Astronomical Optics

Phase correction in interferometers

OUTLINE:

Phase referencing in interferometers

- why phase referencing? beyond V^2 interferometry: astrometry, image synthesis, phase closure

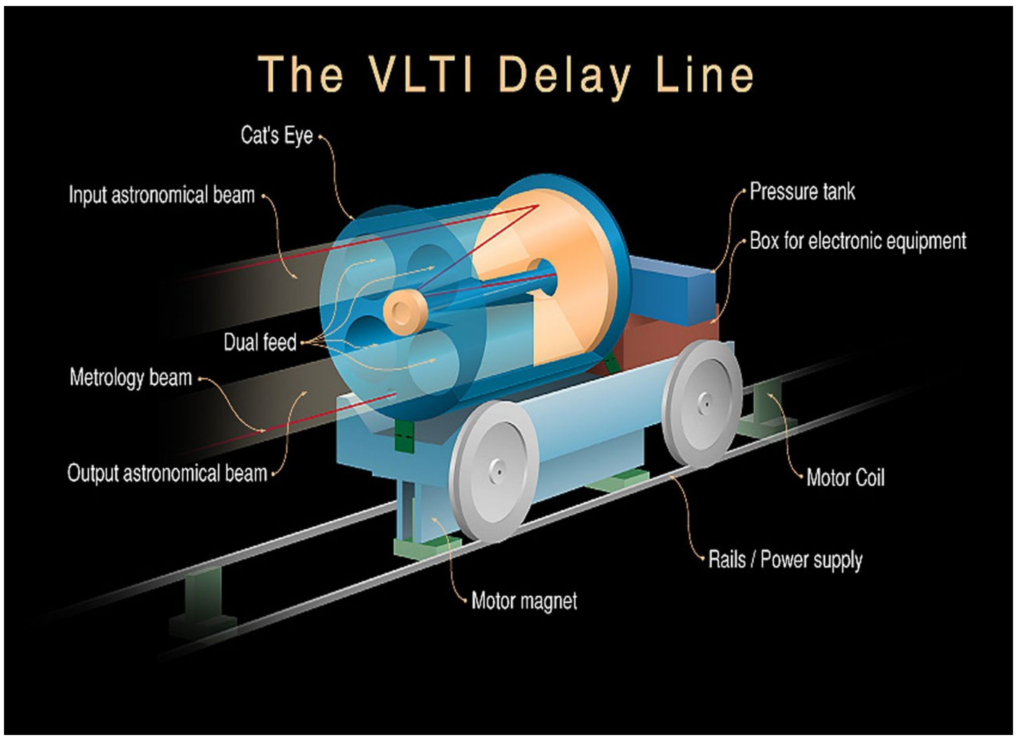
Wavefront correction on individual apertures
tradeoff between calibration accuracy, efficiency and wavefront quality

Technology:

- delay lines
- atmospheric dispersion compensation: vacuum delay lines, ADCs
- Adaptive optics correction in interferometers
- Calibration of residual phase errors with spatial filtering: pinhole, fiber interferometry

