stellar interferometry : an overview about basics

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stellar interferometry : an overview about basics

sections

- introduction : a problem raised
- science context and motivation
- few academic reminders
- basics for interferometry and aperture synthesis
- limitations and subsequent needs
- interferometers : principle, production, typology
- difficulties in real world (and some remedies)
- managing with data and some results
- quick-look at some alternative HAR methods
- nulling interferometry and coronagraphy

Long Baseline Interferometry

the machine

principles for operation

- instrumental functions of an interferometer
- various configurations and associated constraints
- encoding information
- extraction of information (academic case)

functions of a stellar interferometer

as a scientific tool

the interferometer is sampling the incident wavefront (multi-aperture) so as to built (thanks to V anCittert and Zernike)

a sampling of the spatial spectrum of the source

as an optical set-up

the interferometer has (at least) 2 functions :

- **collection** : pick up the fields at P_1 and P_2
- **corrélation** : make available $<\psi_1.\psi_2^*>$, covariance of the fields

in addition Optical Paths Differences must be kept much less than the coherence length $c.t_c = \lambda^2/\Delta\lambda$

entrance				exit
telescopes	beam guiding	recombination	detection	
collection	correlation			

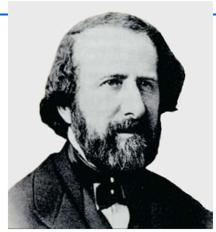
questions of pupils

entrance pupil (or input pupil):
the set of collecting apertures ("collection" stage)
exit pupil (or output pupil) :
a set of images (through the optical set-up) of the collecting apertures ("recombination" stage)

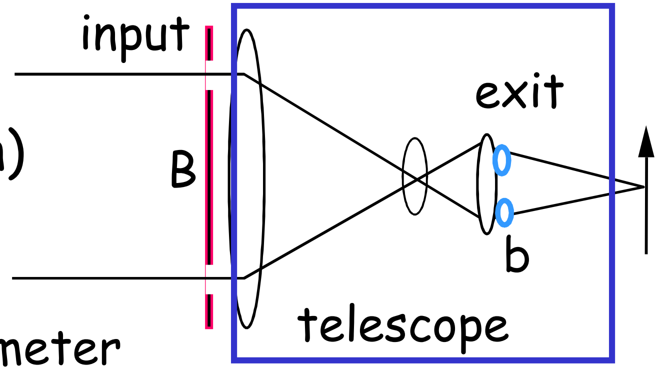
warning :
" exit pupil"
does not mean
"image of the entrance pupil", thoug it can be the case
rather a "re-mapping" of the map of collecting apertures

two schemes :
Fizeau configuration (homothetic mapping)
Michelson configuration (non-homothetic mapping)

Fizeau configuration



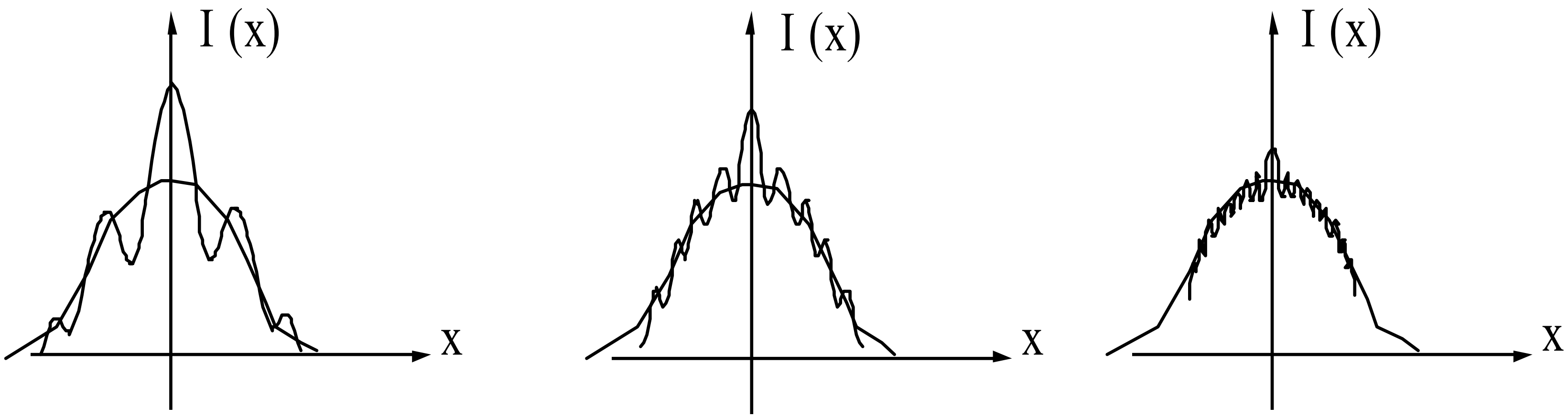
L. H. Fizeau
1819-1896



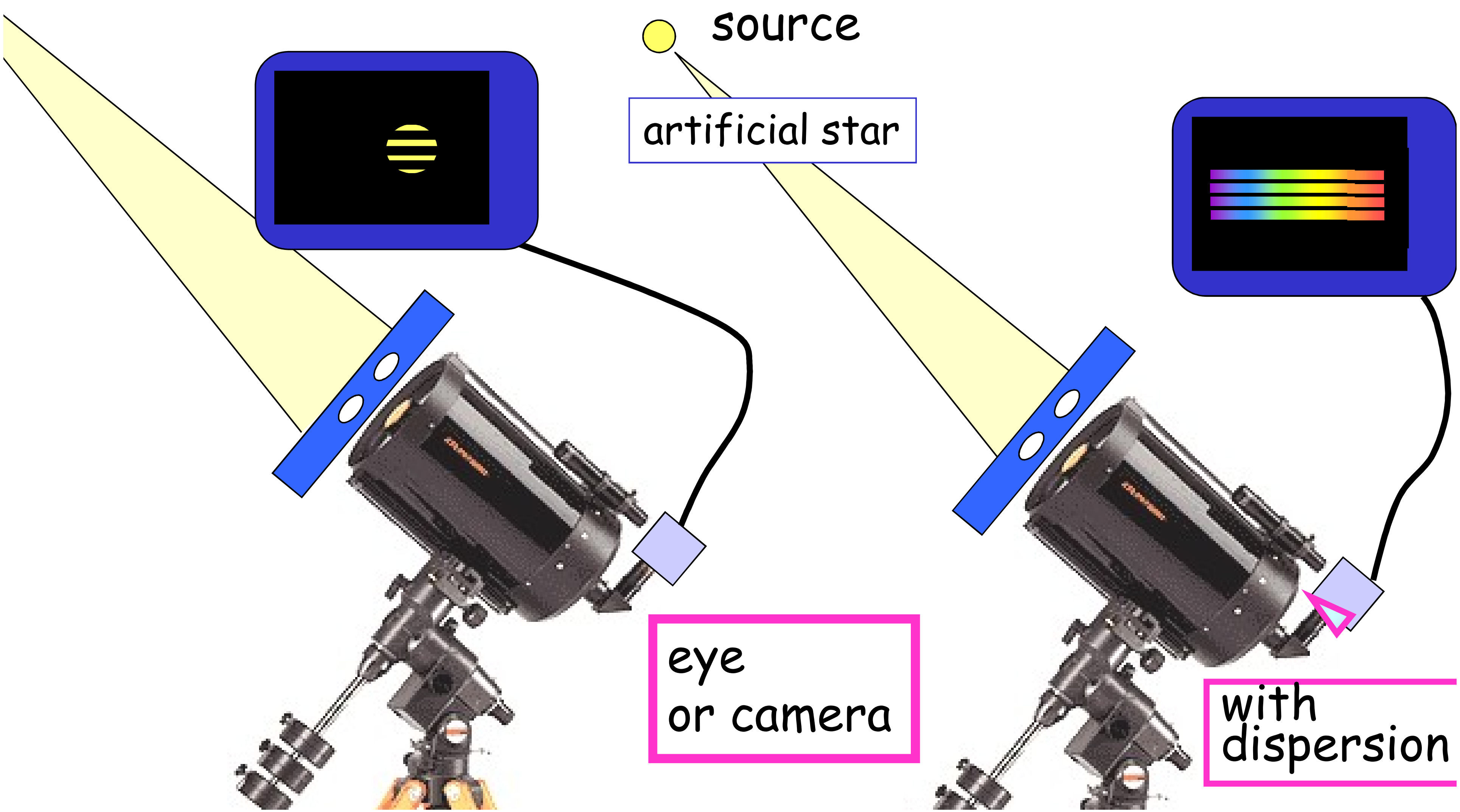
Fizeau , (it is the "do it yourself" already seen)
the telescope performs, just by construction
both collection AND corrélation

maximum baseline is limited by the telescope's diameter
the mappings of entrance and exit distribution of pupils
are homothetic

sampling of the spatial spectrum is made
by changing the baseline (distance between apertures)
note : spatial period changes with baseline



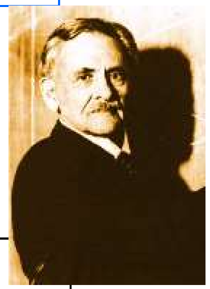
looking at interferences fringes

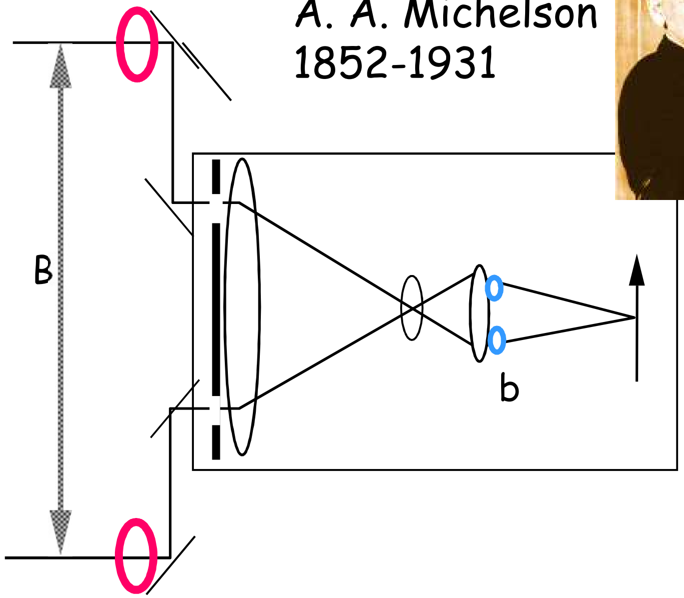


domestic set-up and observation

Michelson configuration

A. A. Michelson
1852-1931





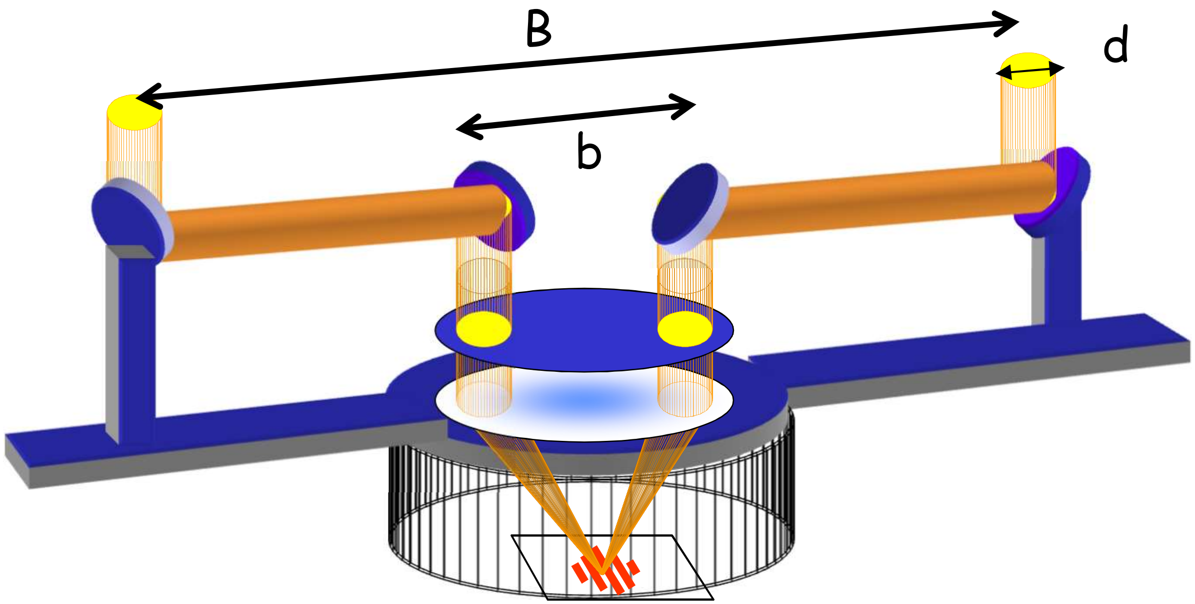
collection and correlation
are well separated and
work independantly

non-homothetic mapping

spatial period of the fringe pattern
is given by "b"
and does not change
with baseline B

