FFYS7086: Signal and Image Processing

Kaj Wiik

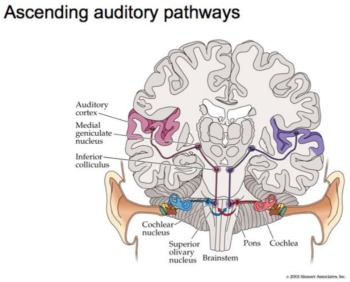
Tuorla Observatory

Spring 2022

{Based partly on 'Essential radio astronomy' from http://www.cv.nrao.edu/course/astr534/Interferometers1.html by J. J. Condon and S. M. Ransom and Ivan Marti-Vidals (OSO, ALMA Nordic ARC) tutorial.}

Outline

We do interferometry all the time...

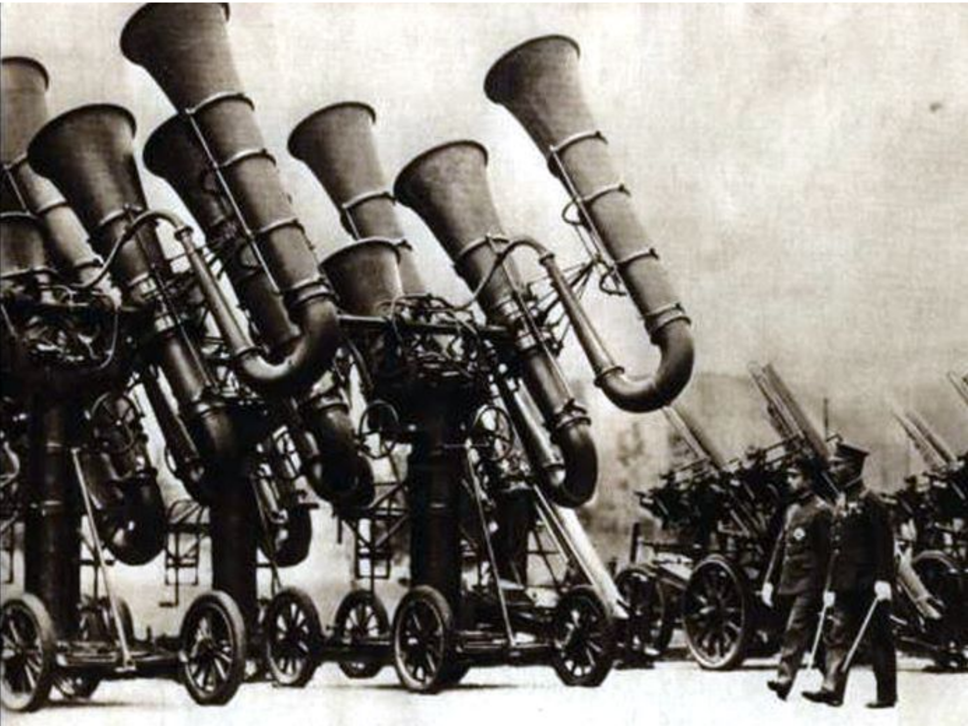


"Significant number of nerve fibers cross the brain and make connections with neurons on the side opposite from the side of the ear in which they begin. This happens very early on in the auditory system. Inter-aural comparisons are an important source of information for the auditory system about where a sound came from."

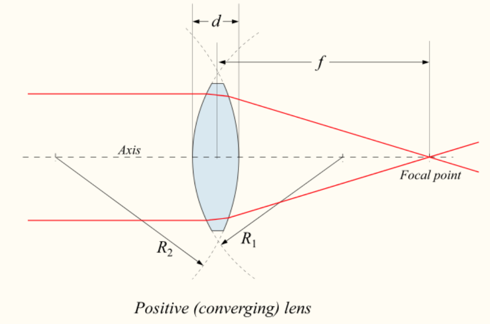
{David Heeger's lecture from http://www.cns.nyu.edu/~david/courses/perception/lecturenotes/localization/localization.html}

And animals too

Long eared bat, korvayökkö, Plecotus auritus



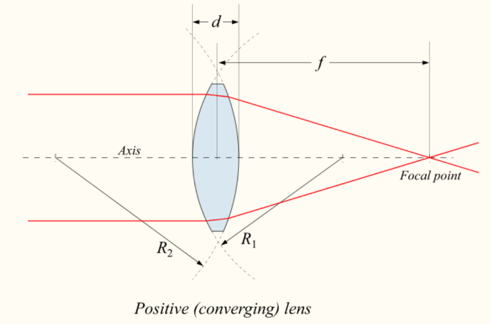
An Introduction to Interferometry



Interferometry is essentially the same thing that happens in an eye or a camera: the electromagnetic field is Fourier transformed by the lens to produce an image. Nothing more, nothing less.

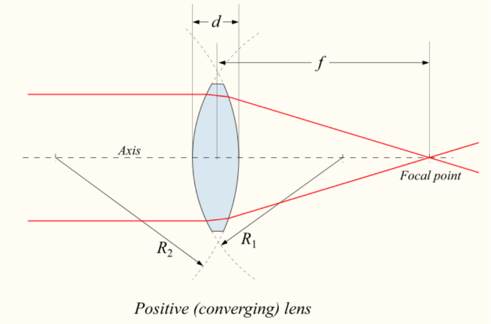
See e.g. `https://en.wikipedia.org/wiki/Fourier_optics#Fourier_transforming_property_of_lenses`

A light Introduction



In interferometry, we discard the lens (or mirror), take samples of the aperture field and produce the image mathematically. This works in radio because wavelength is long enough. It's that simple.

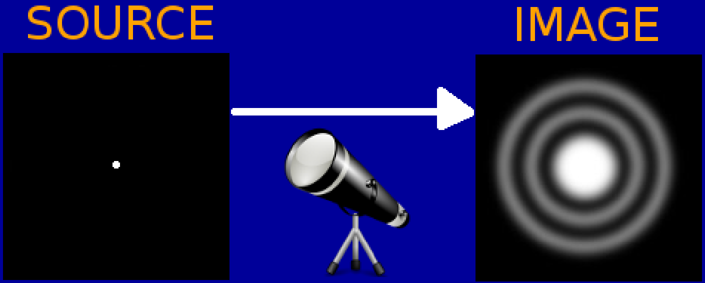
A light Introduction



In interferometry, we discard the lens (or mirror), take samples of the aperture field and produce the image mathematically. This works in radio because wavelength is long enough. It's that simple. Well, of course there are details. . . these are the topics of the lectures.

