Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

11th Lecture: 30 November 2011

Content:

1. Basic Principle
2. Main Components
3. 1D Imaging and Fringes
4. 2D Imaging
5. Fundamental Limitations
6. Radio Interferometers
7. Sub-mm Interferometers

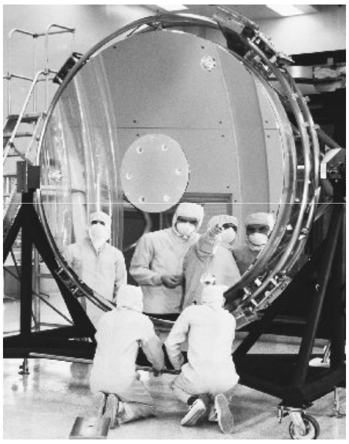
Based on: information provided by ESO on their public website, incl. tutorial by A. Glindemann; Rep. Prog. Phys. 66 (2003) 789–857 by J.D. Monnier, astro-ph/9609092v1 by T. Bedding; and ARA&A 30, 457-98 (1992) by M. Shao & M.M. Colavita.

Basic Principle

The Basic Idea

Angular resolution $\theta = 1.22 \frac{\lambda}{D}$

$D = D_{tel}$ $\qquad$ $D = d_{baseline} + D_{tel}$

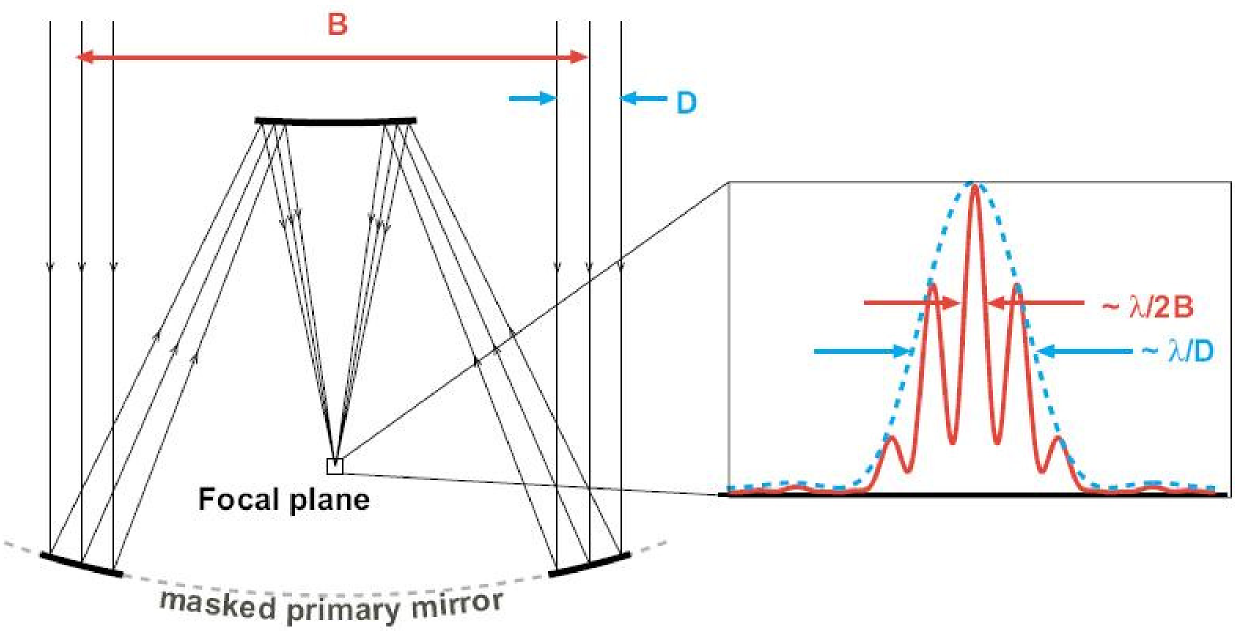


Angular resolution is determined by interference; interference does not need a continuous aperture (see Young's double slit experiment)!