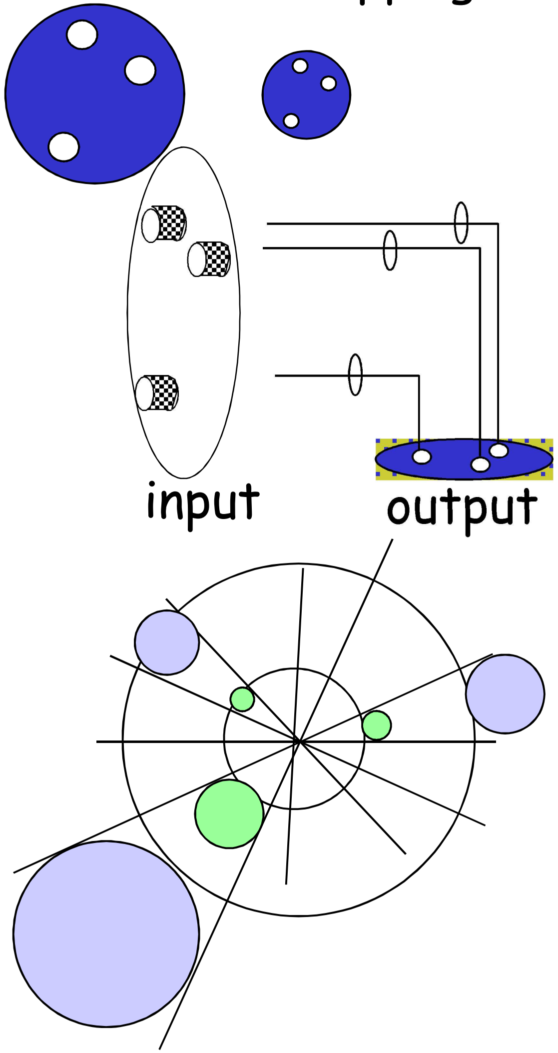
the measured
spectral component is
at spatial frequency B/λ
not at b/λ

cut-off frequency
not limited by the
telescope 's diameter

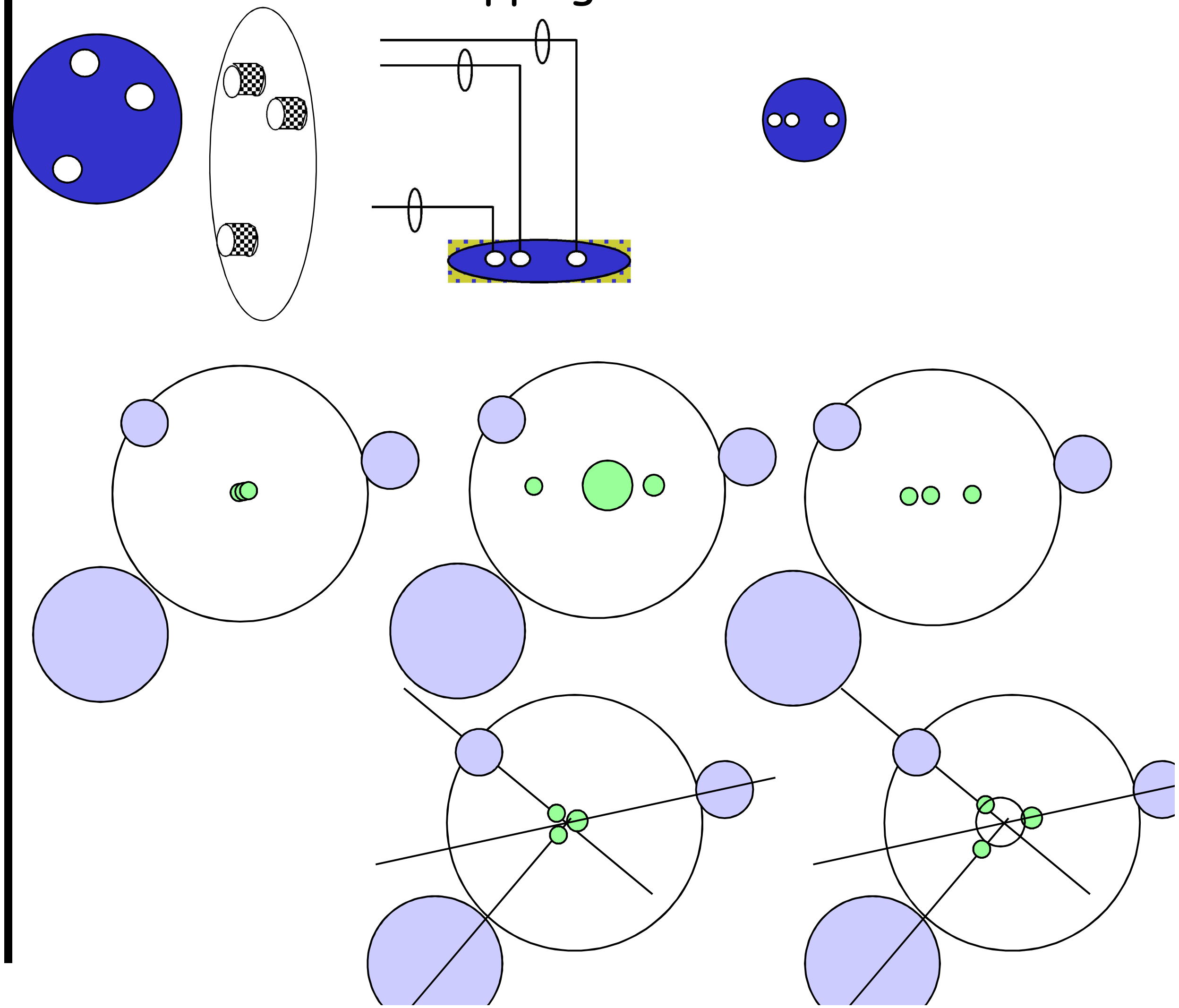


various input and output configuration

Fizeau configuration
homothetic mapping



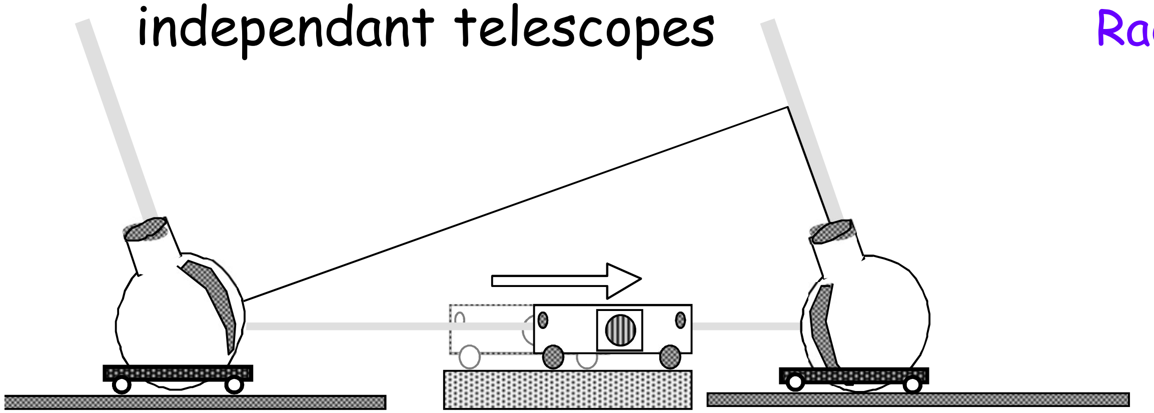
Michelson configuration
non-homothetic mapping



extension of the Michelson configuration

going farther in the separation of collectors :
independant telescopes

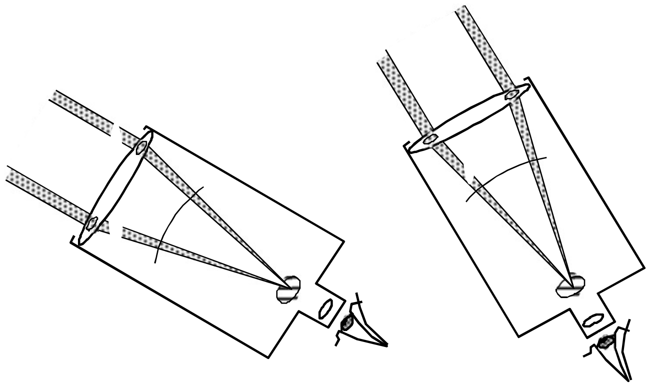
Radioastronomy, Labeyrie



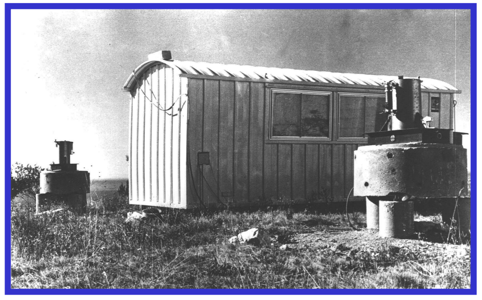
both configurations F et M,
intrinsically achieve
Optical Paths balance

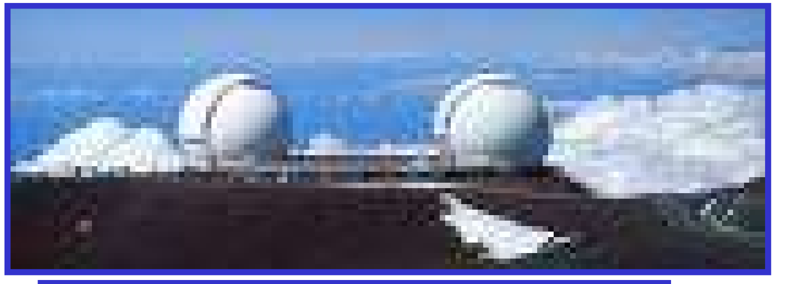
No longer the case here
because of an astronomical misbalance
introducing
severe metrological constraints