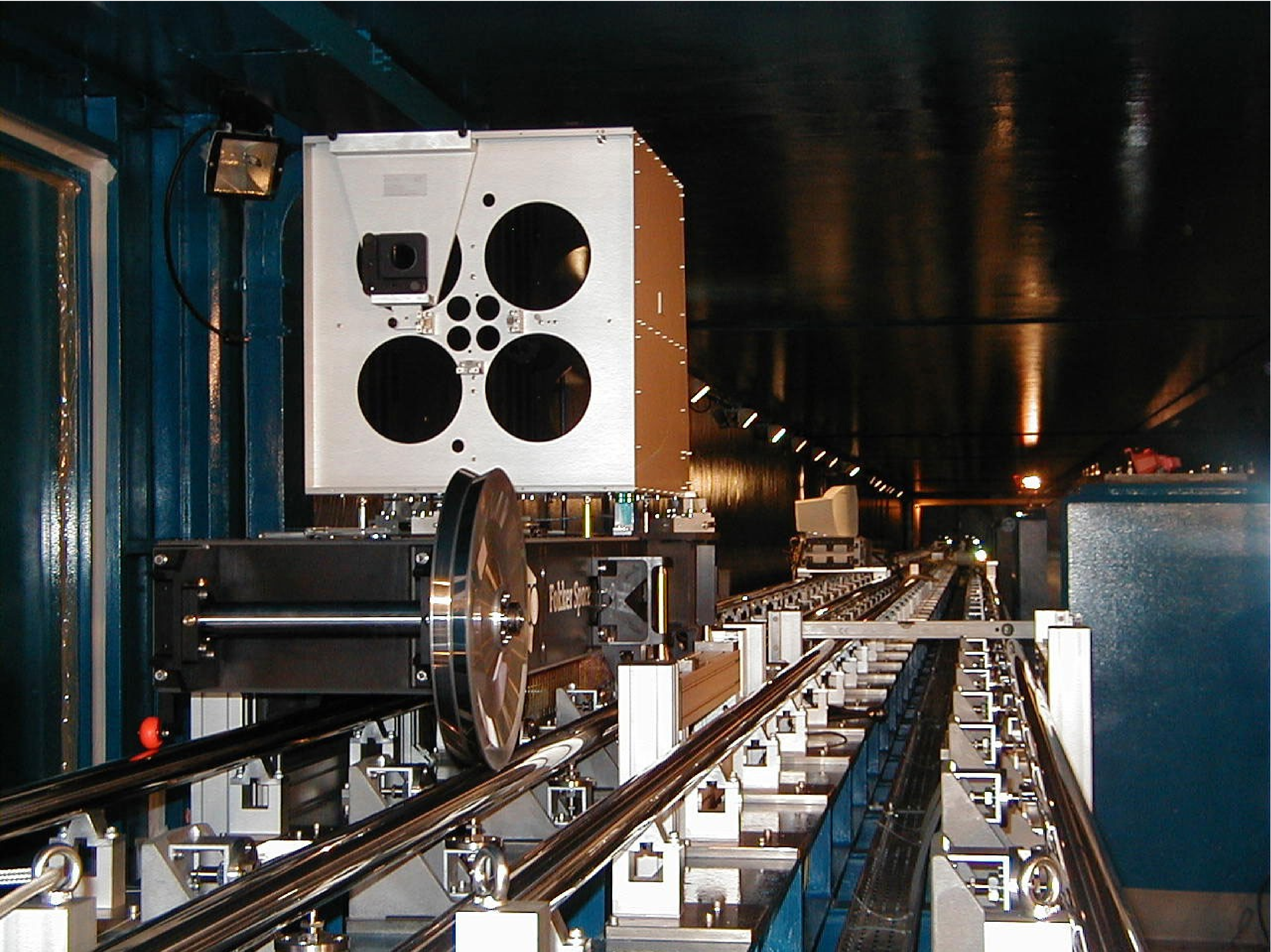
Delay lines

Must maintain near-zero Optical Pathlength Difference (OPD) between arms of the interferometer



VLTI delay line moving cart

Keck interferometer coarse delay lines



Part 1:
Control and calibration of visibility in interferometers

Scientific motivation

Why is fringe visibility accuracy important ?

Example below shows effect of fringe visibility measurement accuracy on measurement of stellar diameters (in this example, used to measure absolute distance to Cepheid stars)

$$V^2(B\theta/\lambda) = \left(2\frac{J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda}\right)^2$$

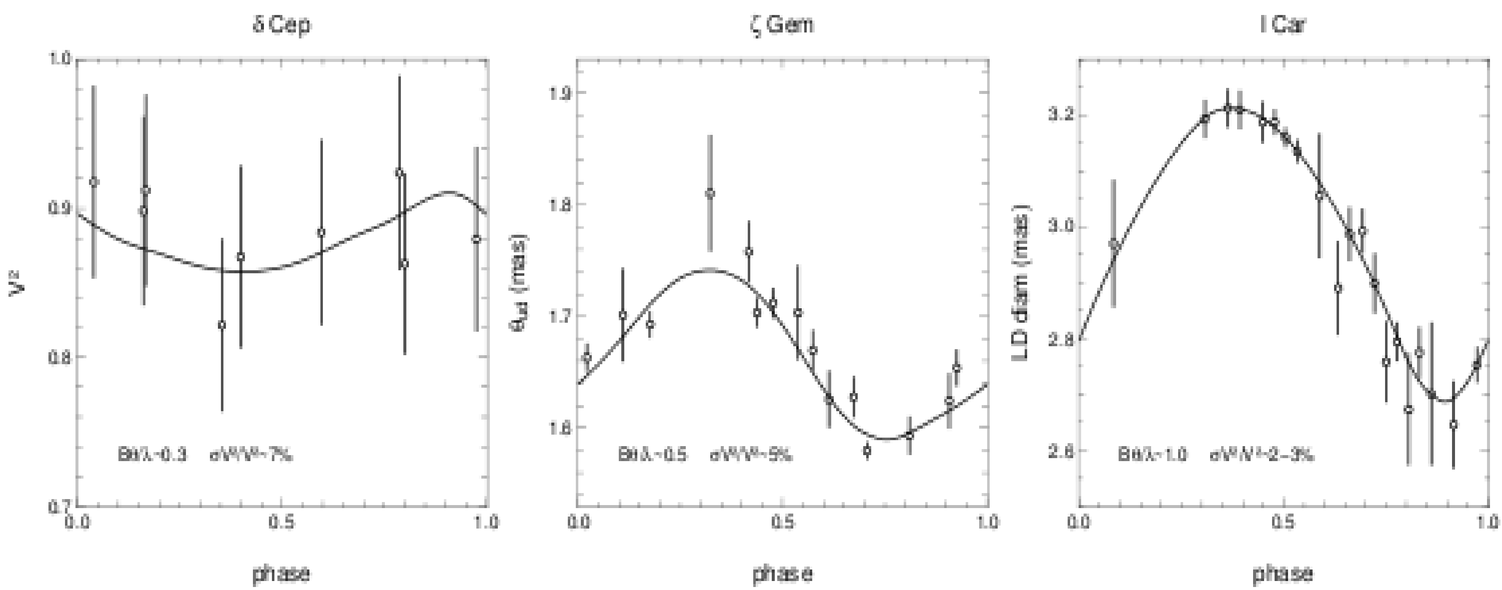


Figure 1. Different interferometric attempts to measure Cepheid angular diameter variations. From left to right: Mourard et al. (1997[6]), Lane et al. (2000[7]) and Kervella et al. (2004[8]). The left panel is V^2 as a function of phase, while the panels to the right are angular diameters with respect to phase. The thin, continuous line is the integration of the pulsation velocity (distance has been adjusted). From left to right, one can see the effect of increasing resolution ($B\theta/\lambda$) and improving precision ($\sigma V^2/V^2$). In the left panel, the pulsation was not claimed to be detected; the middle panel was the first detection, with a 10% precision on the distance; the right panel displays one of the best: 4% in the distance.