→ Hippolyte Fizeau (1868): basic concept of stellar interferometry

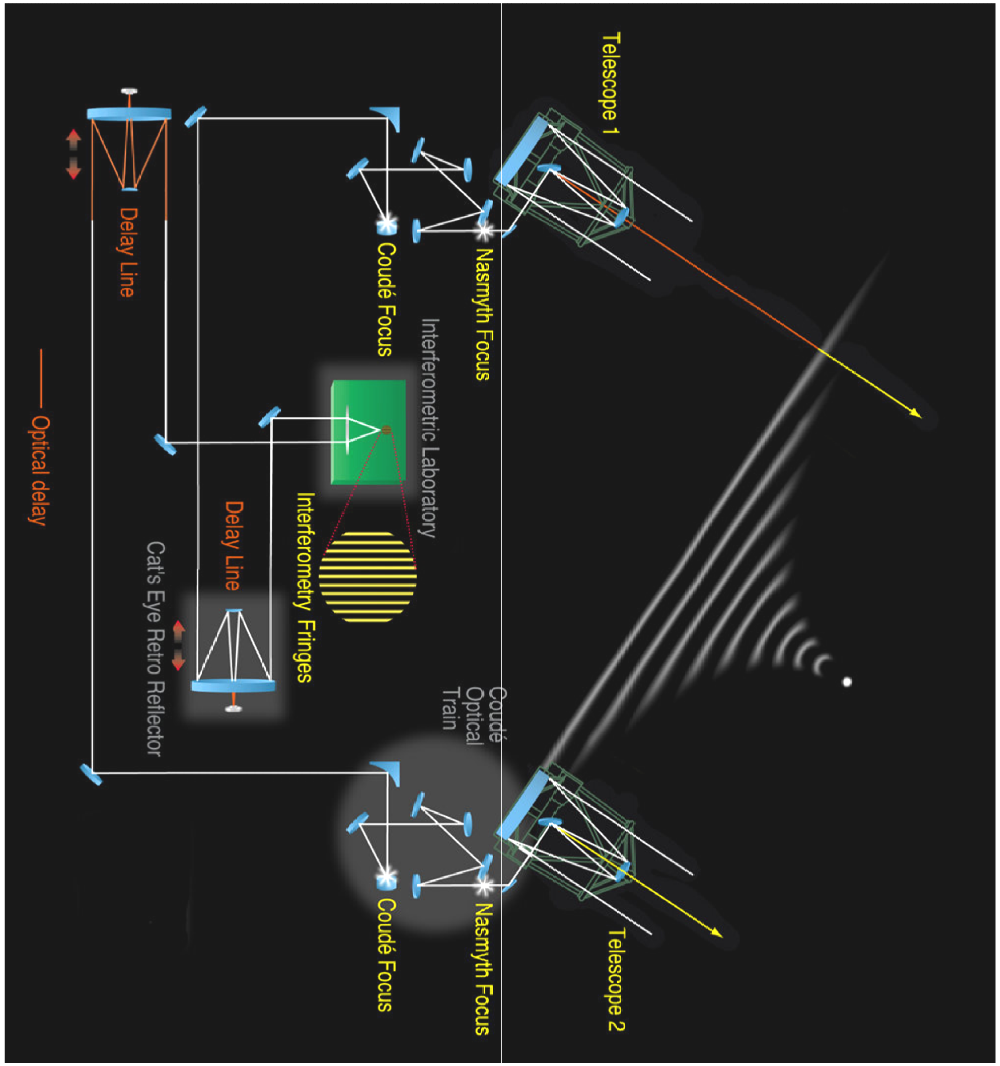
The Consequence

Interferometry is like masking a giant telescope:



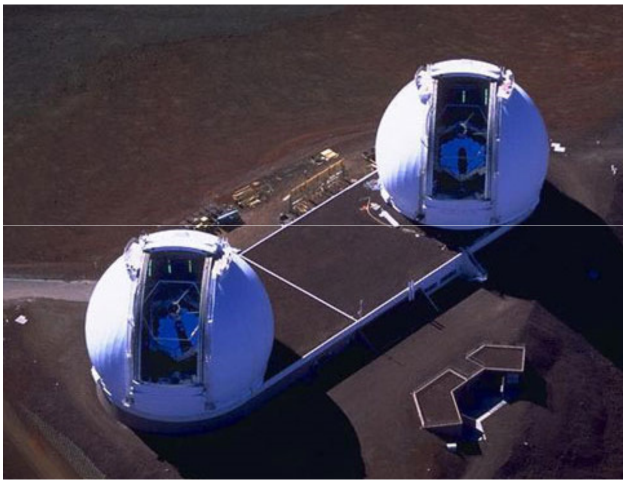
Main Components

The Basic Principle – Optical



Main Components: 1) Telescopes

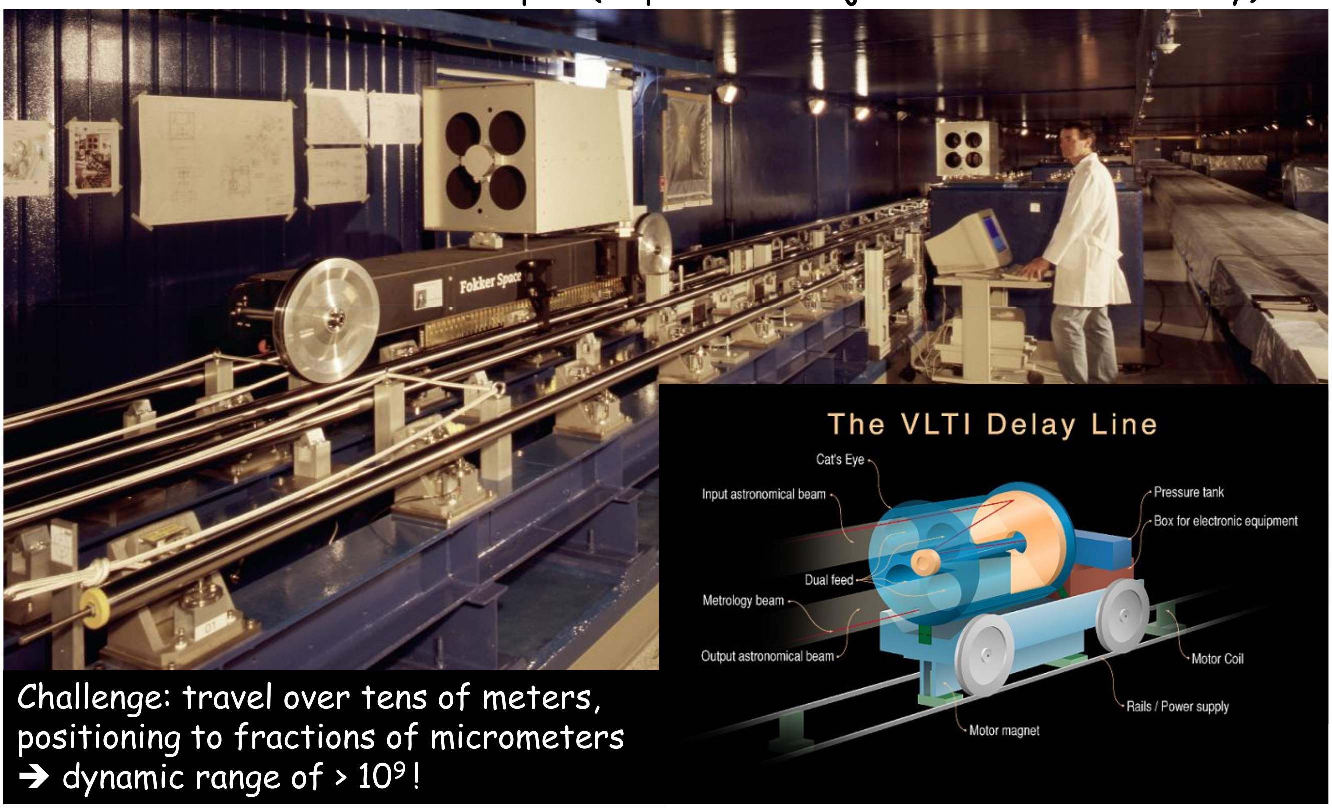
An optical interferometer typically consists of n telescopes of similar type and characteristics



Keck interferometer (Hawaii) ↑
← VLTI (Paranal)

Main Components: 2) Delay Lines

Delay lines are needed to compensate the optical path difference between the various telescopes (depends on object location on the sky)

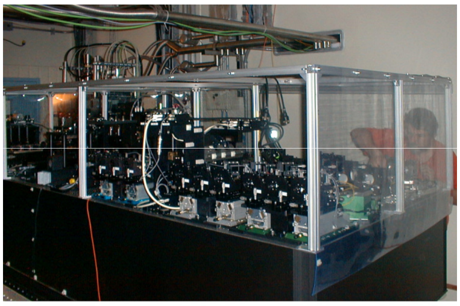


Challenge: travel over tens of meters, positioning to fractions of micrometers
➔ dynamic range of > 10^9!

