Optics in Astronomy
- Interferometry -

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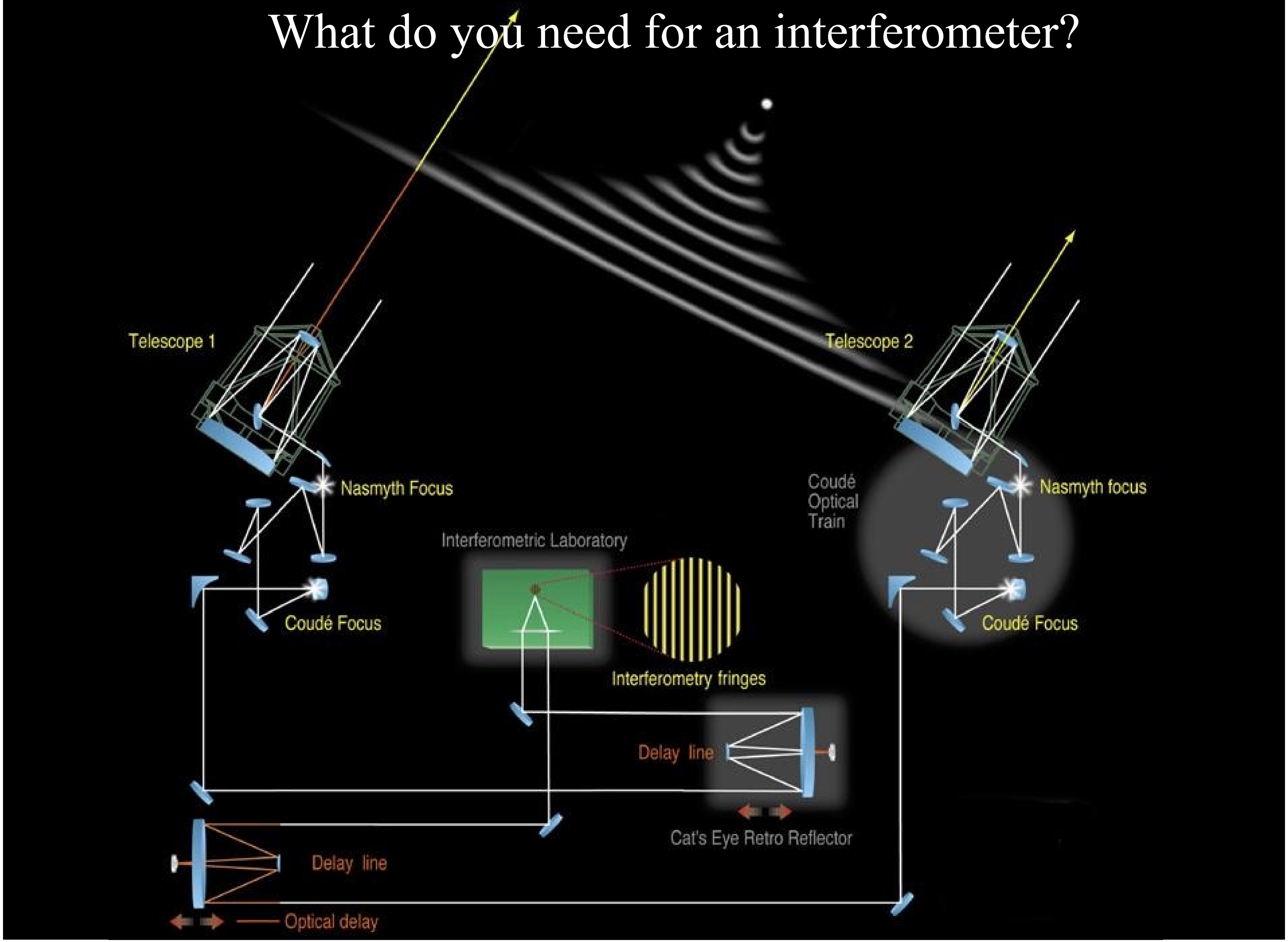
- Concepts of interferometry
  - Elements of an interferometer
  - Baselines
  - Projected baselines
  - Array configuration and Earth-rotational synthesis
  - Methods of beam combination
  - Fizeau and Michelson stellar interferometers

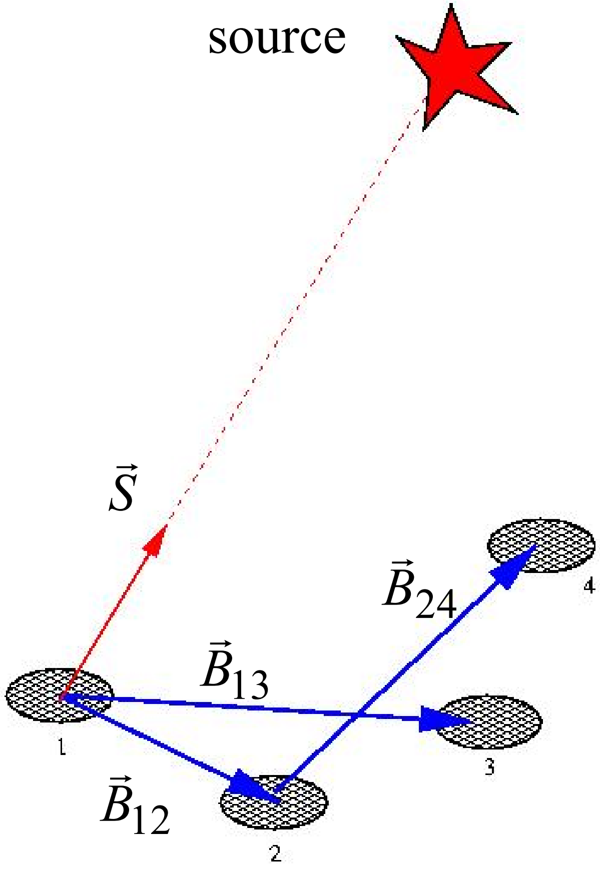
What do you need for an interferometer?



Which baseline is needed for which resolution?

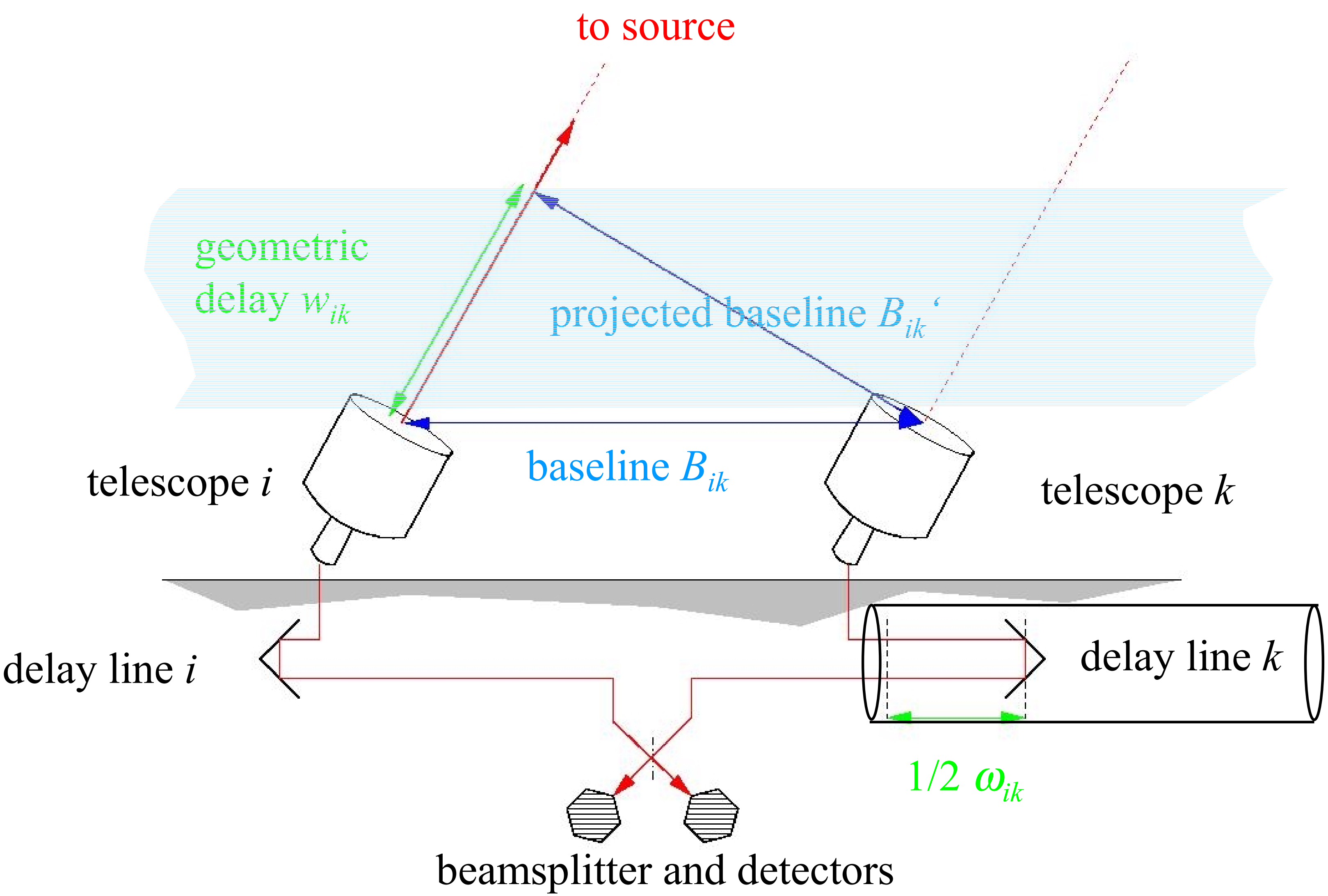
Source of radiation		Wavelength		
		Stars ($T_{\text{eff}} = 5\ 10^{3}$ K)	Gas, dust ($T = 100$ K)	Interstellar hydrogen
Telescope type	Diameter / Baseline [m]	$\lambda = 0.5\ \mu\text{m}$	$\lambda = 10\ \mu\text{m}$	$\lambda = 21$ cm
Optical standard telescope	1	$5\ 10^{-7}$ rad 0.1 arcsec	10^{-5} rad 2 arcsec	-
Optical large telescope	10	$5\ 10^{-8}$ rad 0.01 arcsec	10^{-5} rad 2 arcsec	0.021 rad 72 arcmin
Optical Interferometer	100	$5\ 10^{-9}$ rad 0.001 arcsec	10^{-5} rad 2 arcsec	$2.1\ 10^{-3}$ rad 7.2 arcmin
Radio-Interferometer	10^{4}	-	-	$2.1\ 10^{-5}$ rad 4.3 arcsec
Radio VLBI	10^{7}	-	-	$2.1\ 10^{-8}$ rad 4.3 mas