A. Merand, Cepheids at high angular resolution

Sources of fringe visibility loss (discussed in next slides)

What can go wrong ? Why would the measured fringe visibility be < 1 on a point source ?

Amplitude difference between the 2 beams
Problem: If one beam is brighter than the other, fringe visibility <1
→ measure flux in each arm of the interferometer

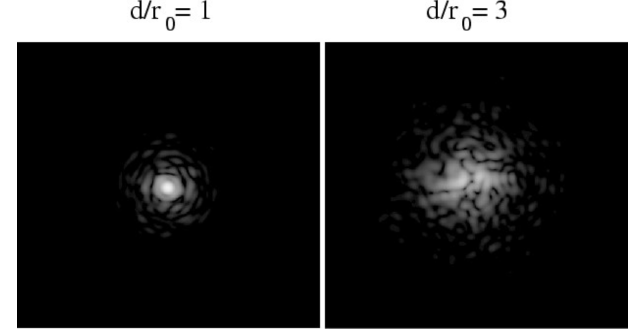
Phase errors within each of the 2 beams
Problem: Wavefront is not flat before entering the beam combiner
→ calibrate visibility loss by observing another star
→ good adaptive optics for each of the telescopes
→ spatial filtering to clean the beams, at the cost of flux

Phase between the 2 beams is changing within detector exposure time
Problem: Measurement is superposition of shifted fringes, with apparent V < 1
→ calibrate visibility loss by observing another star
→ reduce / calibrate internal sources of vibration
→ if possible, fringe tracking on nearby bright source

Phase between the 2 beams is changing within the spectral band of the measurement
Problem: Dispersion in atmosphere and interferometer: measurement is superposition of shifted fringes, with apparent V < 1
→ optically compensate atmospheric dispersion
→ calibrate visibility loss by observing another star
→ disperse fringes on detector
→ use vacuum delay lines

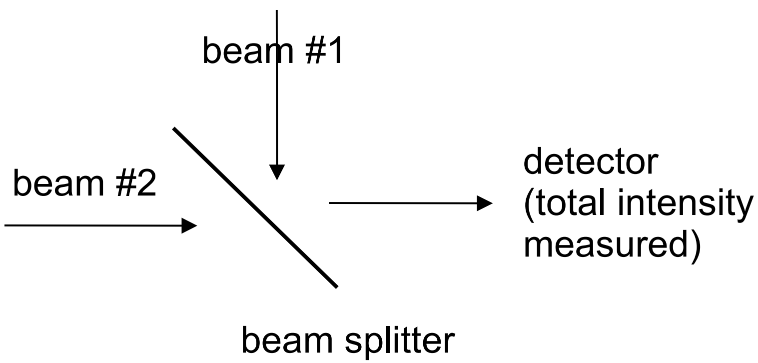
Polarization is different between the 2 beams
Problem: internal instrumental polarization in interferometer
→ calibrate visibility loss by observing another star
→ design telescopes, beam transport and delay lines to minimize differential polarization effects

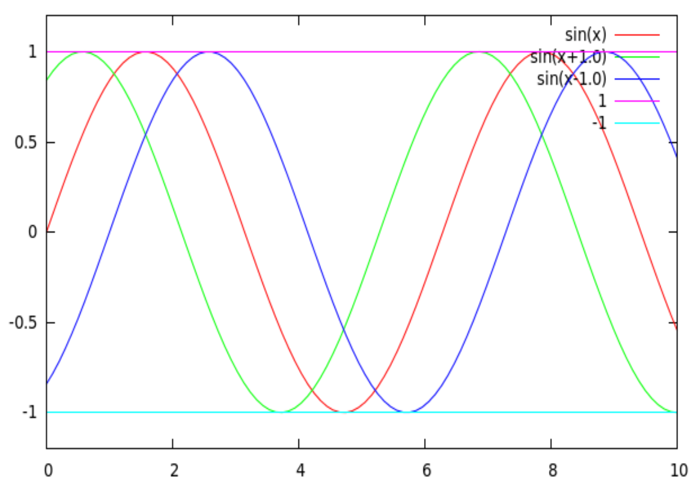
Fringe visibility loss: phase errors in beams



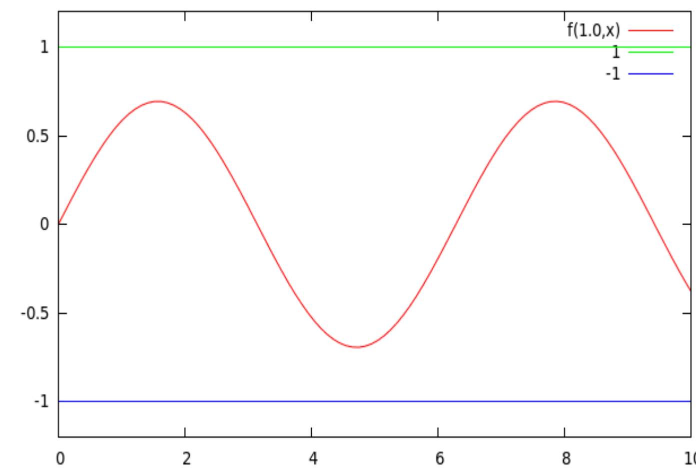
Example:
2 beams are combined with a beam splitter
Each beam has phase errors, and differential phase error between the beams is ~1 rad
consider 3 points in the pupil:

- point 1: phase difference between 2 beams is -1 rad
- point 2: phase difference between 2 beams is 0 rad
- point 3: phase difference between 2 beams is +1 rad





for each of the 3 points, visibility is = 1, but phase is offset



What is observed is the total flux, the sum of the 3 curves on the left
Measured visibility = 0.7 < 1.0
problem:
Is measured visibility due to aberrations, or true object visibility

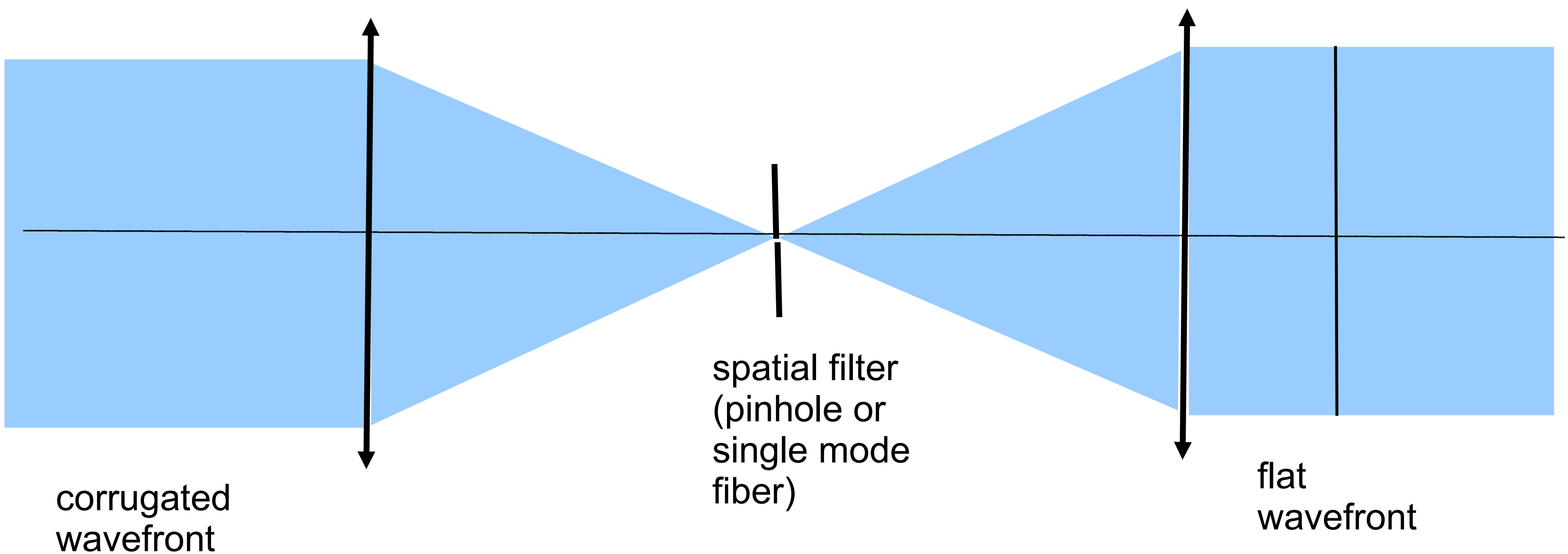
Same concept applies to variations of phase with time and wavelength

Fringe visibility loss: phase errors in beams
Solutions to problem

Visibility loss is approximately equal to Strehl ratio ~ $\exp(-\sigma^2)$
With σ = 1 radian RMS, visibility ~ 0.3

Good **adaptive optics correction** to reduce σ is essential on large telescopes

Spatial filtering can be used to clean beam:
Optically transforms aberrated wavefront into flat wavefront
With aberrated wavefront, light is lost by spatial filtering