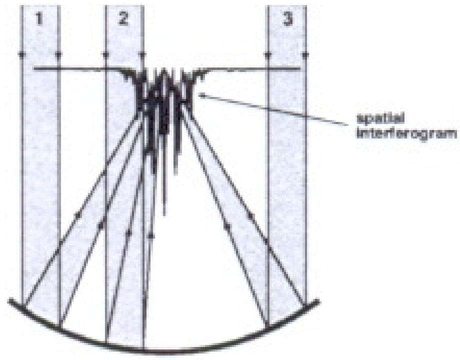
Main Components: 3) Beam Combiner

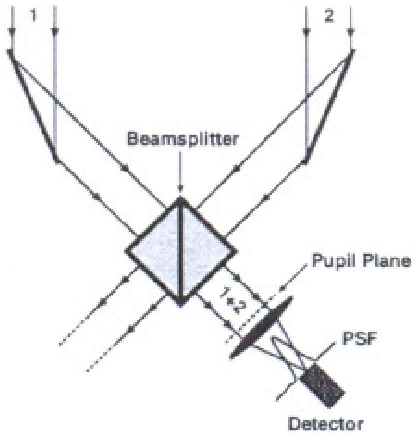
Two main types:

- multi-axial (image plane): beams are place adjacent to each other and form a fringe pattern in space.



The AMBER Instrument at the VLT Interferometer





- co-axial (pupil plane): beams are added on top of each other e.g. via a beam splitter.

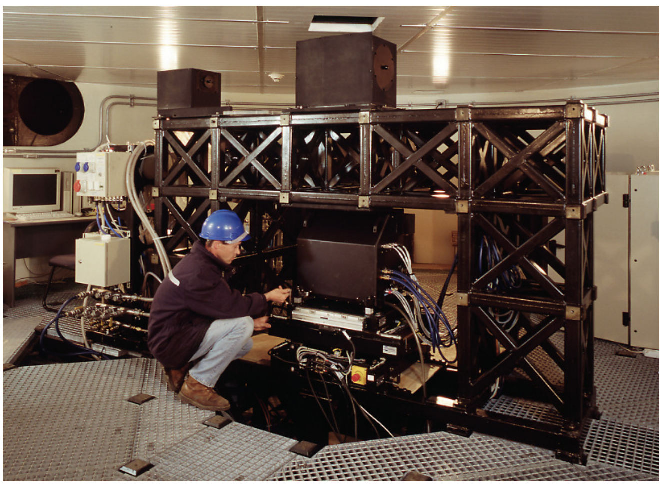
- but also single-mode fibers and integrated optics.

Main Components: 4) Adaptive Optics

Adaptive optics (or for telescopes with D < r_0 tip-tilt correction) is essential to correct wavefront aberrations for good interference.

The amplitude of the fluctuations is: $\sigma = \sqrt{6.88\left(\frac{B}{r_0}\right)^{5/6}}$ rads RMS

Hence, for a baseline B = 100m and a seeing of 1″ this amounts to 70μm!



The MACAO (Multi Application Curvature Adaptive Optics) system on a 8m VLT. Can be used with natural guide stars with 1 < V < 17, seeing < 1.5″, τ_0 > 1.5ms and airmass < 2.

1D Imaging and Fringes

Fringe Visibility – Defintion

The visibility is defined as $V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$

It is the Fourier transform of the object's brightness distribution.

If the dark regions in the fringe pattern go to zero V = 1 → object is unresolved.

If V = 0 then there are no fringes → object is completely resolved.

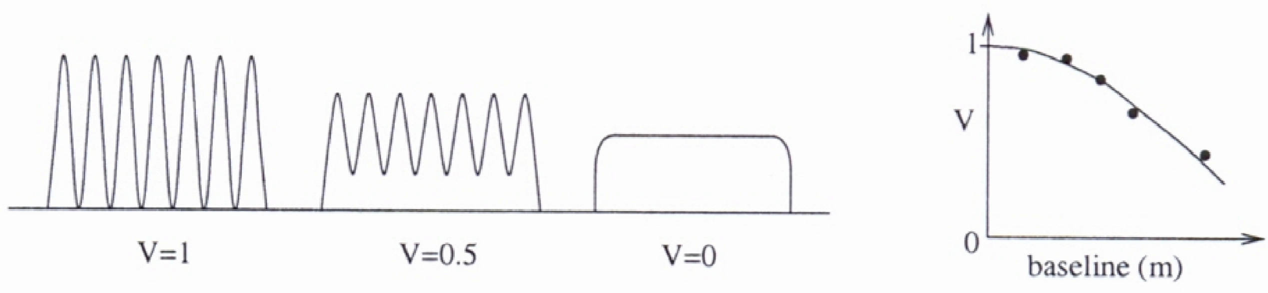
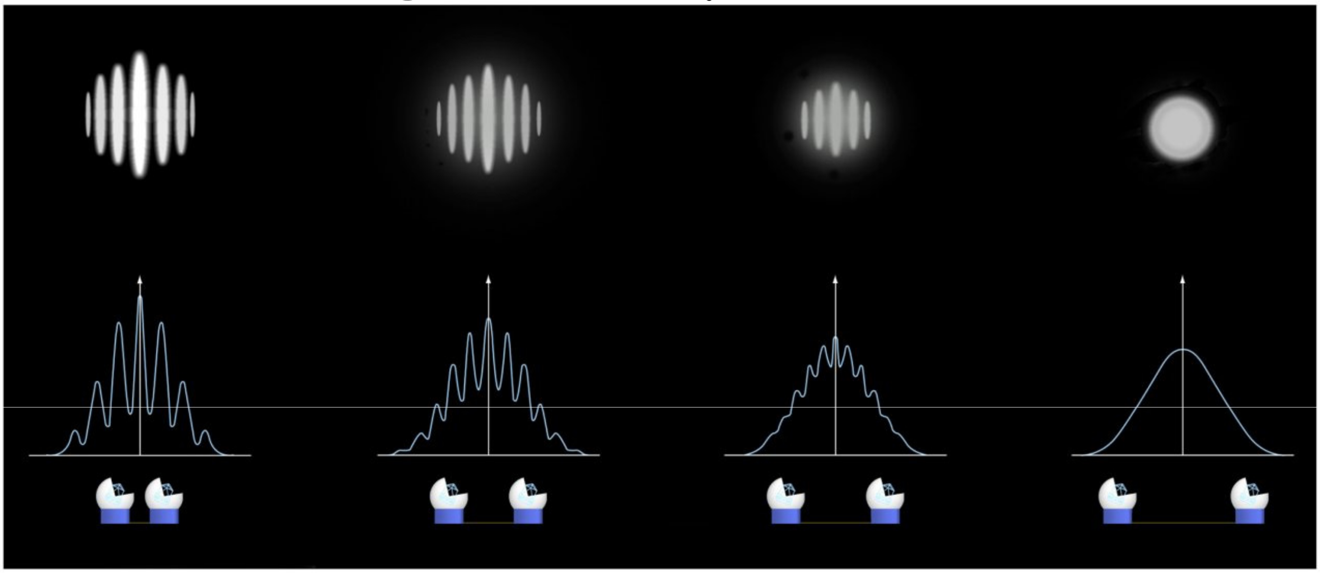