Beam entrance and array configuration



- telescopes $i = 1 \ldots N$
- unit vector $\vec{S}$ pointing at coordinate origin $\vec{\vartheta} = 0$ at source
- **baseline** vectors $\vec{B}_{ik}$ connecting centers of telescope entrance apertures i and k
- $\vec{B}_{ki} = -\vec{B}_{ik}$
- observing wavelength λ determines the angular frequencies $\vec{u}_{ik} = \lambda^{-1}\vec{B}_{ik}$ at which samples of the visibility function are taken

Projected baselines I



Projected baselines II

- The layout detemines the baseline vectors $\vec{B}_{ik}$ which are present the array.
- The source declination δ and hour angle h determine the **projected baseline** $\vec{B}'_{ik}$ (baseline as seen from the direction of the source).
- The observing wavelength λ determines the set of two-dimensional angular frequencies $\vec{u}_{ik}$ which is measured by the interferometer.

Projected baseline: $\vec{B}'_{ik} = \vec{S} \times \left(\vec{B}_{ik} \times \vec{S} \right)$

Geometric delay: $w_{ik} = \vec{B}_{ik} \cdot \vec{S} / \lambda$

frequency projected on celestial sphere: $\vec{u}_{ik} = \begin{pmatrix} u_{ik} \\ v_{ik} \end{pmatrix}$

Projected baselines III

Describe array geometry by 3D element positions:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \begin{matrix} \text{northwards} \\ \text{eastwards} \\ \text{zenithwards} \end{matrix}$$

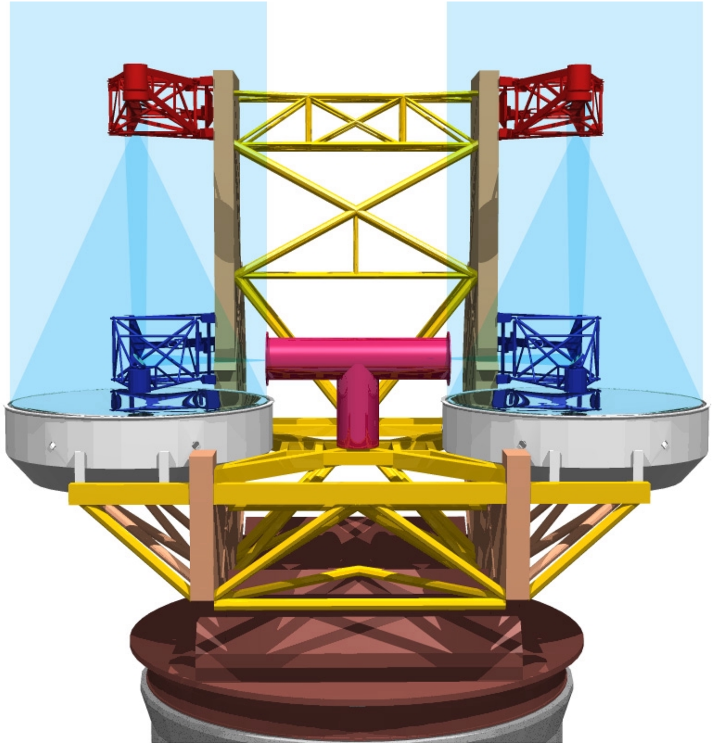
Compute fringe frequency and geometric delay:

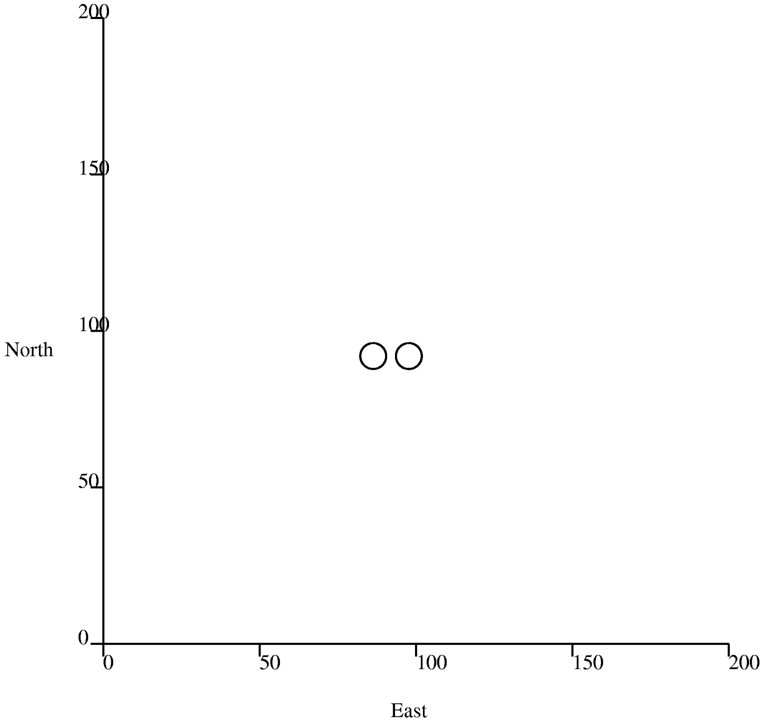
$$\begin{pmatrix} u_{ik} \\ v_{ik} \\ w_{ik} \end{pmatrix} = \frac{1}{\lambda} \begin{pmatrix} -\cos\xi \sin h - \sin\xi \cos\delta \cos h & \sin\xi \cos\delta \sin h - \cos\xi \cos h & -\sin\xi \sin\delta \\ -\sin\delta \cos h & \sin\delta \sin h & \cos\delta \\ \sin\xi \sin h - \cos\xi \cos\delta \cos h & \sin\xi \cos h + \cos\xi \cos\delta \cos h & -\cos\xi \sin\delta \end{pmatrix} \begin{pmatrix} X_k - X_i \\ Y_k - Y_i \\ Z_k - Z_i \end{pmatrix}$$