Resolution of an optical device

Any optical device is fundamentally limited by diffraction
Due to diffraction, the image of a point source is not a point image, but a blurry point-like shape called Point Spread Function (PSF)



The PSF of an optical device

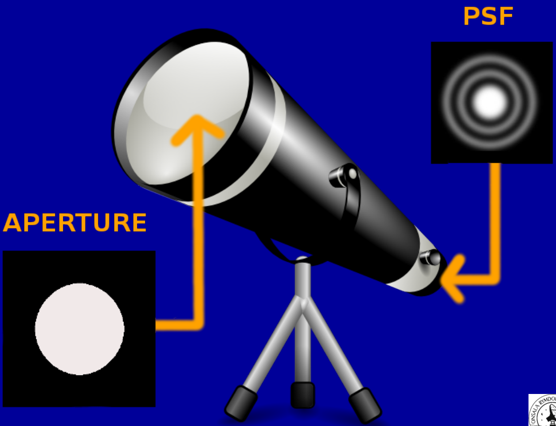
The PSF of an instrument is equal to the Fourier transform of the aperture's autocorrelation (in units of λ)

$\mathrm{PSF} = \mathcal{F}(\mathrm{APERTURE} * \mathrm{APERTURE})$

The PSF of an optical device

The PSF of an instrument is equal to the Fourier transform of the aperture's autocorrelation (in units of λ)

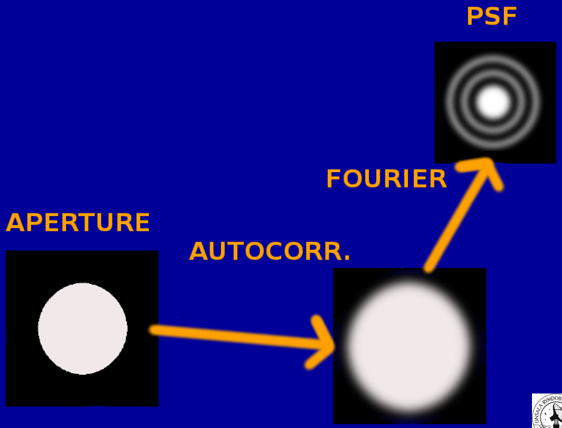
$\mathrm{PSF} = \mathcal{F}(\mathrm{APERTURE} * \mathrm{APERTURE})$



The PSF of an optical device

The PSF of an instrument is equal to the Fourier transform of the aperture's autocorrelation (in units of λ)

$\mathrm{PSF} = \mathcal{F}(\mathrm{APERTURE} * \mathrm{APERTURE})$



The PSF of an optical device

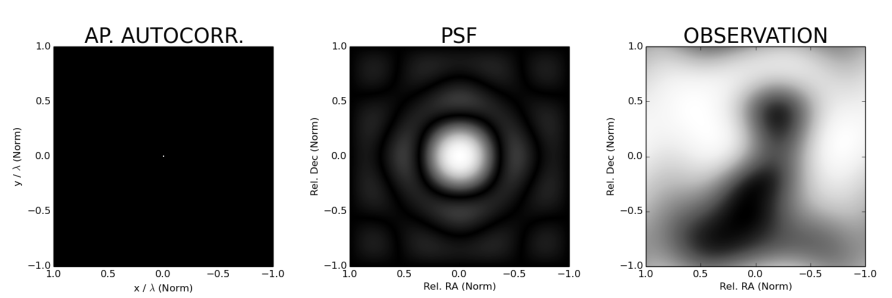
The size of the PSF depends on the wavelength and the aperture size:

$$\Delta\theta \sim \frac{\lambda}{D}$$

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size:

$$\Delta\theta \sim \frac{\lambda}{D}$$

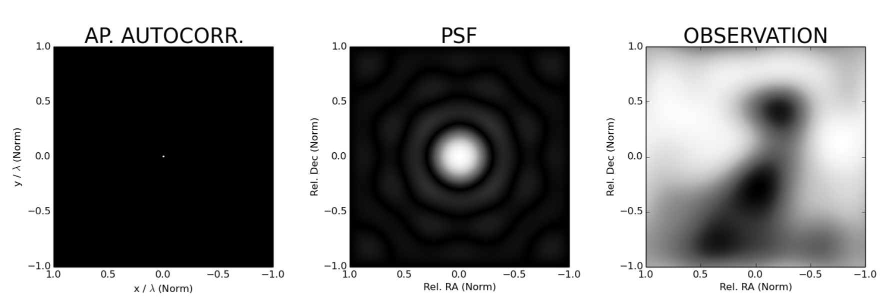


The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size:

$$\Delta\theta \sim \frac{\lambda}{D}$$

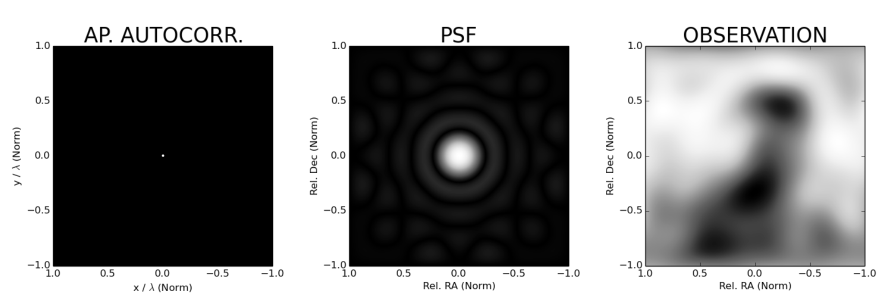


The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size:

$$\Delta\theta \sim \frac{\lambda}{D}$$

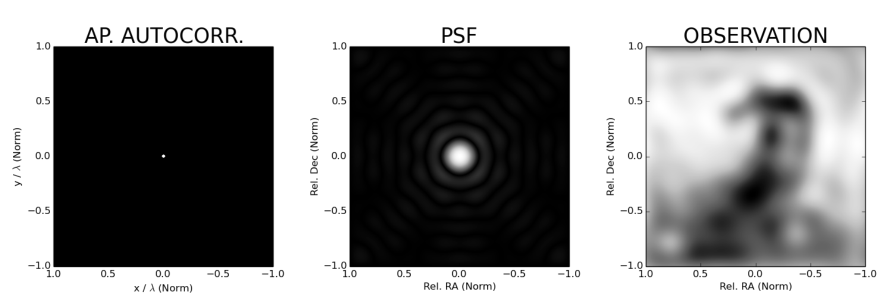


The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size:

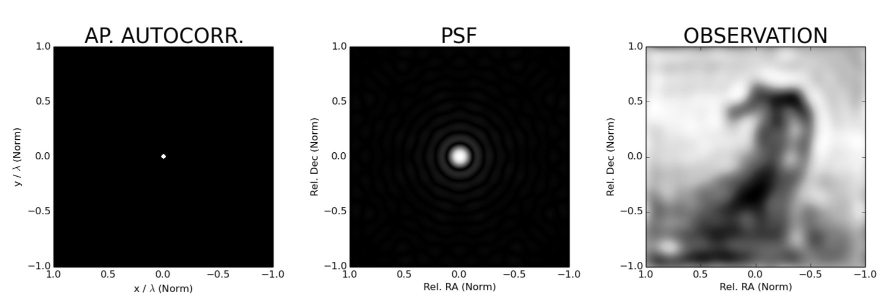
$$\Delta\theta \sim \frac{\lambda}{D}$$



The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size: $\Delta\theta \sim \dfrac{\lambda}{D}$

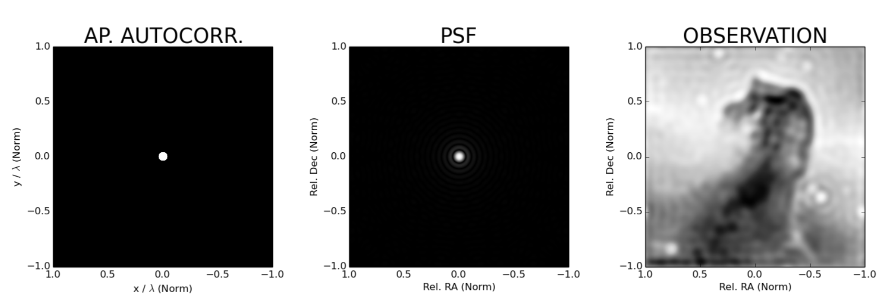


The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size:

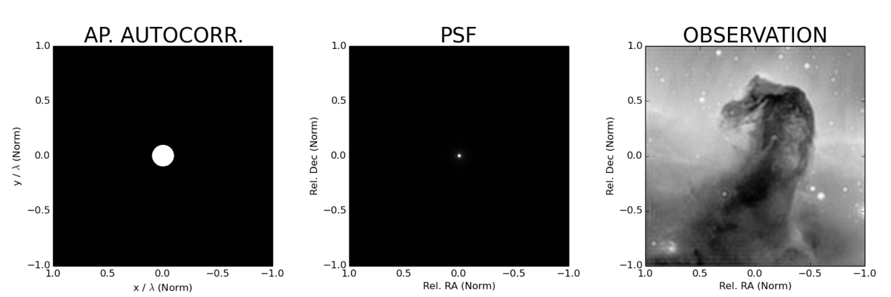
$$\Delta\theta \sim \frac{\lambda}{D}$$



The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size: $\Delta\theta \sim \frac{\lambda}{D}$

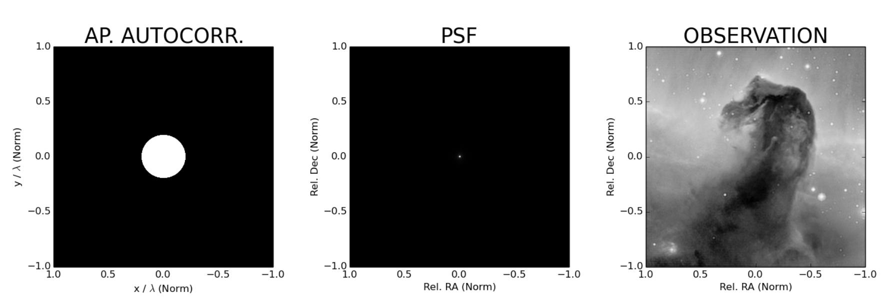


The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size:

$$\Delta\theta \sim \frac{\lambda}{D}$$

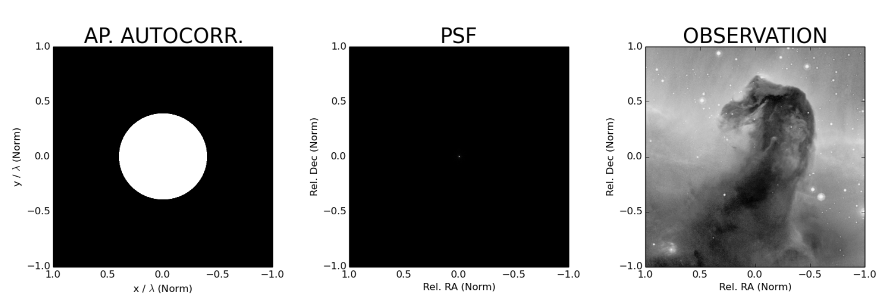


The resolution increases if the aperture increases (in units of λ)

The PSF of an optical device

The size of the PSF depends on the wavelength and the aperture size:

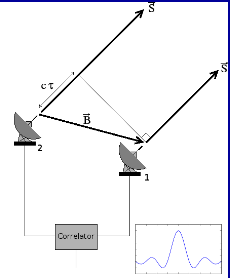
$$\Delta\theta \sim \frac{\lambda}{D}$$



The resolution increases if the aperture increases (in units of λ)

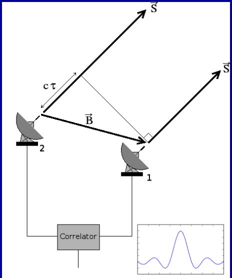
The two-element interferometer

Observing with a two-element interferometer



A BASIC OBSERVABLE OF AN INTERFEROMETER IS THE CROSS-SPECTRUM (a.k.a. COMPLEX VISIBILITY):

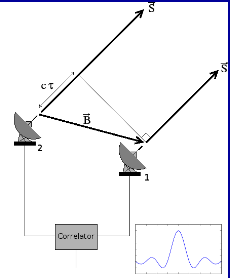
Observing with a two-element interferometer



A BASIC OBSERVABLE OF AN INTERFEROMETER IS THE CROSS-SPECTRUM (a.k.a. COMPLEX VISIBILITY):

$E_i(t)$

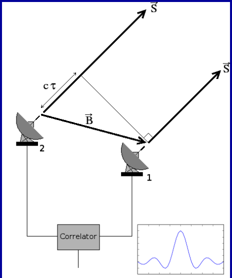
Observing with a two-element interferometer



A BASIC OBSERVABLE OF AN INTERFEROMETER IS THE CROSS-SPECTRUM (a.k.a. COMPLEX VISIBILITY):

$E_i(t) \rightarrow$

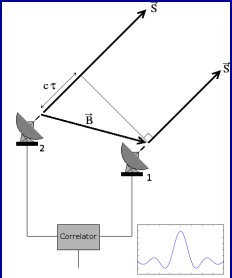
Observing with a two-element interferometer



A BASIC OBSERVABLE OF AN INTERFEROMETER IS THE CROSS-SPECTRUM (a.k.a. COMPLEX VISIBILITY):

$$E_i(t) \rightarrow S_i(\nu) = \mathcal{F}\left(E_i(t)\right)$$

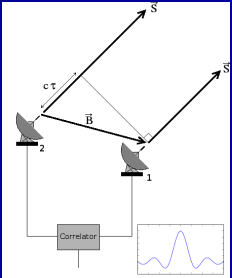
Observing with a two-element interferometer



A BASIC OBSERVABLE OF AN INTERFEROMETER IS THE CROSS-SPECTRUM (a.k.a. COMPLEX VISIBILITY):

$$E_i(t) \rightarrow S_i(\nu) = \mathcal{F}\left(E_i(t)\right) \rightarrow$$

Observing with a two-element interferometer



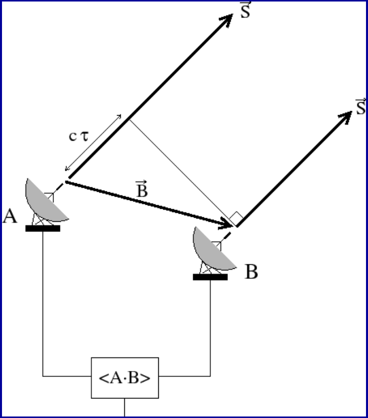
A BASIC OBSERVABLE OF AN INTERFEROMETER IS THE CROSS-SPECTRUM (a.k.a. COMPLEX VISIBILITY):

$$E_i(t) \rightarrow S_i(\nu) = \mathcal{F}\left(E_i(t)\right) \rightarrow V_{ik}(\nu) = S_i(\nu) \times S_k^*(\nu)$$