Fig. 2. Left: examples of fringes with visibilities of 1, 0.5 and 0. Right: visibility as a function of baseline for a resolved star.

Fringe Visibility – Baseline

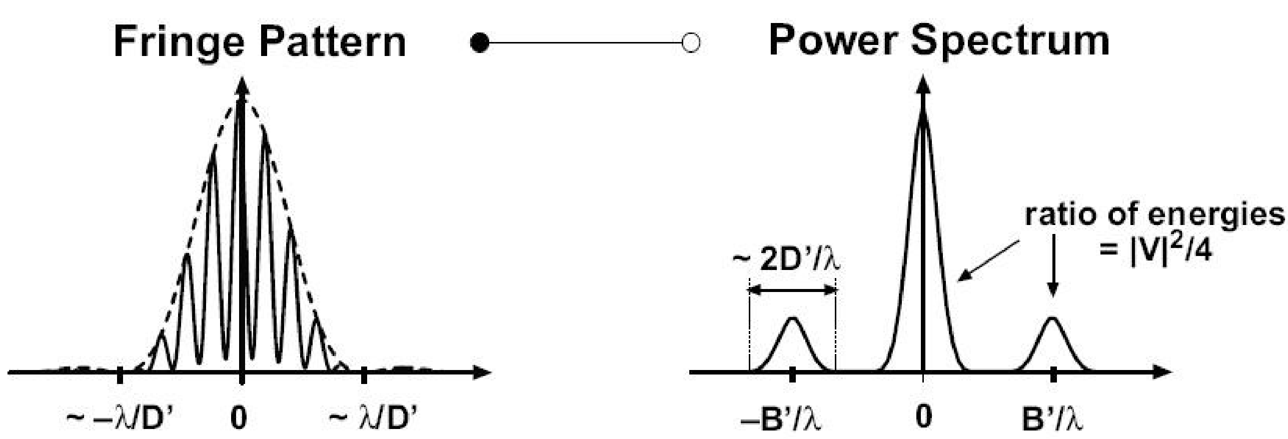


Interferometric Fringes at Different Telescope Baselines
(Simulation)

ESO PR Photo 10e/01 (18 March 2001) © European Southern Observatory

The observed pattern from a single star at the focal plane clearly changes as the distance between the two telescopes is gradually increased. The "fringes" disappear completely when the star is resolved.

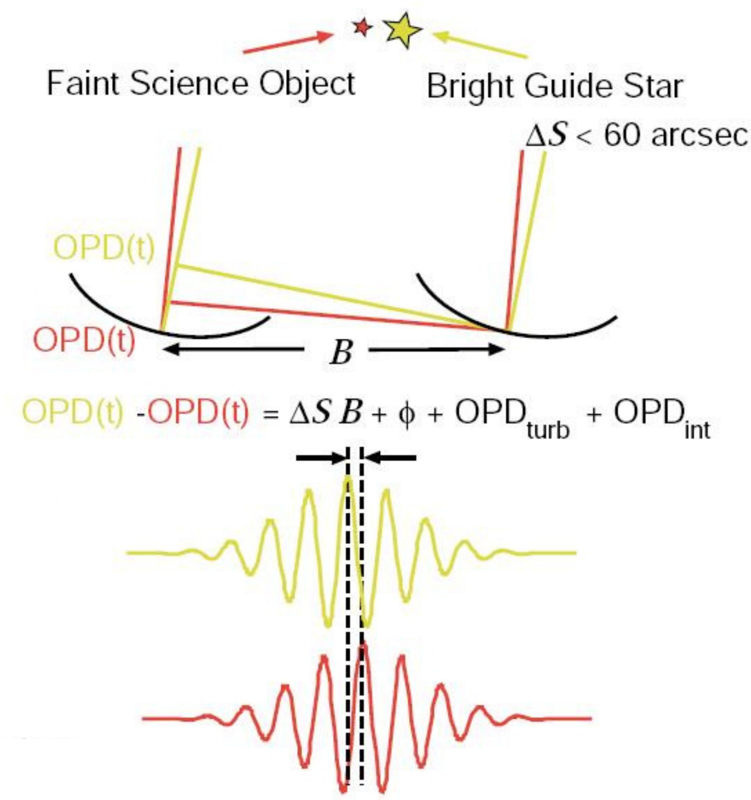
Fringe Visibility and Power Spectrum



Fringe Tracking (Co-Phasing)

The white-light fringe has to be actively tracked, which requires tracking fluctuations within a small fraction of wavelength in real-time.

Example: ESO's FINITO scans the center of the fringe packet in H band with high speed and sends a co-phasing signal to the VLTI delay lines.
FINITO operates on two channels, i.e. tracks three baselines.



Closure Phase (1)

Fringe visibility tells one component of the objects Fourier transform = amplitude of the fringes

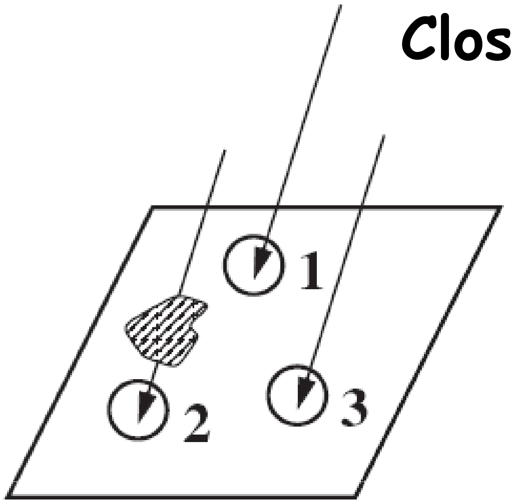
The phase is determined by the position of the fringes.