site latitude ξ
source declination δ
hour angle h

Array configuration and Earth-rotational synthesis I

Large Binocular Telescope (LBT), Arizona





LBT on Mt. Squirrel

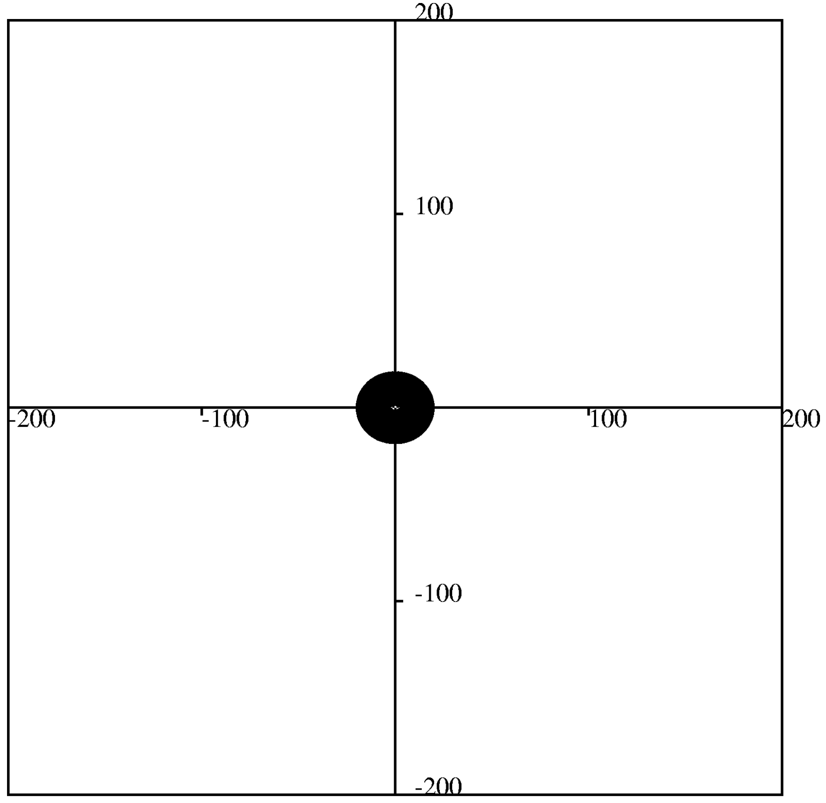
Placement of interferometer elements

Array configuration and Earth-rotational synthesis I

Large Binocular Telescope (LBT), Arizona

UV coverage - range of frequencies that can be reached by ERS

UV coverage is independent of source position with the LBT

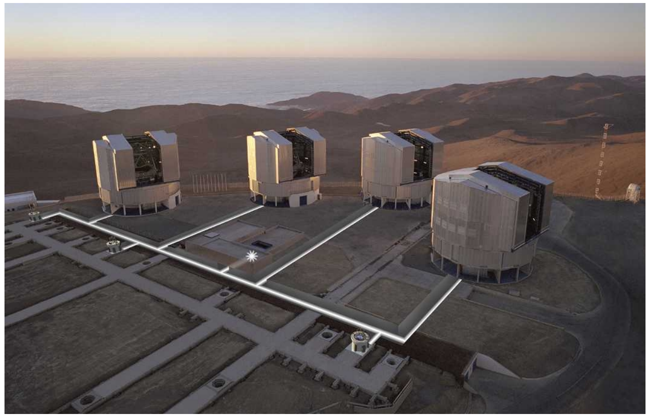


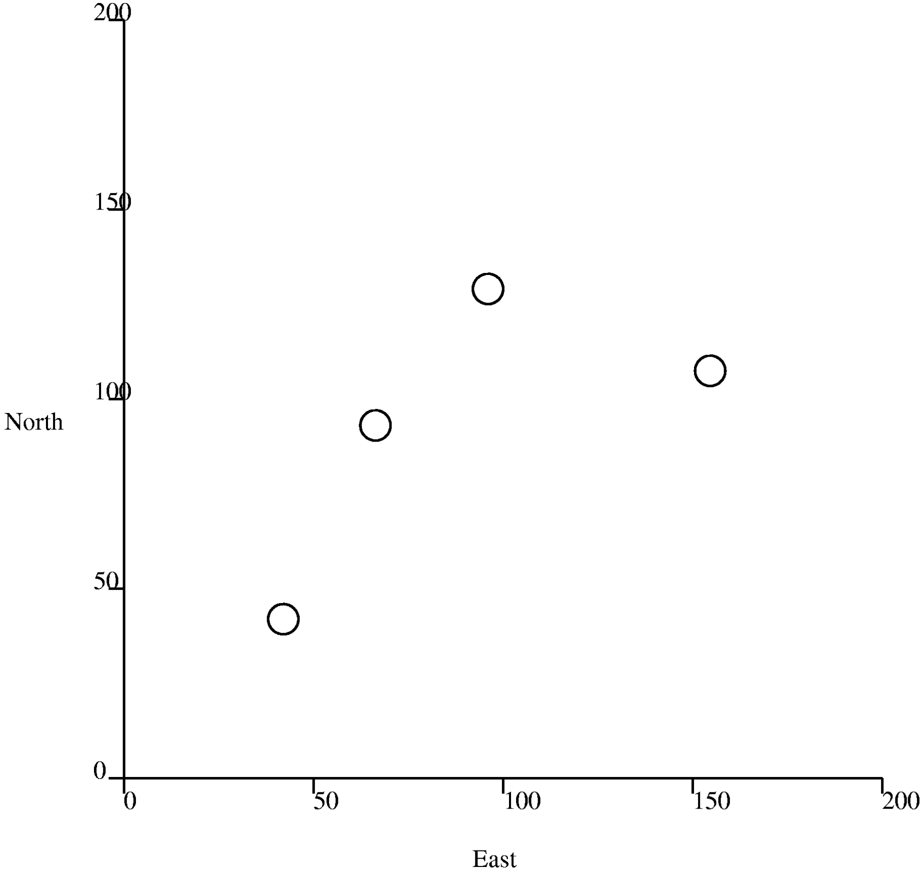
LBT on Mt. Squirrel

Earth-rotational synthesis, source declination 60 degrees.

Array configuration and Earth-rotational synthesis II

ESO VLT Interferometer -
Cerro Paranal, Chile



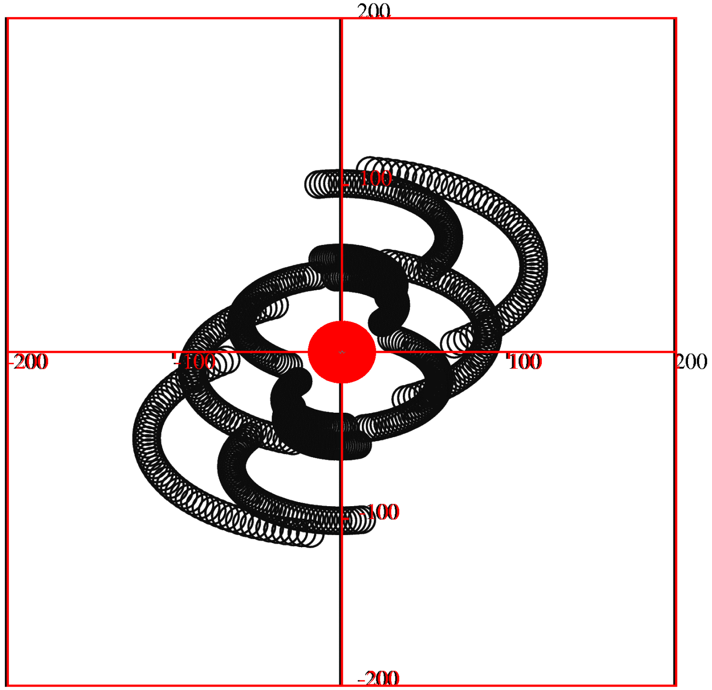


VLT Interferometer Main Array

Placement of interferometer elements

Array configuration and Earth-rotational synthesis II

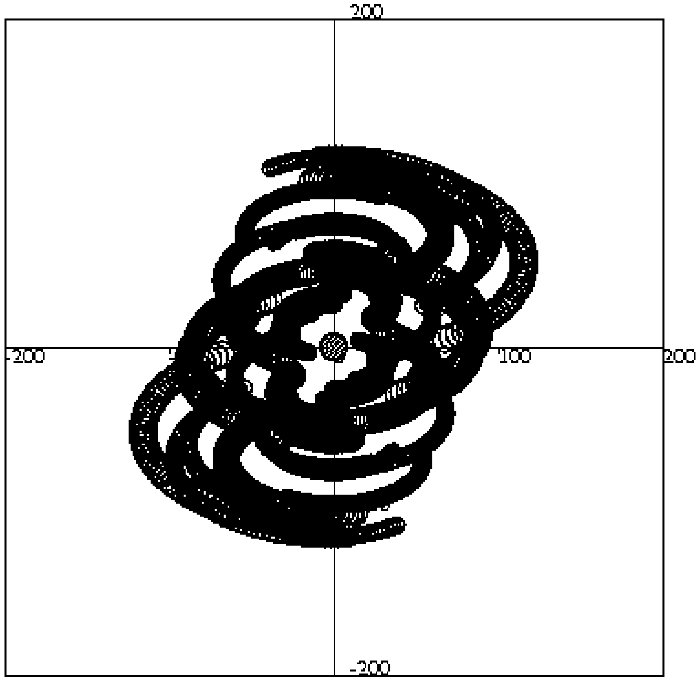
VLTI - 4 Unit telescopes,
source at $\delta = -30°$



VLT Interferometer Main Array

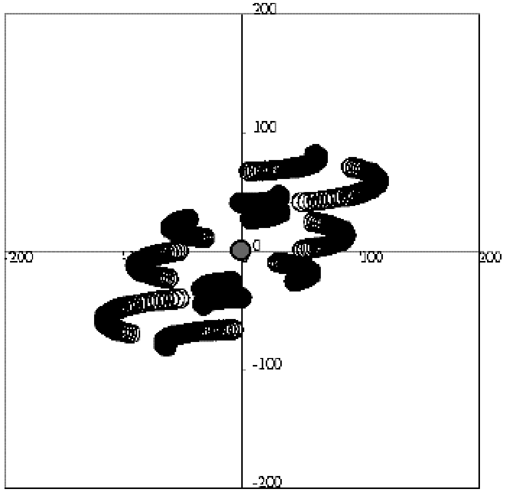
Earth-rotational synthesis, source declination -30 degrees.