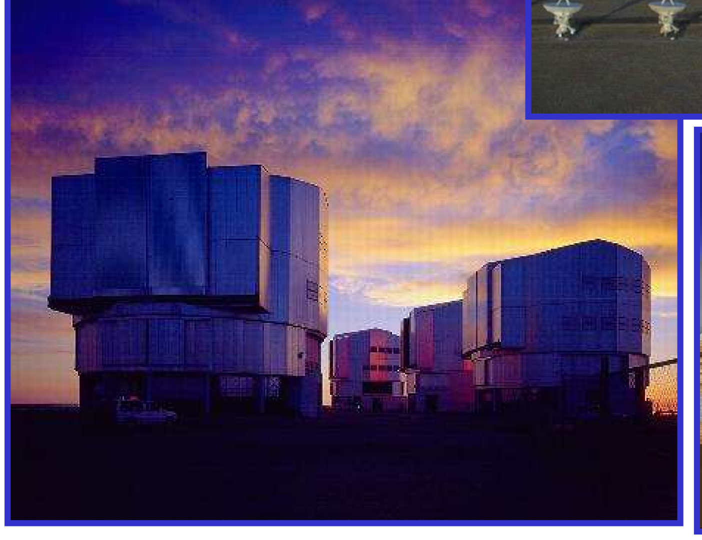
equal optical paths, automatically
kept well balanced
whatever pointing direction is



extended Michelson : mostly the usual scheme for years





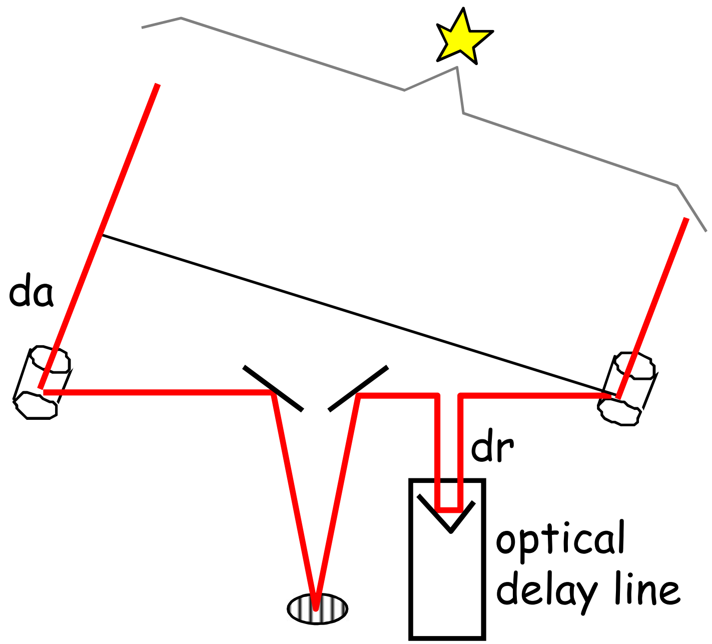


metrological constraints when using separated telescopes

an extra optical path "da" must be taken into account to achieve the balance. Equating paths must be control permanently

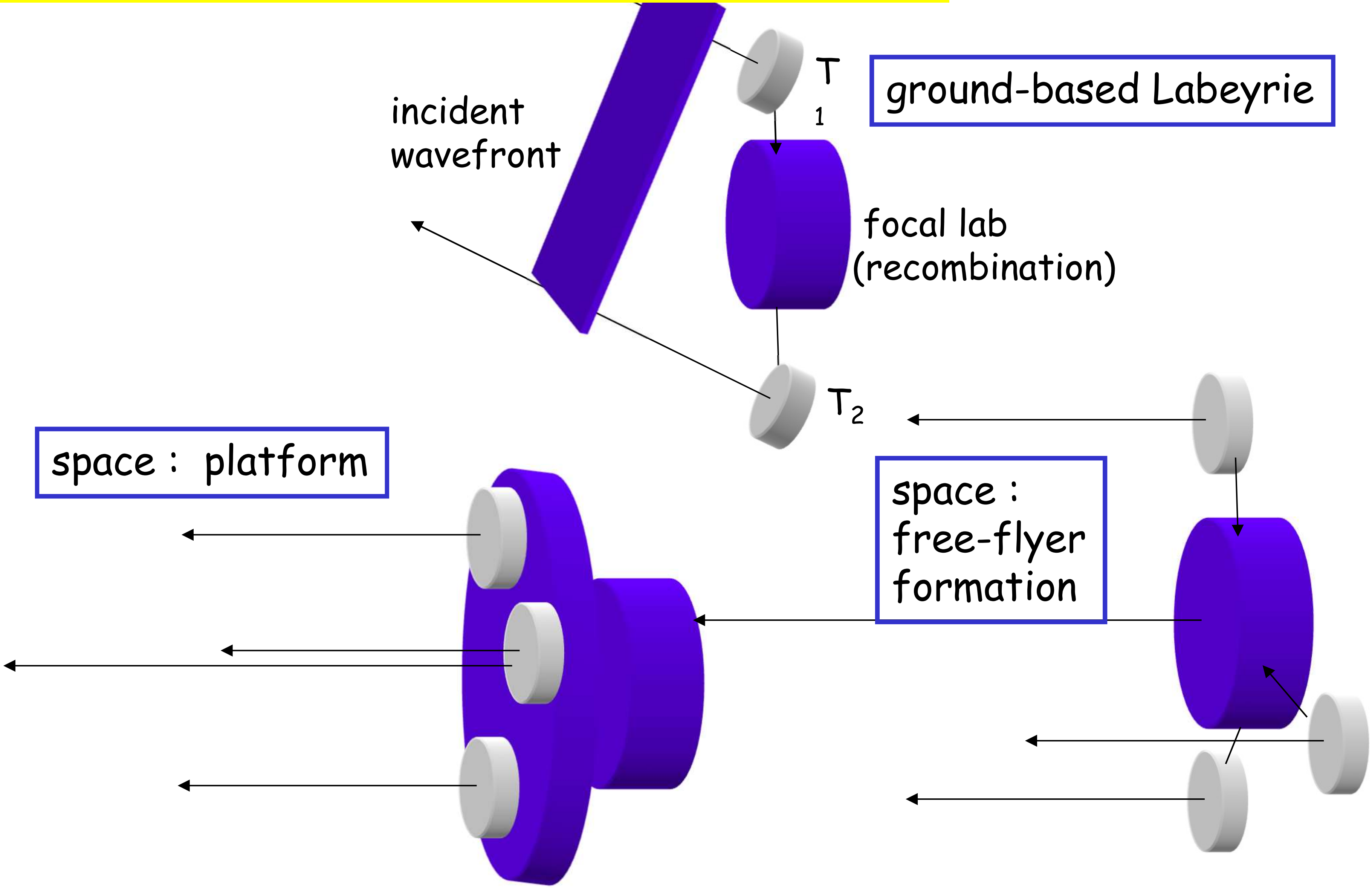
Balance is made by
an adjustable Optical Delay Line
continuously moving during observation
and inserting optical path "dr"

required accuracy
a small fraction
of coherence length $\lambda^2/\Delta\lambda$



relative accuracy regime :
coherence length/baseline → dynamical nanometrology

ground-based and space-based situations



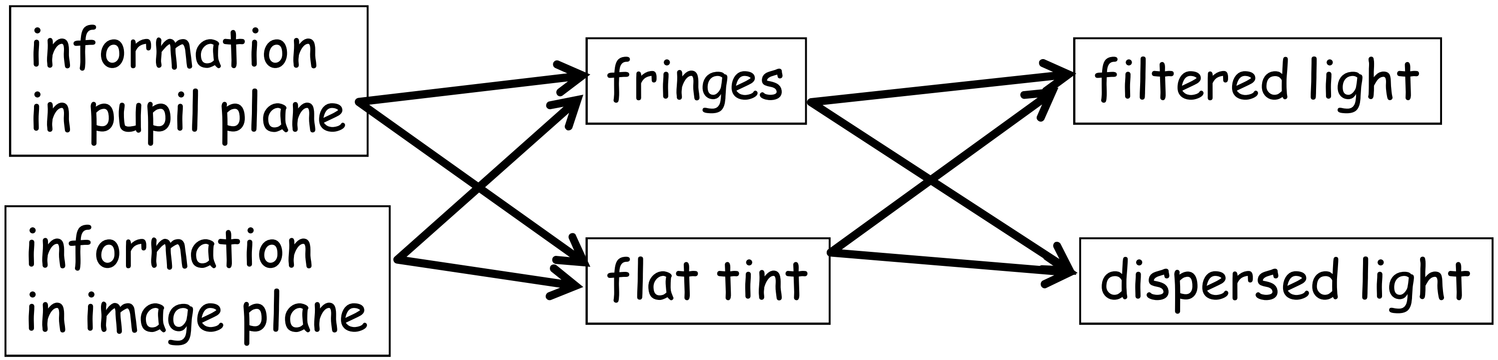
Long Baseline Interferometry

using the machine

information encoding : recombination stage

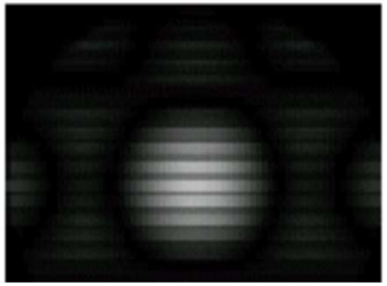
up to now only the "fringe pattern" has been mentioned
other schemes exist

here below : some combinations and denominations



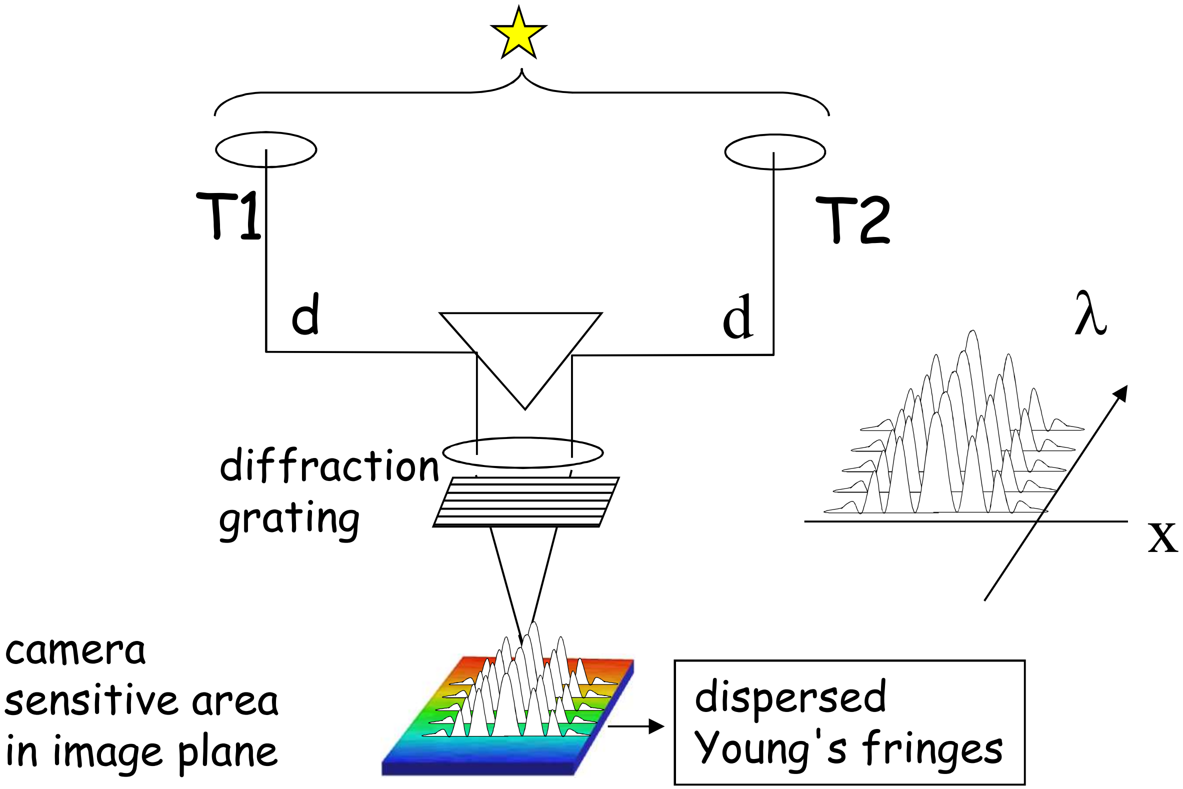
we consider here only the two main encoding schemes