Problem: due to atmospheric turbulence (which changes the optical path length), the fringes move constantly forward and backward.

Idea: use three telescopes → three sets of fringes:
(1-2), (2-3), (1-3)
In all three sets the fringes move, but not independently!

→ this information is called closure phase (or self-calibration in aperture synthesis imaging – the standard technique in radio interferometry) and can be used to cancel out phase error terms.

Closure Phase (2)



Observed		Intrinsic		Atmosphere
$\Phi(1\text{-}2)$	=	$\Phi_o(1\text{-}2)$	+	$[\phi(2)-\phi(1)]$
$\Phi(2\text{-}3)$	=	$\Phi_o(2\text{-}3)$	+	$[\phi(3)-\phi(2)]$
$\Phi(3\text{-}1)$	=	$\Phi_o(3\text{-}1)$	+	$[\phi(1)-\phi(3)]$

$$\boxed{\text{Closure Phase } (1\text{-}2\text{-}3) = \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)}$$

The error terms cancel out!

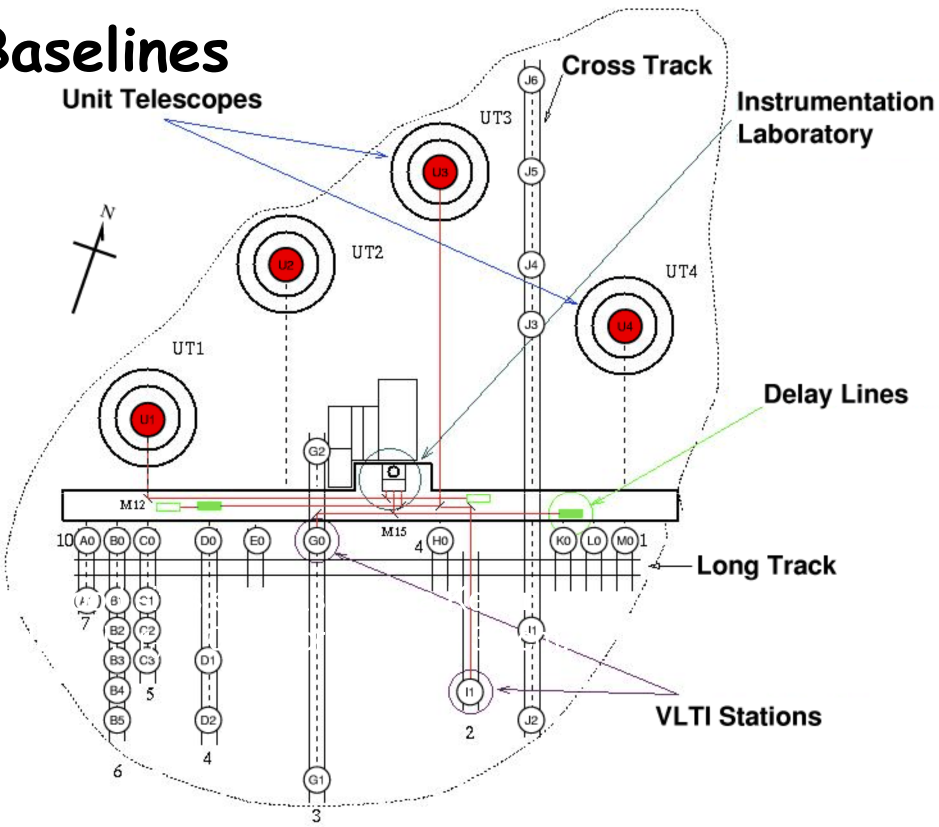
Table 1. Phase information contained in the closure phases alone.

Number of telescopes	Number of Fourier phases	Number of closing triangles	Number of independent closure phases	Percentage (%) of phase information
3	3	1	1	33
7	21	35	15	71
21	210	1 330	190	90
27	351	2 925	325	93
50	1225	19 600	1176	96

2D Imaging

(requires more baselines)

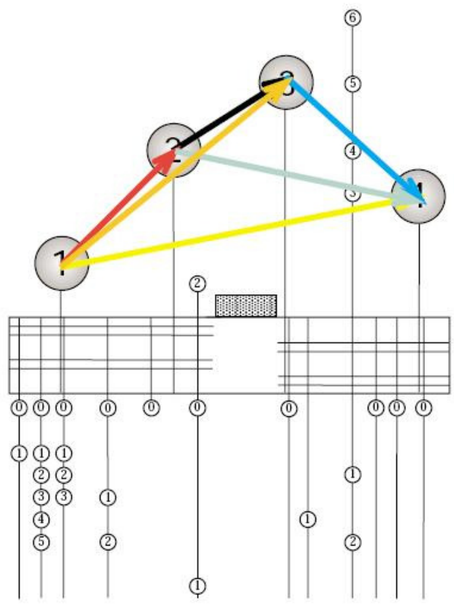
The VLTI Baselines

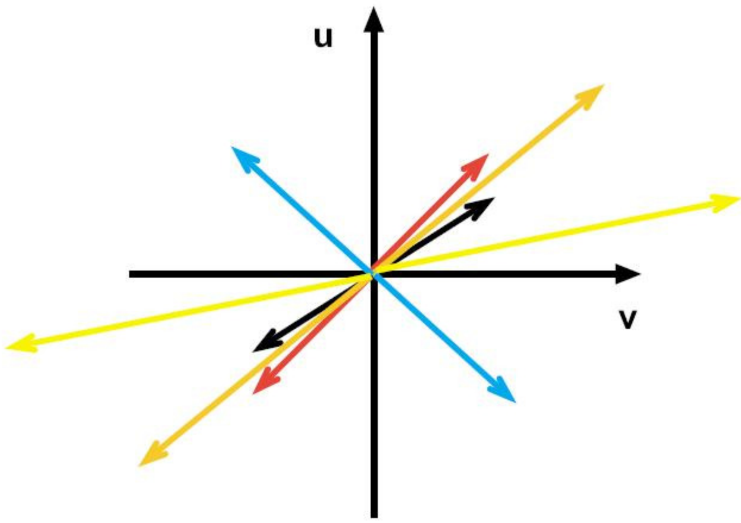


The three ATs move on rails between the thirty observing stations above the holes that provide access to the underlying tunnel system. The light beams from the individual telescopes are guided towards the centrally located, partly underground Interferometry Laboratory

Baseline Coverage (1)

A smooth reconstruction of the object's intensity distribution I requires a good coverage of the (u,v) plane.