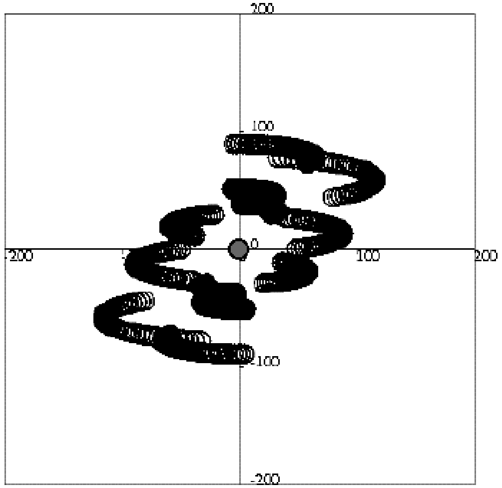
VLTI - 4 Unit telescopes
plus 4 Auxiliary telescopes

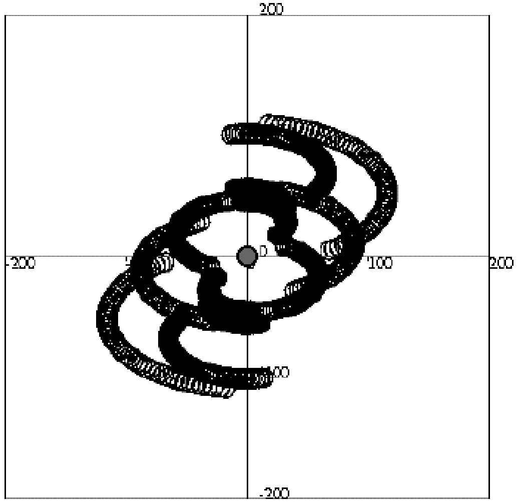


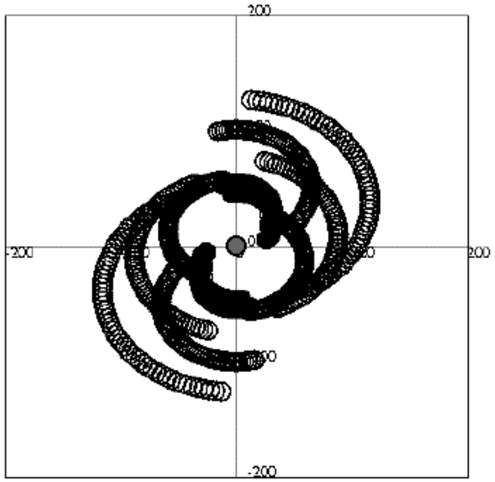
Array configuration and Earth-rotational synthesis II

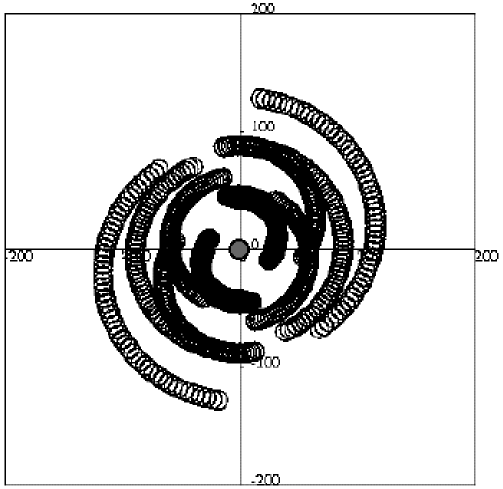
Dependence of VLTI „sausage pattern“ on source declination (+10°, -10°, -30°, -50°, -70°)