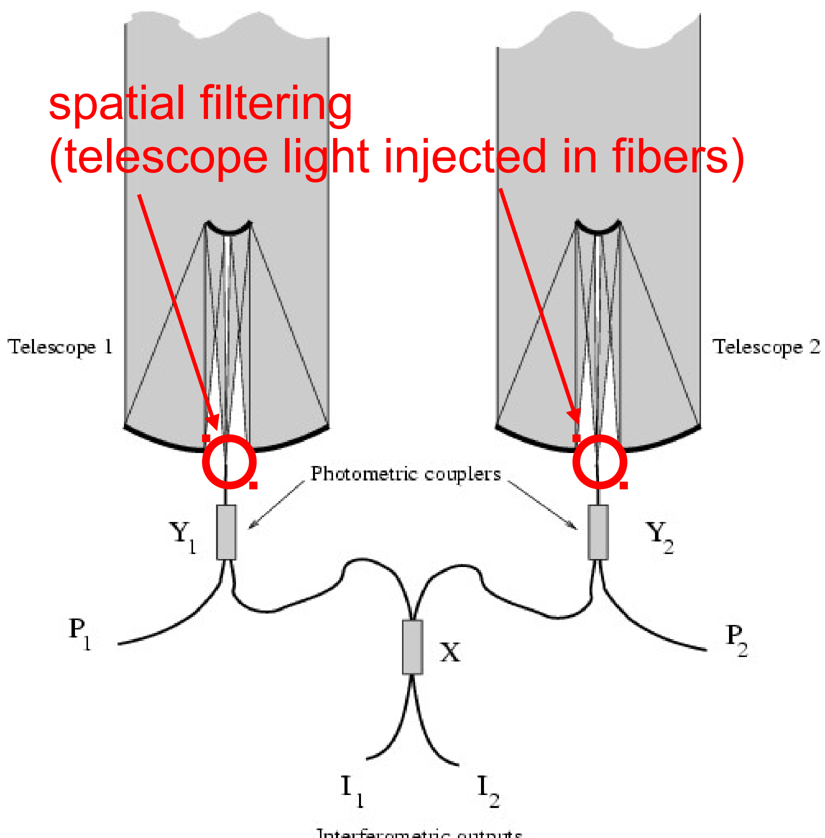


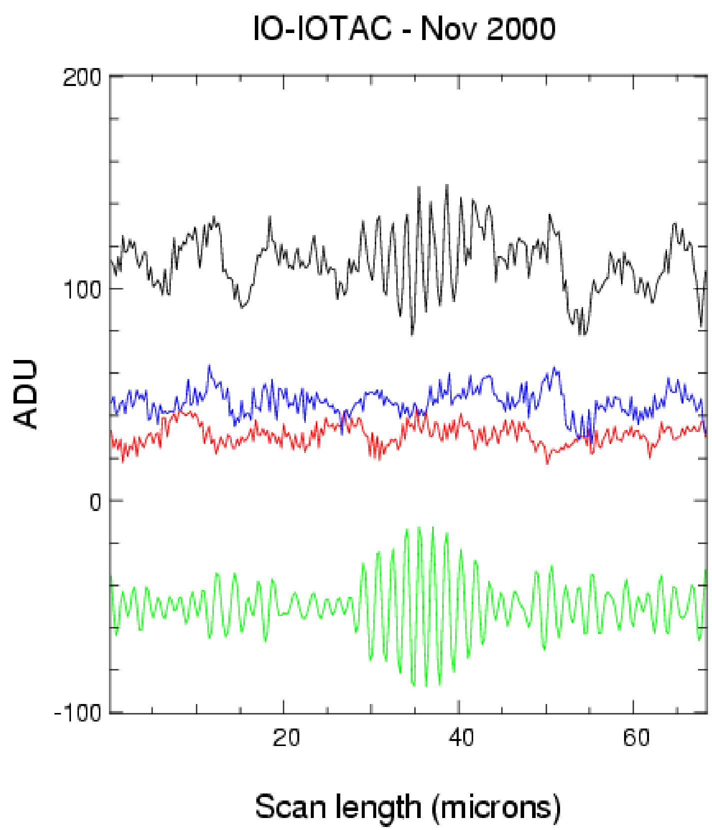
Spatial filtering

Spatial filtering alone does not help, as flux variations in interferometer arms are strong

Photometric calibration, achieved by measuring light in both arms of the interferometer AFTER spatial filtering, can calibrate visibility loss due to flux variations.

Spatial filtering + photometric calibration is powerful solution, and has achieved < % visibility accuracy on sky





Uncalibrated signal: I_1

photometric channels P_1, P_2

Calibrated signal takes into account mismatch between P1 and P2

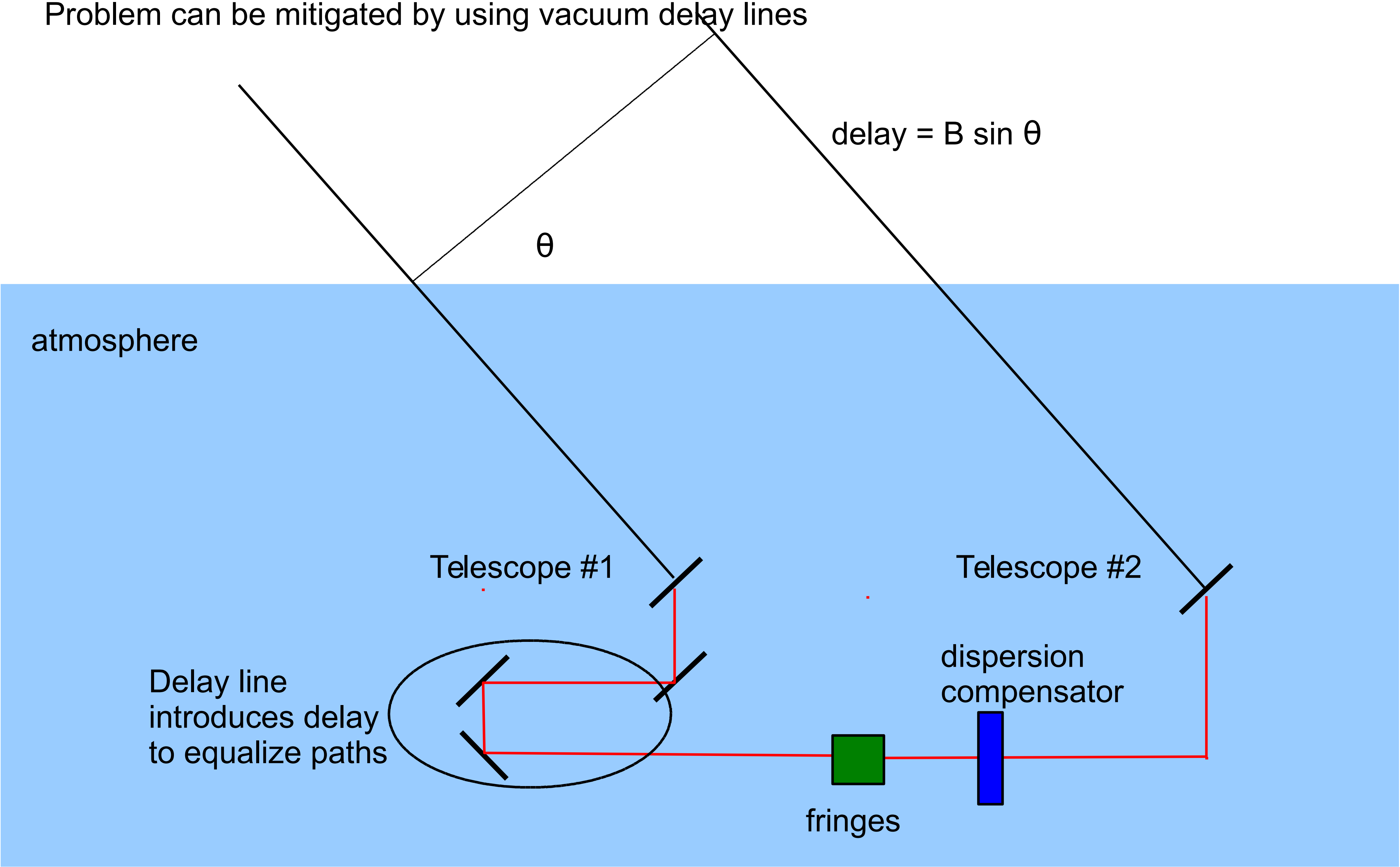
IOTA fiber interferometer (Berger et al. 2001)