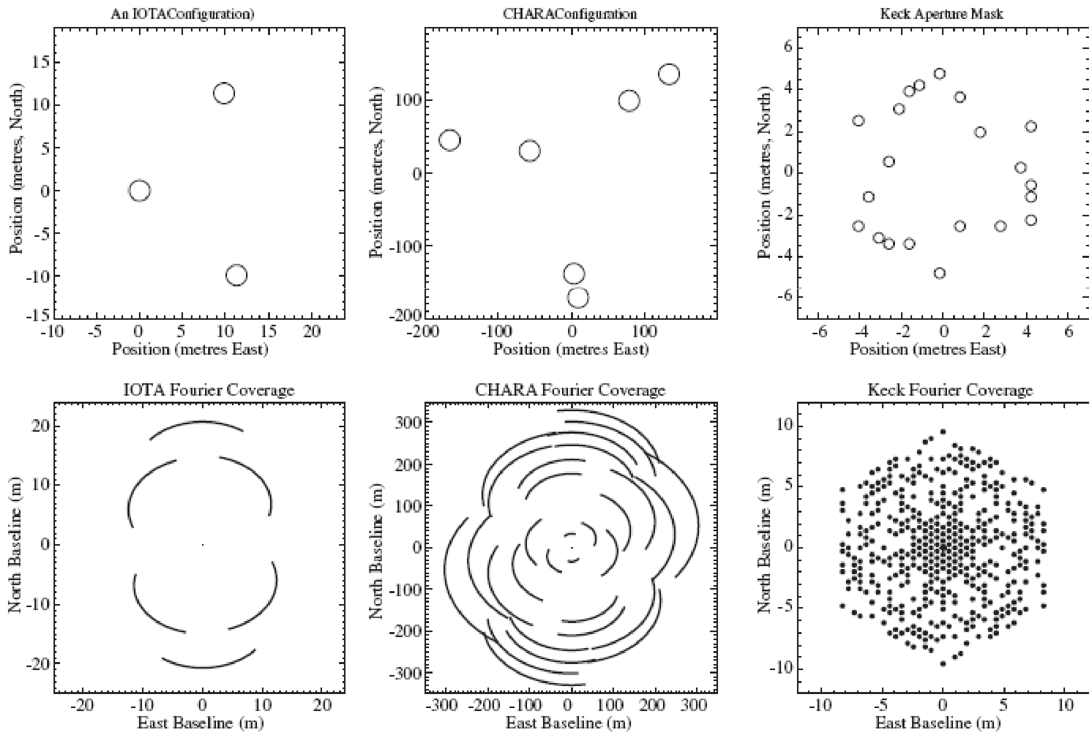




Note: This is the uv-plane for an object at zenith.
In general, the projected baselines have to be used.

Baseline Coverage (2)

The Earth's rotation helps to fill the (u,v) plane. Assumed is a source at 45° declination, observed for 3 hr both before and after transit.



Fundamental Limitations

Field of View and Limiting Magnitude

The field of view is typically limited to a few arcseconds only (except for Fizeau intererometers): $\theta_{\max} \le \frac{\lambda}{D}\frac{\lambda}{\Delta\lambda}$

- the size of the complex transfer optics. Larger field = larger optical elements

- spatial filters, which limit the FOV

The limiting magnitude is given by the atmospheric turbulence, which requires either:

- to use integration times shorter than τ_0 or

- to use an AO system (guide stars!)

Sensitivity of an Interferometer

The signal-to-noise for the measurement of visibility or phase with an interferometer is:

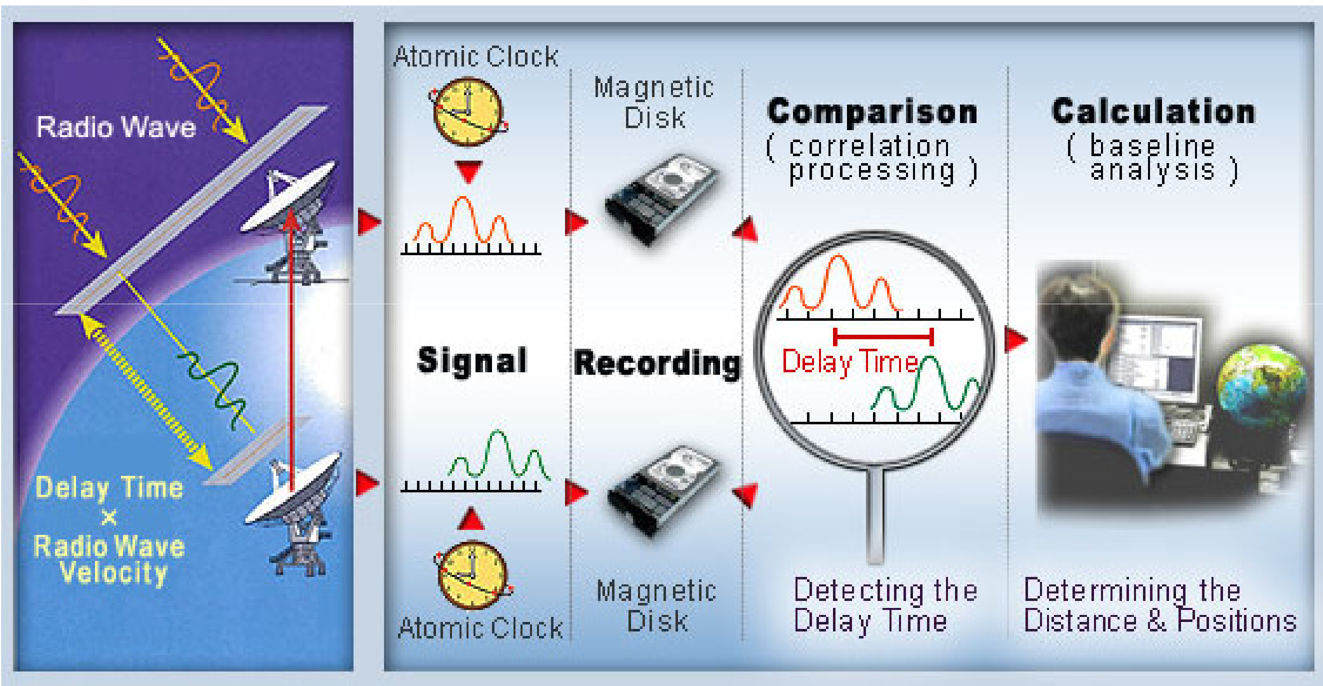
in the photon-limited regime (visible): $SNR_{Poisson} = \sqrt{\frac{nV^2}{1+\frac{1}{nV^2}}} \propto \sqrt{n}\cdot V$