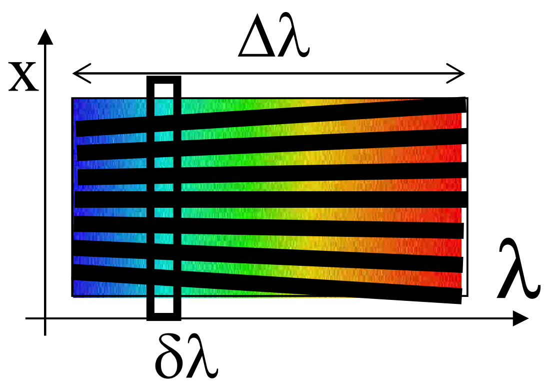
fringe pattern in filtered and in dispersed light



fringe pattern
filtered light, (x,y) mode

spatial
multi-axial
mode : x-λ





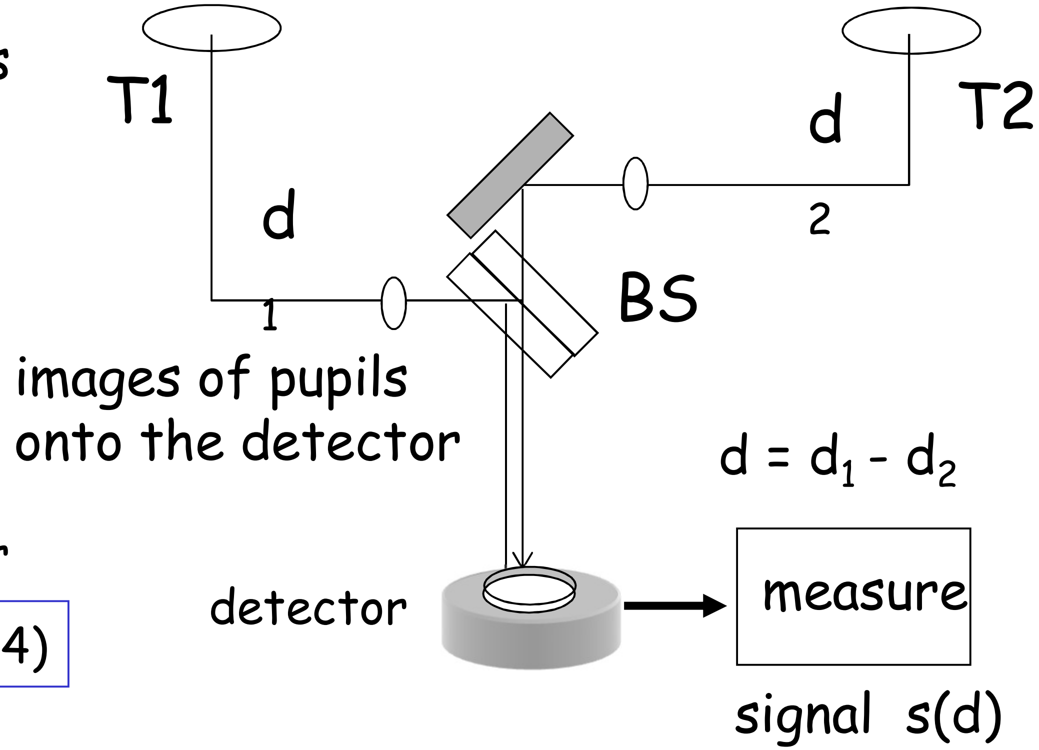
modulated flat-tint, pupil plane _ 1

superimposition of output pupils

separation is made ZERO

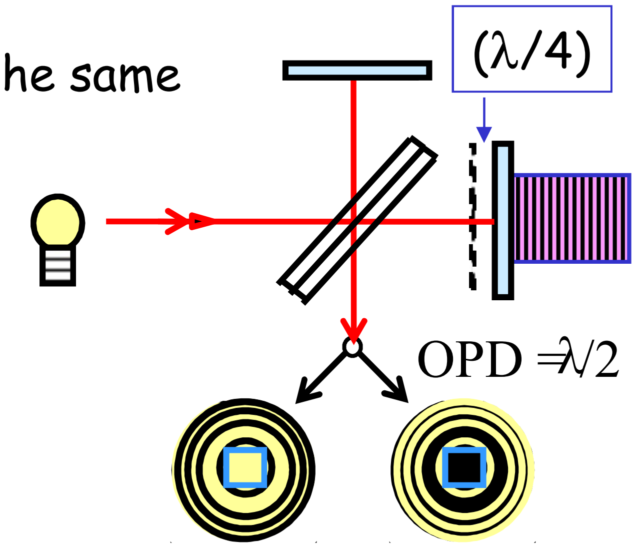
ring pattern

mono-axial mode



reminder :
laboratory Michelson interferometer

nearly just the same

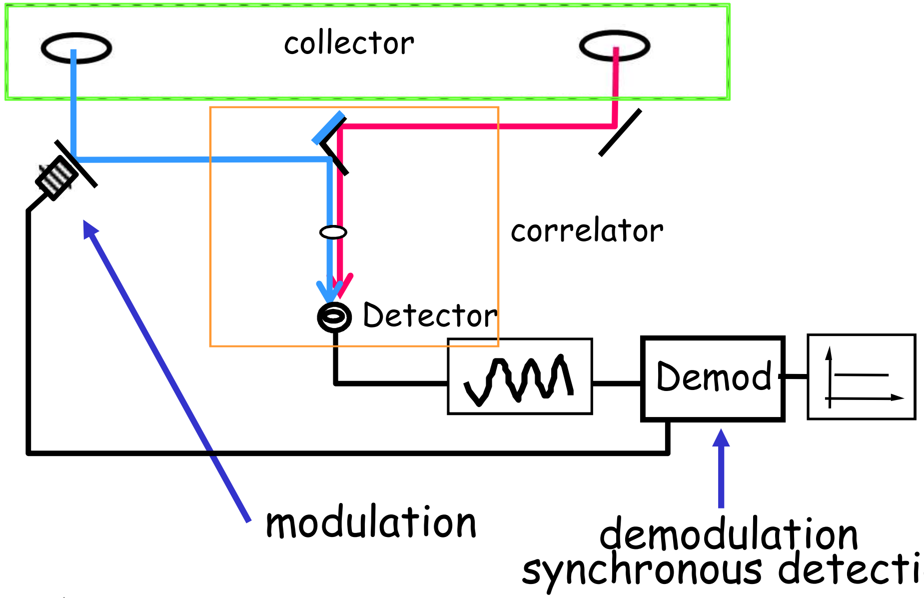


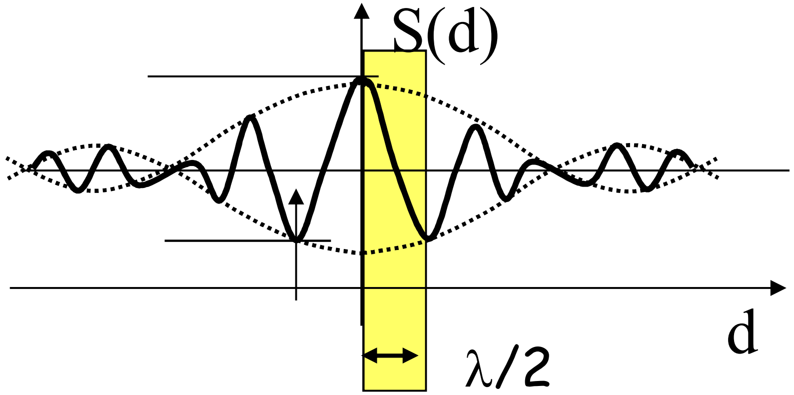
time modulation
of Optical Path Difference (λ/4)

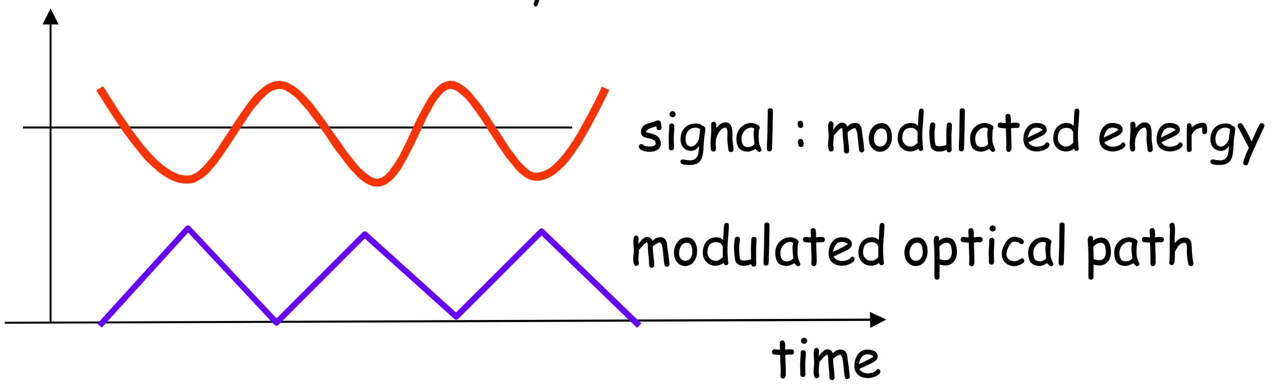
detector only sees the center
of the ring pattern
where bright/dark alternate

modulated flat-tint, pupil plane _2

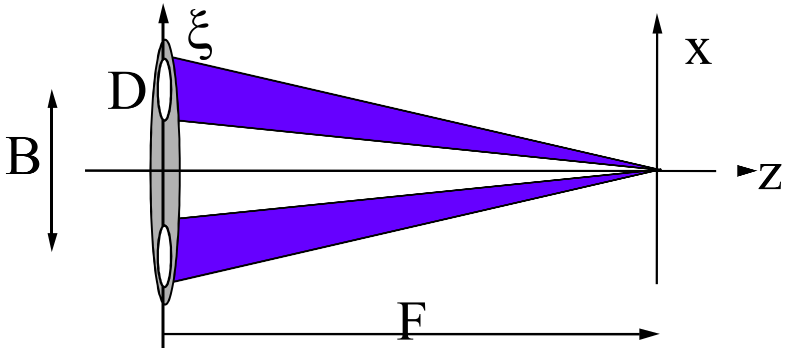
how measure a fringe contrast ?
encoding using time modulation of optical paths,
yielding intensity modulation