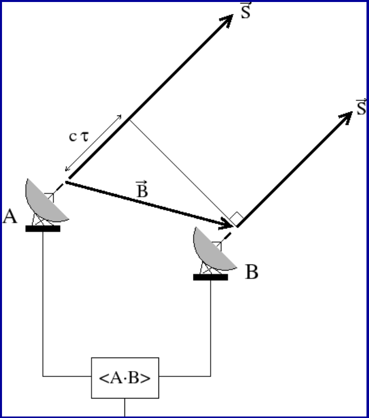
Notice the similarity with the power spectrum used in single dish:

$$P_i(\nu) = S_i(\nu) \times S_i^*(\nu) = |S_i(\nu)|^2$$

Cross-spectrum of a monochromatic point source

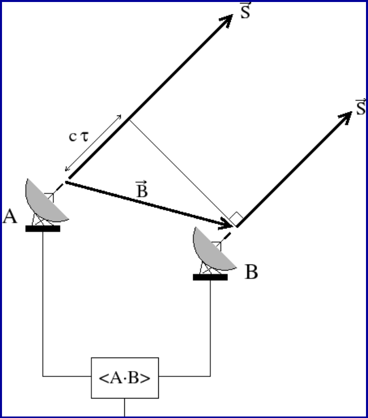


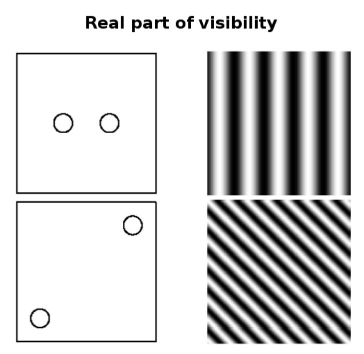
Cross-spectrum of a monochromatic point source



$$\tau = \frac{\vec{B}\,\vec{S}}{c}$$

Cross-spectrum of a monochromatic point source





$$\tau = \frac{\vec{B}\,\vec{S}}{c} \rightarrow V(\nu_0) = I \times (\cos 2\pi\nu_0\tau - j\,\sin 2\pi\nu_0\tau)$$

Visibilities of extended sources

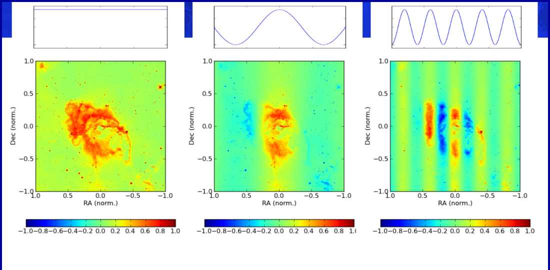
For extended sources, the overall measured visibility is the integral of the source structure times the response.

$$V(\vec{B}, \nu_0) = \int I_{\nu_0}(\vec{S}) \exp\left(-2\pi j \frac{\vec{B}\vec{S}}{\lambda_0}\right) d\vec{S}$$

Visibilities of extended sources

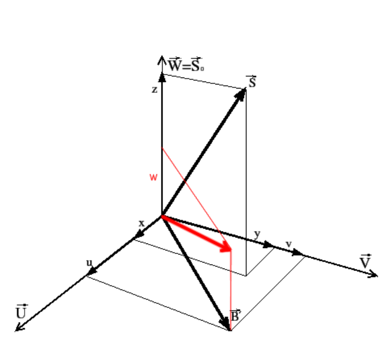
For extended sources, the overall measured visibility is the integral of the source structure times the response.

$$V(\vec{B},\nu_0) = \int I_{\nu_0}(\vec{S})\,\exp\left(-2\pi j \frac{\vec{B}\vec{S}}{\lambda_0}\right) d\vec{S}$$



For small fields of view, this is just the integral of the source structure multiplied by a *complex fringe*.

The Full Interferometer Equation

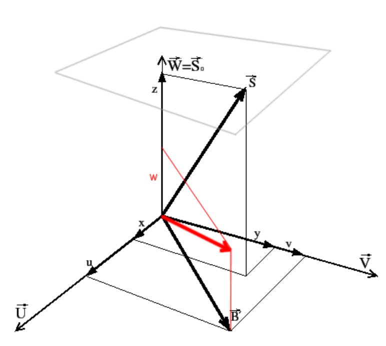


$$V(u,v,w) = \int_{x,y} I_\nu(x,y)\, e^{-\frac{2\pi j}{\lambda}(u\,x+v\,y+w\,z)}\, \frac{dx\,dy}{z}$$

where $z = \sqrt{1-x^2-y^2}$. The term $w\,z$ can be made zero by adding the right time delay between the antennae. This equation reduces to a Fourier Transform relationship between $I(x,y)$ and $V(u,v)$, for small x and y.

Notice the λ dividing in the exponent. If u and v are given in units of λ, the exponent becomes $-2\pi j(u\,x+v\,y)$, i.e. the *exact* definition of Fourier transform.

The Full Interferometer Equation

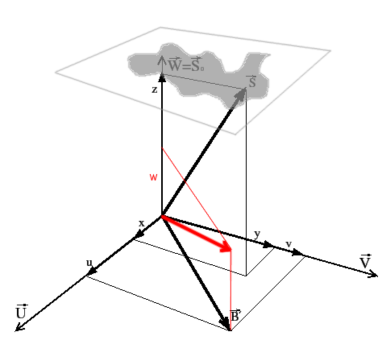


$$V(u,v,w) = \int_{x,y} I_\nu(x,y)\, e^{-\frac{2\pi j}{\lambda}(u\,x+v\,y+w\,z)}\, \frac{dx\,dy}{z}$$

where $z = \sqrt{1-x^2-y^2}$. The term $w\,z$ can be made zero by adding the right time delay between the antennae. This equation reduces to a Fourier Transform relationship between $I(x,y)$ and $V(u,v)$, for small x and y.

Notice the λ dividing in the exponent. If u and v are given in units of λ, the exponent becomes $-2\pi j(u\,x + v\,y)$, i.e. the *exact* definition of Fourier transform.

The Full Interferometer Equation



$$V(u,v,w) = \int_{x,y} I_\nu(x,y)\, e^{-\frac{2\pi j}{\lambda}(u\,x+v\,y+w\,z)}\, \frac{dx\,dy}{z}$$

where $z = \sqrt{1-x^2-y^2}$. The term $w\,z$ can be made zero by adding the right time delay between the antennae. This equation reduces to a Fourier Transform relationship between $I(x,y)$ and $V(u,v)$, for small x and y.

Notice the λ dividing in the exponent. If u and v are given in units of λ, the exponent becomes $-2\pi\, j(u\,x+v\,y)$, i.e. the *exact* definition of Fourier transform.

The two-element interferometer. Summary

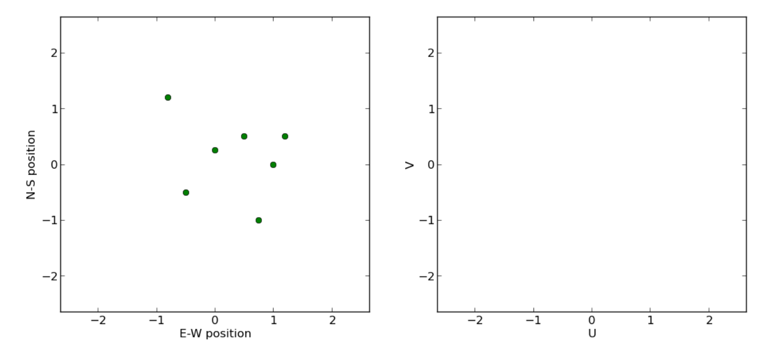
- Diffraction limit is one of the main limitations of optical devices. It is specially important at long wavelengths, where extremely large apertures are needed for a reasonable angular resolution.
- The cross-spectrum between the signals of two telescopes (observing the same source) is directly related to the Fourier transform of the source structure, computed at the point of Fourier space given by the baseline projection of the telescopes into the UV plane (i.e., the plane perpendicular to the source direction).
- This result will allow us to synthesize large apertures through interferometric observations (see next lecture).

