AMBER
The near infrared VLTI focal instrument

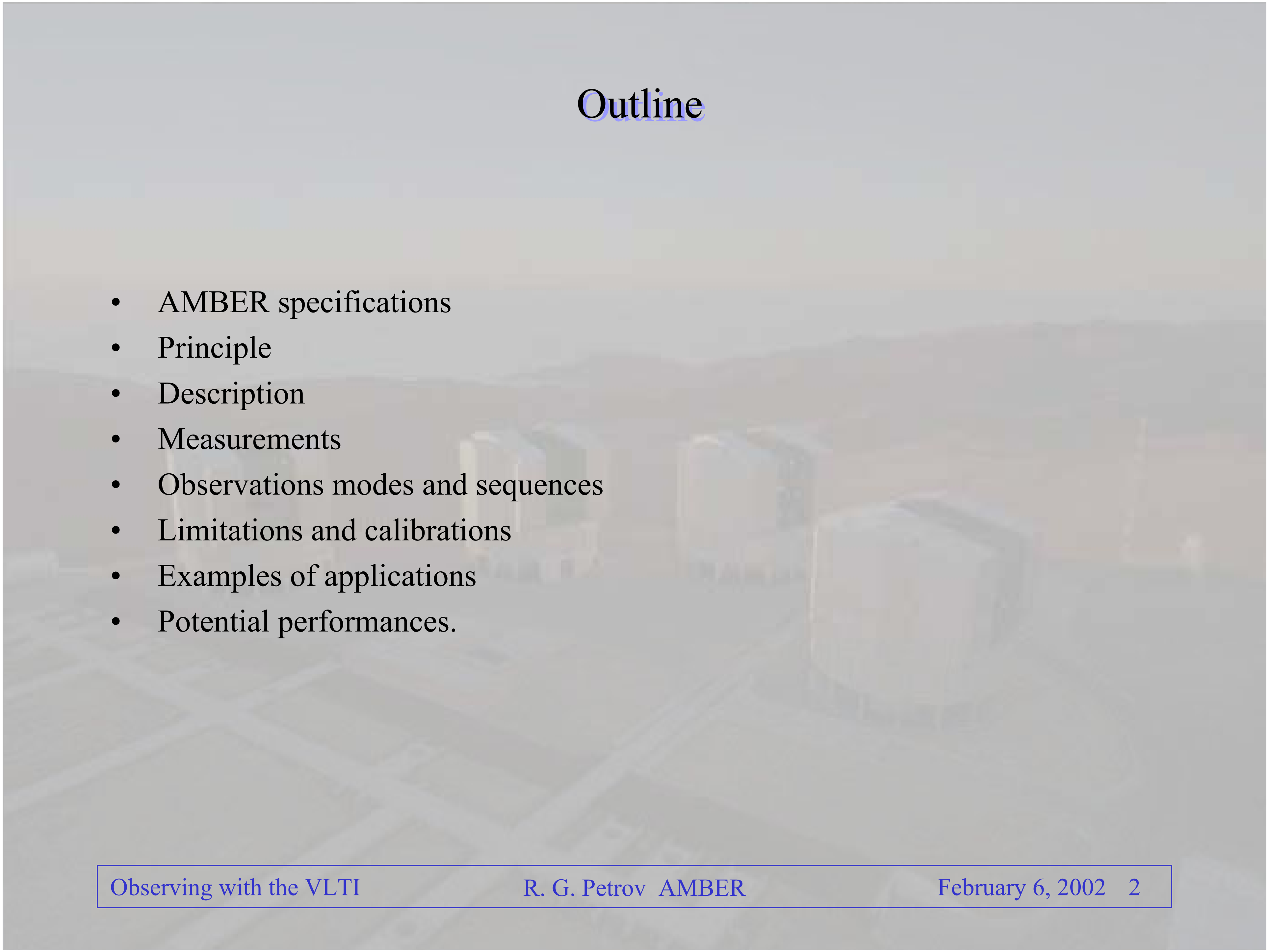
EuroWinter School

Observing with the Very Large Telescope Interferometer

Les Houches, France
February 3-8, 2002

Romain G. Petrov
Université de Nice - Sophia Antipolis / CNRS
February 6, 2002

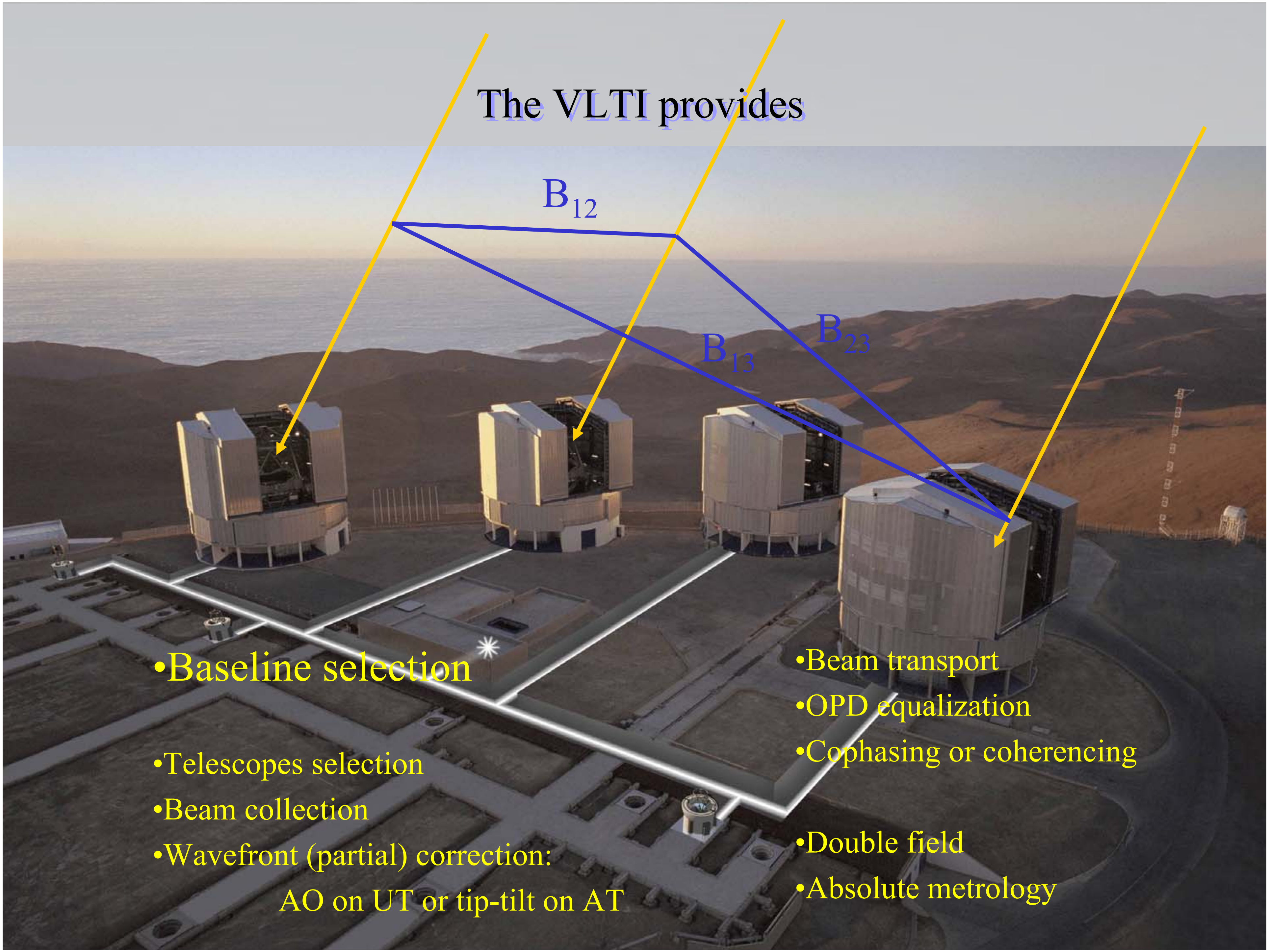
Osservatorio
Astrofisico di
Arcetri



Outline

- AMBER specifications
- Principle
- Description
- Measurements
- Observations modes and sequences
- Limitations and calibrations
- Examples of applications
- Potential performances.

The VLTI provides



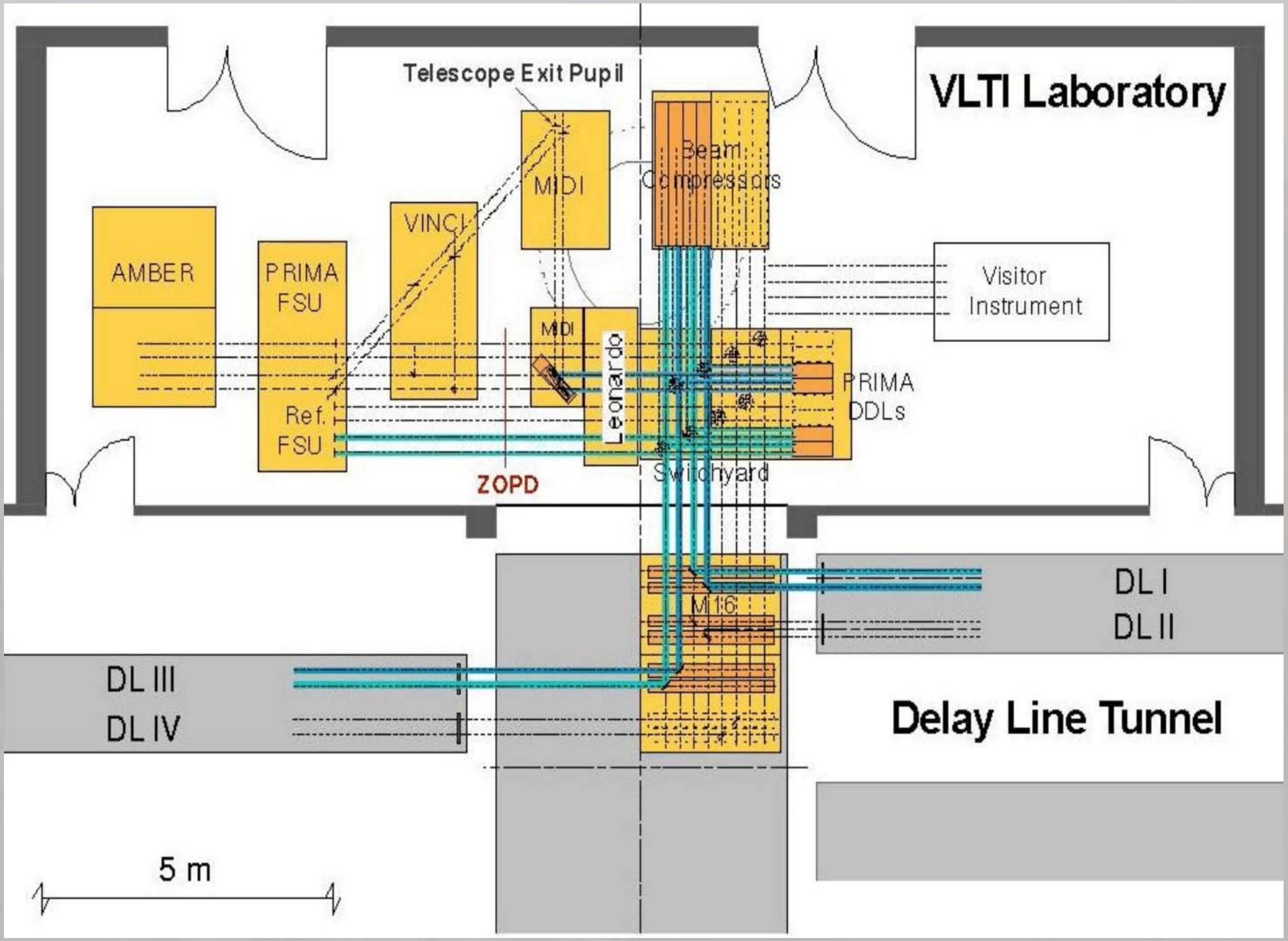
- Baseline selection

- Telescopes selection
- Beam collection
- Wavefront (partial) correction:
  AO on UT or tip-tilt on AT

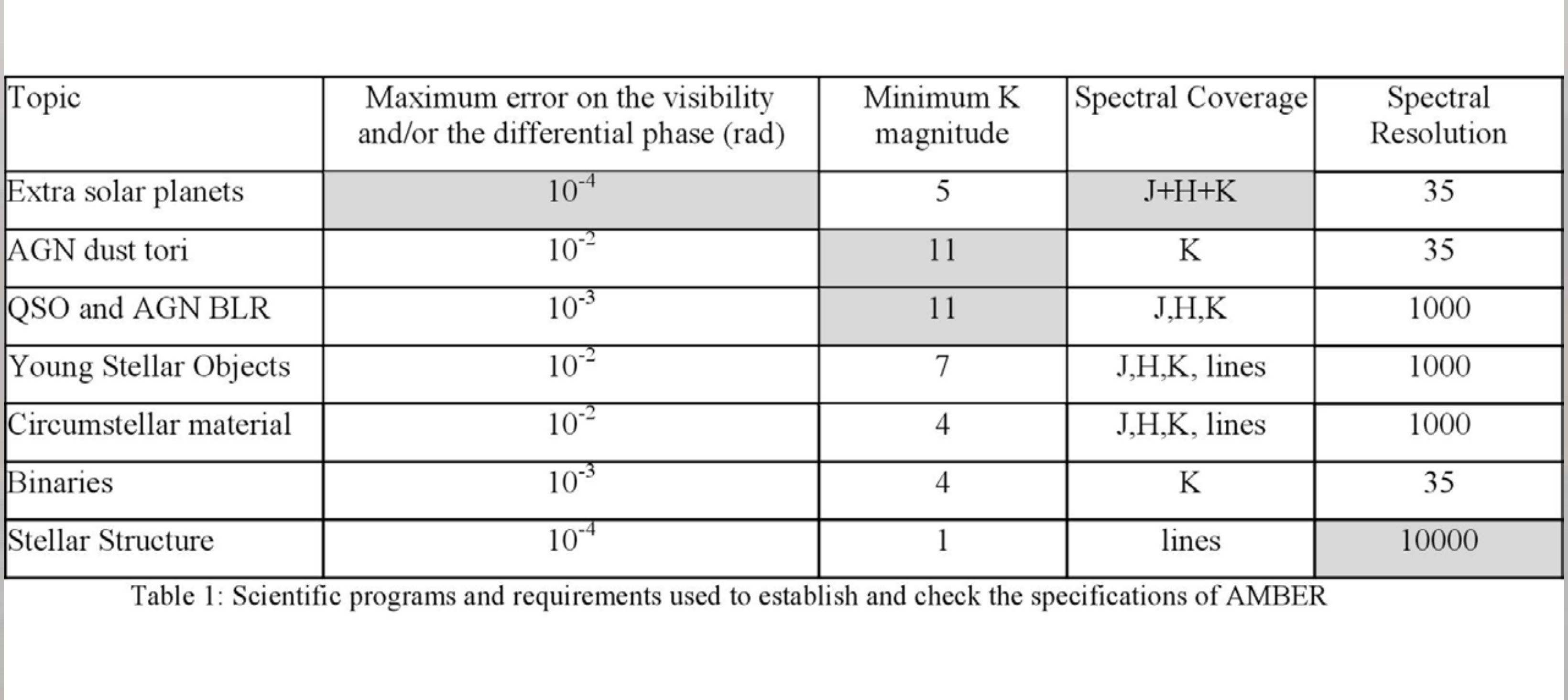
- Beam transport
- OPD equalization
- Cophasing or coherencing