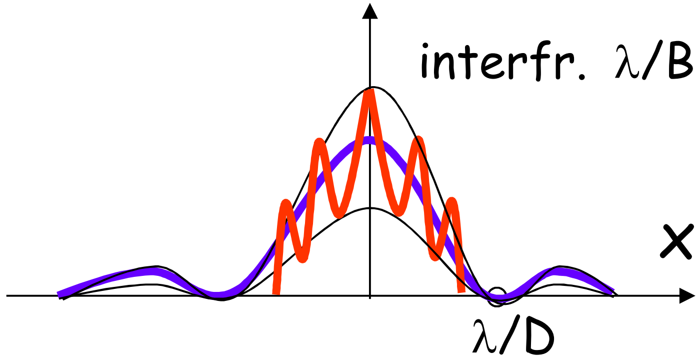






extracting information academic case_1



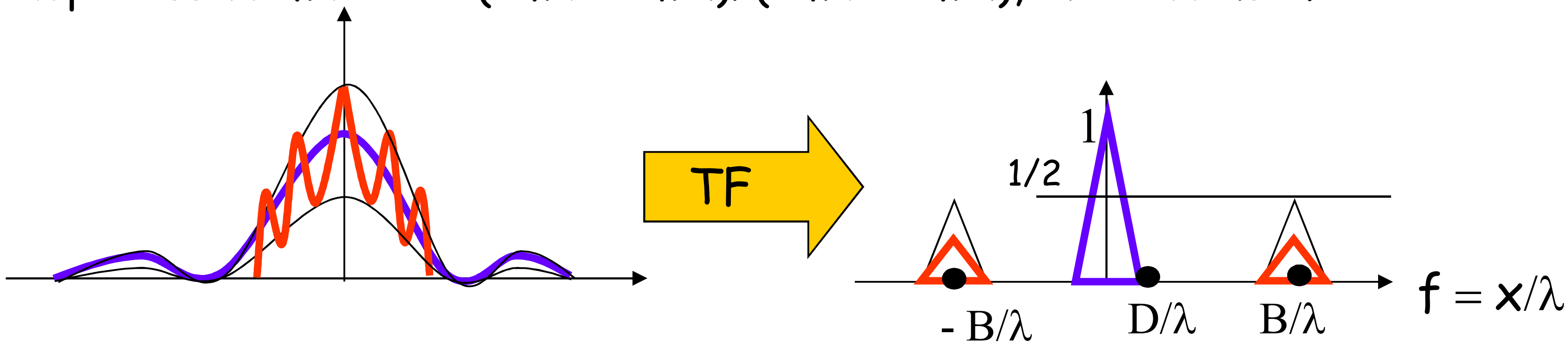


observed intensity : fringe pattern

info = modulation rate = nearly VISIBILITY

$$I(x) = Airy(x)\,.2.I.\left\{\ 1 + V.\ \cos\left(2.\pi.\frac{B}{\lambda}.\frac{x}{F}\right)\ \right\} \qquad V = \left|\frac{\hat{O}(B/\lambda)}{\hat{O}(0)}\right|$$

hope less to make C = (Imax-Imin)/(Imax+Imin), need to use FT

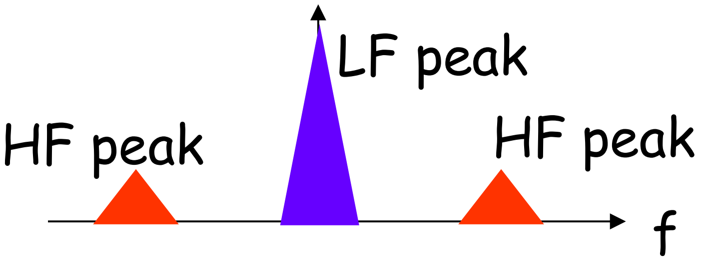


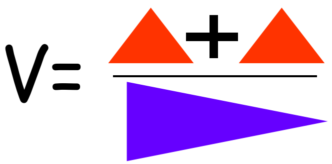
extracting information academic case_2

$$I(x) = Airy(x).\left\{ 1 + V . \cos\left(2.\pi.\frac{B}{\lambda}.\frac{x}{F}\right) \right\} \qquad V = \left|\frac{\hat{O}(B/\lambda)}{\hat{O}(0)}\right|$$

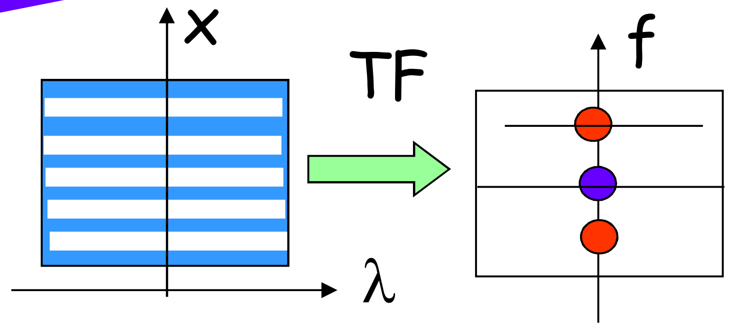
$$\hat{I}(f) = \hat{Airy}(f) * \left\{ \delta(f) + \frac{V}{2}.\left[\delta(f - \frac{B}{\lambda}) + \delta(f + \frac{B}{\lambda}) \right] \right\}$$

$$\hat{I}(f) = \hat{Airy}(f) + \frac{V}{2}.\hat{Airy}(f - \frac{B}{\lambda}) + \frac{V}{2}.\hat{Airy}(f + \frac{B}{\lambda})$$





$$V = \frac{2.\int HF\ peak.df}{\int BF\ peak.df} = \frac{coherent\ energy}{incoherent\ energy}$$

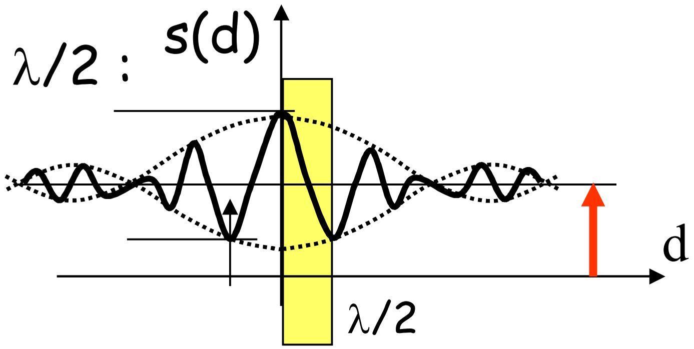


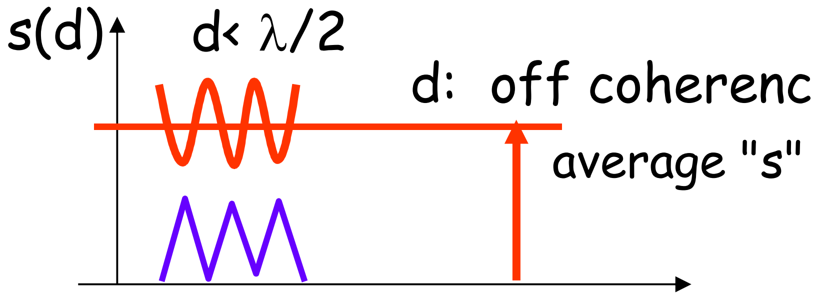
extracting information modulated flat-tint

two approaches :

modulation $\lambda/2$ and sequence of interferograms

modulation $\lambda/2$:

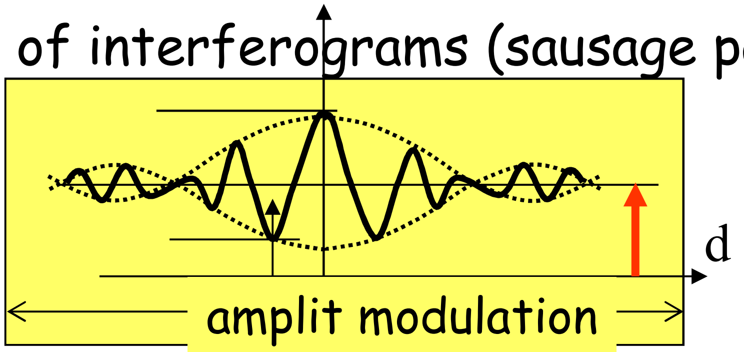


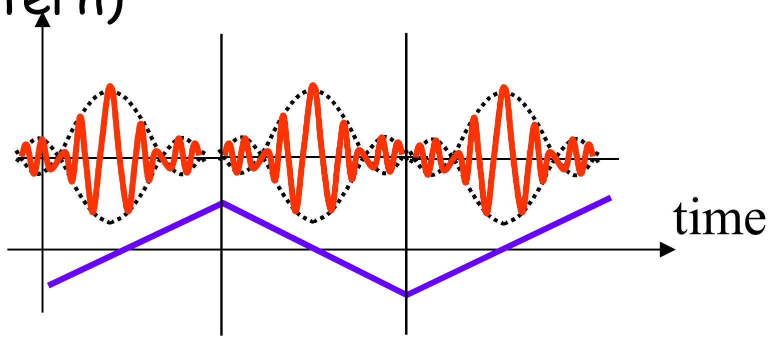


$$\boxed{V = \frac{energie\_coherente}{energie\_incoherente} = \frac{Q.\frac{s\max}{s\min}}{s\,moyen}}$$

Q = shape factor

sequence of interferograms (sausage pattern)





managing with data

data produced with a 2-telescope interferometer_1

an interferometer does not measure angular diameters

a 2-T- interferometer measures raw-Visibilities (modulus of γ)

after a long and tedious process for

calibrating the interferometer response and unbiasing of data,

it gives an estimate of the true-visibility

(one component of the spatial spectrum of the source)

the job of the interferometer is to **sample the spatial spectrum**

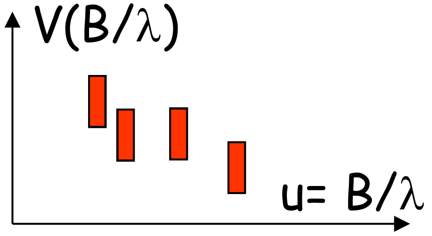
of the brightness distribution of the source

one baseline , one component

baseline after baseline is built a "**visibility curve**"

or a "visibility surface"

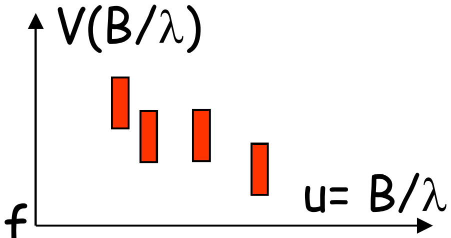
when baselines of various orientations are used



frequently said : interferometer samples the u-v plane

data produced with a 2-telescope interferometer_2

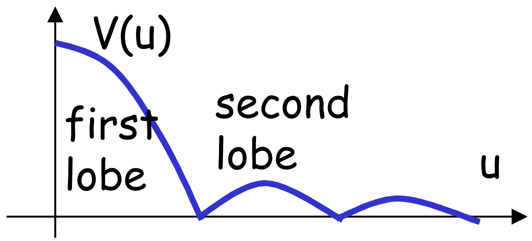
what to do with visibility curves or surfaces ?