Aperture Synthesis

Multi-element interferometers I:

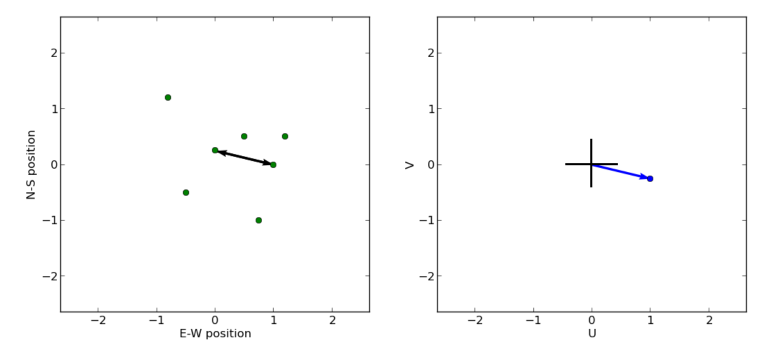
Snapshot observations

The UV plane



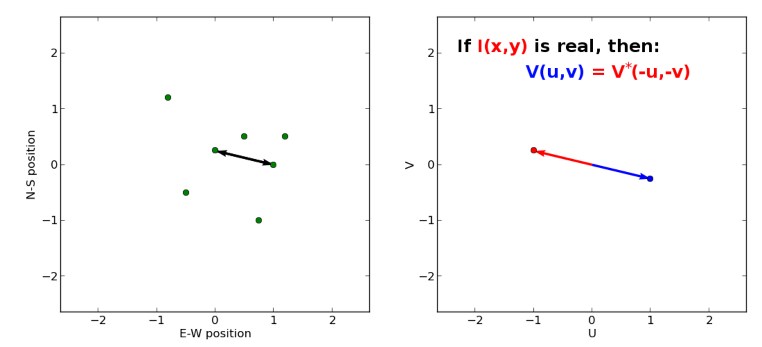
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



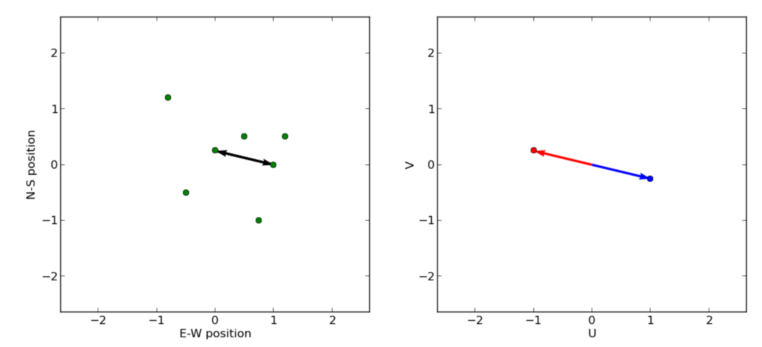
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



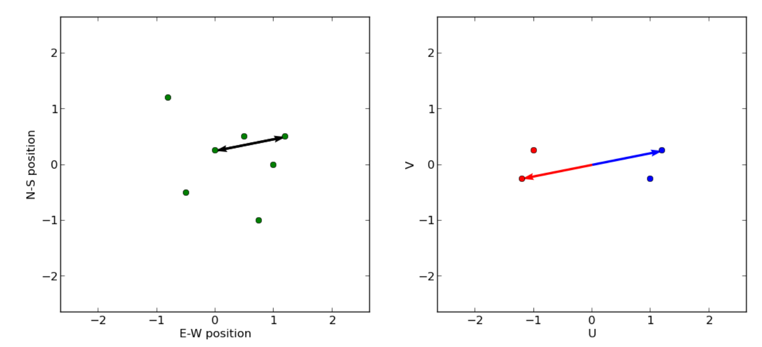
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



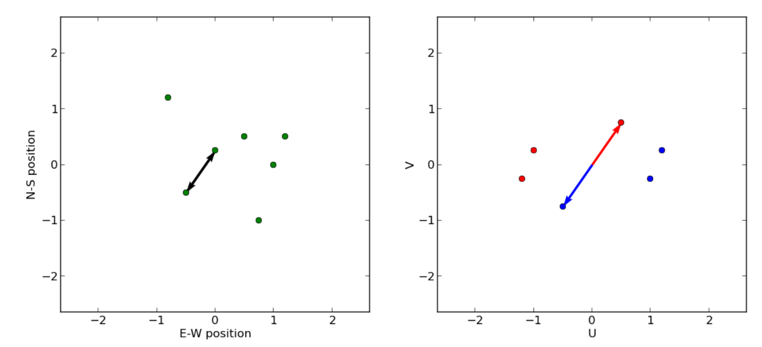
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



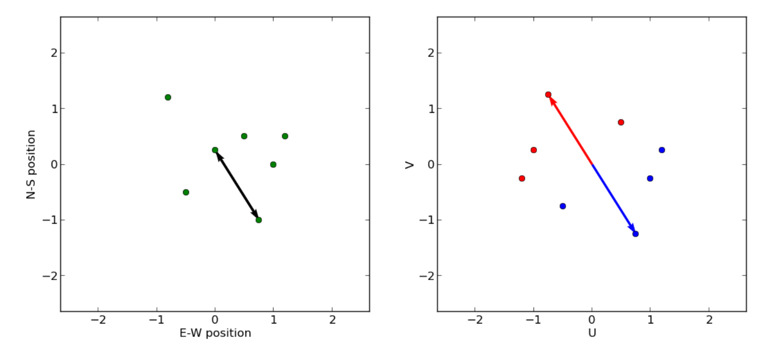
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



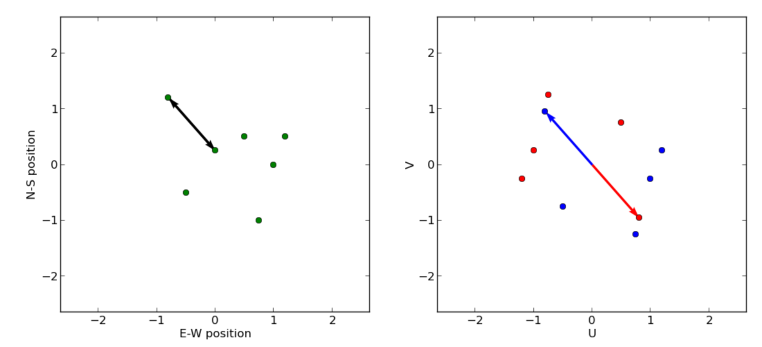
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



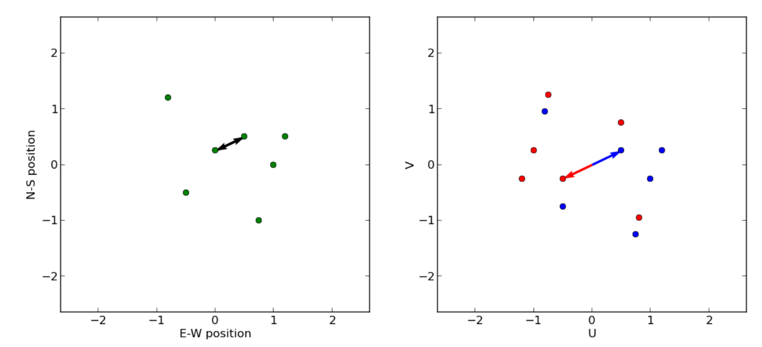
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