Fringe visibility loss: chromatic dispersion

Atmosphere introduces strong chromatic dispersion which needs to be compensated

In conventional interferometer, delay line introduces a delay (in air) to compensate for a vacuum delay → dispersion compensator is required.

Problem can be mitigated by using vacuum delay lines



Part 2:
Control and calibration of fringe phases

Fringe tracking:
essential to allow observation of faint sources

Throughput in an interferometer is often low, due to large number of optical elements:
telescope, beam transport, delay lines, beam combiner

Atmospheric turbulence and vibrations move fringes very rapidly
Measurement is only possible if individual exposure time << time it takes for fringe to move by a wavelength → with no phase tracking, difficult to observe faint targets
Typical limiting magnitudes for interferometers: 5 to 10 in visible / near-IR
To extend this limit, one needs to track and lock fringes to allow long exposures

Observations typically requires 100-1000 Hz sampling to “freeze” the seeing.

Consider fringe sensing carried out in K band (2.0-2.4 microns):

an 8 m aperture receives ~15,000 photons from a K=10 star in 1 ms.

sky background is ~1500 photons/ms.

Telescope background is ~15,000 photons/ms.

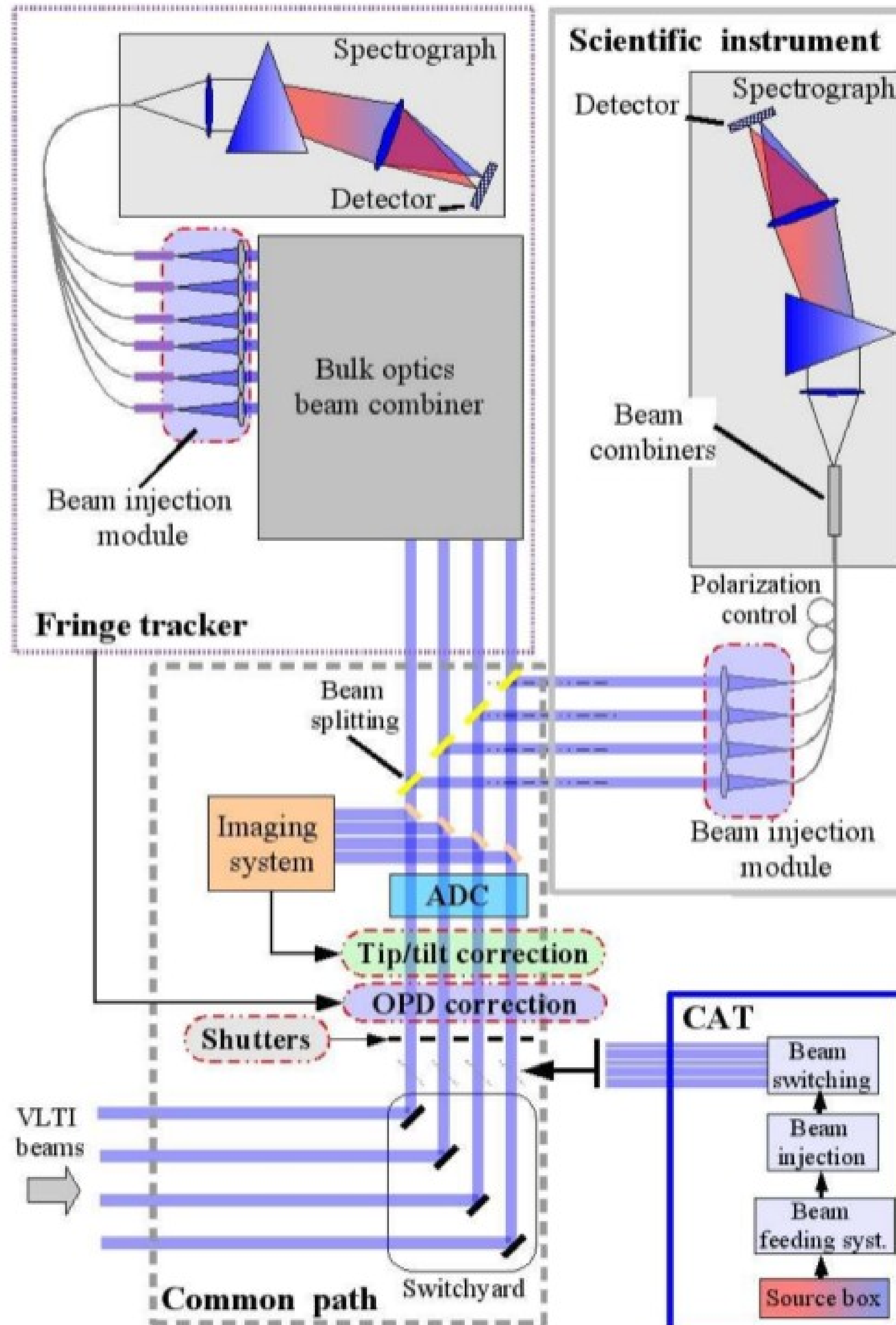
throughput is 6%.