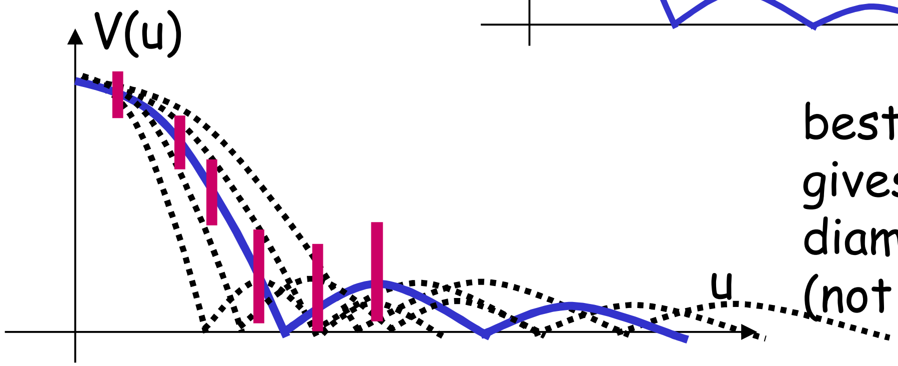
from a model, expected for the source
a family of theoretical visibility surfaces are calculated (modulus of spatial spectrum) according to parameters of the model
(examples : angular diameter, angular separation of binaries)

a **model-fitting** process yields
parameters of the selected model, not the ones of the source

a typical visivility curve
(model : uniform disk, UD)

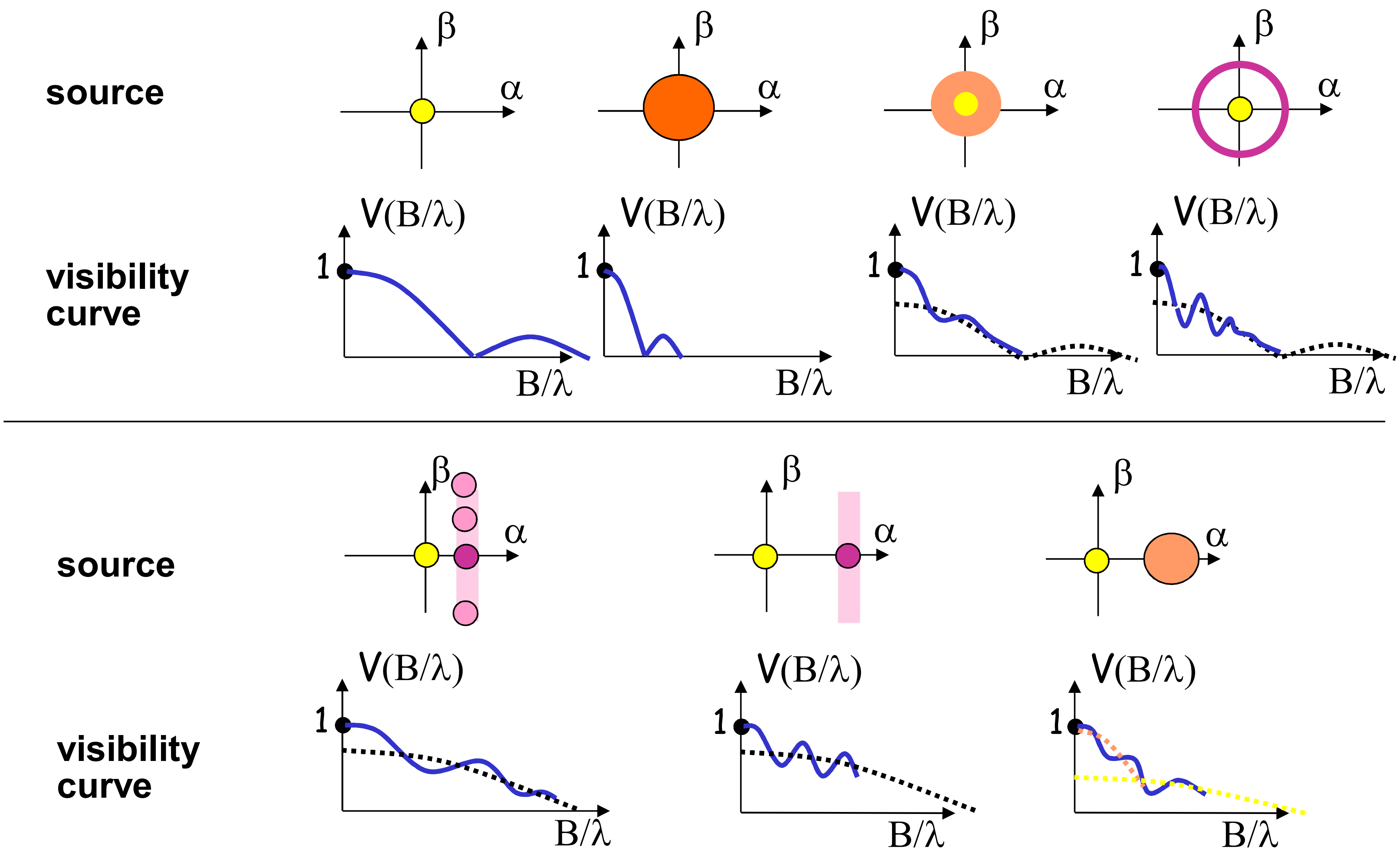


model-fitting

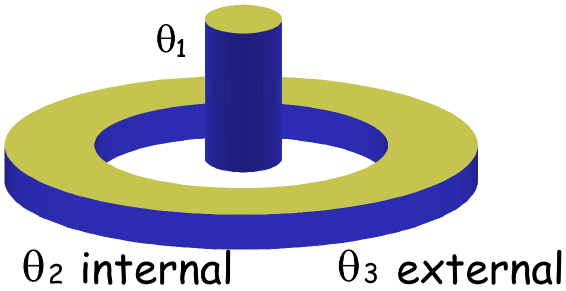


best fit (in blue)
gives the
diameter of the UD
(not a star has a UD)

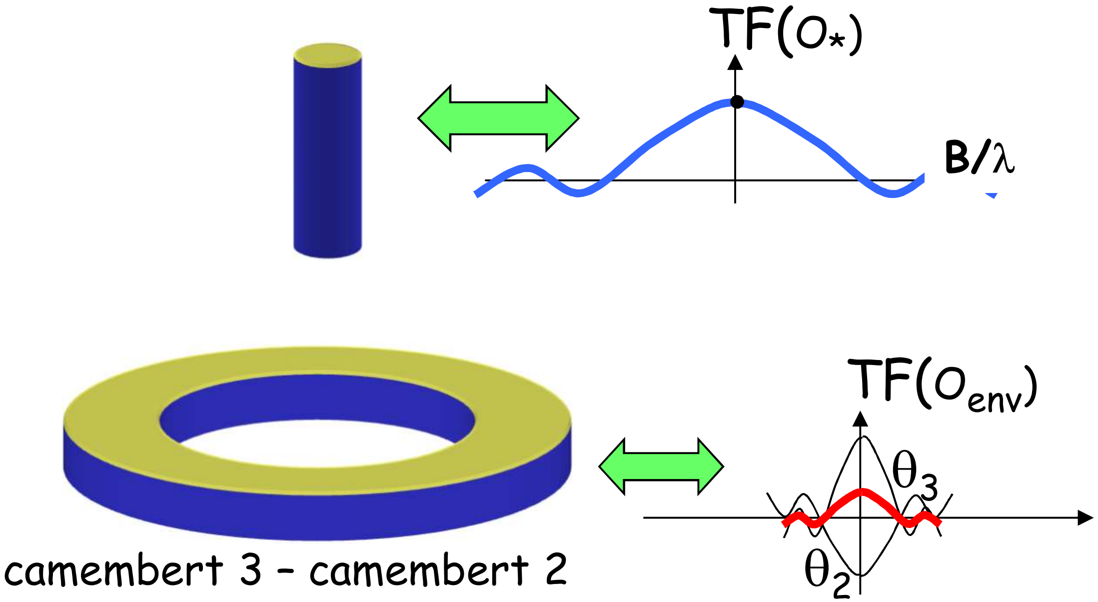
a pictorial for some couples (source,visibility)

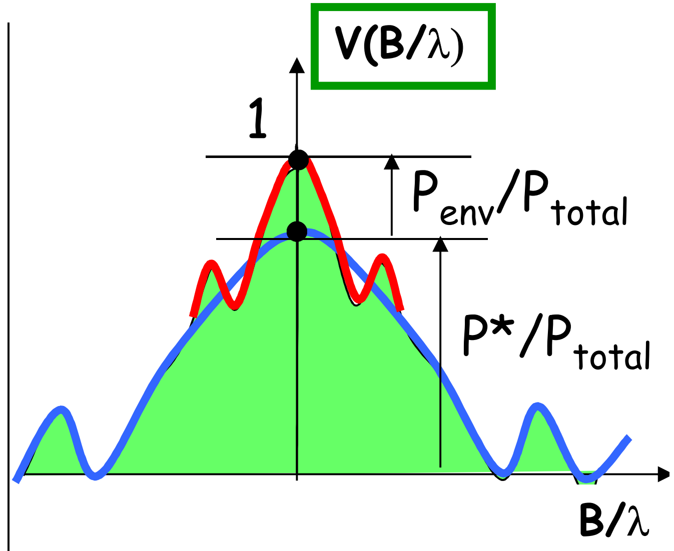


a non-realistic but illustrative example



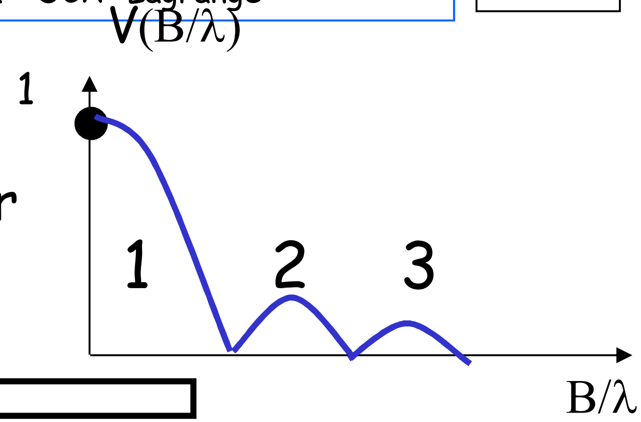
$$O(\alpha) = O_*(\alpha) + O_{env}(\alpha)$$





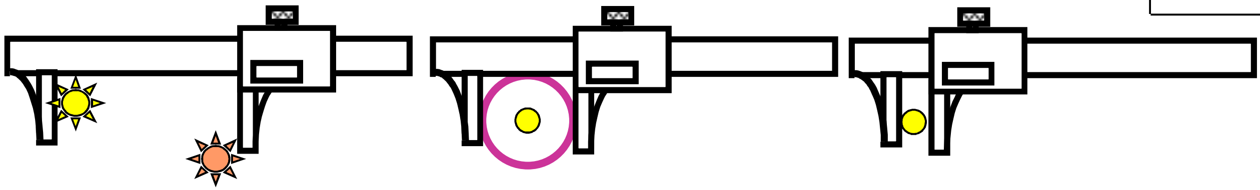
here visibility curve yields an estimate of P*/Penv

visibility playground : phenomenology



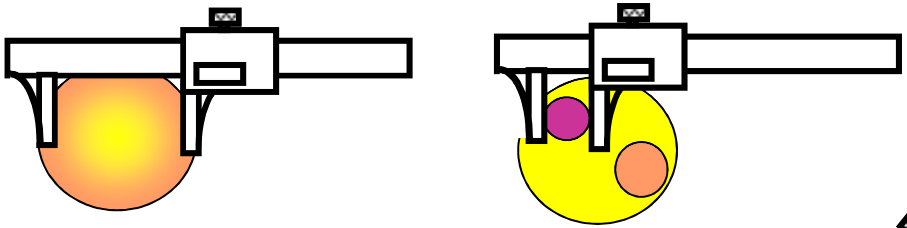
lobe 1 : features larger or equal to diameter

separations, enveloppes, diameters

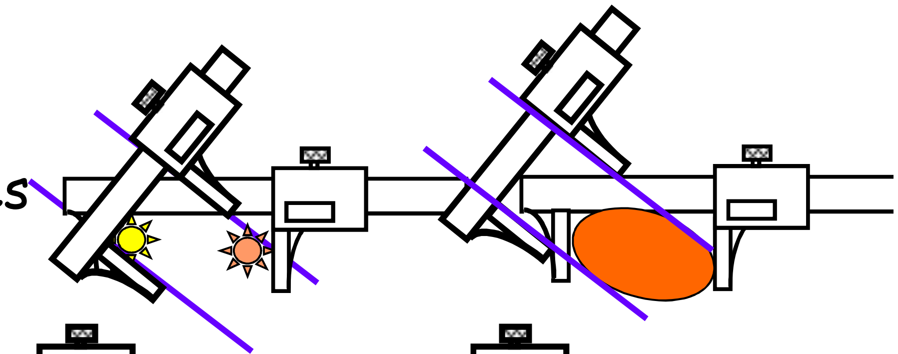


lobe 2, 3,... : features smaller and smaller than diameter

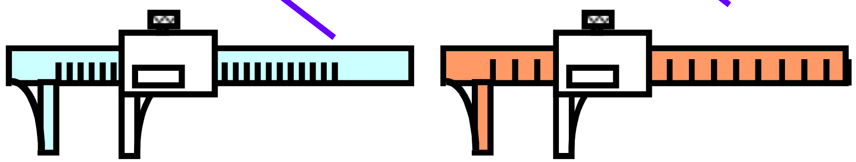
limb darkening and rotation (oblateness), photospheric features