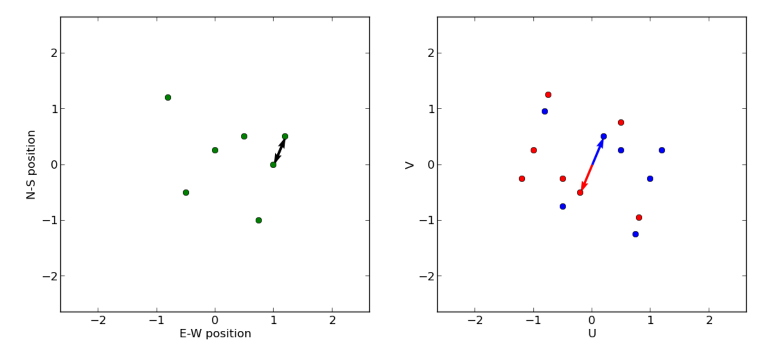
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



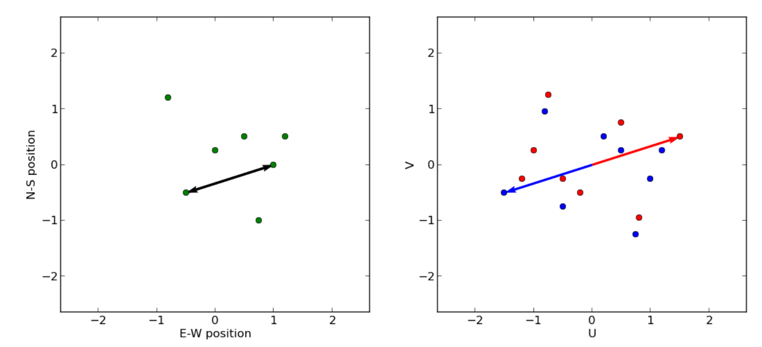
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



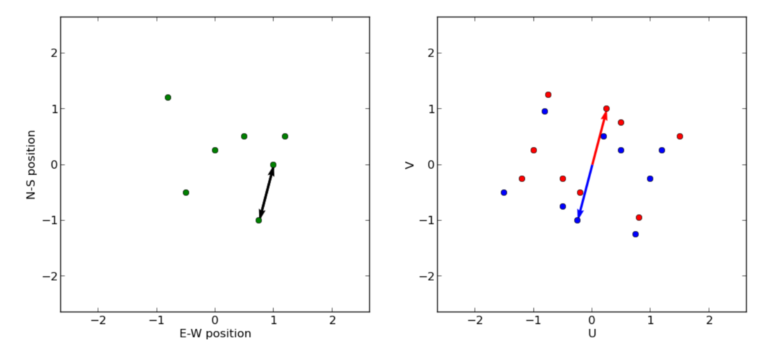
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



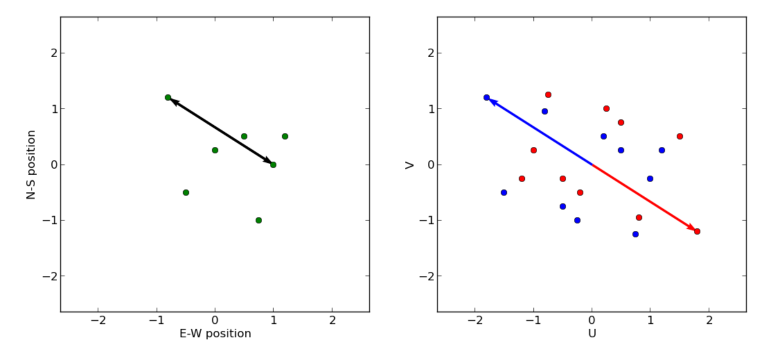
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



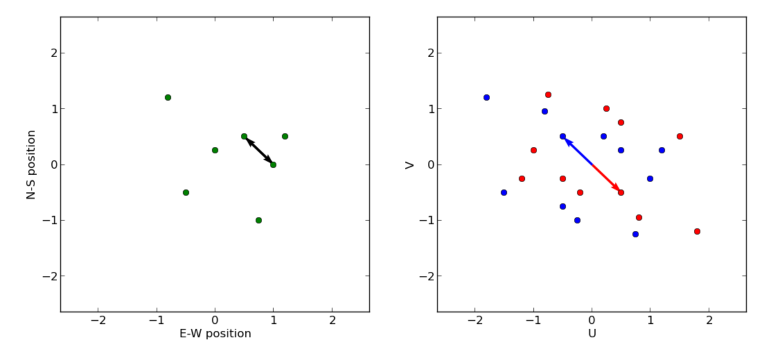
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



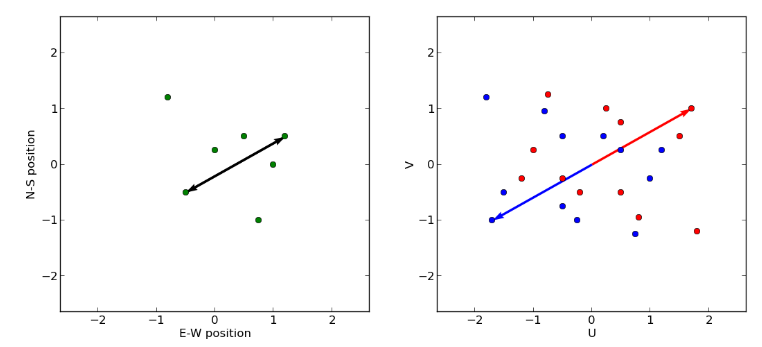
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



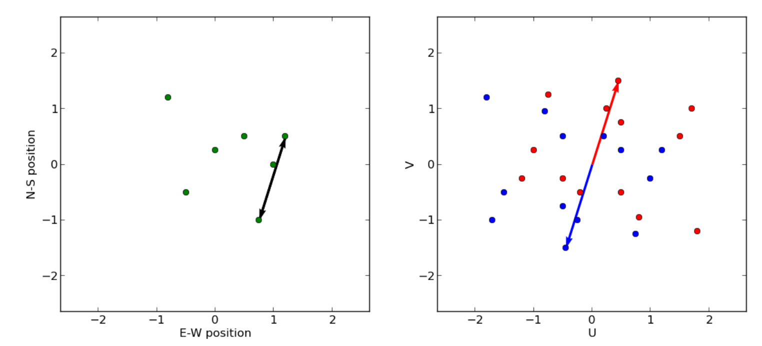
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



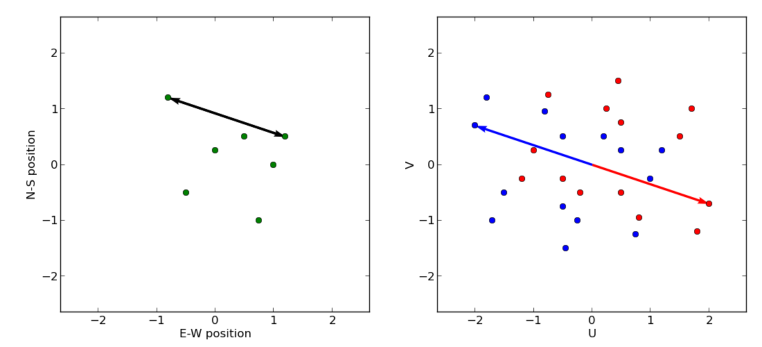
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



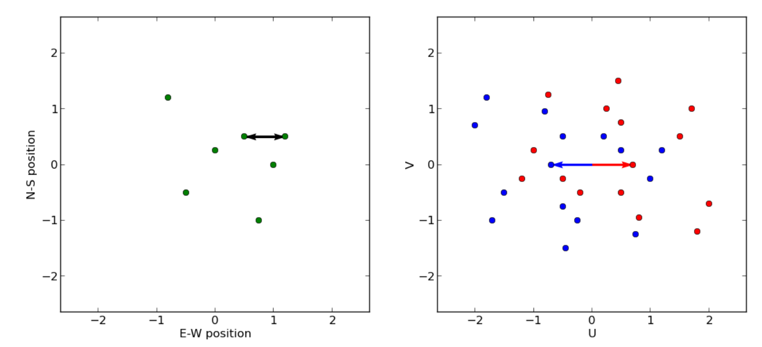
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