in the background-limited regime (IR): $SNR_{BLIP} = \sqrt{\frac{n^2V^2/b}{1+\frac{1}{n^2V^2/b}}} \propto n\cdot V$

where n is the number of source photons per coherence volume $D^2 \cdot \tau_0$, b is the number of background photons per coherence volume, and V is the fringe visibility.

Radio Interferometry Projects

The Basic Principle – VLBI



credit: http://vldb.gsi.go.jp/sokuchi/vlbi/en/whatisvlbi/principle.html

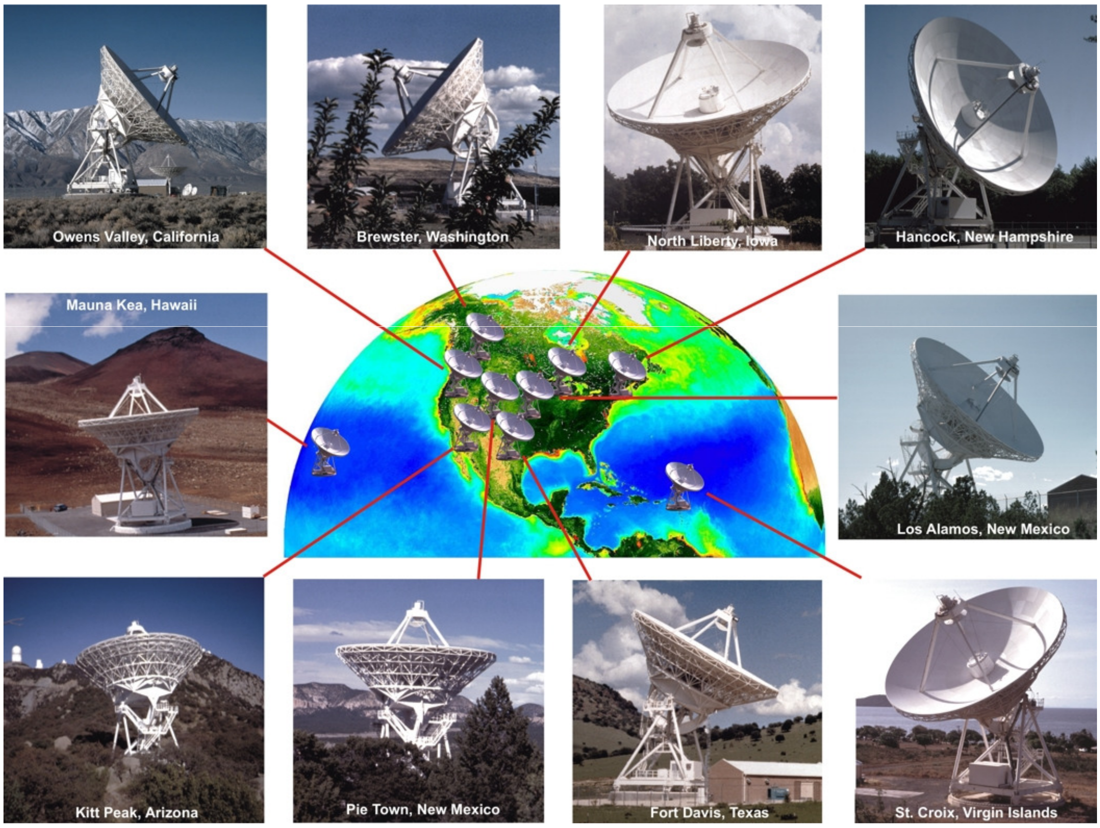
European VLBI (Very Long Baseline Interferometry) Network

Very Large Array VLA

- *Y-shaped array of 27 telescopes moved on railroad tracks*
- *telescope diameter 25-m each*
- *located: high Plains of San Augustin in New Mexico*
- *"D", "C", "B", and "A" configurations, spanning 1.0, 3.4, 11, and 36 km, respectively*

Very Long Baseline Array VLBA

Ten 25 m antennas form an array of 8000 km in size.



Australia Telescope Compact Array ATCA

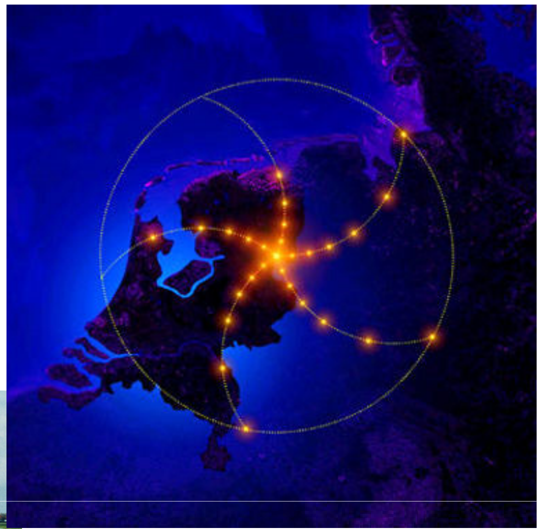
Six 22 m telescopes on an east-west baseline

Westerbork

- *Westerbork Synthesis Radio Telescope (WSRT)*
- *14 telescopes*
- *25-meter each*
- *East-west baseline*
- *3 km in length*
- *effective collecting area of a 92 m dish*