- Double field
- Absolute metrology

The focal laboratory



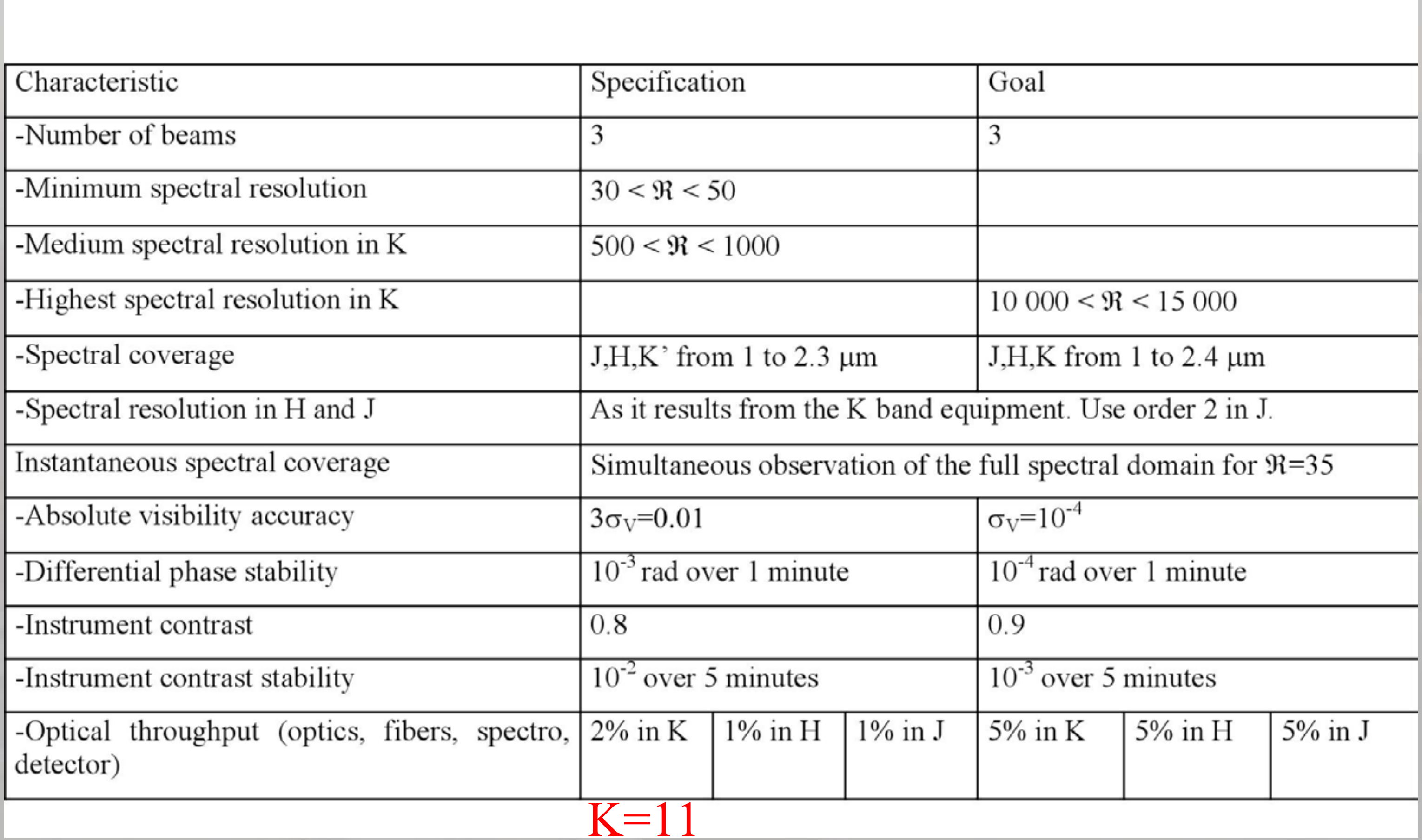
Key programs for specifications choice



Topic	Maximum error on the visibility and/or the differential phase (rad)	Minimum K magnitude	Spectral Coverage	Spectral Resolution
Extra solar planets	10^{-4}	5	J+H+K	35
AGN dust tori	10^{-2}	11	K	35
QSO and AGN BLR	10^{-3}	11	J,H,K	1000
Young Stellar Objects	10^{-2}	7	J,H,K, lines	1000
Circumstellar material	10^{-2}	4	J,H,K, lines	1000
Binaries	10^{-3}	4	K	35
Stellar Structure	10^{-4}	1	lines	10000

Table 1: Scientific programs and requirements used to establish and check the specifications of AMBER

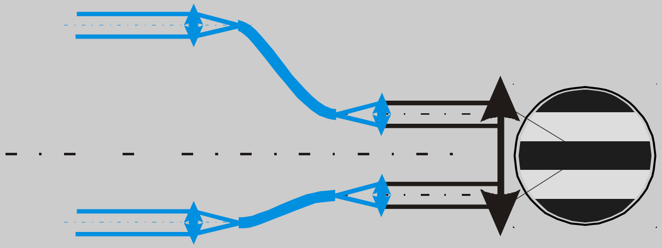
AMBER general specifications



Characteristic	Specification			Goal		
-Number of beams	3			3		
-Minimum spectral resolution	$30 < \mathfrak{R} < 50$					
-Medium spectral resolution in K	$500 < \mathfrak{R} < 1000$					
-Highest spectral resolution in K				$10\,000 < \mathfrak{R} < 15\,000$		
-Spectral coverage	J,H,K' from 1 to 2.3 μm			J,H,K from 1 to 2.4 μm		
-Spectral resolution in H and J	As it results from the K band equipment. Use order 2 in J.					
Instantaneous spectral coverage	Simultaneous observation of the full spectral domain for $\mathfrak{R}=35$					
-Absolute visibility accuracy	$3\sigma_V=0.01$			$\sigma_V=10^{-4}$		
-Differential phase stability	10^{-3} rad over 1 minute			10^{-4} rad over 1 minute		
-Instrument contrast	0.8			0.9		
-Instrument contrast stability	10^{-2} over 5 minutes			10^{-3} over 5 minutes		
-Optical throughput (optics, fibers, spectro, detector)	2% in K	1% in H	1% in J	5% in K	5% in H	5% in J

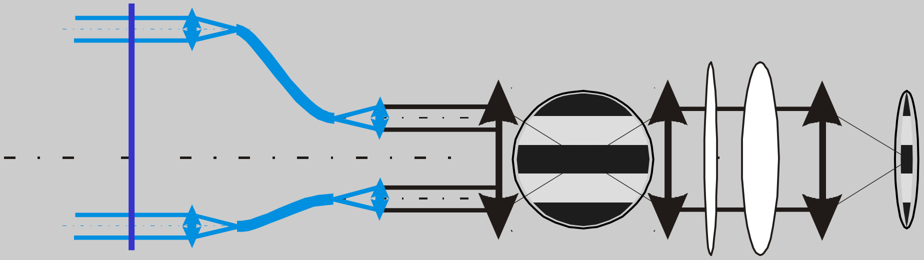
K=11

AMBER Principle : 2 T



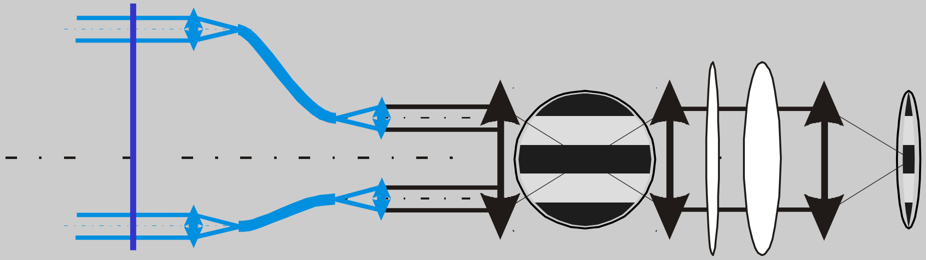
- 2 Telescope multi axial beam combiner
- spatial filtering

AMBER Principle

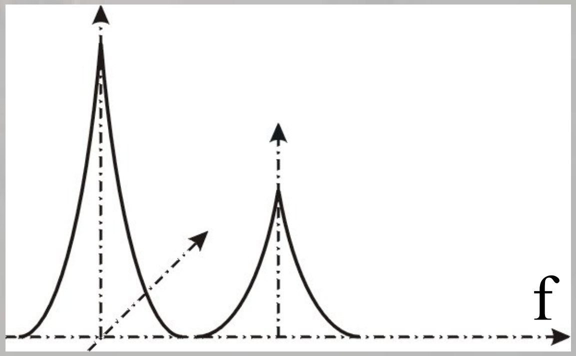


- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- spatial filtering

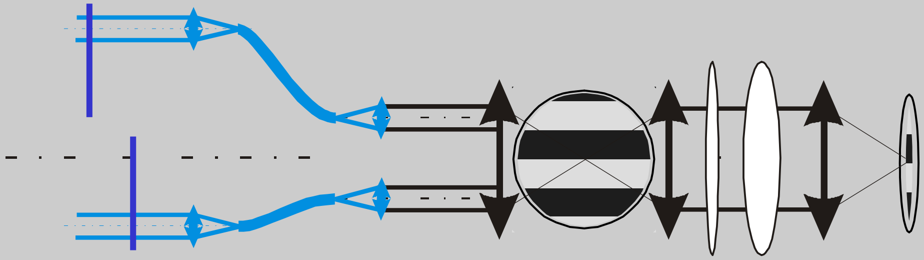
AMBER Principle



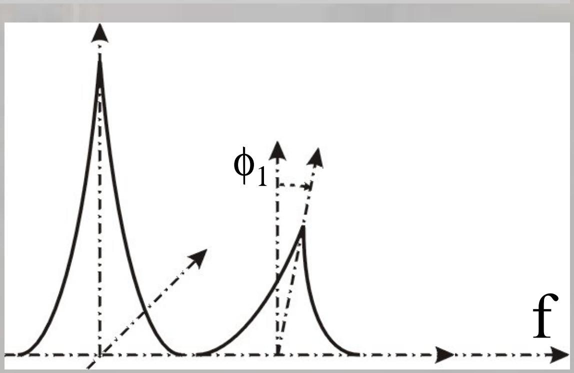
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- spatial filtering
- fringe peak with with zero piston



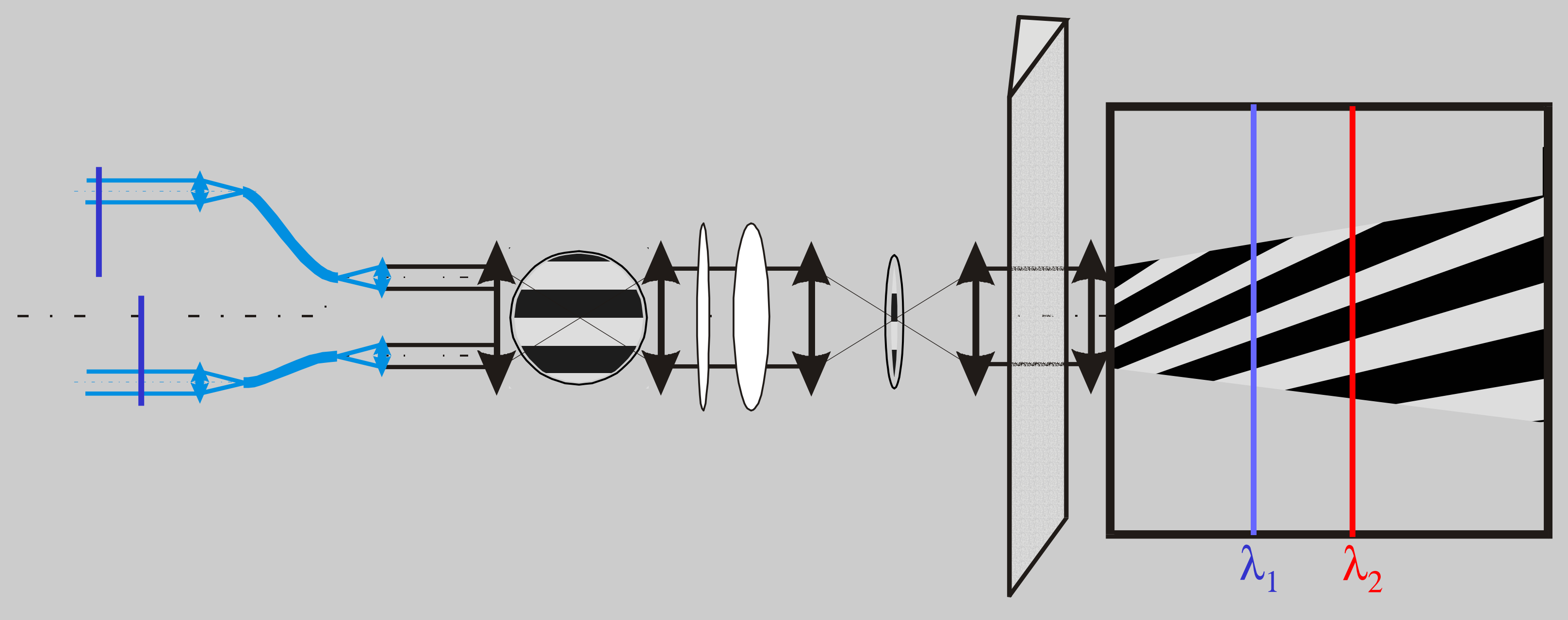
AMBER Principle: 2 T, effect of piston



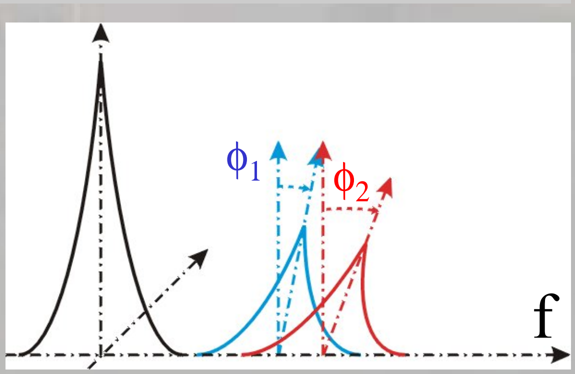
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- spatial filtering
- fringe peak with piston



