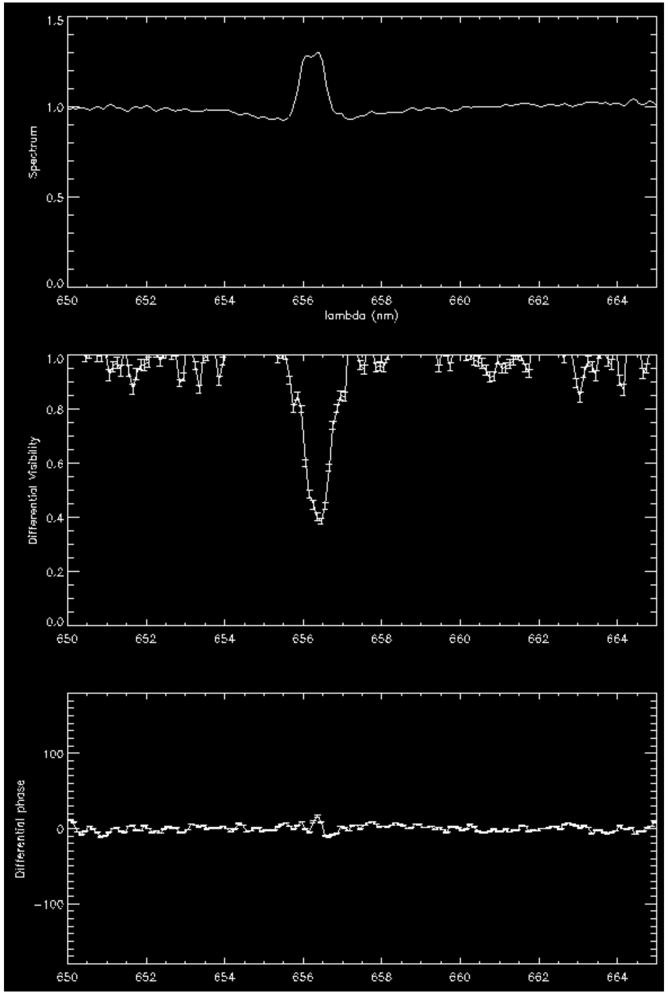
Vega Data Reduction GUI V1.1 (on pc-datarvega)
Computer
Grasse
Load Processing Settings
Night
/data/STAR/2019.02.26/./
Data Directory
/data/STAR/2019.02.26/HD58715.2019.02.26.03.03/
Detector
Red
Working Directory
/data/robert/bet_cmi/IC_2A/
Compute + Display Integration
Compute + Display Spectrum
Scenario
Inter Correl
Add Observation
Generate Command File
List of observations
Spectrum Corrected (Lambda,flux)
Log
Local Integration completed
Local Integration completed
exit integration
exit SpectrumTool
Spectrum Band Selection (on pc-datarvega)
Selected Mode
Inter Correlation
Nb Frame/block
10
649.000
Band 1 Min
664.000
Band 1 Max
649.000
Band 2 Min
649.200
Band 2 Max
Step in nm
0
Range in nm
0
Step in nm
0.1
Range in nm
15

```
WORKINGDIR      /data/robert/bet_cmi/IC_2A
NIGHT   2019.02.26
CAMERA  algolr
SCENARIO        IC
LMIN1          6500.00
LMAX1          6650.00
STEPL1          0.0000000
RANGL1          0.0000000
LMIN2          6500.00
LMAX2          6502.00
STEPL2          1.0000000
RANGL2          150.00000
YMAX              420
YMIN               60
POLDEG  3
NBCONT  3
CONTMIN3                512
CONTMAX3                659
CONTMIN2                212
CONTMAX2                312
CONTMIN1                 52
CONTMAX1                397
NBOBS          1
OBS1    HD58715.2019.02.26.05.01
```

- vega_gen_conf_file 2019-02-26_SCI.cmd
- csh lance_ic_2019.02.26.csh

if bad blocks were selected based on AC processing, make sure to discard them for IC processing

idl -> vega_post_ic



What to check

- if AC looks bad (no fringe in cumul plot) – IC will not work
- if AC looks good:
  - estimate the number of speckles entering the spectrograph entrance slit per esposure – this is based on seeing – ~20 speckles in bad seeing (5cm), ~7 speckles in good seeing (15 cm)
  - check the number of photons per wavelength bin (NBPHOT) -> estimate photons/speckle – recommended that is is >1 – if not, widen the wavelength bin

VEGA tips

- start with 2T mode on short baselines with medium spectral resolution and go on from there
- VEGA is very sensitive to seeing – select targets for different conditions – targets close to the magnitude limit will be difficult unless there are excellent conditions
- do not attempt 4T mode without MIRC or 2T/3T mode without CLIMB

SPICA

- built on the combination of the new AO systems, single mode fibres for spatial filtering, and modern EMCCD detectors.
- It will operated in LR (R=300) and MR (R=3000) dispersed fringes of 6T (15 baselines).
- It is assisted by a H-band fringe tracking system.
- many science goals but the top level requirements are given by the idea of a large survey of stellar fundamental parameters.