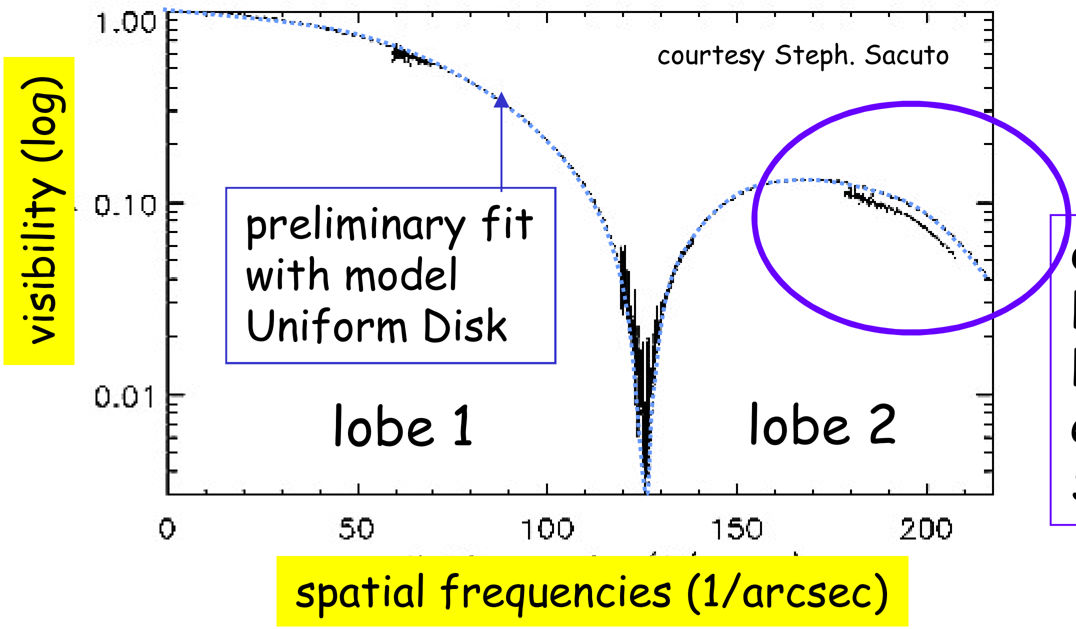
baseline orientation: asymmetries



wavelength :
change of resolution scale



examples of visibilities from observation



departure from UD model
look for
limb darkening ?
enveloppe ?
Surface Brightness Asymetries ?

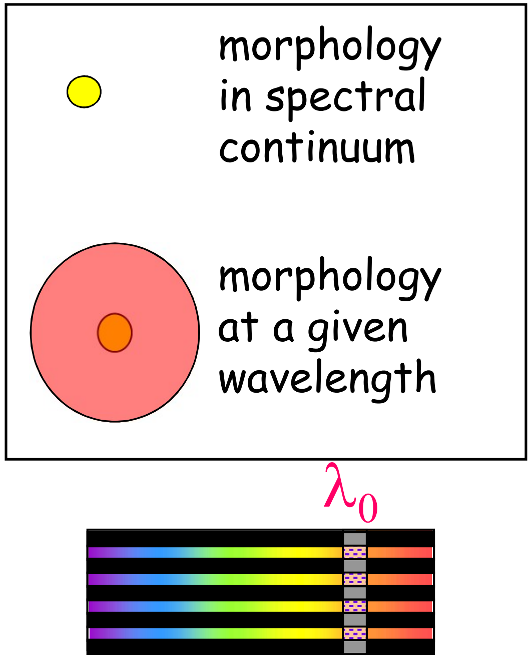
spectro interferometry

up to now, only one wavelength used

observing fringes in dispersed light provides chromatic visibilities

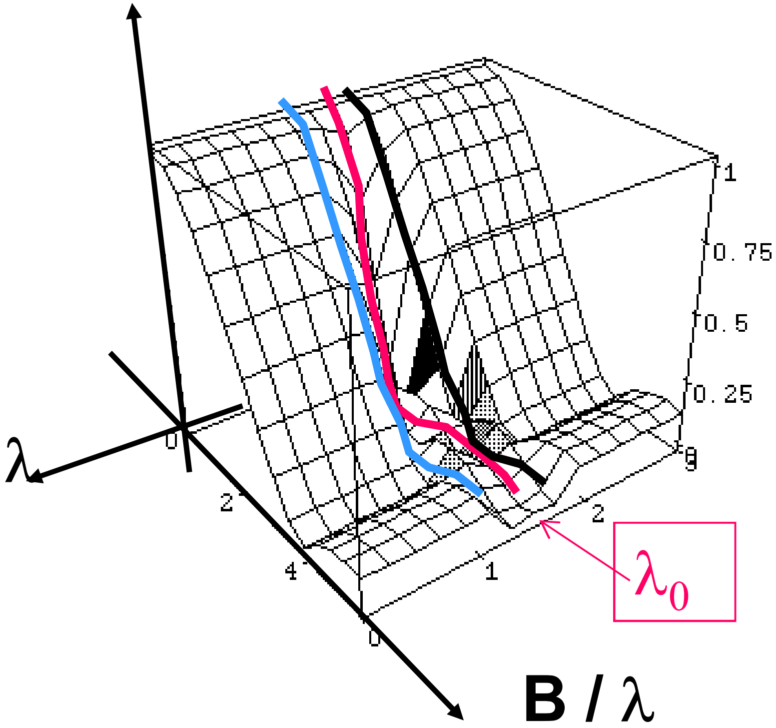
possible chromatic morphology can be exhibited

observed source



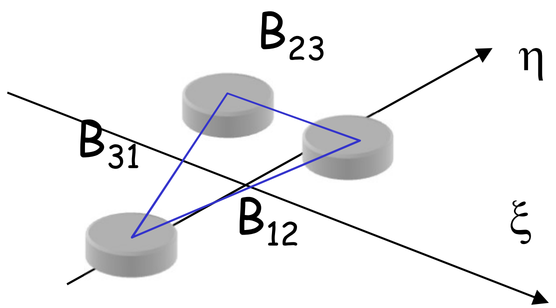
lowered visibility at λ_0

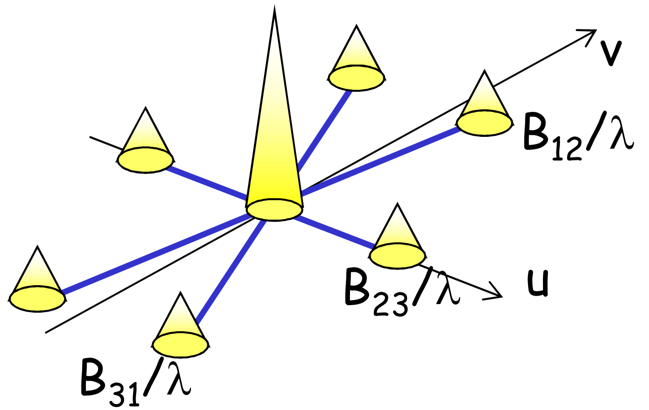
Visibility (λ, B / λ)



more than 2 telescopes, more than one baseline

N telescopes ➔ N.(N-1)/2 baselines
N.(N-1)/2 spatial frequencies simultaneously





moreover :
as soon as we have 3 telescopes combined
some information pertaining to the phases of γ_{nk} can be recovered from the composite fringe pattern

namely : observation yields a **phase closure** (a number)
which is $\phi clos = \phi 12 + \phi 23 + \phi 31$

phase closure _ 1

preliminary comment : the context

2 telescopes, 1 baseline : sampling u-v plane along a line
several orientations : sampling along several lines
N telescopes , N.(N-1)/2 baselines used independantly :
as many (u,v) components

there, no information regarding the phase of γ (complex)
exception in some cases via spectral dispersion

N telescopes used simultaneously : composite fringe pattern
sampling N.(N-1)/2 (u,v) within u-v plane in one snapshot

phases respective to individual baselines yet not available

BUT as soon as 3 telescopes are combined

the sum of phases can be extracted from fringes
this sum named "phase closure" provides constraints on
models to fit on the spatial spectrum

phase closure _2

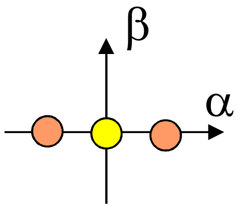
constraint on what ?

phase closure allows diagnosis on asymetries

in short : centro-symmetry of the brightness distribution :
all phases are zero , phase closure is zero

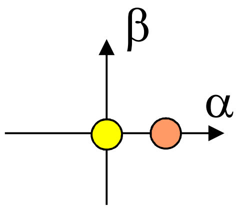
departure from symmetry, phase closure NOT ZERO

example (academic) : *source :* $O(\alpha)$, *spectrum* $\hat{O}(u) = \left|\hat{O}(u)\right|.exp(i\,\phi)$



$$O(\alpha) = \delta(\alpha) + h.\left[\delta(\alpha-\rho) + \delta(\alpha+\rho)\right]$$
$$\hat{O}(u) = 1 + h.\left[exp(i.2\pi.u.\rho) + exp(-i.2.\pi.u.\rho)\right]$$

$\hat{O}(u) = 1 + 2.h.cos(2\pi.u.\rho)$ *REAL ! , phase ZERO ,* $\forall u$



$$O(\alpha) = \delta(\alpha) + h.\delta(\alpha-\rho)$$

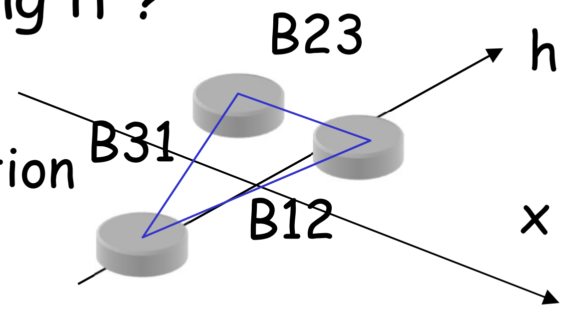
$\hat{O}(u) = 1 + h.exp(i.2\pi.u.\rho)$ *a priori COMPLEX*

phase non ZERO

hep !, simply Fourier parity properties

phase closure _3

OK, a little short !
how to perform ?
and what, as for using it ?