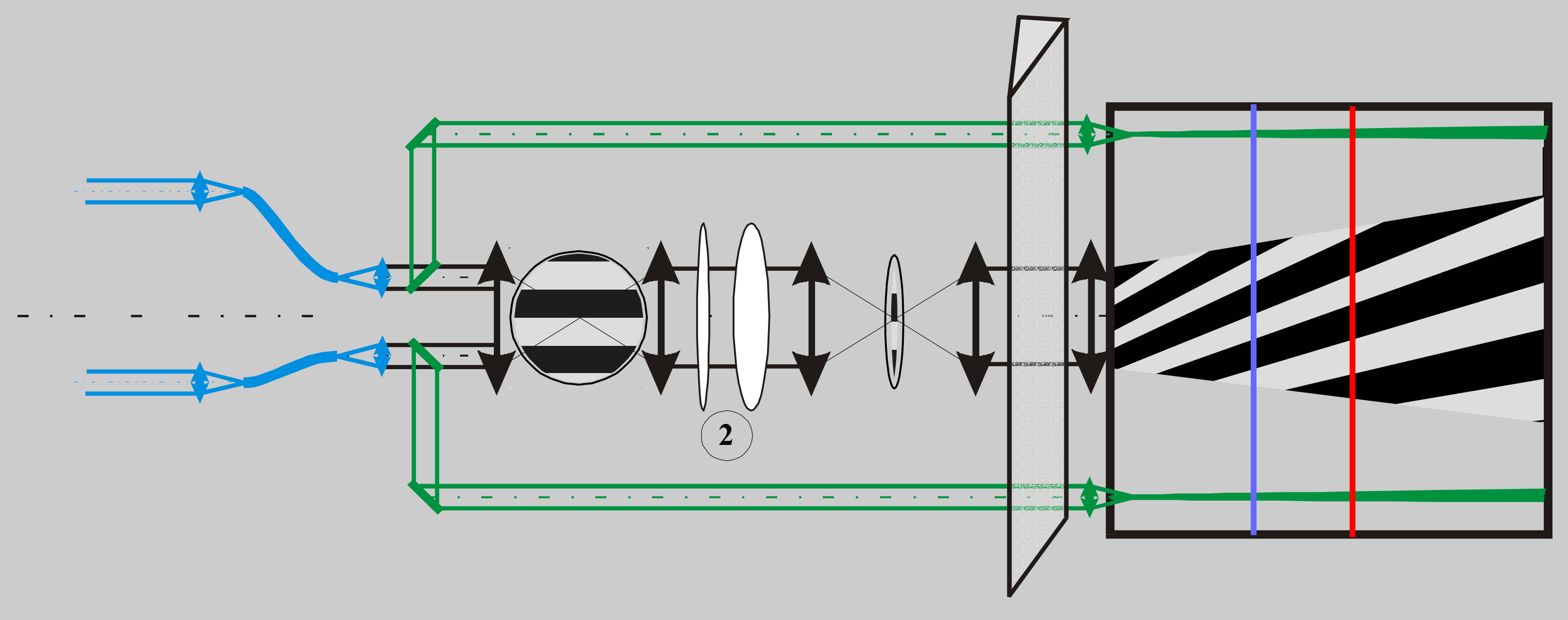
AMBER Principle: 2 T, correction of piston



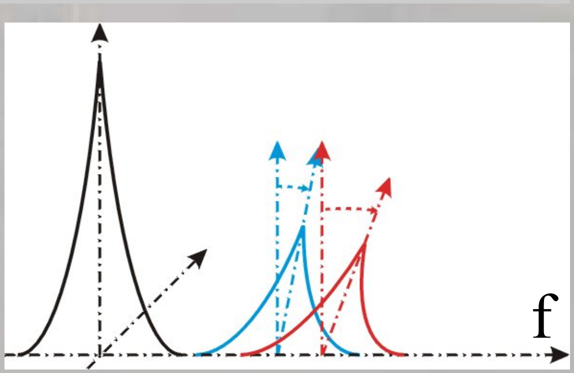
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- spatial filtering
- fringe peaks with piston and differential phase
- dispersed fringes



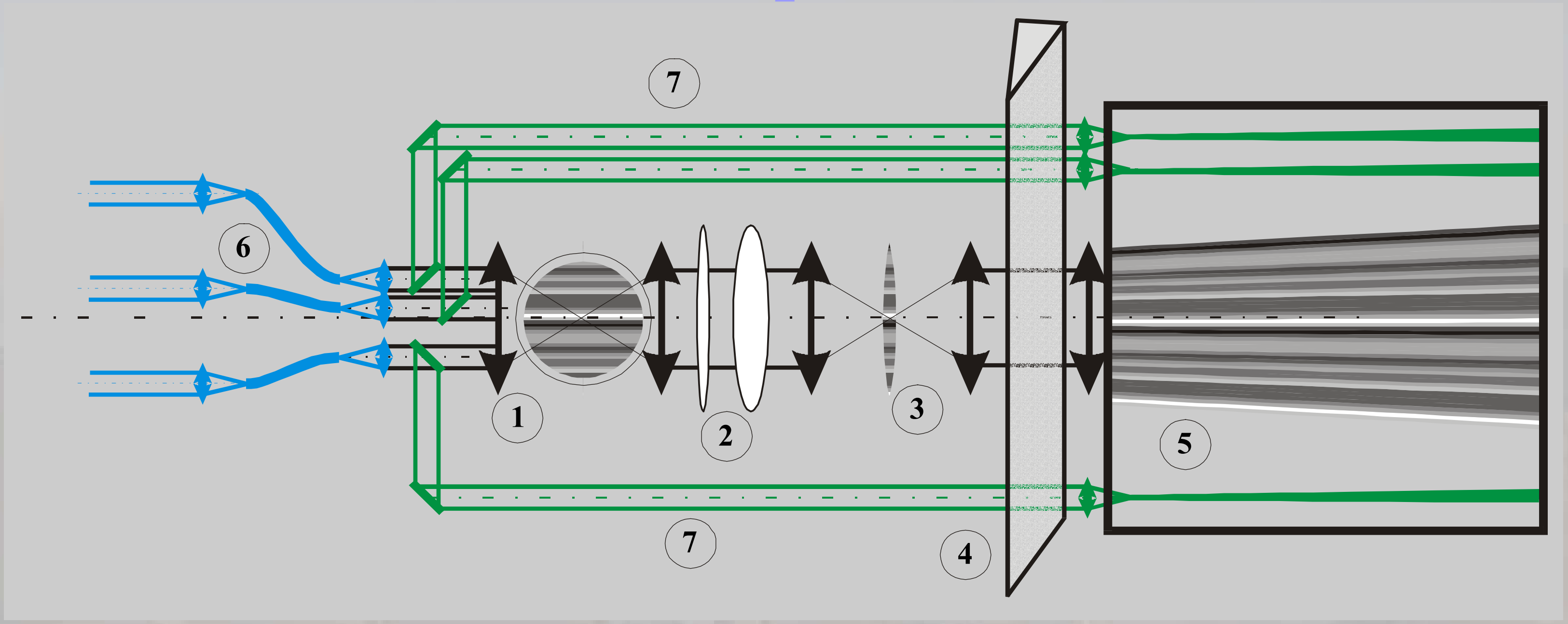
AMBER Principle: 2 T, correction of piston



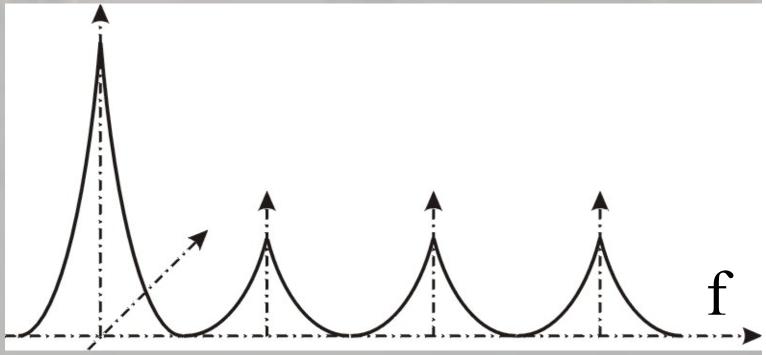
- 2 Telescope multi axial beam combiner with cylindrical optics anamorphosis
- spatial filtering
- fringe peaks with piston and differential phase
- dispersed fringes
- photometric monitoring



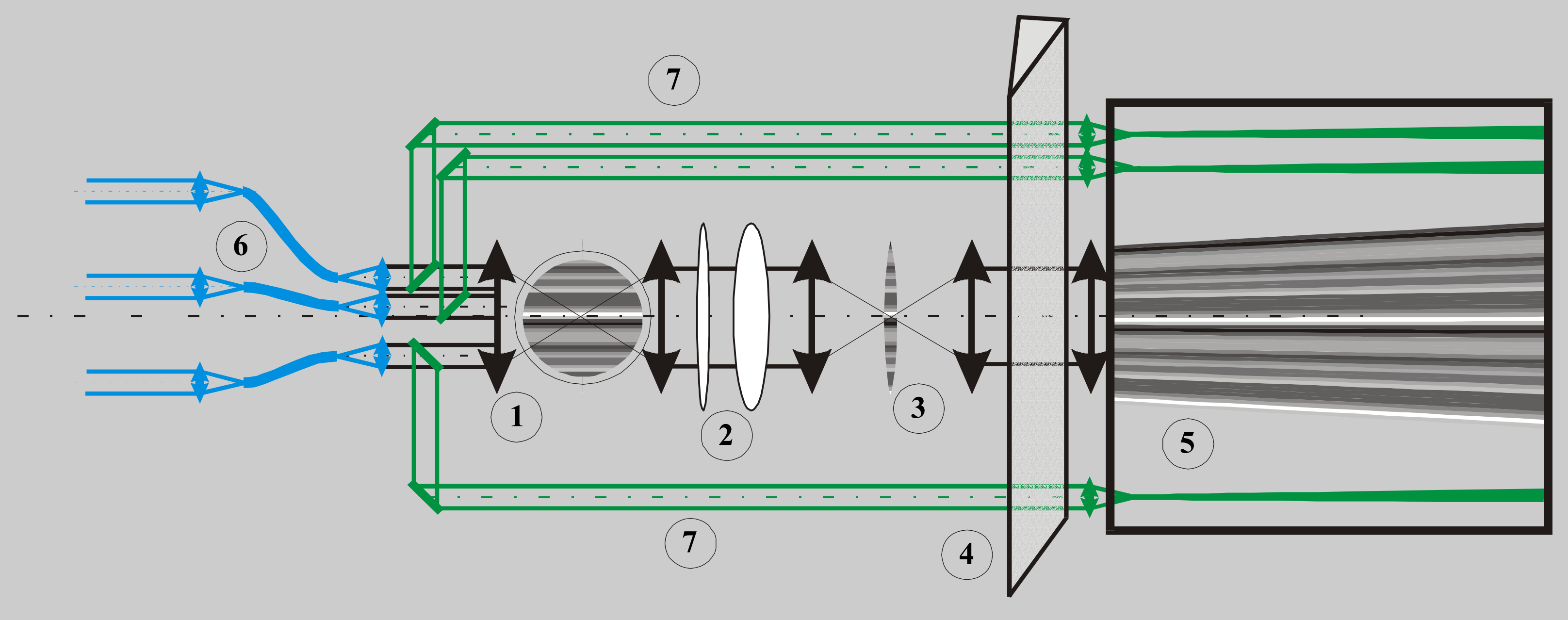
AMBER Principle: 3 T instrument



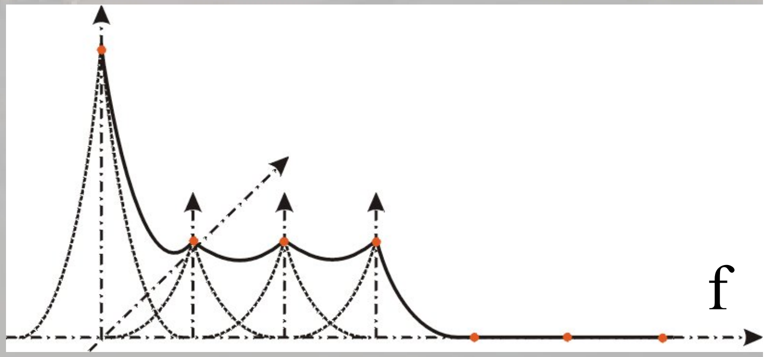
- 3 Telescopes implementation with non redundant fringe coding