SPICA, a new 6T visible beam combiner for CHARA: science, design and interfaces

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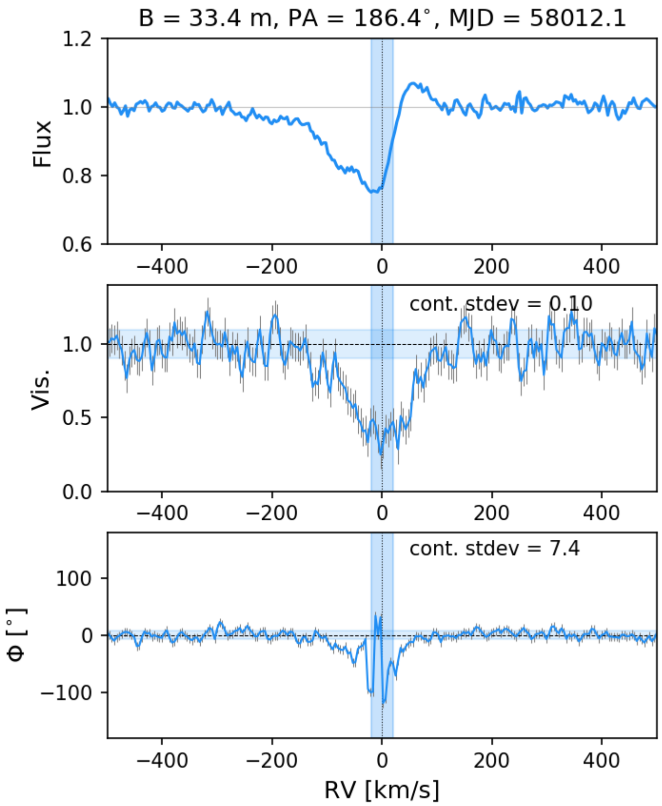
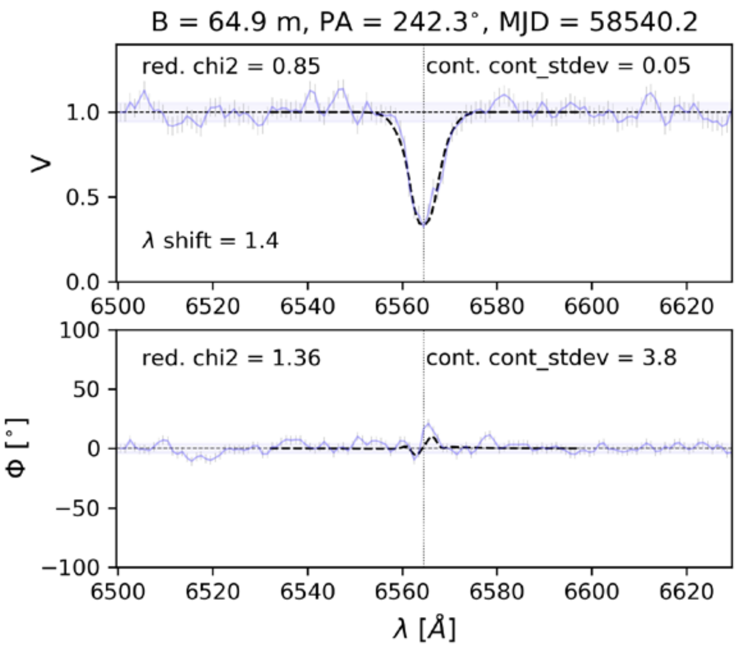
[a]Université Côte d'Azur, OCA, CNRS, Lagrange, Parc Valrose, Bât. Fizeau, 06108 Nice cedex 02, France
[b]CHARA Array, Mount Wilson Observatory, Mount Wilson, CA 91023, USA
[c]ONERA/DOTA, Université Paris Saclay, 92322 Châtillon, France
[d]Université Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[e]Université de Lyon, Université Lyon 1, Ecole Normale Supérieure de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France

Abstract. We present the recent developments preparing the construction of a new visible 6T beam combiner for the CHARA Array, called SPICA. This instrument is designed to achieve a large survey of stellar parameters and to image surface of stars. We first detail the science justification and the general idea governing the establishment of the sample of stars and the main guidance for the optimization of the observations. After a description of the concept of the instrument, we focus our attention on the first important aspect: optimizing and stabilizing the injection of light into single mode fibers in the visible under partial adaptive optics correction. Then we present the main requirements and the preliminary design of a 6T-ABCD integrated optics phase sensor in the H-band to achieve long exposures and reach fainter magnitudes in the visible.

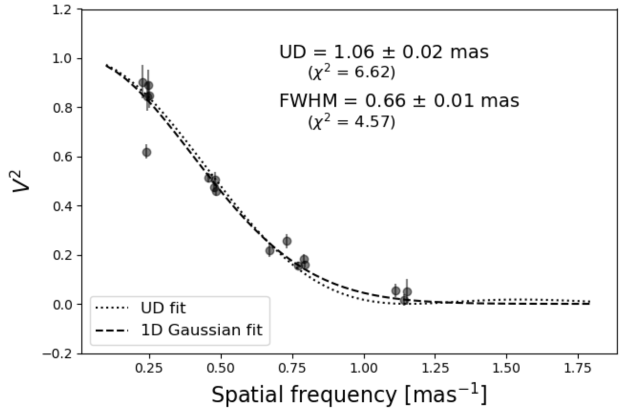
VEGA data



high-resolution data centered on Hα



medium-resolution data with a model overplotted



calibrated V^2 for diameter measurement