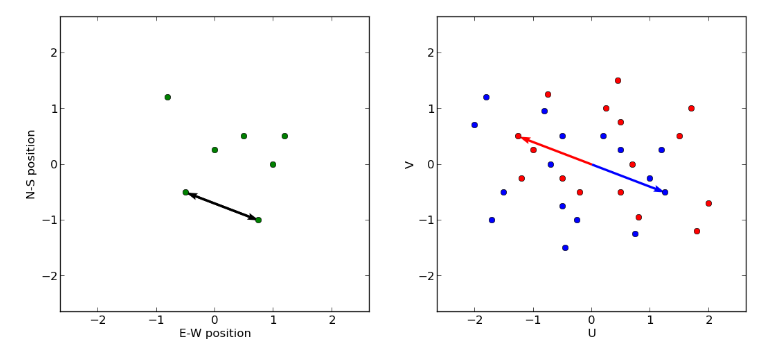
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



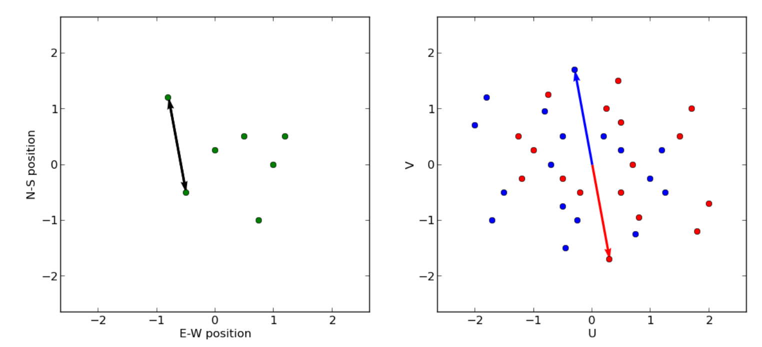
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



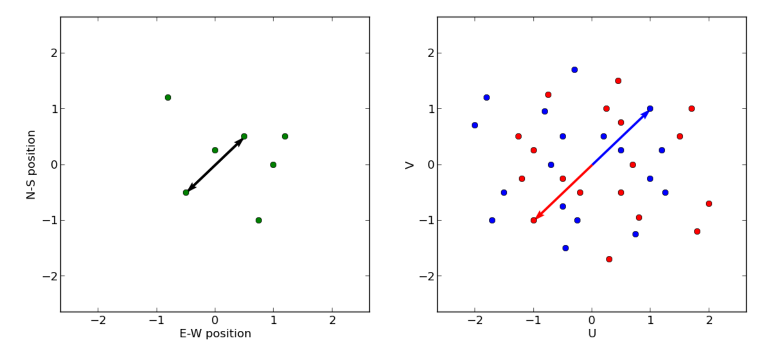
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



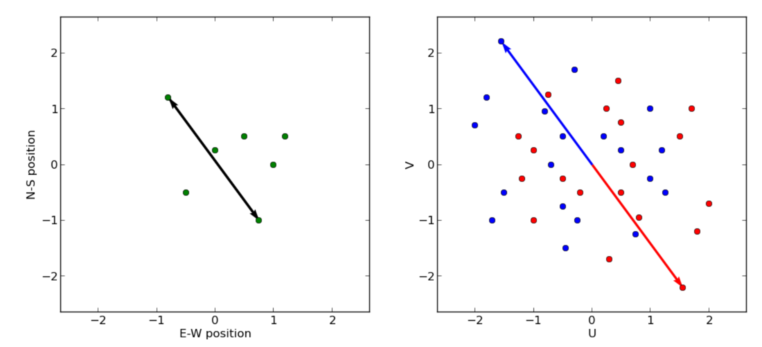
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



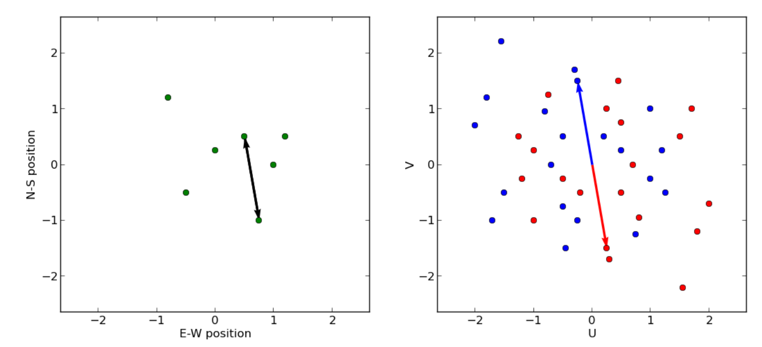
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



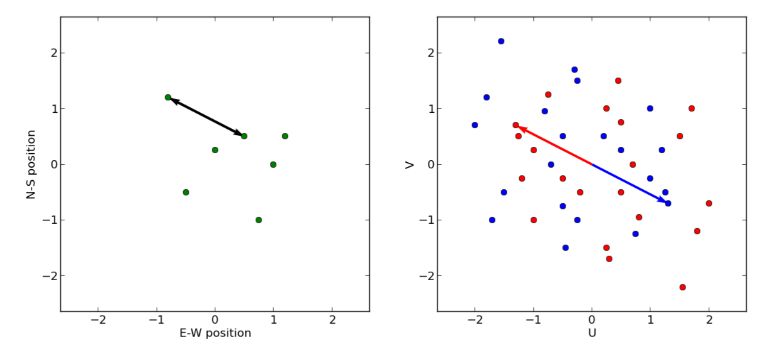
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



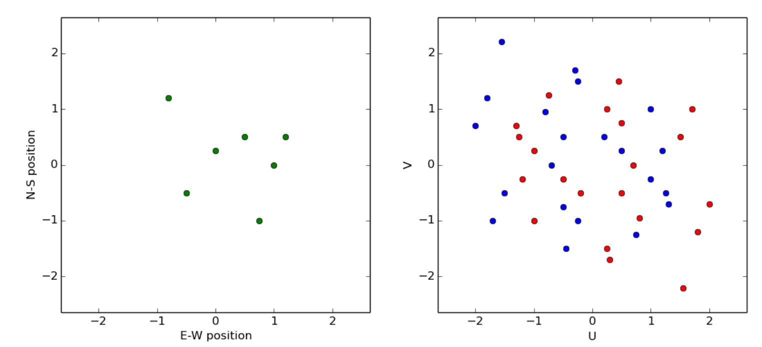
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



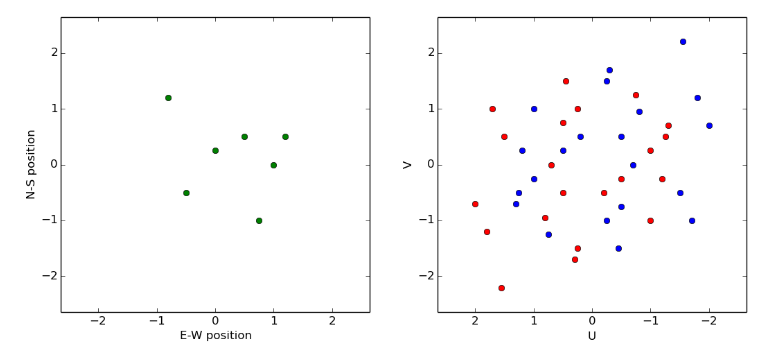
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