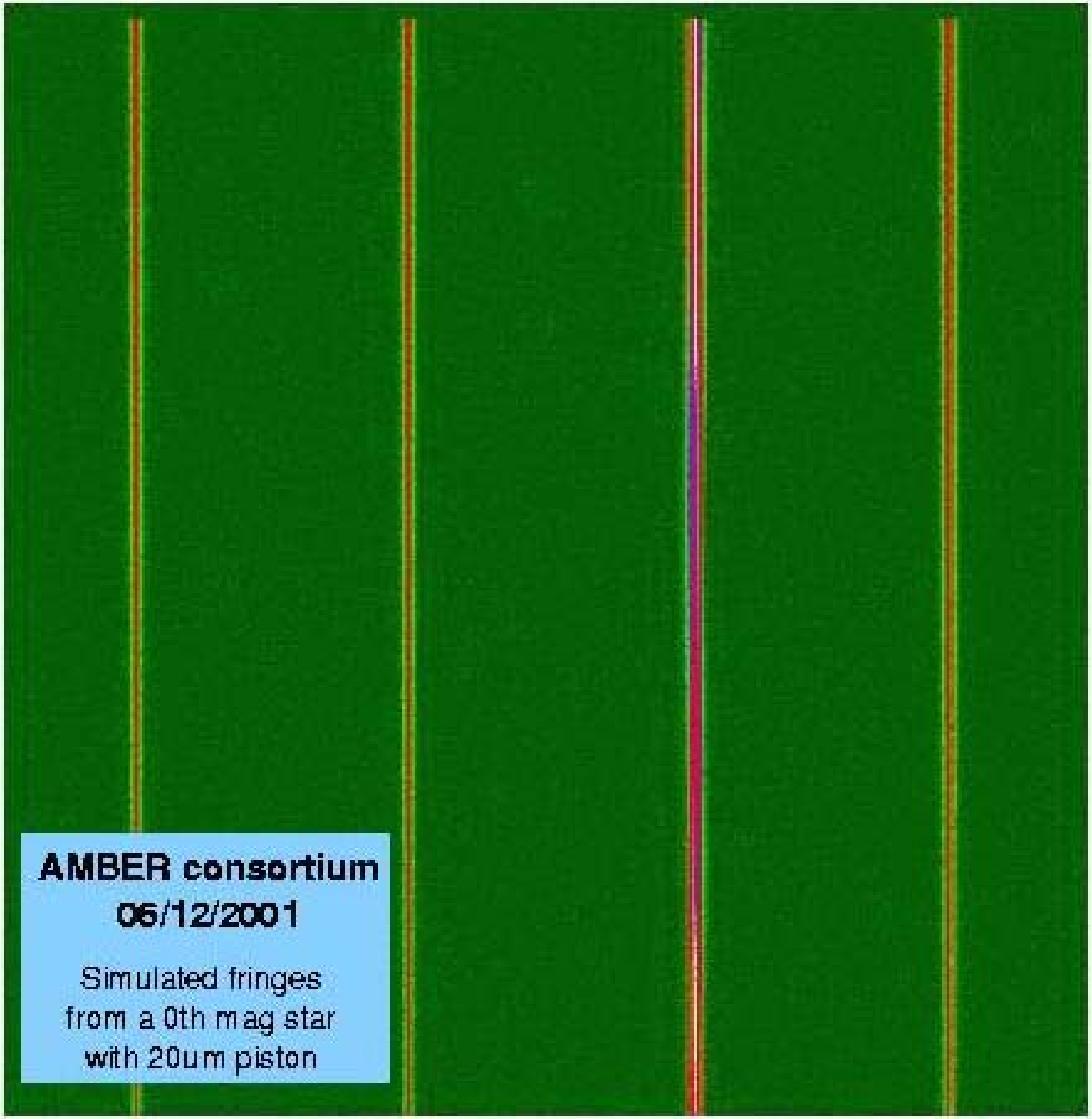
AMBER Principle: 3 T instrument



- 3 Telescopes implementation with **compact** non redundant fringe coding



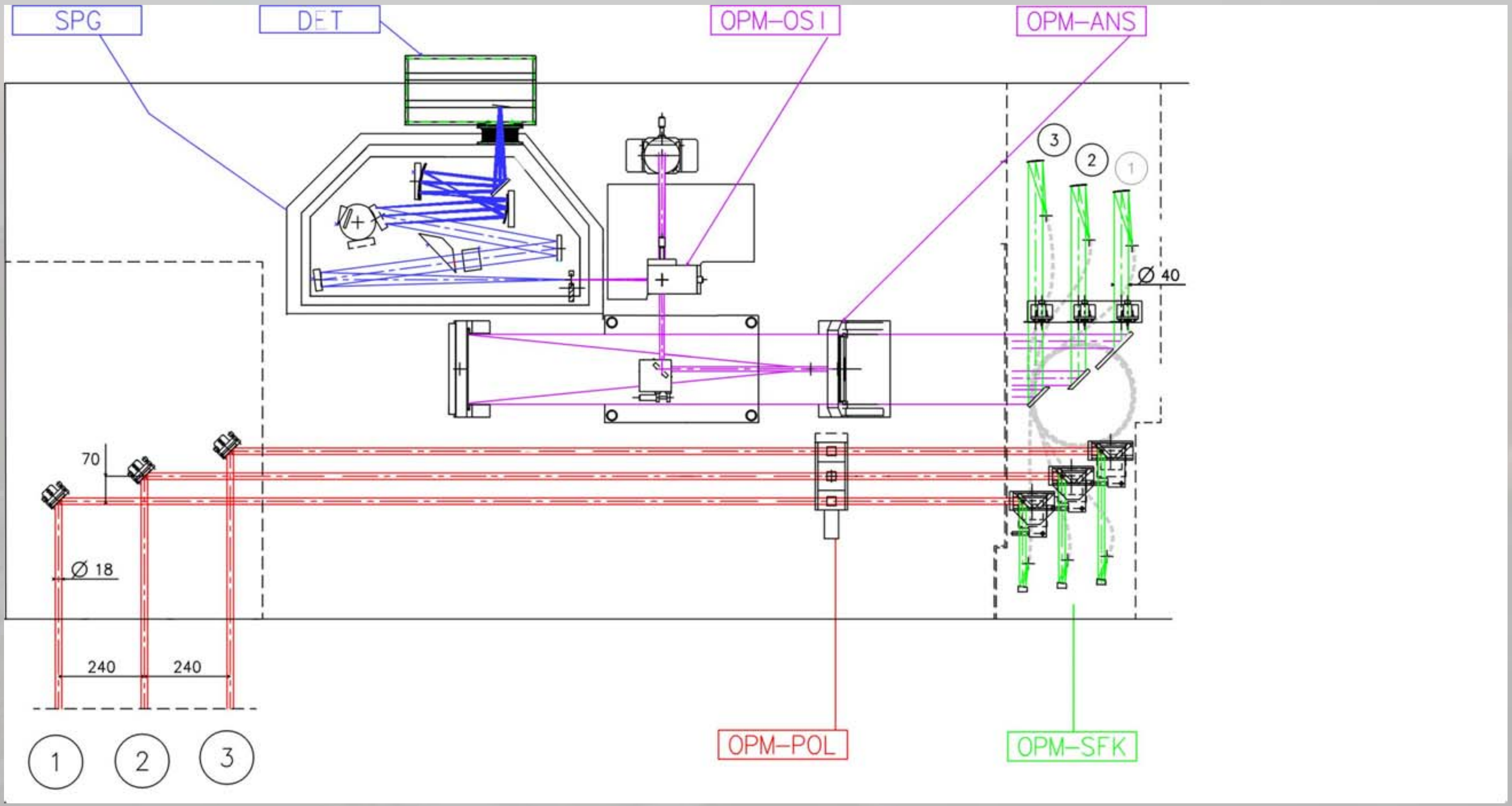
Simulated detector image



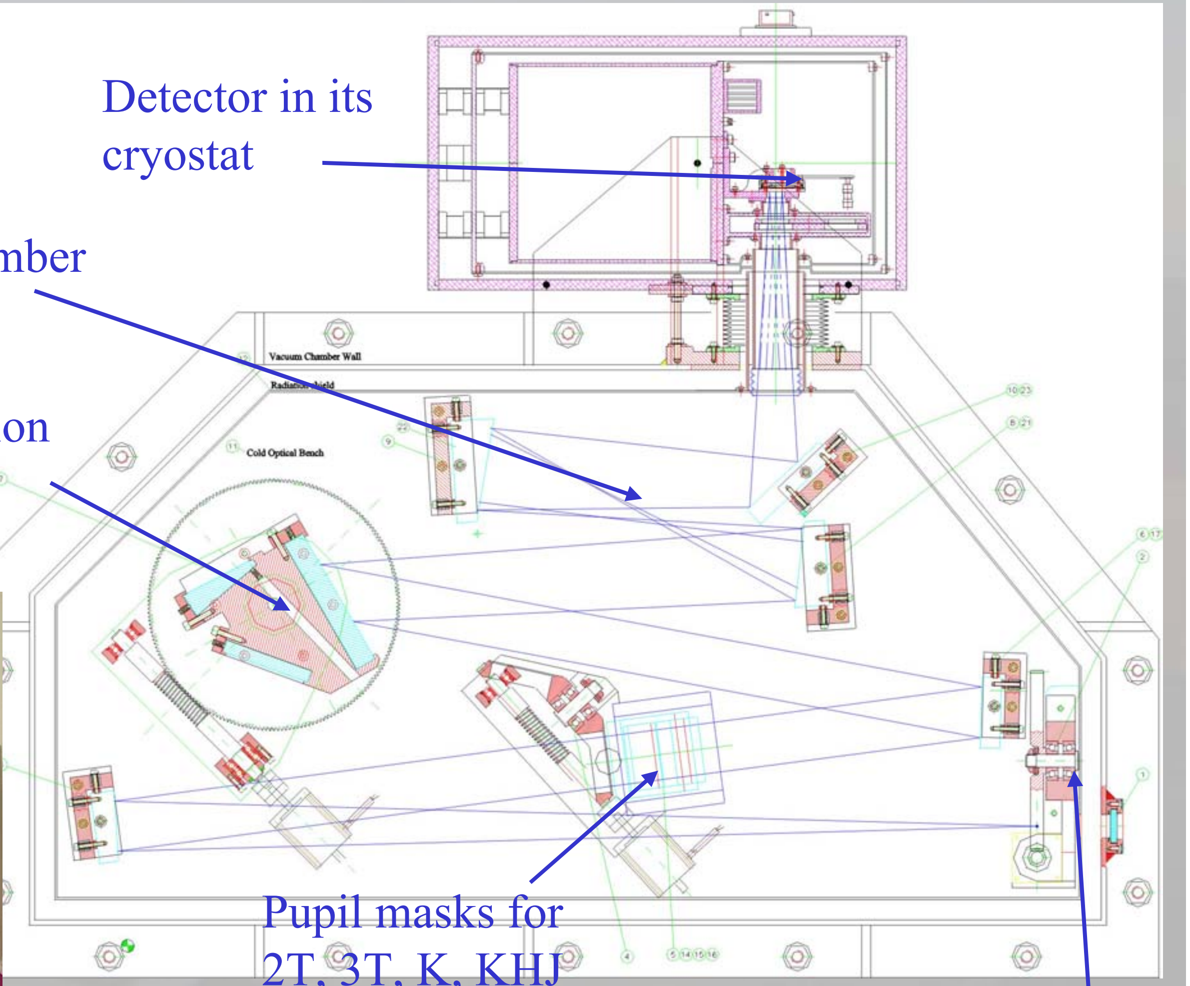
AMBER consortium
06/12/2001

Simulated fringes
from a 0th mag star
with 20um piston

K Band Instrument



Spectrograph



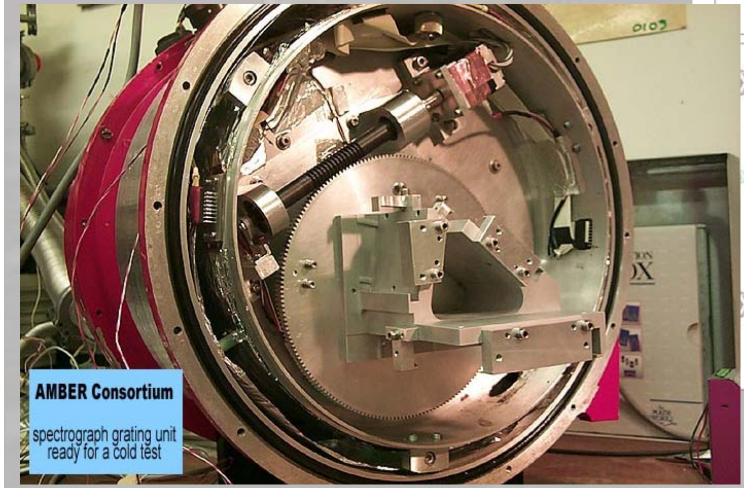
Detector in its cryostat

Chamber

Grating wheel selects resolution and central λ

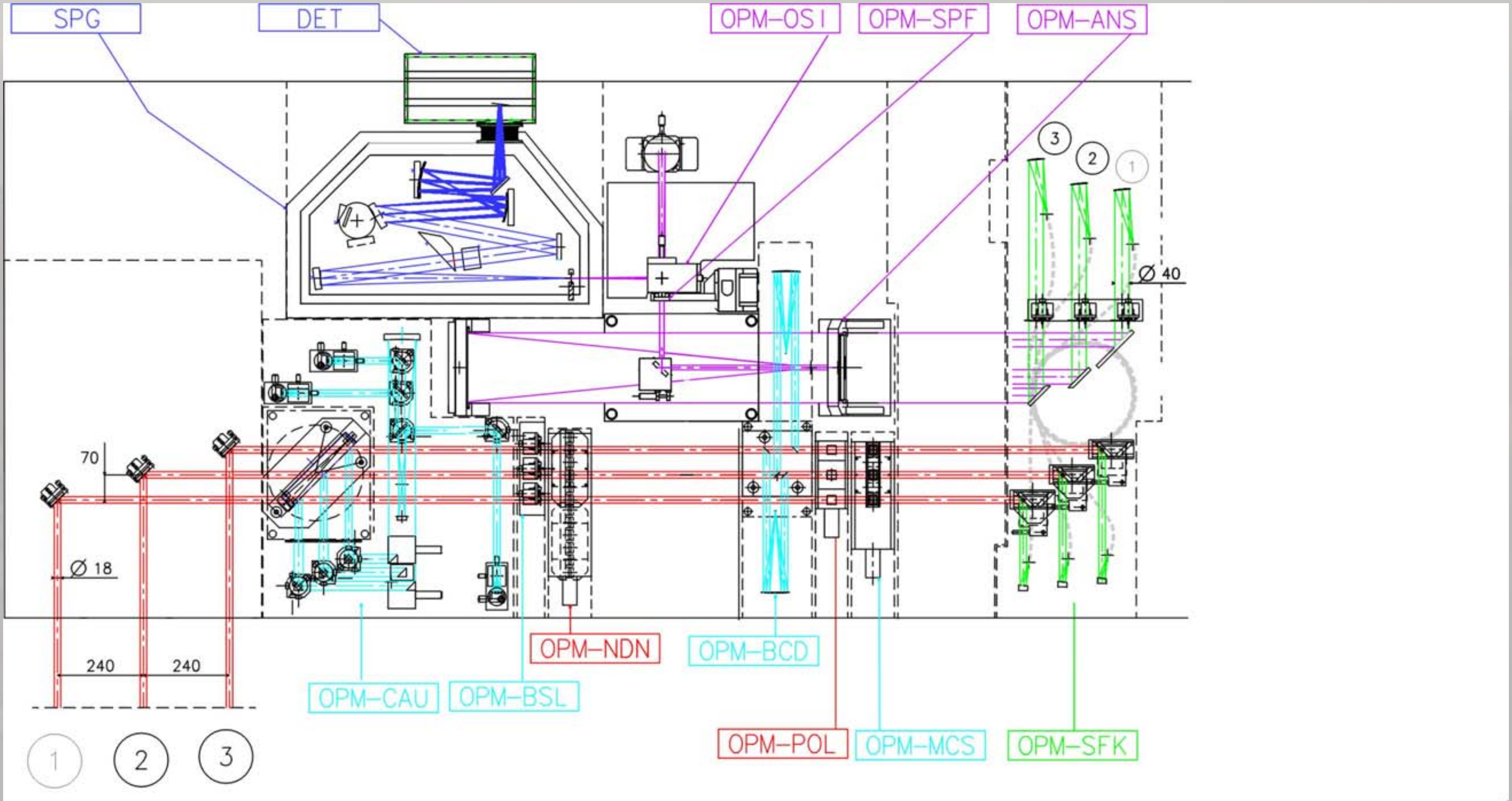
Pupil masks for 2T, 3T, K, KHJ selection