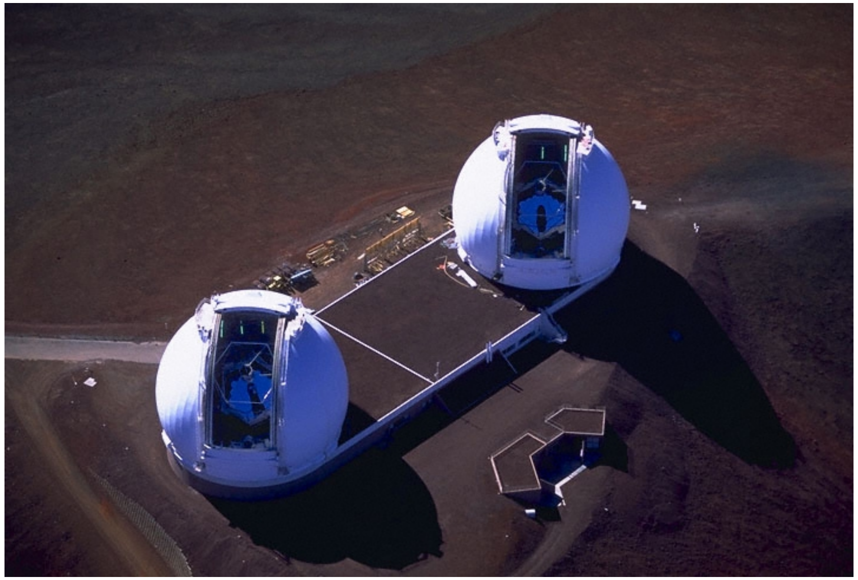


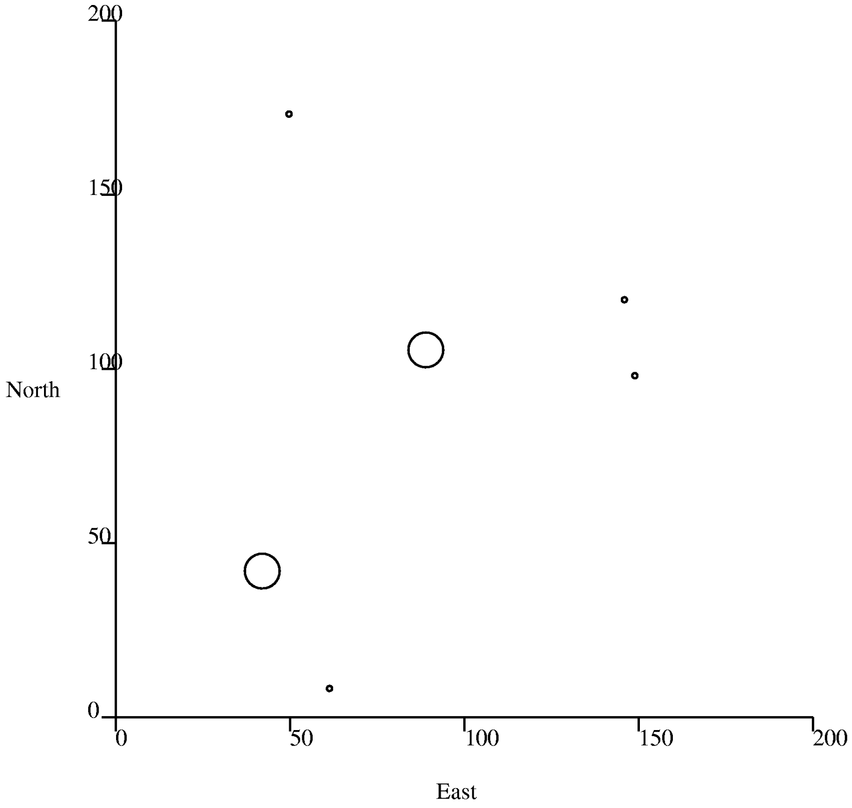




Array configuration and Earth-rotational synthesis III

Keck Imaging Interferoemtric
Array - Mauna Kea, Hawaii

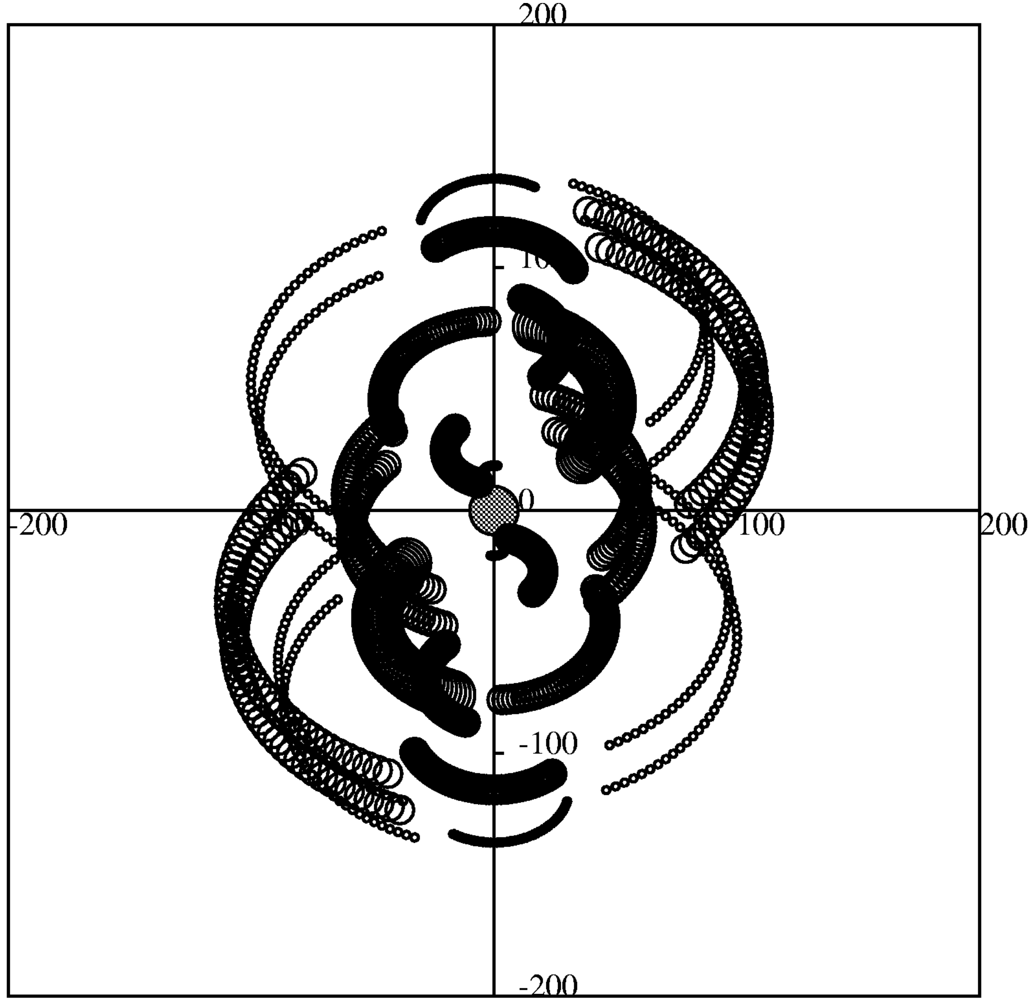




Keck interferometric array with 4 outriggers

Placement of interferometer elements

Array configuration and Earth-rotational synthesis III



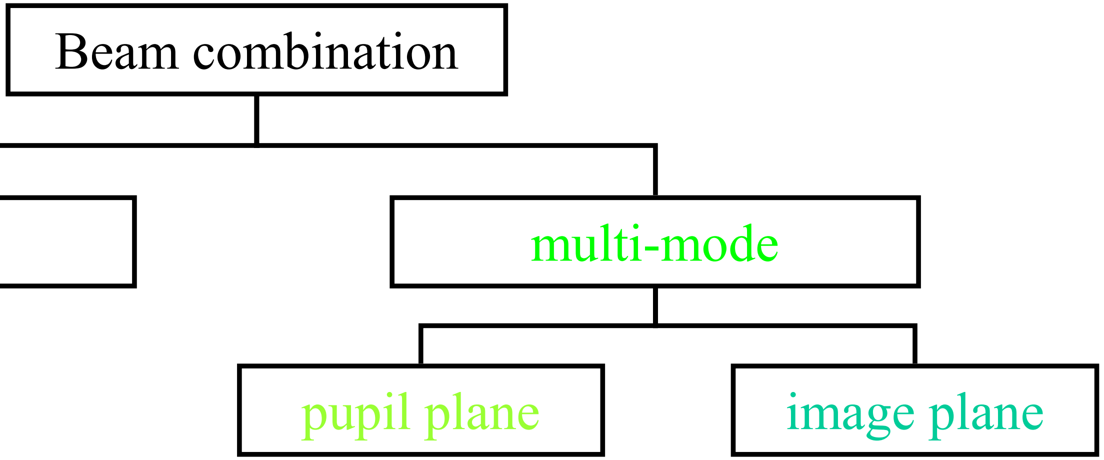
Keck interferometric array with 4 outriggers

Earth-rotational synthesis, source declination 45 degrees.

Principle of a Multiple Telescope Interferometer

- Telescopes i, ..., k track sources during observation
- Baselines between telescopes rotate with Earth
- "Projected" baselines change with source declination and hour angle ⇨ extended coverage of Fourier ("UV") plane
- Electromagnetic fields are superimposed at point of beam combination
- Geometric delays changes with source declination and hour angle ⇨ optical delay tracking required
- Off-set sources suffer a differential geometric delay ⇨ differential optical delay tracking required

Methods of beam combination


Beam combination

single mode

multi-mode

pupil plane

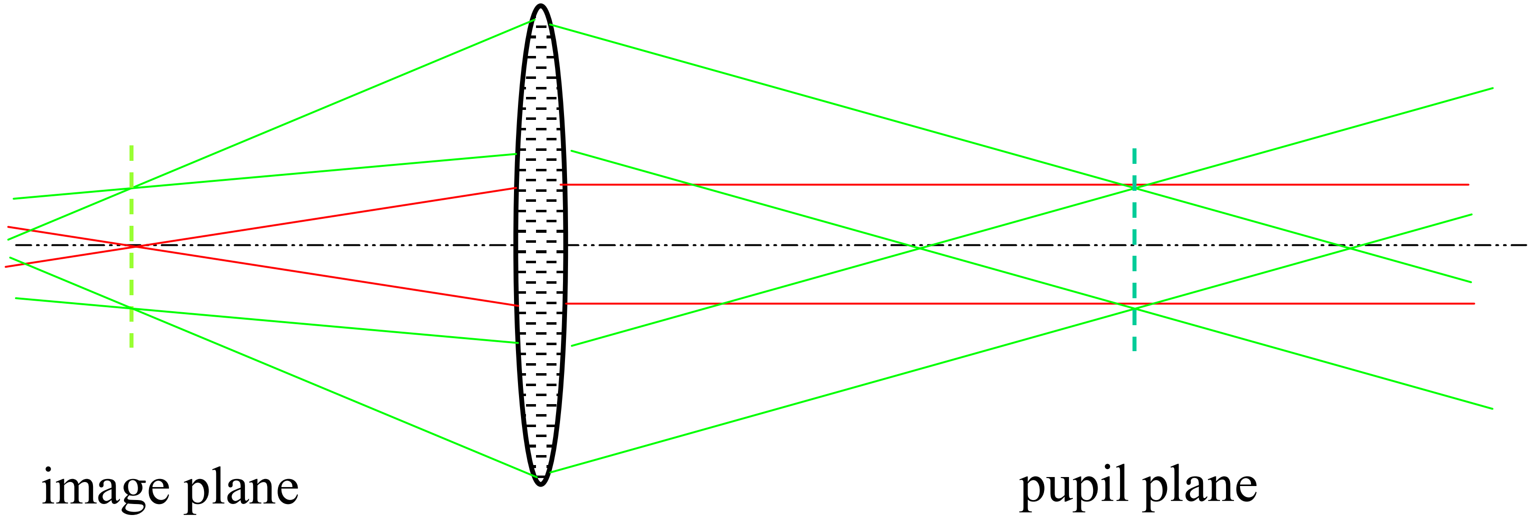
image plane

The detected field of view is equivalent to the Airy disk of an array element

The detected field of view exceeds the Airy disk of an array element.

Beam combination takes place in the plane of a transferred pupil or an image.

Methods of beam combination

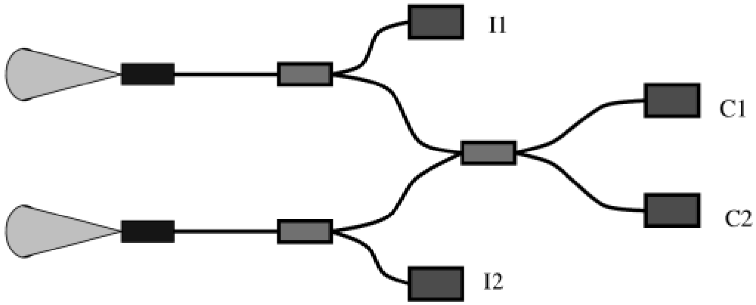


Focused and collimated beams of a single array element accepting an extended field of view.

The red (on-axis) beam only is used for single mode beamcombination.

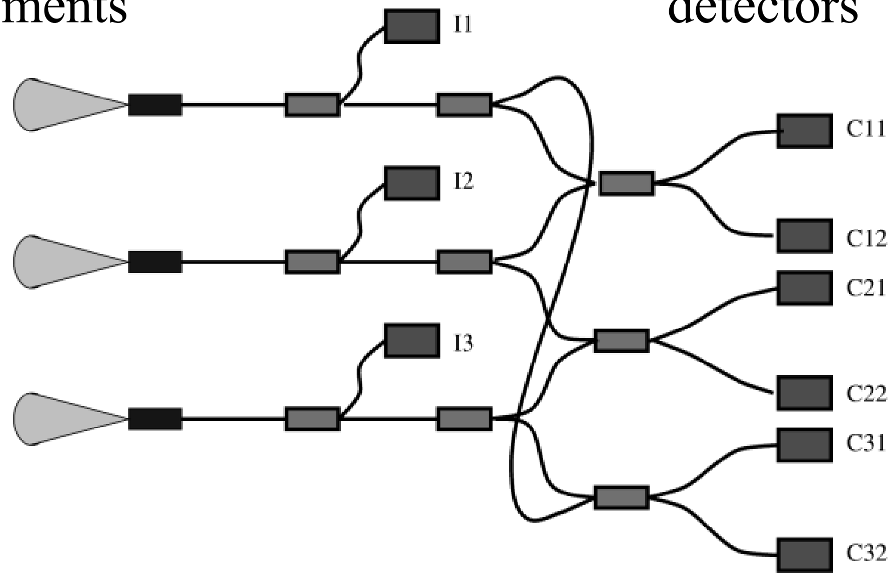
Both red and green beams are used for multimode beamcombination.

Single mode beam combination



from array
elements

single pixel
detectors



Popular implementation with optical fibers

Field stops with size of Airy disk and beamsplitteralso possible.

Fibers make good mixers once the light has entered.

Two-way combiner (top) and three-way combiner (below).