LOFAR

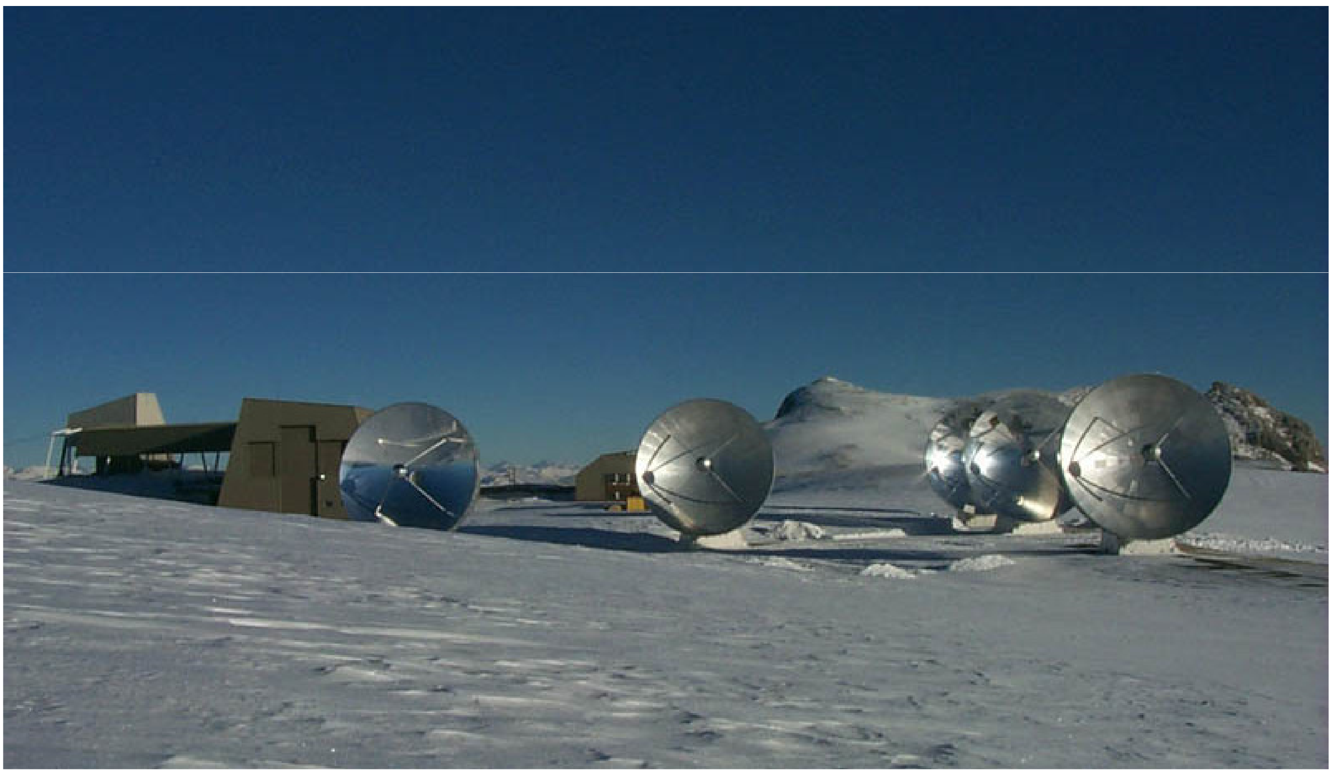
25,000 antennas for radio frequencies below 250 MHz.



Sub-mm Interferometry Projects

Plateau de Bure

Interferometer of six 15 m antennas



Combined Array for Research in Millimeter-wave Astronomy (CARMA)

CARMA = six 10-meter telescopes from Caltech's Owens Valley Radio Observatory + nine 6-meter telescopes from the Berkeley-Illinois-Maryland Association → Cedar (CA)

Sub-Millimeter Array (SMA)

The SMA consists of eight 6 m antennas on Mauna Kea (HI)

ALMA

- Giant array of 50 antennas (12m each)
- Baselines from 160m – 16 km.
- Additional compact array of twelve 7m and four 12m antennas
- Located on the Chajnantor plain at 5000m altitude
- Wavelength range 3 mm – 400 μm (84 to 720 GHz)

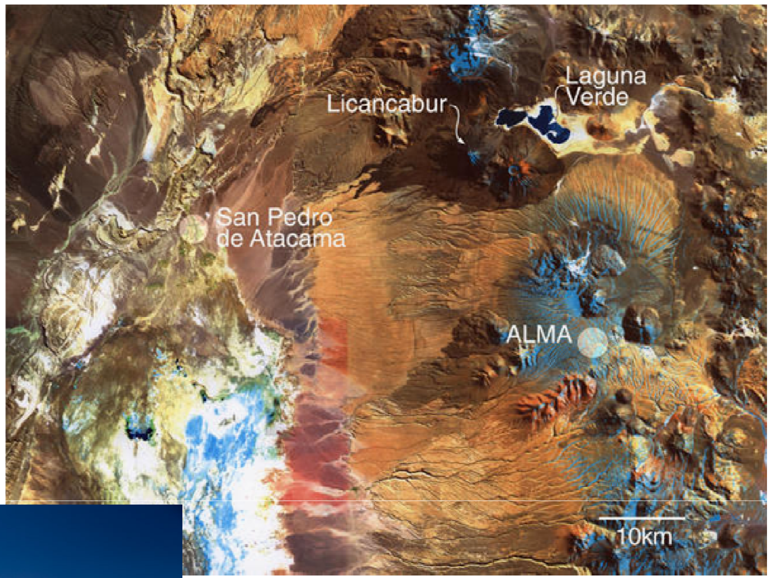
Observing frequencies: Band 3 (>84 GHz) to band 9 (<720 GHz).

Field of view ~ size of individual antennas & frequency (but independent of array configuration!). FWHM of beam is 21" at 300 GHz *To* . *To achieve uniform sensitivity over a larger field mosaicking is required.*

Spatial resolution: ~ frequency & maximum baseline.
Most extended configuration (~16 km): 6 mas at 675 GHz
Structures > 0.6»λ/b_{min} (b_{min}=shortest baseline) are not well reproduced in reconstructed images → measure with the ALMA Compact Array (ACA) using the 7-m antennae (come closer).

Spectral resolution: up to 8192 frequency channels (spectral resolution elements). At 110 GHz, R=30,000,000 or 10m/s velocity resolution.

Sensitivity: use ALMA Sensitivity Calculator to estimate noise levels or required integration times at
http://almascience.eso.org/call-for-proposals/sensitivity-calculator


Licancabur
Laguna Verde
San Pedro de Atacama
ALMA
10km