Slit wheel

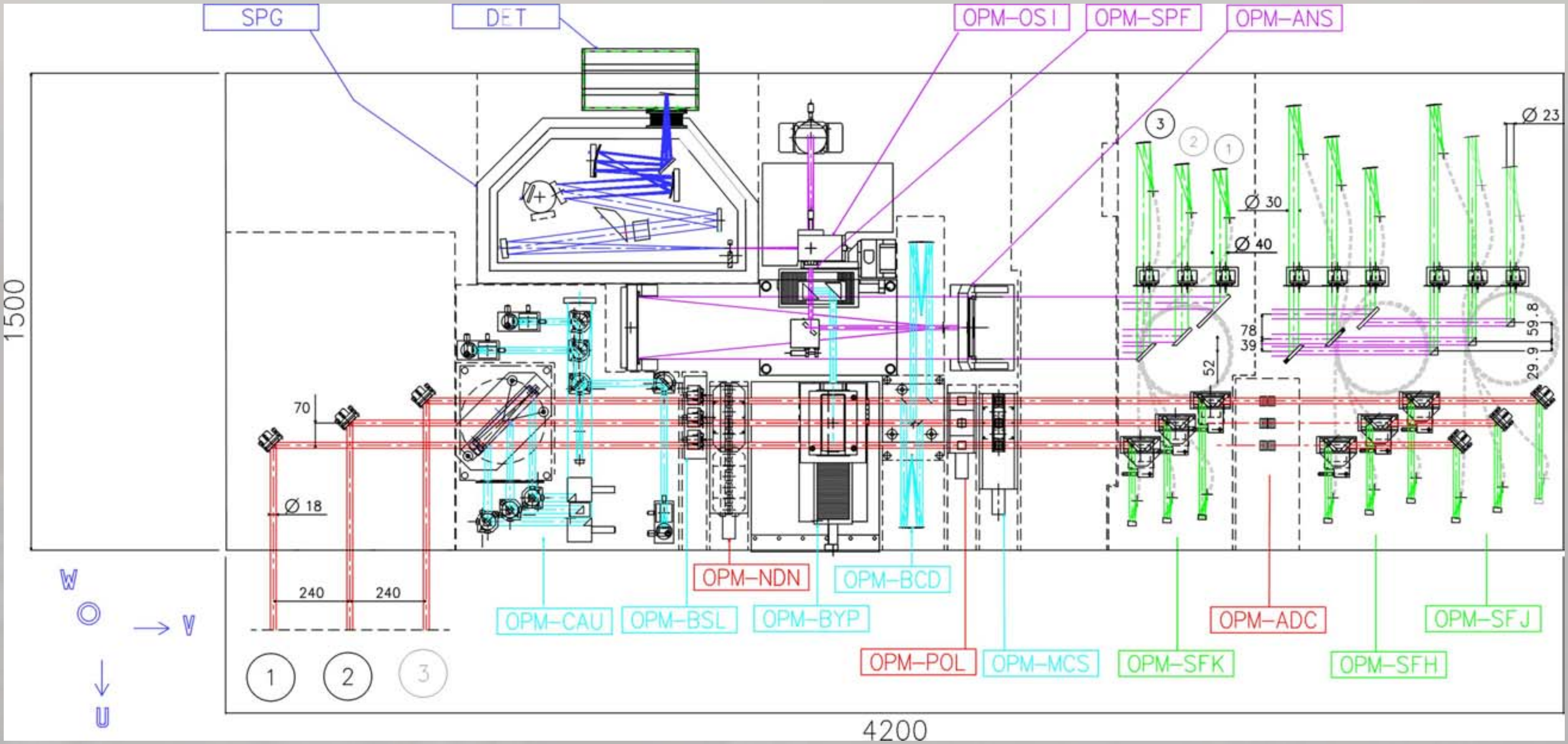


K Band and calibration tools

Artificial fringes + artificial fringes shifted by λ/4 = PTVM calibration



AMBER: K, H and J bands



AMBER consortium
06/12/2001

K Spatial Filter
at INSU Tech. Division

AMBER measurements

For each baseline B_{lm} (12, 23, 13)

Absolute visibility $V_{lm}(\lambda)$

Differential visibility $V_{lm}(\lambda)/V_{lm}(\lambda_0)$

Differential phase $\Phi_{lm}(\lambda)-\Phi_{lm}(\lambda_0)$

Phase closure $\Phi_{123}(\lambda)$

- Eventually: absolute metrology -> absolute phase $\Phi_{lm}(\lambda)$ -> phase referencing imagery.

These measurements are integrated over a patch around the spatial frequency B_{lm}/λ

Accuracy modes

With or without fringe tracker:

- High precision (σ_V<<1%): 10 ms frames (limit in spectral coverage)

Without fringe tracker:

- High sensitivity (K>11): 50 to 100 ms frames

With fringe tracker:

- "long exposures" : 100 ms to 100 s frames

AMBER data processing

Frame: frame time defines observing mode

HP:10 ms; HS: 50 ms; LE: ->100s

- detector cosmetics
- conversion to number of photons
- background subtraction
- computation of $V(\lambda)$ and $\Phi(\lambda)-\Phi(\lambda_0)$ for each spectral channel
- computation and correction of achromatic piston

Exposure: sequence of frames without source or set-up change

Typically 5 minutes

- averaging
- simple bias corrections (example: effect of finite frame time)

Exposure cycles: all exposures needed for full calibration

Minimum 10 minutes

- exposures on sky, science target, calibrator star
- exposures after internal changes (spatial or spectral modulation)

“Fundamental” measurement errors

On the visibility modulus:

$$\sigma^2_{f\,V}(\lambda) \approx N^2_T\,(n(\lambda)+N_p\sigma_{RON}+n_{th})\;/\;M\;V^2\,(\lambda)\;n^2\,(\lambda)$$

On the phase:

$$\sigma^2_{f\,\Phi}(\lambda) \approx N^2_T\,(n(\lambda)+N_p\sigma_{RON}+n_{th})\;/\;2\;M\;V^2\,(\lambda)\;n^2\,(\lambda)$$

- N_T: number of telescopes
- $n(\lambda)$: number of photons per frame in channel λ
- N_p: number of pixels per channel
- $n_{th:}$ number of background photons in channel λ
- $V(\lambda)$: source visibility x instrument visibility
- M: number of frames used for the measurement

Effects introducing measurement errors

Optical aberrations before the fibers:
  - changes in coupling efficiency: monitored and corrected
  - piston variation during frame: minimized, corrected from estimation
  - “antenna” function variations field limitation

Polarization one polarization selected

Optical aberrations after the fibers calibrated and corrected

Instrument temporal drifts
  - variable chromatic piston
    - coupling between beam residual motion and diopters
    - fibers thermal changes
  - spectrograph deformation
  - temporal variation of detector gain
  - ………
    - Calibrated using a reference star
    - Calibrated using internal modulation

Errors introduced by instrument variations

Measurement affected by a variable instrument effect:

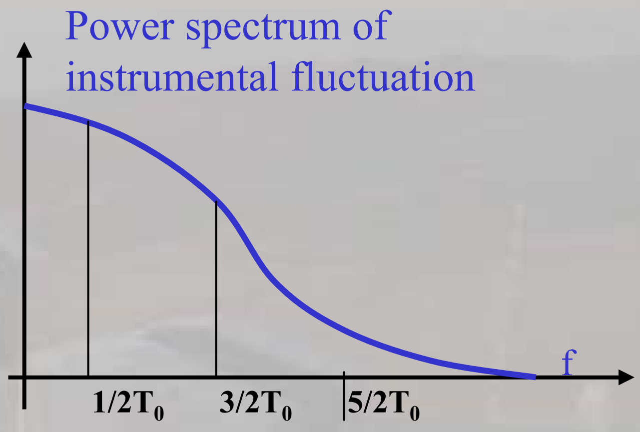
measurement: $m_{2p} = m_* + m_{I2p}$

reference: $m_{2p+1} = m_{I(2p+1)}$

Estimator: $E(m_*) = s\xi_p (m_{2p} - m_{2p+1})$

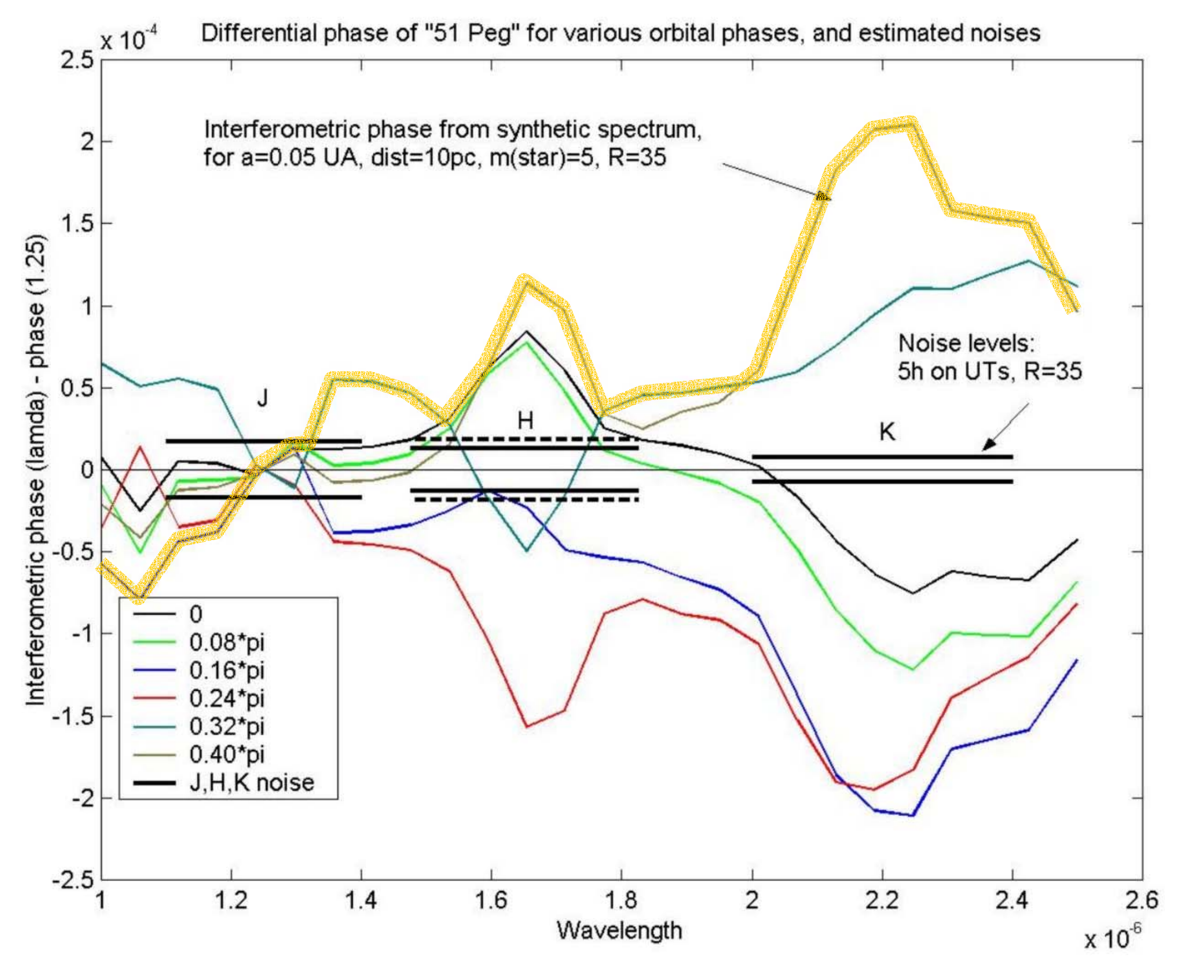
Variance: $V(m_*) = \sigma_{f\,m}^2 + D_m(f = 1/2T_0) + D_m(f = 3/2T_0) + \ldots$

- $2T_0$= calibration period
- $D_m(f)$ = Power spectrum of the instrument effect $m_I(t)$
- $\sigma_{f\,m}^2$= « fundamental » variance


Power spectrum of instrumental fluctuation

If the instrumental drifts are lower than the fundamental noise averaged over one calibration period T_0, the final accuracy is limited only by photon, detector and background noise.