Single mode beam combination

Intensities from Telescopes A and B: I_1, I_2

Measured intensities at Detectors 1 and 2: C_1, C_2

Measured intenstites as function of delay *Δ*:

$$C_1 = I_1 + I_2 + 2\sqrt{I_1 I_2}\, V \sin\left(2\pi \tfrac{\Delta}{\lambda} + \varphi\right)$$

$$C_2 = I_1 + I_2 - 2\sqrt{I_1 I_2}\, V \sin\left(2\pi \tfrac{\Delta}{\lambda} + \varphi\right)$$

Calibrated visibility:

$$\frac{C_1 - C_2}{4\sqrt{I_1 I_2}} = V \sin\left(2\pi \tfrac{\Delta}{\lambda} + \varphi\right)$$

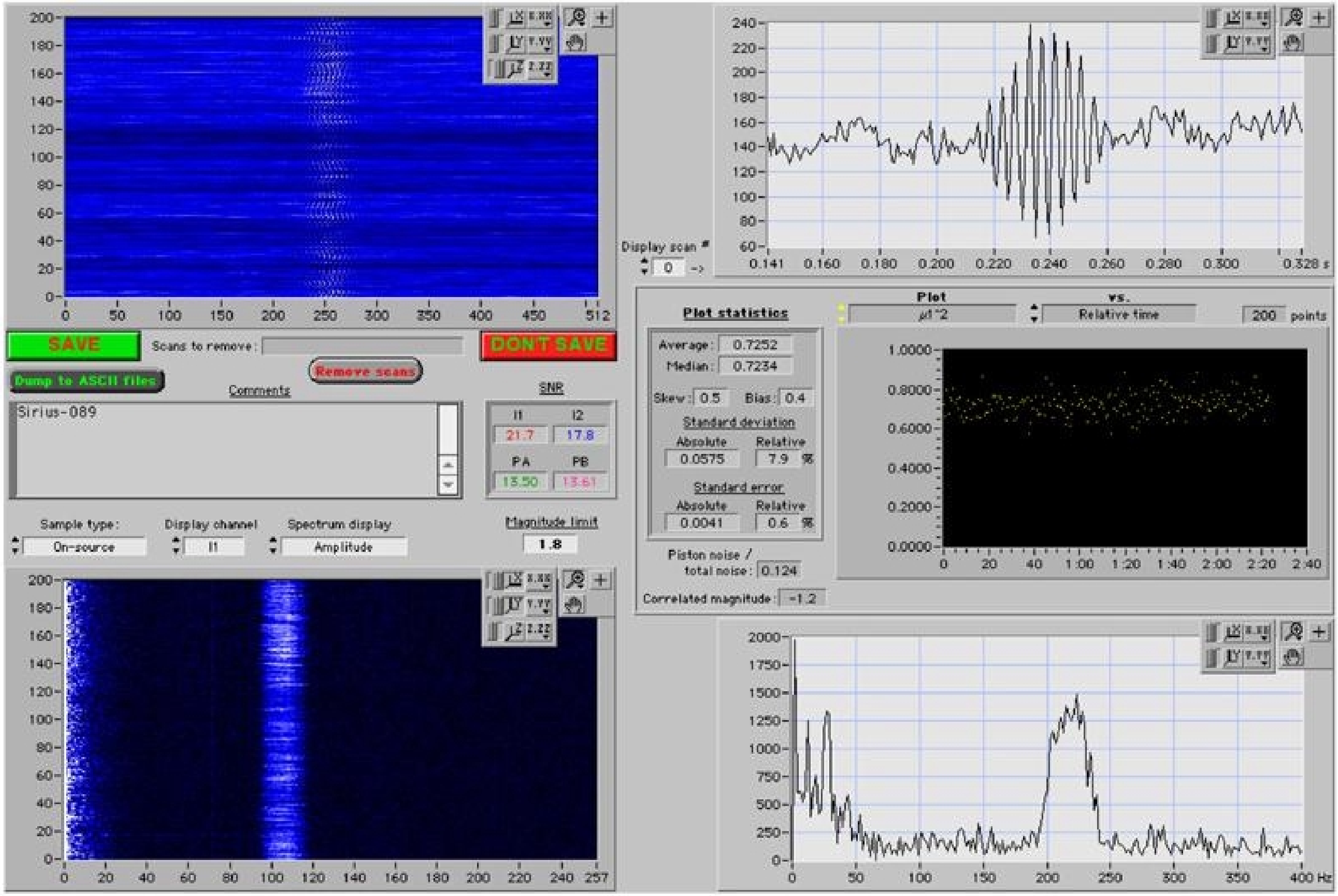
Visibility V due to all sources in the Airy disk of the elements

Fringe detection by scanning of coherence envelope :

IOTA/FLUOR, VLTI/VINCI

Beam combination with fibers of more than two elements prone to baseline dependent errors!

VLTI/VINCI GUI



Scans to remove:

Comments: Sirius-089

SNR
I1: 21.7
I2: 17.8
PA: 13.50
PB: 13.61

Sample type: On-source
Display channel: I1
Spectrum display: Amplitude
Magnitude limit: 1.8

Display scan #: 0

Plot statistics
Average: 0.7252
Median: 0.7234
Skew: 0.5
Bias: 0.4

Standard deviation
Absolute: 0.0575
Relative: 7.9 %

Standard error
Absolute: 0.0041
Relative: 0.6 %

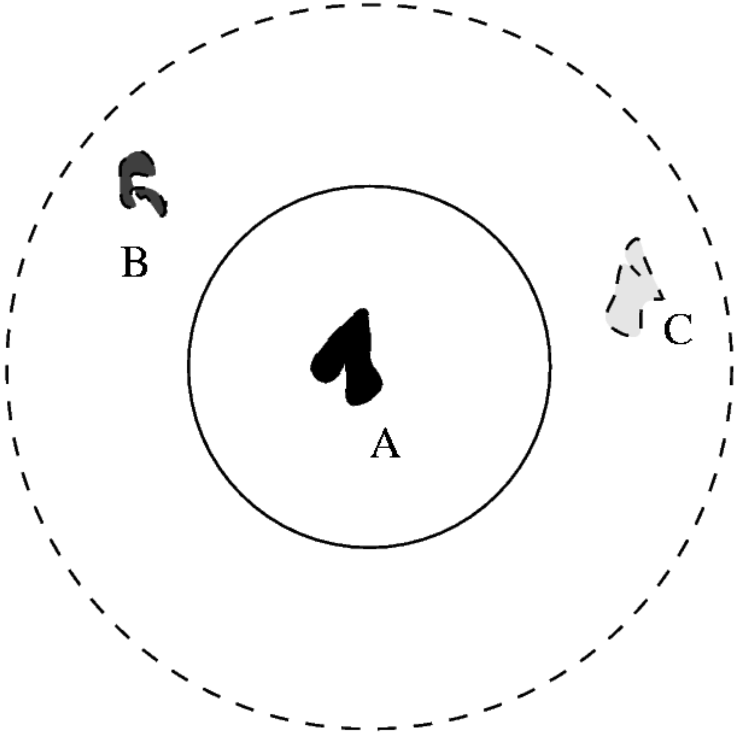
Piston noise / total noise: 0.124
Correlated magnitude: -1.2

Plot μ1^2 vs. Relative time, 200 points

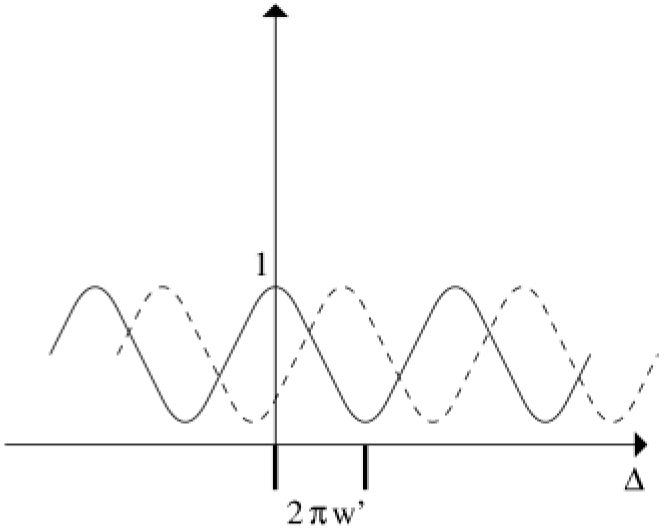
The visibility of which source is detected with pupil plane beam combination?

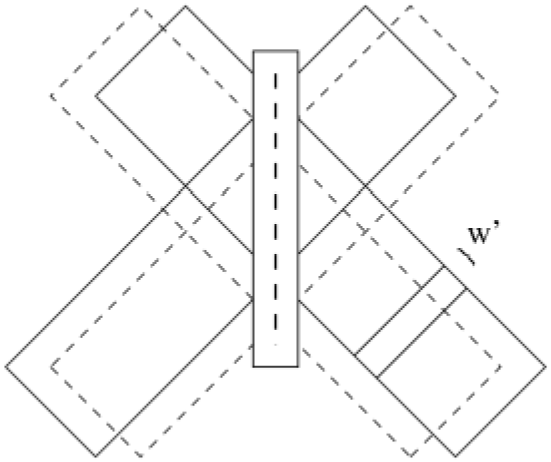
The common visibility of all sources which are allowed to interfere!

Field stops need to be used for sources which are not desired.