This gives an SNR of 8 in a 1 ms exposure.

Fringe tracking

Fringe tracker measures rapidly fringe position, and actively controls optical pathelength corrector (=fast delay line) at the input of the beam combiner

Enables longer exposures with the scientific instrument



VLTI fringe tracker shown at the upper left corner of this figure (Corcione et al., 2008)

Phase referencing

Scientific motivations

Image reconstruction with multiple baselines requires measurement of phases and visibilities (with no phases, only centro-symmetric component of the image can be estimated)

Astrometric measurement (measuring position of sources) requires fringe phase

On a single baseline: astrometric error [rad] = phase error [rad] x (λ / 2π) / Baseline

How to reference phase ? - or what to use as a refence

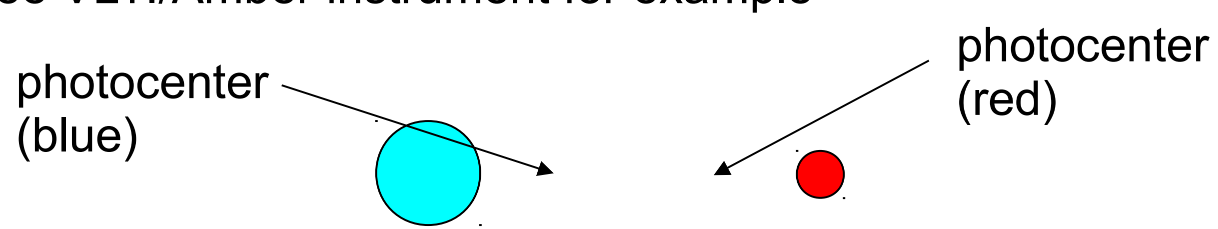
A **nearby star** can be used to reference phase on a single baseline interferometer

Phase closure relationships can be used to separate instrumental phases from object phases (see next slides)

Phase can be measured as a function of wavelength:
object itself (at different wavelength) provides a refence
Example:

Accurately measuring photocenter as a function of wavelength with an interferometer can reveal planets, as hot planet is redder than star

See VLTI/Amber instrument for example



Phase closures

The fringe packet moves back and forth in an interferometer, due to phase changes that are caused by the atmosphere.

This variation causes the real phase to be unmeasurable for a single object.

Individual phases change with atmospheric terms, alpha:

$$\phi_{12} = \theta_{12} + \alpha_1 - \alpha_2$$

$$\phi_{23} = \theta_{23} + \alpha_2 - \alpha_3$$

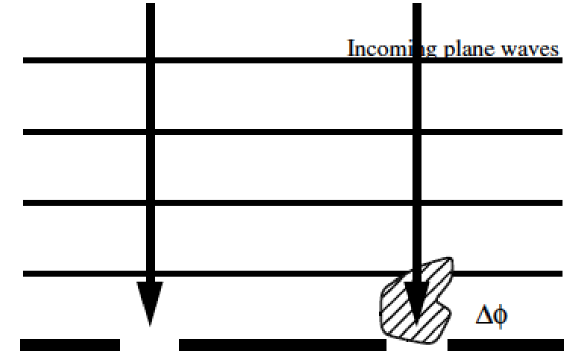
$$\phi_{31} = \theta_{31} + \alpha_3 - \alpha_1$$

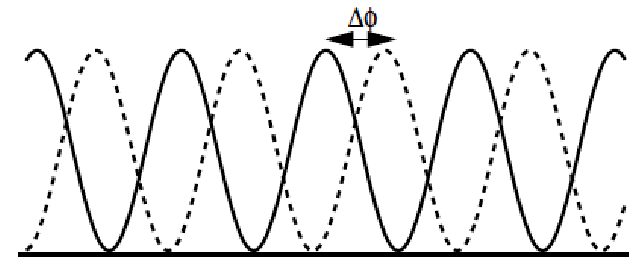
Define a **closure phase** which gets rid of the atmosphere:

$$\Phi_{123} = \phi_{12} + \phi_{23} + \phi_{31} = \theta_{12} + \theta_{23} + \theta_{31}$$

There are (N-1)(N-2)/2 closure phases in an array.
3: 1 closure phase, 3 visibilities -> 33% of phase information recovered.
10: 36 closure phases, 45 visibilities -> 80% of phase information recovered.