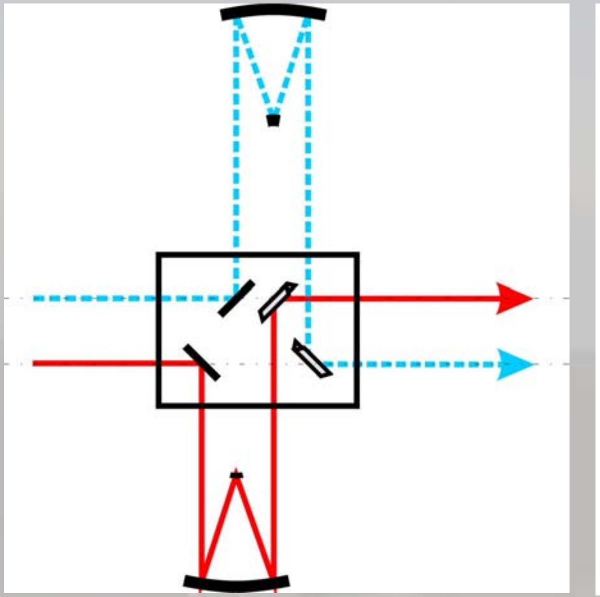
Differential phase and Extra Solar Planets



Instrumental limits to differential interferometry of bright sources

Calibration period	60 s		600 s		Calibration or correction
Band	J	K	J	K	
Fundamental differential OPD noise	6 10^{-11}	6 10^{-11}	2 10^{-11}	2 10^{-11}	
Detector stability	To be measured, slow ?				
Spectrograph distortion	< 10^{-11}		10^{-11}		BCD
Beam residual jitter and tip-tilt + diopters defects	2 10^{-11}	2 10^{-11}	10^{-10}	10^{-10}	Instrument design + BCD
Fiber temperature changes	2 10^{-11}	3 10^{-11}	10^{-10}	3 10^{-10}	BCD
Chromatic atmospheric piston	7 10^{-13}	4 10^{-13}	2 10^{-13}	1 10^{-13}	negligible
Changes in differential dispersion	3 10^{-10}	6 10^{-11}	3 10^{-9}	6 10^{-10}	Measure in J and correct in H and K ?

Spatial modulation calibration



Beam Commuting Device (BCD).
It commutes two of the beams without image inversion. It is activated by inserting the central plate in the beams. It allows to reduce the calibration period down to 60 s or less. To avoid introducing extra effects the specifications are:

- tip-tilt accuracy: 2 arc seconds
- beam jitter accuracy: 10µm
- pupil motion: <30 cm
- opd accuracy: 1 µm

Without BCD:

$$\Delta\Phi_m(\lambda,t_1) = \Delta\Phi_*(\lambda,t_1) + \Delta\Phi_a(\lambda,t_1) + \Delta\Phi_i(\lambda,t_1) + e_\Phi(\lambda,t_1)$$

With BCD:

$$\Delta\Phi_{\underline{m}}(\lambda,t_2) = -\Delta\Phi_*(\lambda,t_2) - \Delta\Phi_a(\lambda,t_2) + \Delta\Phi_i(\lambda,t_2) + e_\Phi(\lambda,t_2) + \Delta\Phi_{BCD}(\lambda,t_2)$$

Difference:

$$\Delta\Phi_m(\lambda,t_1) - \Delta\Phi_{\underline{m}}(\lambda,t_2) = 2\Delta\Phi_*(\lambda) + 2\Delta\Phi_a(\lambda) + e_\Phi(\lambda,t_1) - e_\Phi(\lambda,t_2) + \Delta\Phi_{BCD}(\lambda,t_2)$$

Photocenter displacement and super angular resolution

Non resolved object: $\Phi(u=B/\lambda) = 2\pi\ (B/\lambda)\ \varepsilon(\lambda)$

Photocenter:

$$\varepsilon(\lambda) = \int \underline{r}\ o(\underline{r},\lambda)\ d\underline{r}\ \ / \int o(\underline{r},\lambda)\ d\underline{r}$$

yields the first order moment of the brightness distribution $o(\underline{r},\lambda)$, interesting parameter for any object showing spectral features possibly due or connected to "large scale" spatial features.

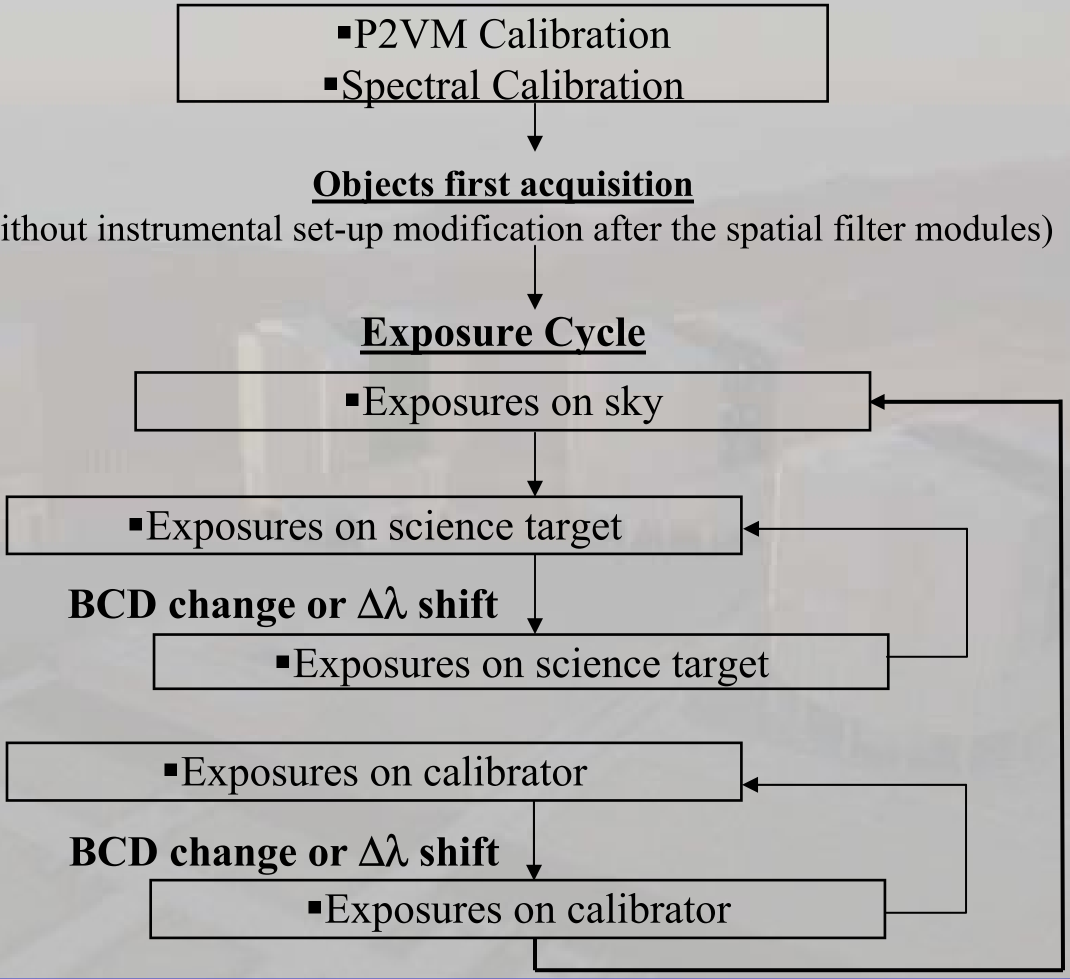
K=5, UTs, R=1000, 5h $\sigma_\varepsilon(\lambda) = 0.1\ \mu\mathrm{as}$

K=10, UTs, R=1000, 5h or K=7, ATs, R= 1000, 5 h $\sigma_\varepsilon(\lambda) = 1\ \mu\mathrm{as}$

Observation sequences

Set-up dependant calibrations

(Before observation or after a spectral set-up change)



- P2VM Calibration
- Spectral Calibration

Objects first acquisition

(Without instrumental set-up modification after the spatial filter modules)

Exposure Cycle

- Exposures on sky
- Exposures on science target

BCD change or Δλ shift

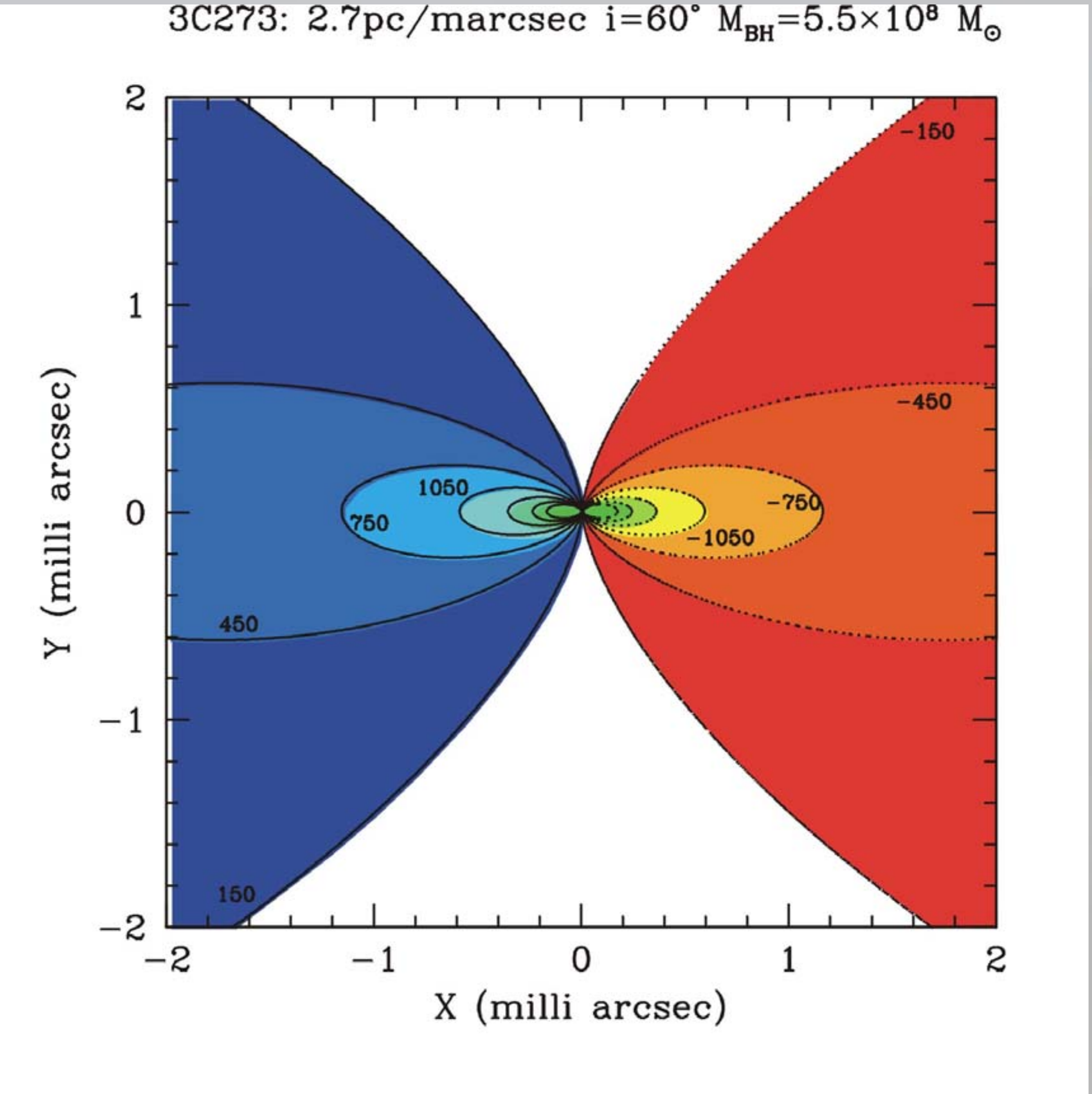
- Exposures on science target
- Exposures on calibrator

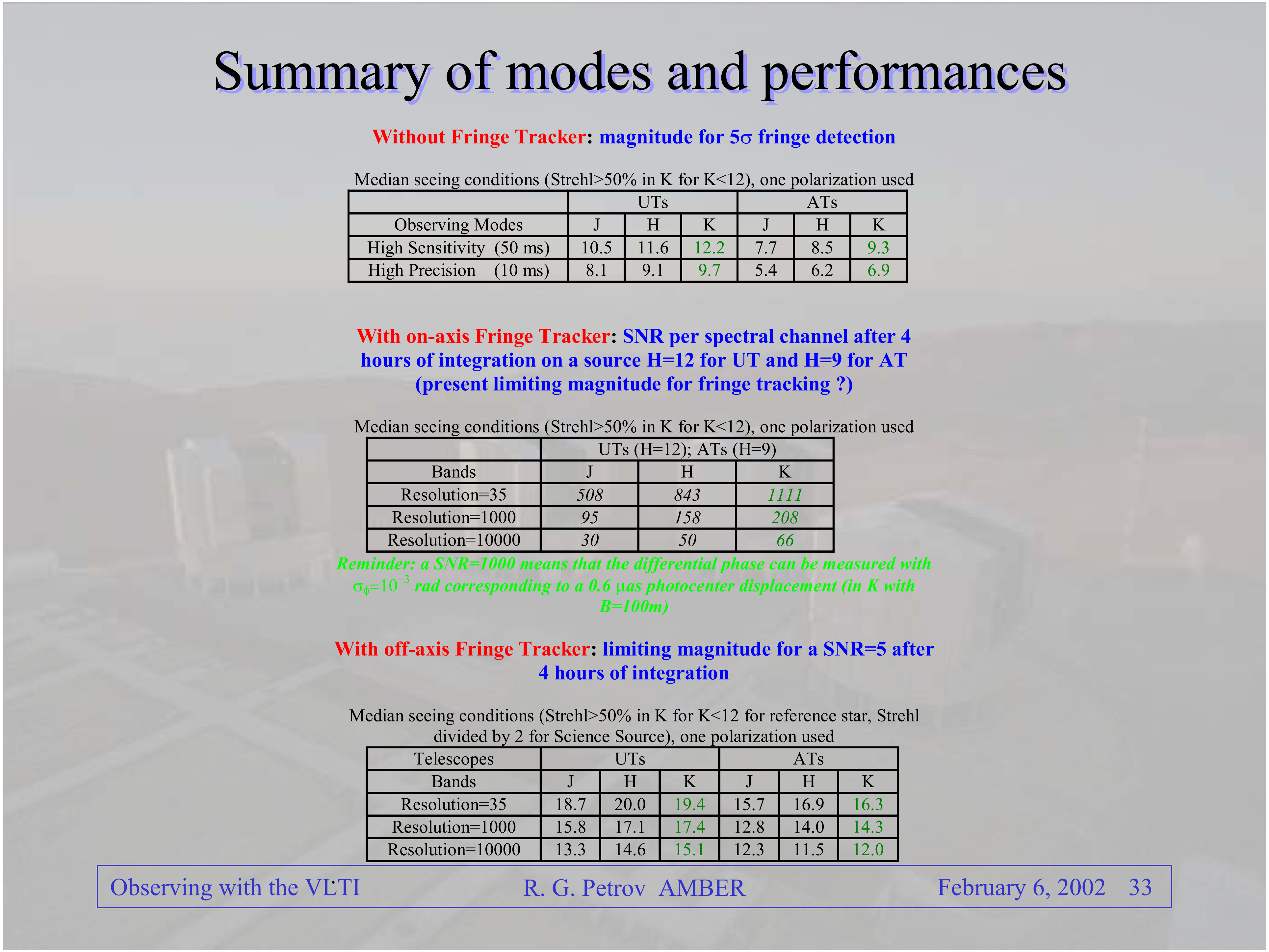
BCD change or Δλ shift

- Exposures on calibrator

AMBER observations of a BLR

- **Broad band visibility: BLR size if (partially) resolved.**
- **Narrow channel visibility (R=1000): constraints on velocity field.**
- **For resolved object: differential phase + differential visibility ~ quasi imagery**
- **Differential phase with low spectral resolution: constrains size of extremely unresolved object.**
- **Differential phase with spectral resolution 1000: constrains velocity field on very unresolved source.**





Summary of modes and performances

Without Fringe Tracker: magnitude for 5σ fringe detection

Median seeing conditions (Strehl>50% in K for K<12), one polarization used

	UTs			ATs		
Observing Modes	J	H	K	J	H	K
High Sensitivity (50 ms)	10.5	11.6	12.2	7.7	8.5	9.3
High Precision (10 ms)	8.1	9.1	9.7	5.4	6.2	6.9

With on-axis Fringe Tracker: SNR per spectral channel after 4 hours of integration on a source H=12 for UT and H=9 for AT (present limiting magnitude for fringe tracking ?)