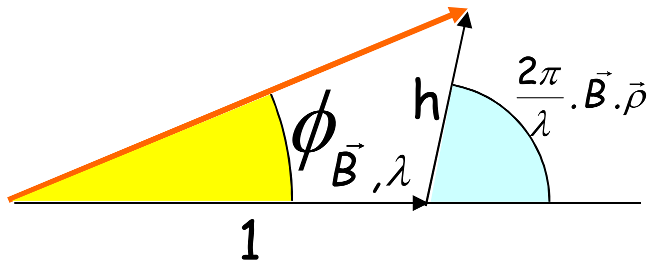


for individual baselines,
atmospheric turbulence corrupts phase information
but for a closed network this corruption
is eliminated and we can extract (measure) :

$$\phi_{clos} = \phi_{12} + \phi_{23} + \phi_{31}$$

any asymmetry results in a double photometric barycenter,
say separation r (vector)

so we find $\phi_{\vec{B},\lambda} = Arg\left[1 + h.exp(\,i.\frac{2\pi}{\lambda}.\vec{B}.\vec{\rho})\right]$
involving λ and vectors B and r

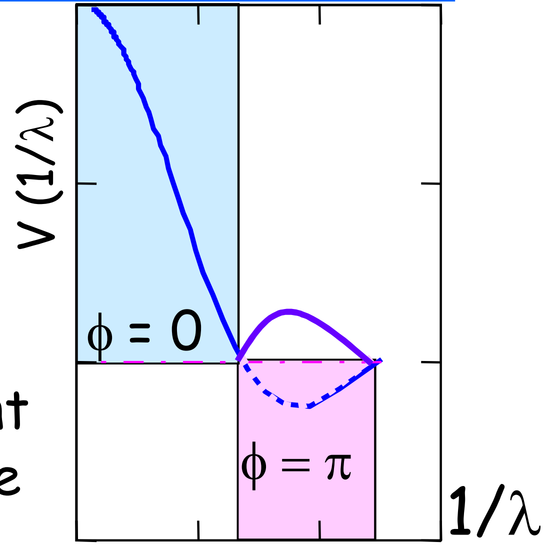


WARNING :

ϕclos actually is not a single number, it is a function of wavelength and time (baseline network and source evolution)

phase closure _4

even with a centro symmetric object
phase closure is not always zero
it is 0 or π depending on λ



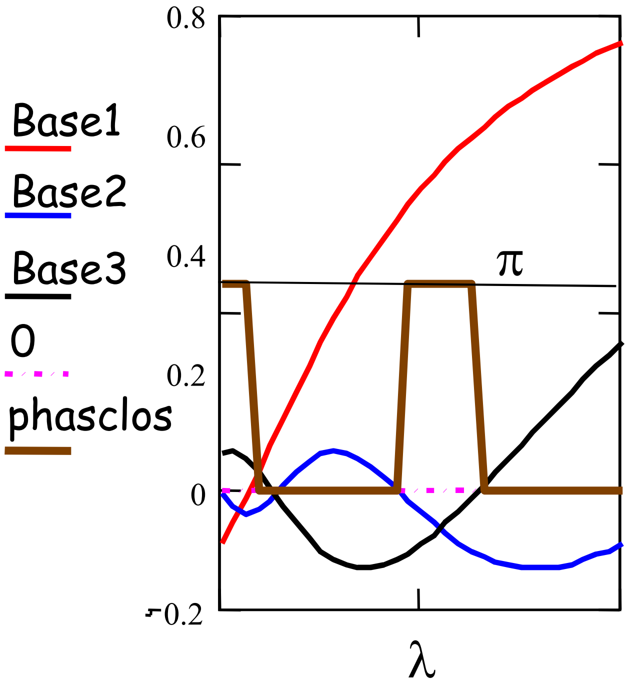
phase of γ is present
in UD visibility curve

chromatic phase closure with UD
3 baselines (3 visibility curves)

change of sign occurs
when crossing a "zero visibility"

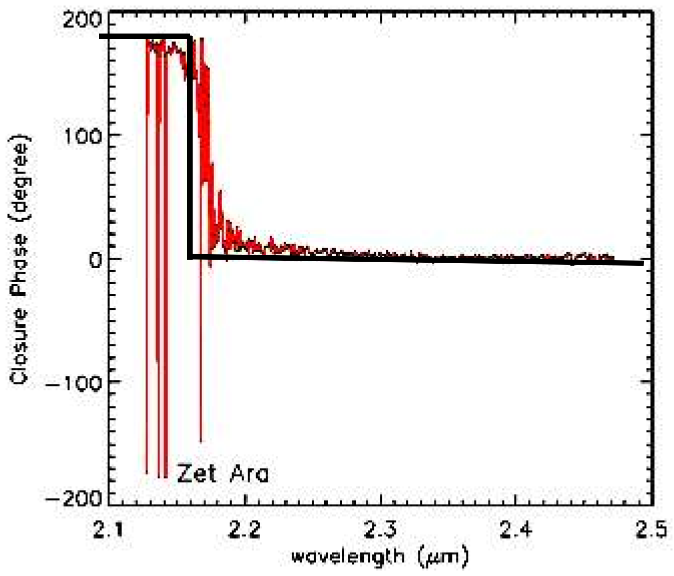
phase closure = sum of 0 and π,
varying along the spectral interval

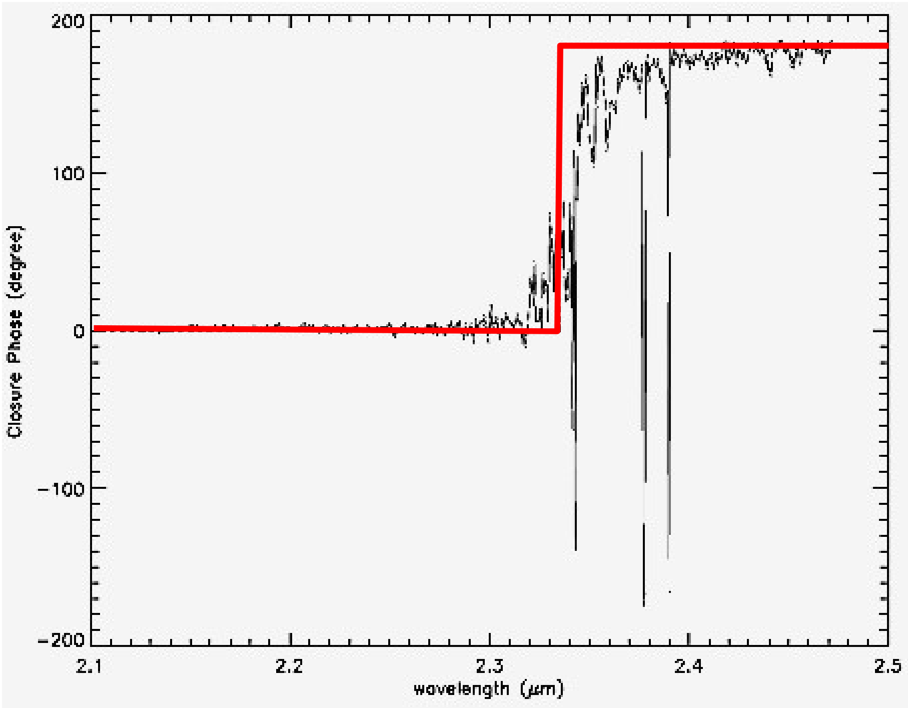
steps from 0 to π trace pure UD



phase closure _5

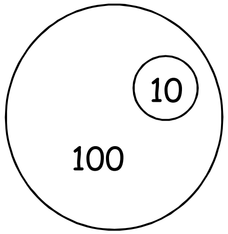
departing from steps $(0,\pi)$
indicates complex structure
various assumptions depend on which visibility lobe
is considered





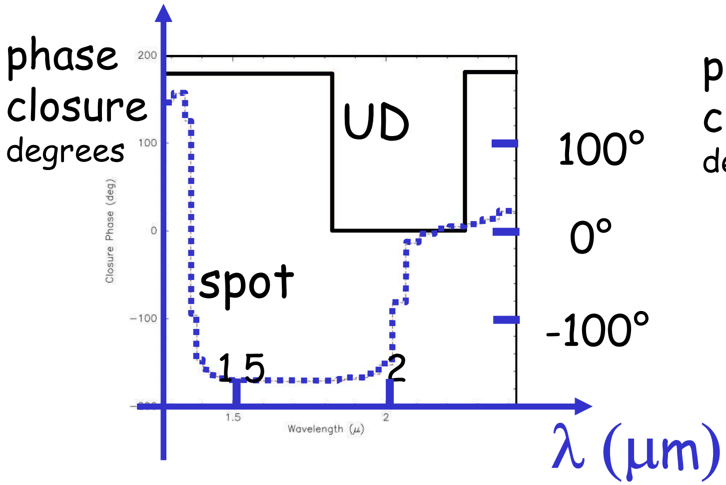
using phase closure : (very short)

numerical simulations and observations (thanks Steph Sacuto)

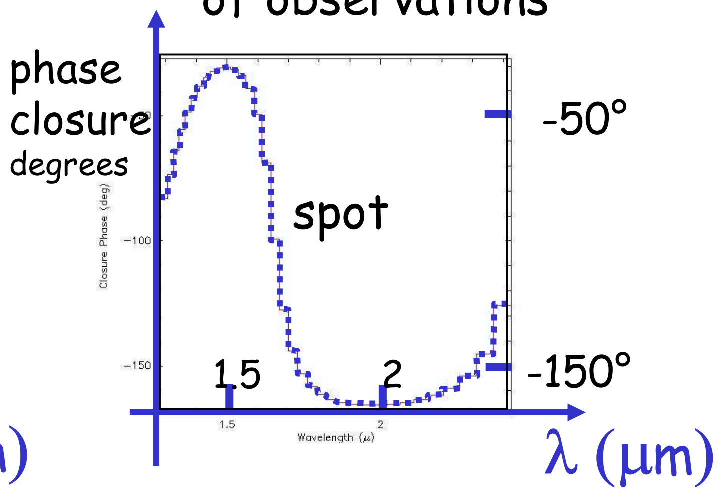


model

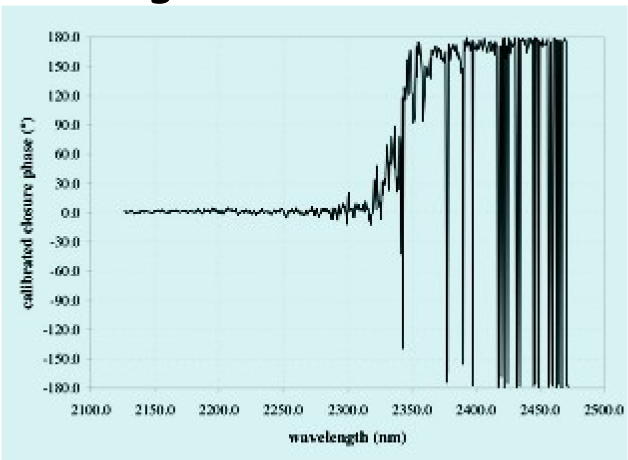
TW Oph, second lobe



with help
of observations

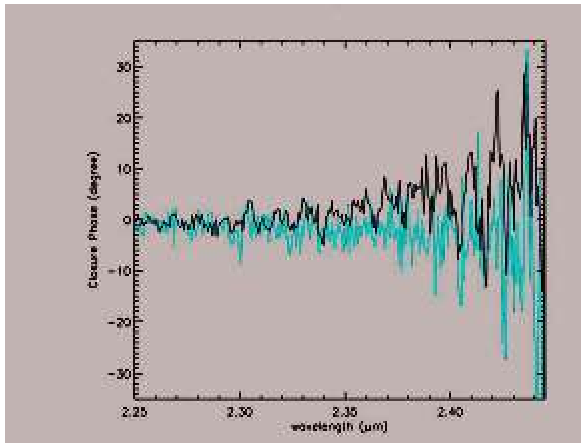


nearing second lobe



time effect

same object
same network
different dates



difficulties in real world

and some remedies