Good Reference: Monnier 2007





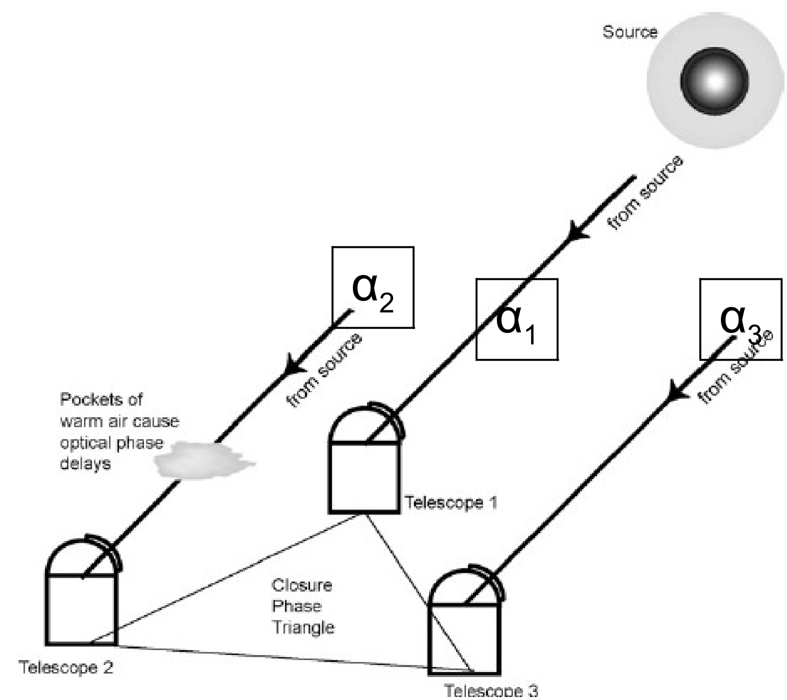
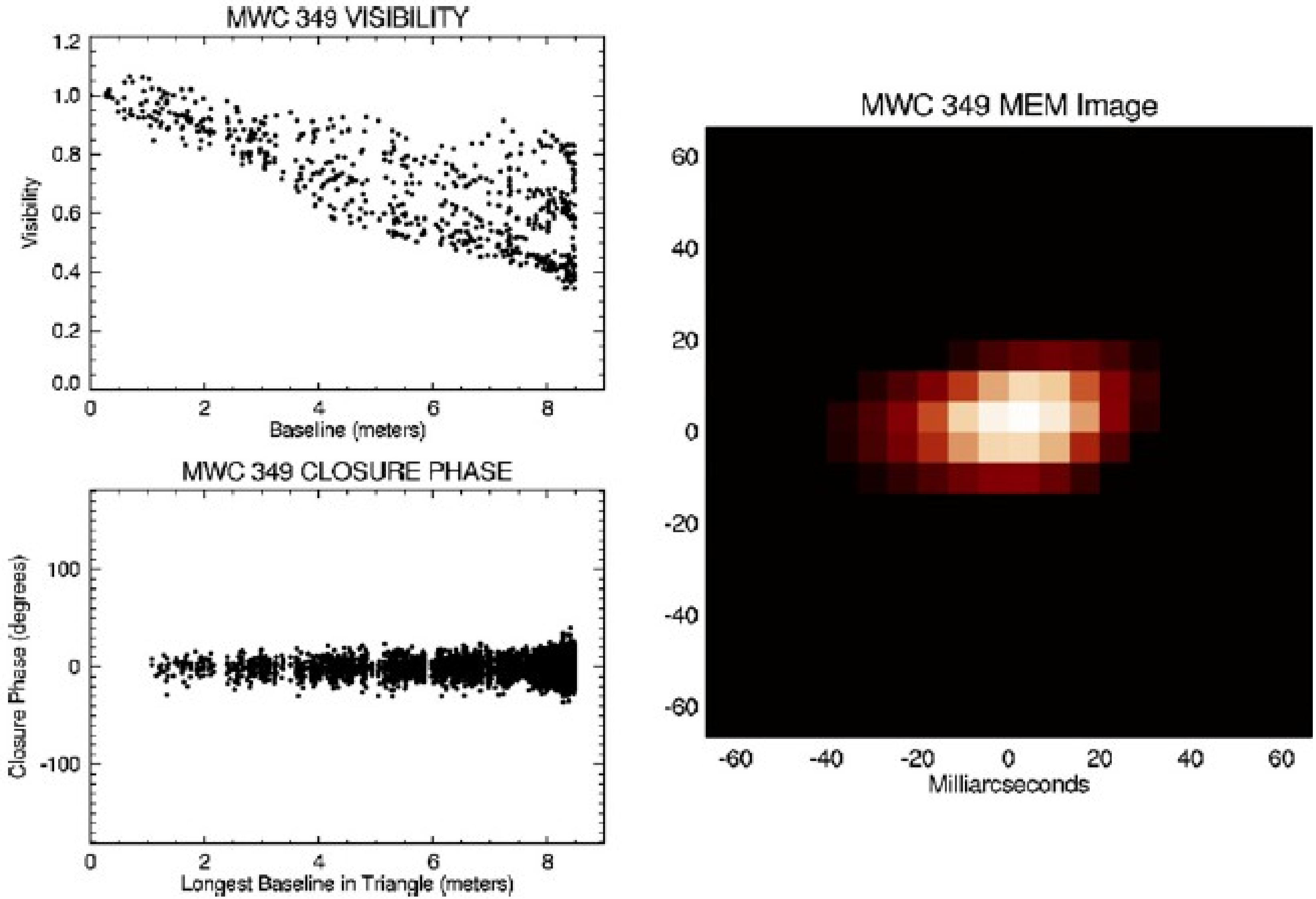


Fig. 4. Phase errors introduced at any telescope causes equal but opposite phase shifts in adjoining baselines, canceling out in the *closure phase* (see also Readhead et al., 1988; Monnier et al., 2006a).

Example 1 from Monnier 2007



Example 2 from Monnier 2007