Median seeing conditions (Strehl>50% in K for K<12), one polarization used

	UTs (H=12); ATs (H=9)		
Bands	J	H	K
Resolution=35	*508*	*843*	*1111*
Resolution=1000	*95*	*158*	*208*
Resolution=10000	*30*	*50*	*66*

Reminder: a SNR=1000 means that the differential phase can be measured with $\sigma_\phi=10^{-3}$ rad corresponding to a 0.6 μas photocenter displacement (in K with B=100m)

With off-axis Fringe Tracker: limiting magnitude for a SNR=5 after 4 hours of integration

Median seeing conditions (Strehl>50% in K for K<12 for reference star, Strehl divided by 2 for Science Source), one polarization used

Telescopes	UTs			ATs		
Bands	J	H	K	J	H	K
Resolution=35	18.7	20.0	19.4	15.7	16.9	16.3
Resolution=1000	15.8	17.1	17.4	12.8	14.0	14.3
Resolution=10000	13.3	14.6	15.1	12.3	11.5	12.0

Conclusion

AMBER will be basically used for model fitting using interferometric measurements = f(λ).

In a few cases it can be used to provide “imaging” information.

Typical schedule is:

- **Delivery of integrated sub systems to Grenoble: April - May 2002**
- **Laboratory tests in Grenoble: July-November 2002**
- **Preliminary Acceptance Europe (without BCD and may be without H filter): 12/2002**
- **Commissioning with Siderostats: February-May 2003**
- **First ATs and/or UTs+MACAO observations: Summer 2003**
- **First operation semester: October 2003 - April 2004**
- **Deadline for first applications: April 2003**
- **Deadline for SDT applications: December 2002 ??**

Output pupils

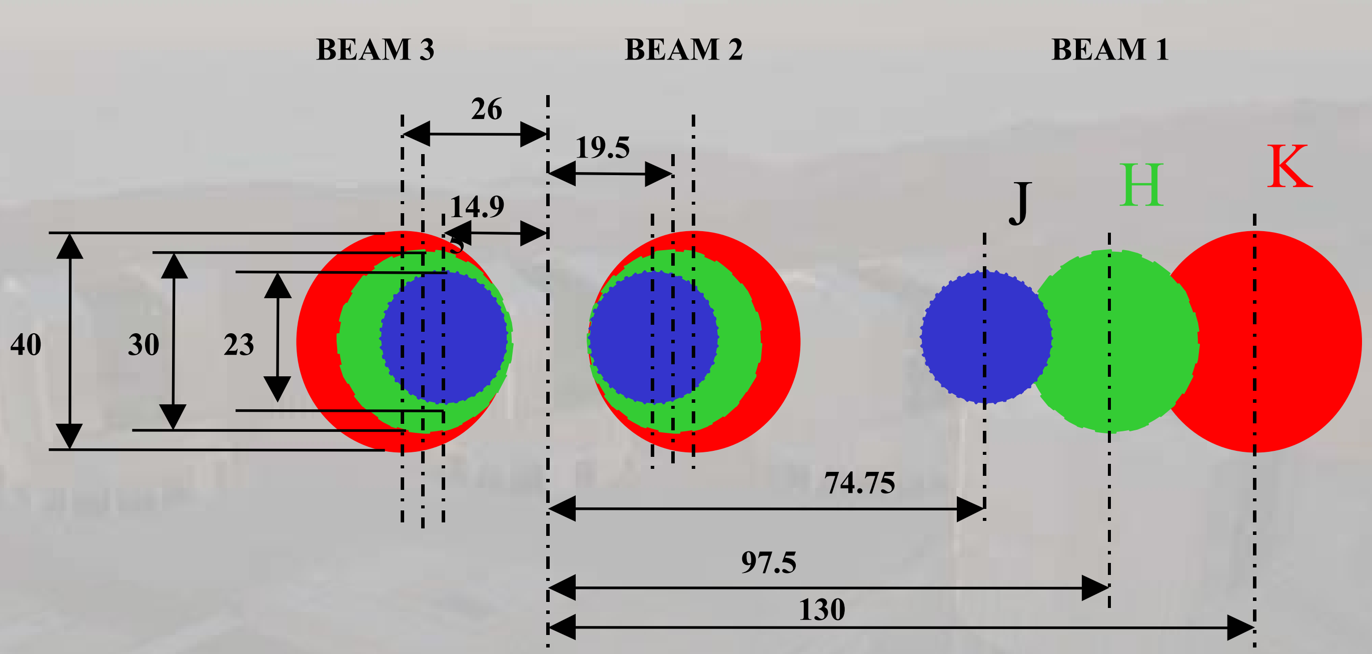
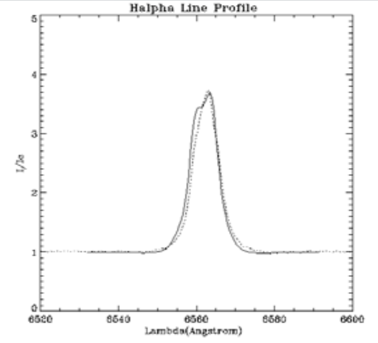
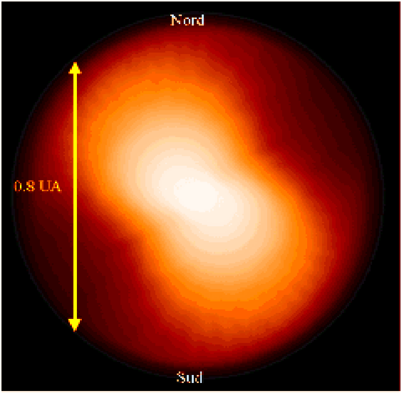


Figure 1 : Pupils diameters and distances:
the fringe size is the same in the middle of each band.

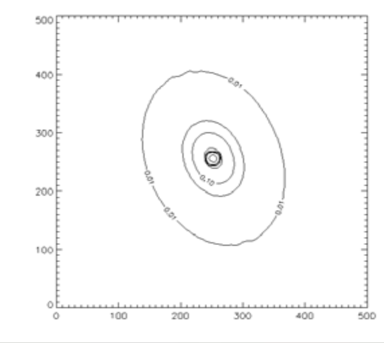
γ Cas and AMBER measurements



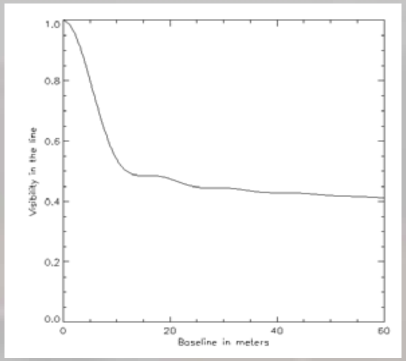
Line profile



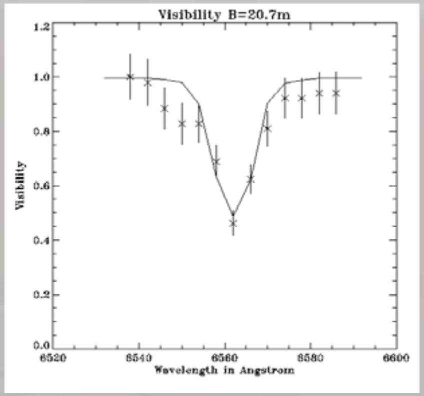
Map in spectral line



Map in continuum

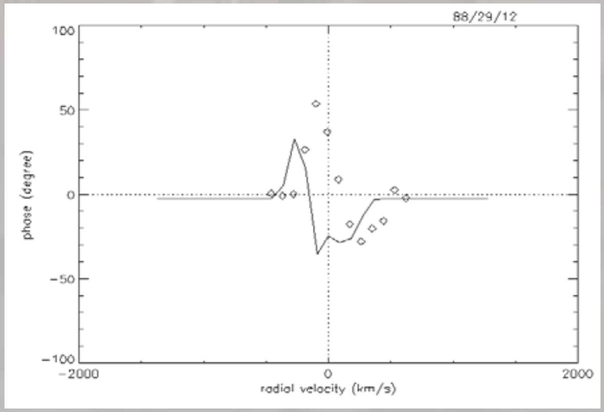


V=f (B)

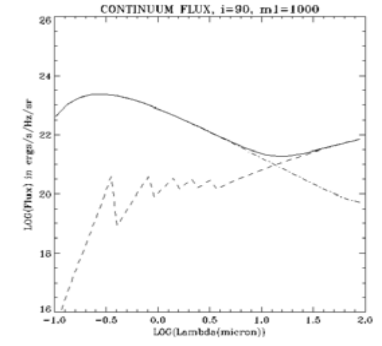


V=f (λ)

Stee & Bittar 2001, A&A, 367, 532

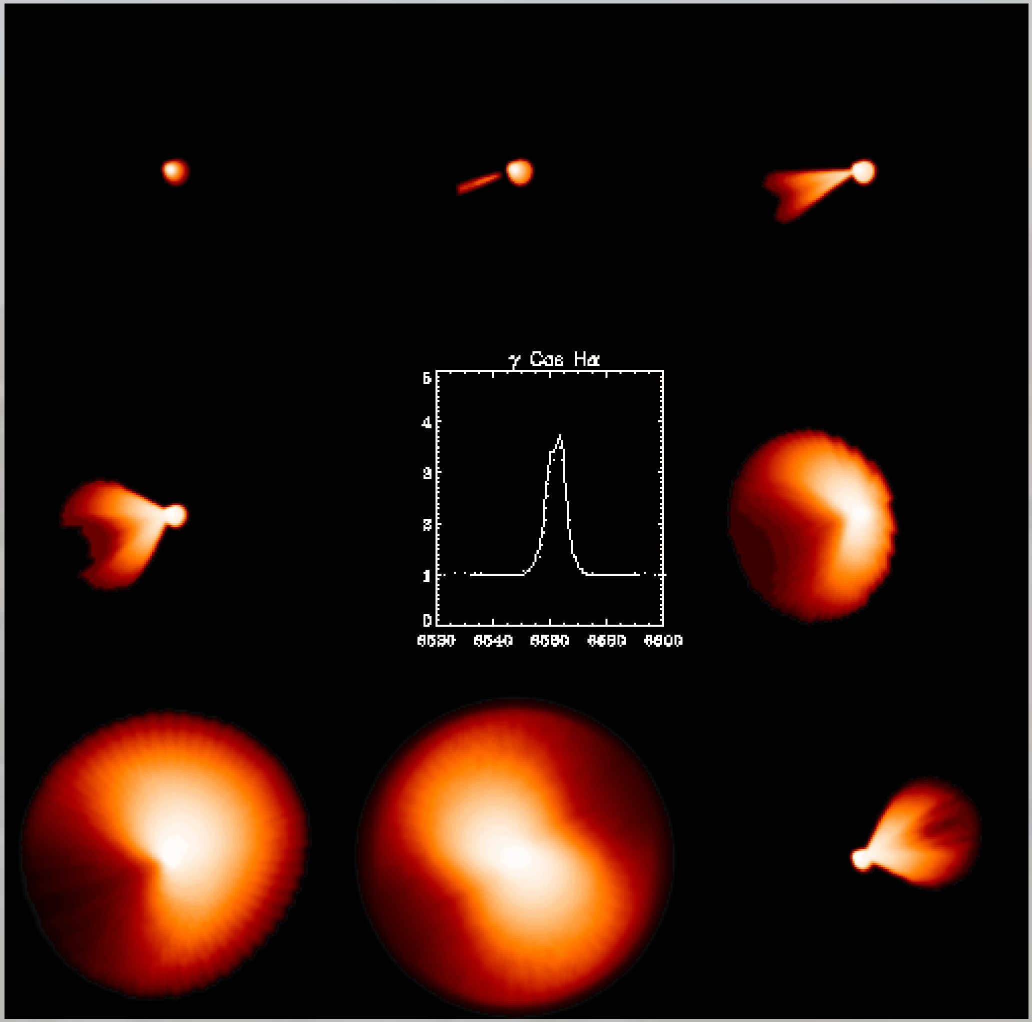


Phase = f(λ)