Multimode pupil plane beamcombination





Detection thesame as with single mode beamcombination

Visibility V due to all sources in the Airy disk of the elements

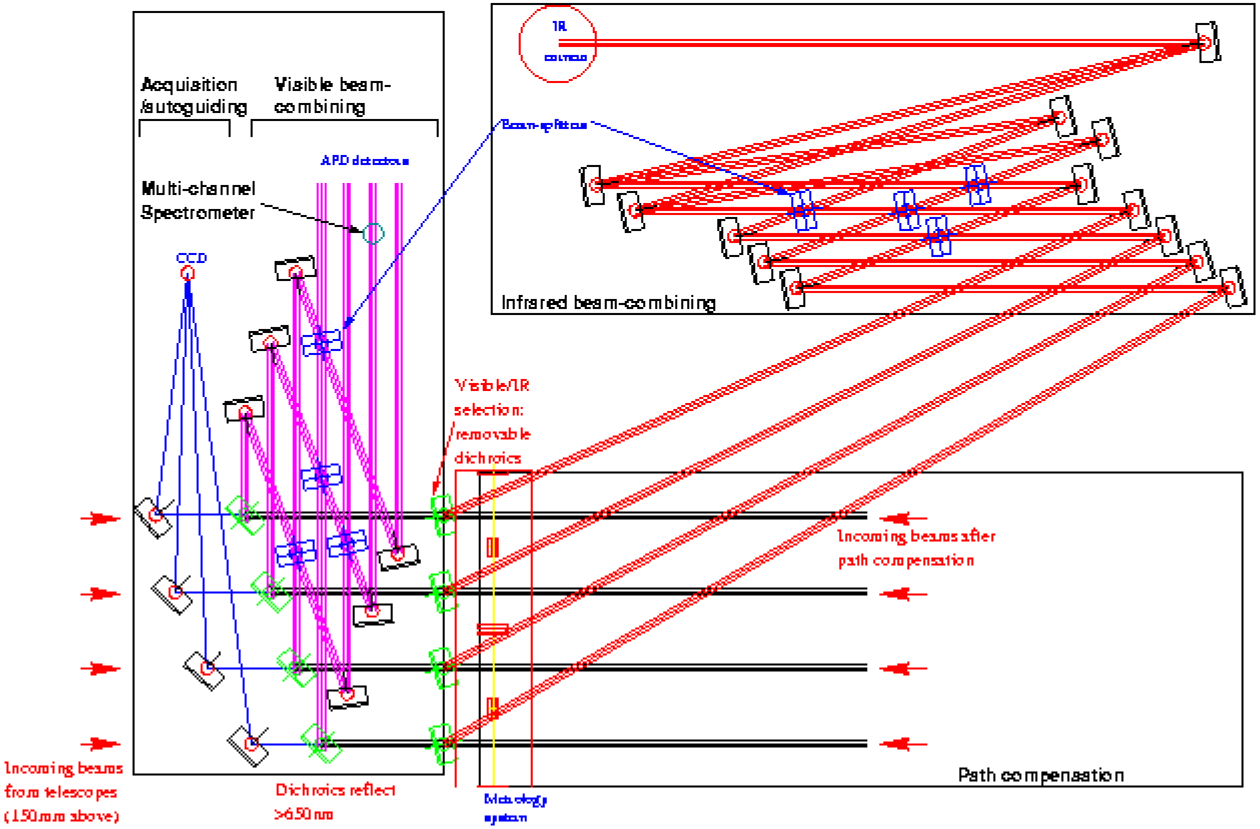
Fringe detection by:

- modulation of optical path length: **NPOI, PTI, KIIA, VLTI/MIDI**
- scanning of coherence envelope: **COAST**

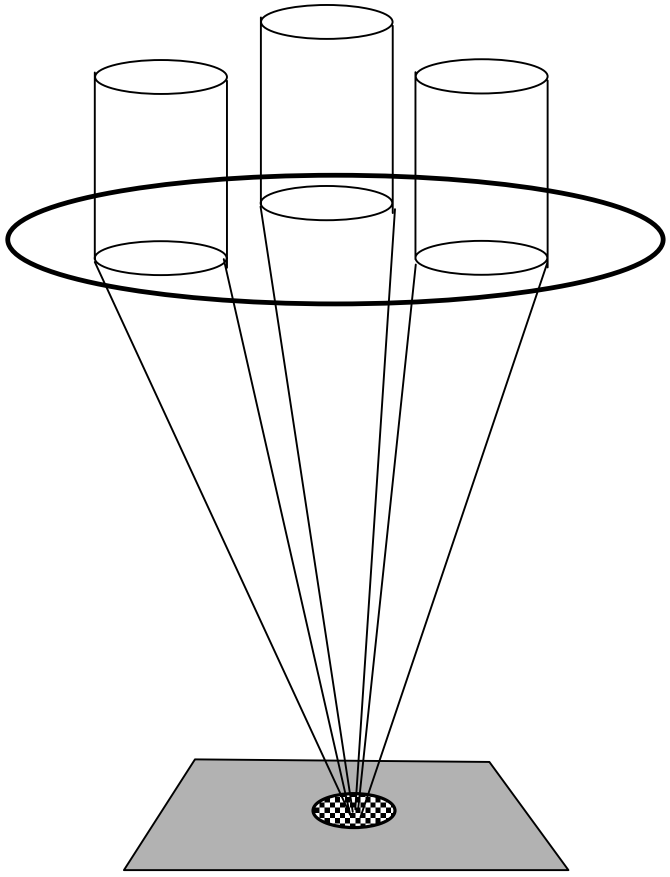
Multimode pupil plane beamcombination

Example: beam-combiner of COAST

Up to four elements can be combined simultaneously



Multimode image plane beamcombination



Focus collimated beams from elements with the same optical element onto a common detector

Easy simultaneous combination of more than two elements

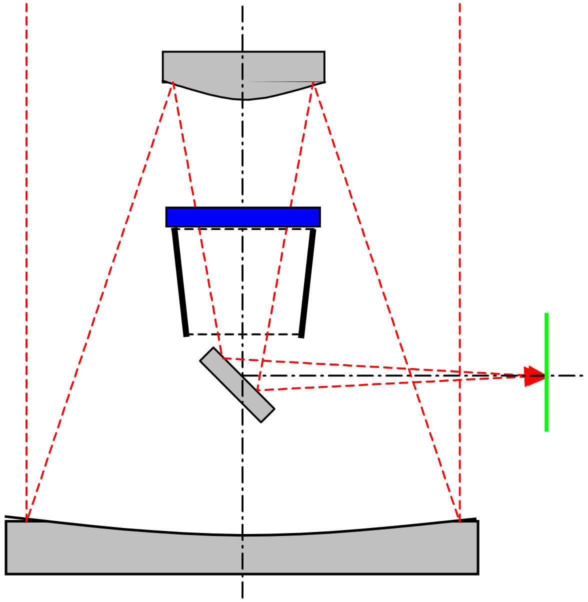
Easy detection of fringes in an extended field

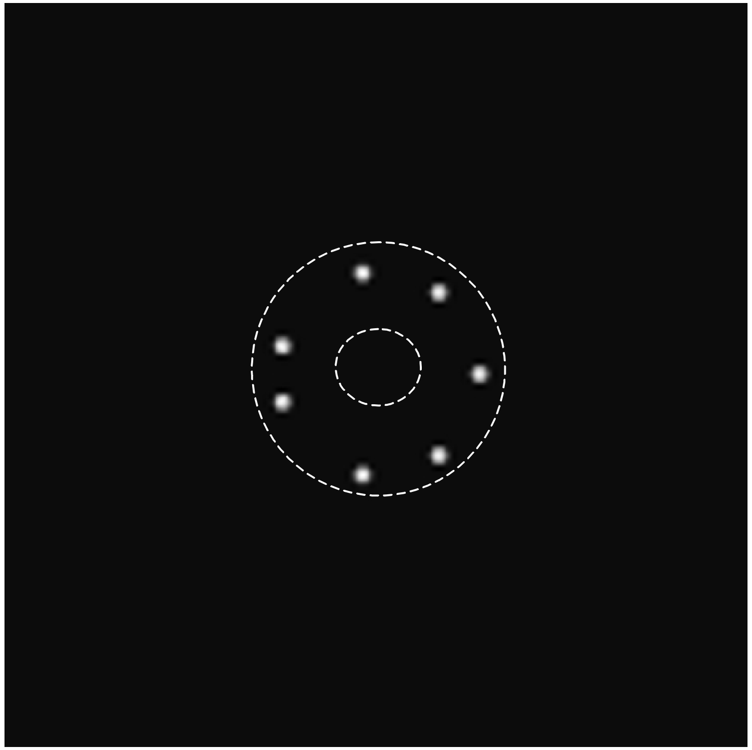
Needs detectors with many pixels

Image plane fringe detection by fringe dispersion: **GI2T**

Imaging beamcombination example:

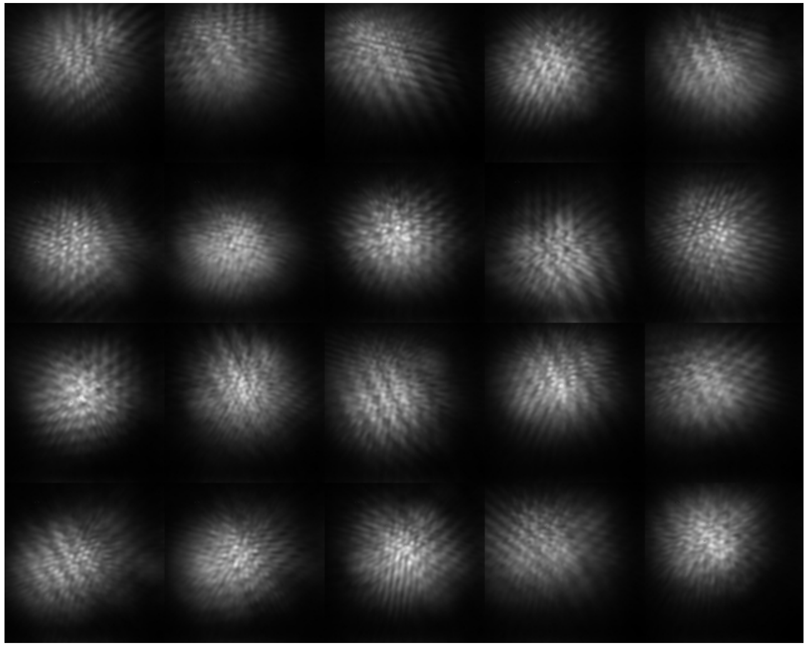
Pupil masking at ESO/NTT



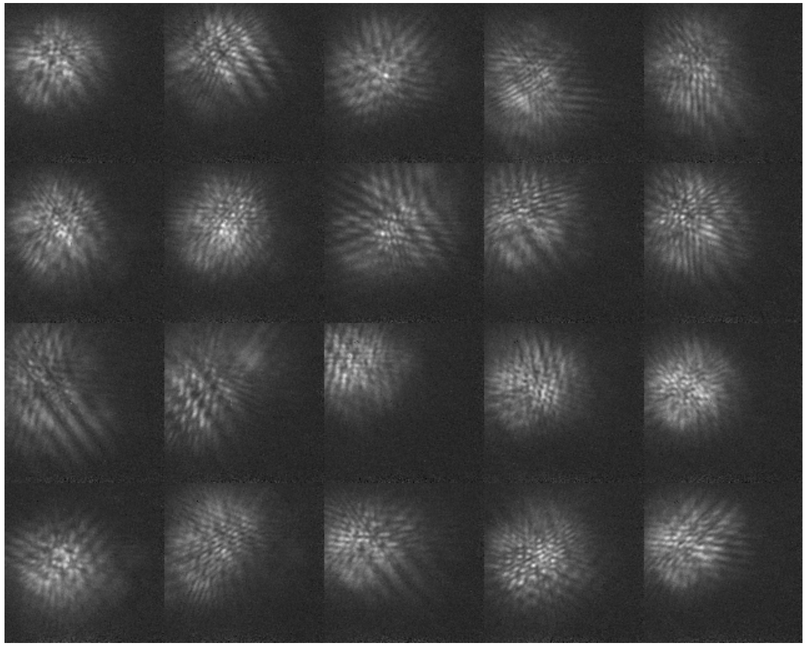


Imaging beamcombination example:

Pupil masking at ESO/NTT



program star



reference star

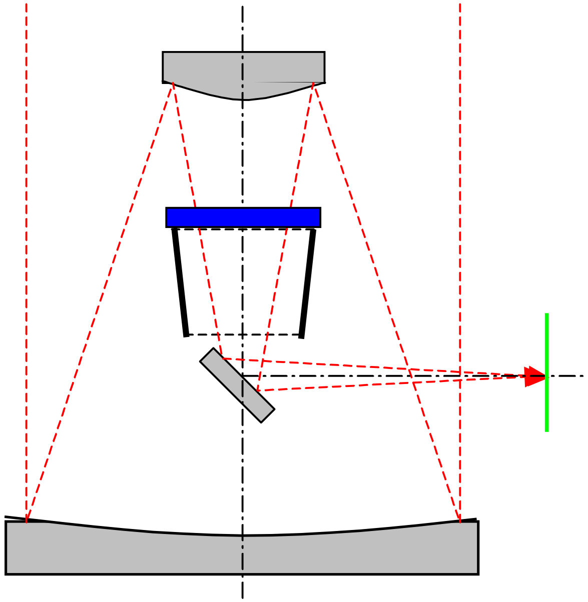
Fizeau vs. Michelson interferometers: a continuing confusion

Def.: A **Fizeau stellar interferometer** is an interferometer where the Helmholtz-Lagrange (optical) invariant is preserved throughout the optical train.

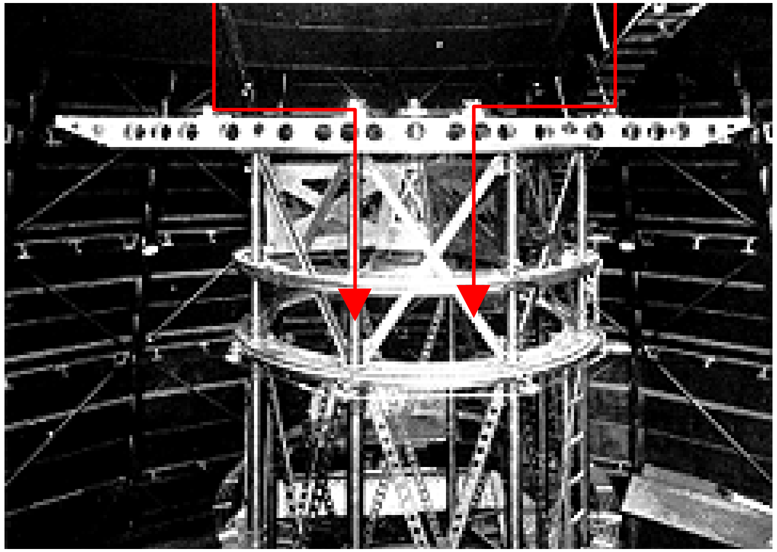
A **Michelson stellar interferometer** is an interferometer where this is not the case.

Helmholtz-Lagrange invariant: the product of (object sided) field angle and radius of entrance pupil. This quantity characterizes a given optical system.

Fizeau vs. Michelson interferometers: a continuing confusion

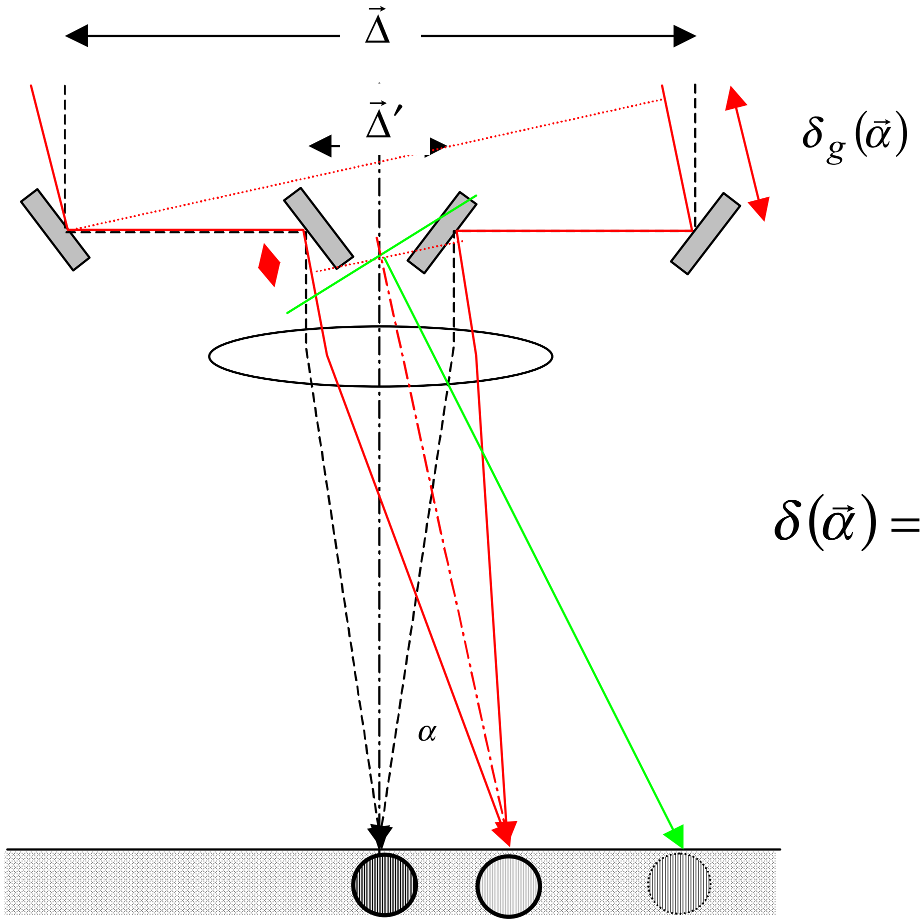


Fizeau interferometer



Michelson interferometer

Field effect in a Michelson interferometer



$$\delta(\vec{\alpha}) = \delta_g(\vec{\alpha}) - \delta'_g(\vec{\alpha}) = \vec{\alpha}\left(\vec{\Delta} - \vec{\Delta}'\right)$$