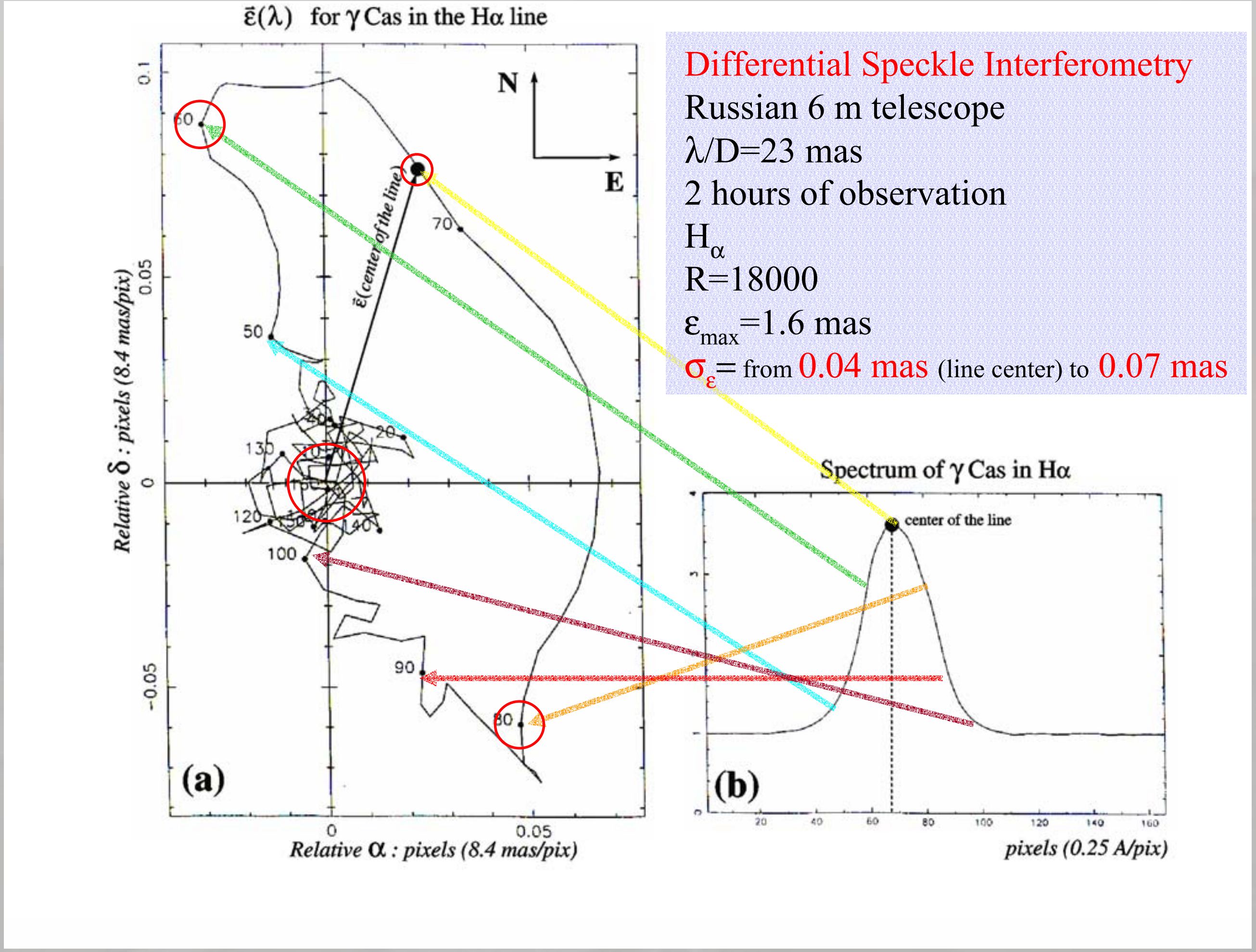
Energy distribution

Images of γ Cas in narrow channels in an emission line



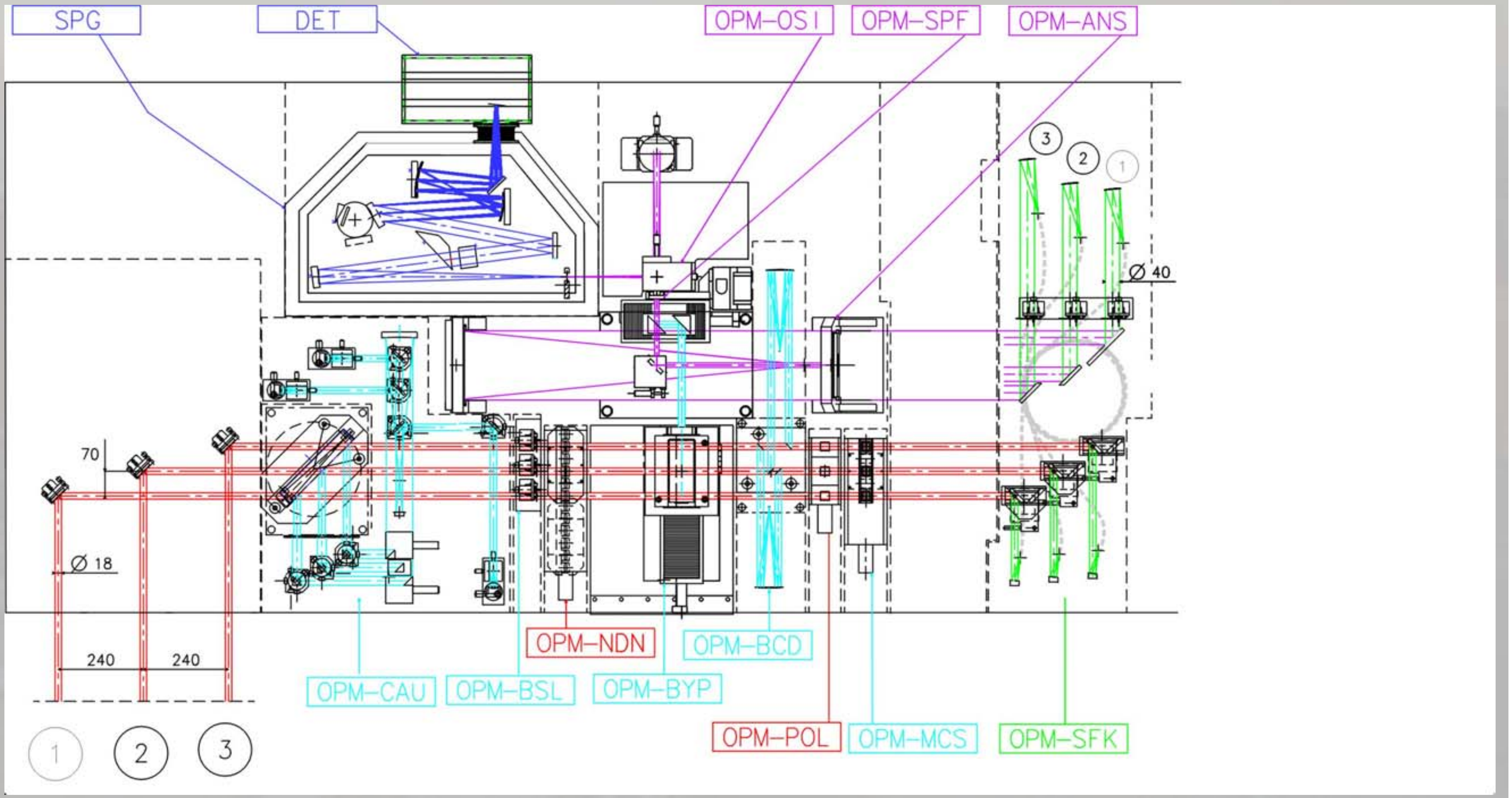
Stee et al. 1995
A&A, 300, 219

Differential Interferometry of γ Cas



Differential Speckle Interferometry
Russian 6 m telescope
λ/D=23 mas
2 hours of observation
H_α
R=18000
ε_{max}=1.6 mas
σ_ε= from 0.04 mas (line center) to 0.07 mas

K Band, calibration and service tools



Model-fitting correction

(de M. Vannier et al., conférence ESO « Science Drivers for future VLT/VLTI instruments)

General behaviour of chromatic dispersion is known :

- Smooth over λ
- dependent on few unknown parameters

Reference channel(s)

$\delta_{astro}(\lambda_0) = 0 \Rightarrow \delta(\lambda_0)$ is a calibrator for chromatic bias

(ex: Dispersion in air ≈ f(λ). G(t))

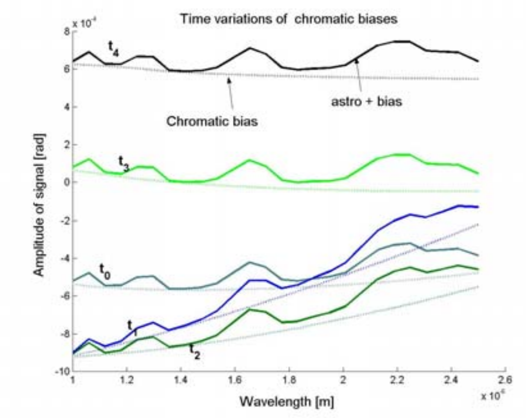
Model fitting

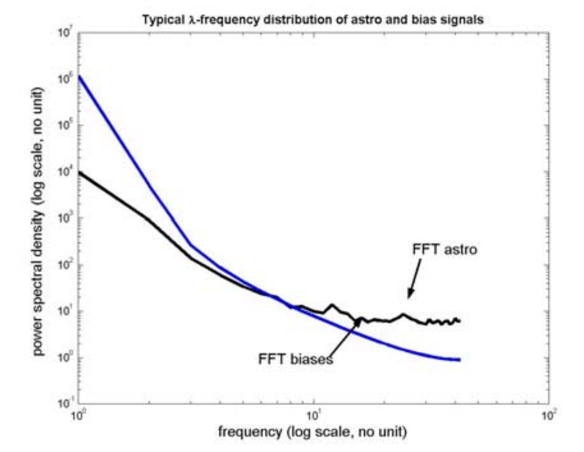
- Well constrained ⇒ few degrees of freedom

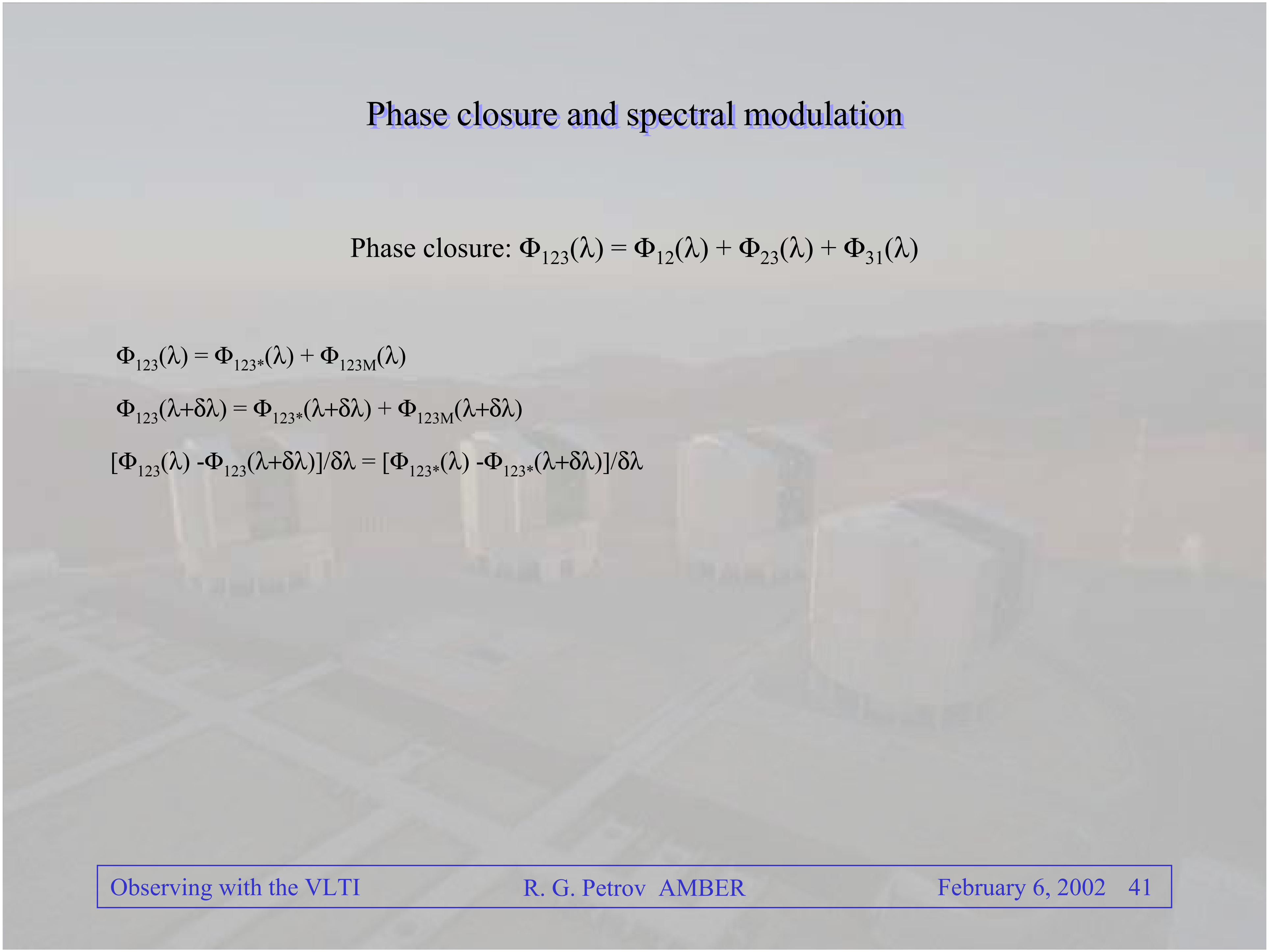
Filtering

low-frequency filtering (in λ) removes chromatic bias

☹: Also suppresses low frequencies from astro signal







Phase closure and spectral modulation

Phase closure: $\Phi_{123}(\lambda) = \Phi_{12}(\lambda) + \Phi_{23}(\lambda) + \Phi_{31}(\lambda)$

$\Phi_{123}(\lambda) = \Phi_{123*}(\lambda) + \Phi_{123M}(\lambda)$

$\Phi_{123}(\lambda+\delta\lambda) = \Phi_{123*}(\lambda+\delta\lambda) + \Phi_{123M}(\lambda+\delta\lambda)$

$[\Phi_{123}(\lambda) - \Phi_{123}(\lambda+\delta\lambda)]/\delta\lambda = [\Phi_{123*}(\lambda) - \Phi_{123*}(\lambda+\delta\lambda)]/\delta\lambda$

AMBER Consortium

- Funding, Detector, data acquisition, real time processing

Osservatorio Astrofisico di Arcetri

- Funding, Cooled spectrograph
- Instrument operation software, data processing, final integration
- Warm Optics and mechanics, electronics, instrument control software
- Funding, assistance from the technical division