The UV plane



Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

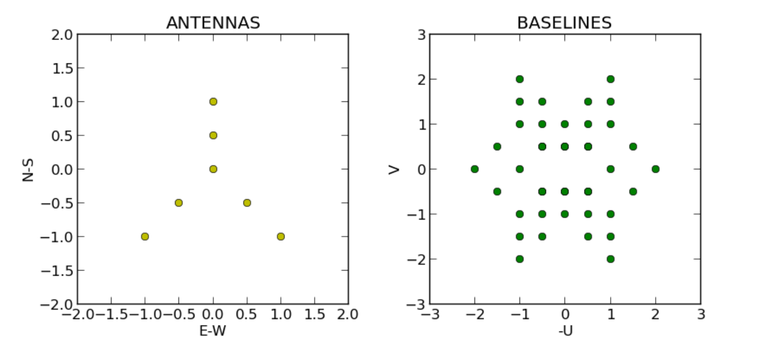
The UV plane



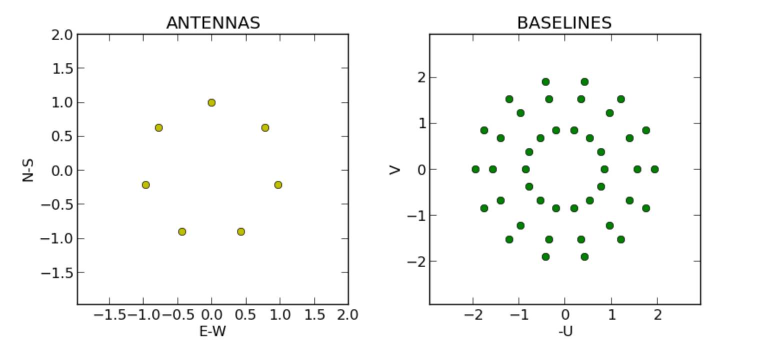
Each pair of telescopes is separated by its baseline vector. The measured visibility is the Fourier transform of the source structure measured at the points of the UV plane given by the baseline. A multi-element interferometer is, hence, just a set of many two-element interferometers!

BEWARE! The U axis must point to East (like the Right Ascension!)

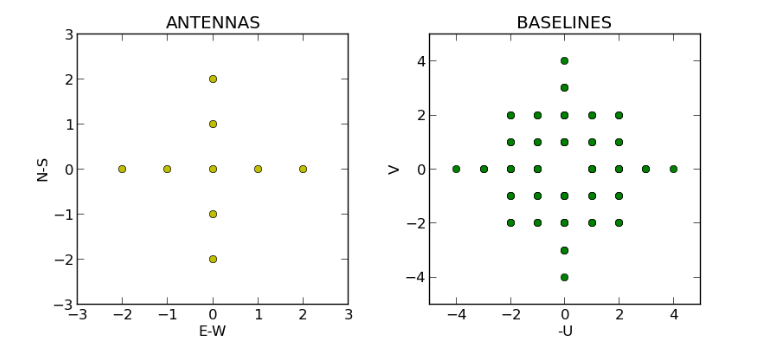
The UV coverage



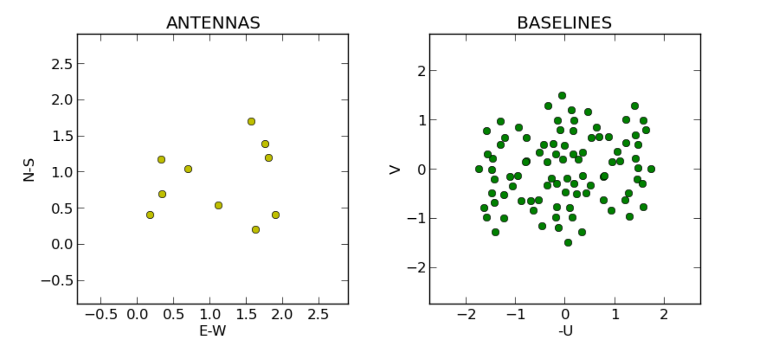
The UV coverage



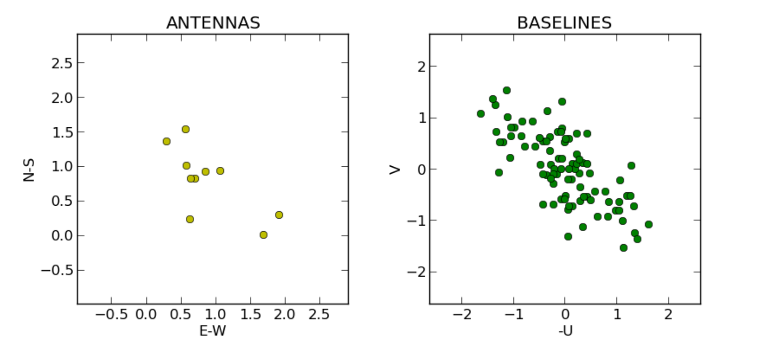
The UV coverage



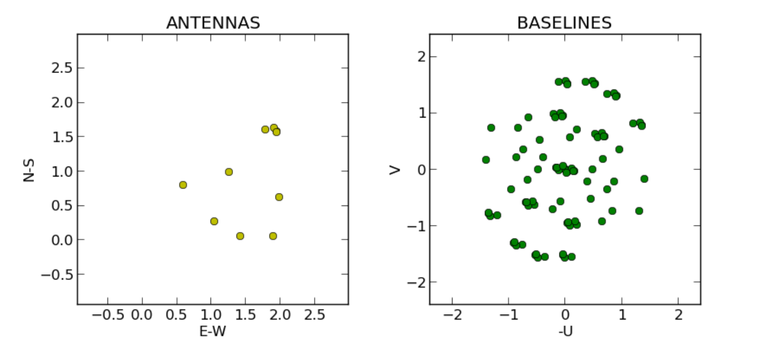
The UV coverage



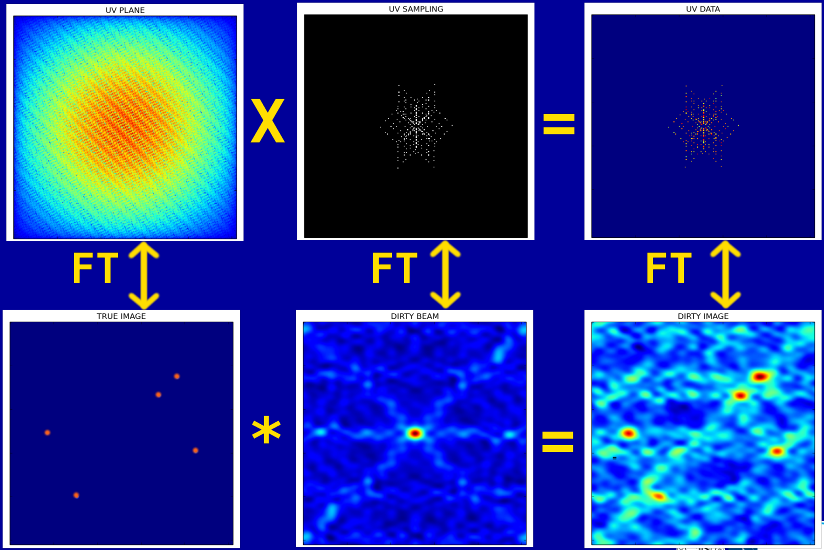
The UV coverage



The UV coverage

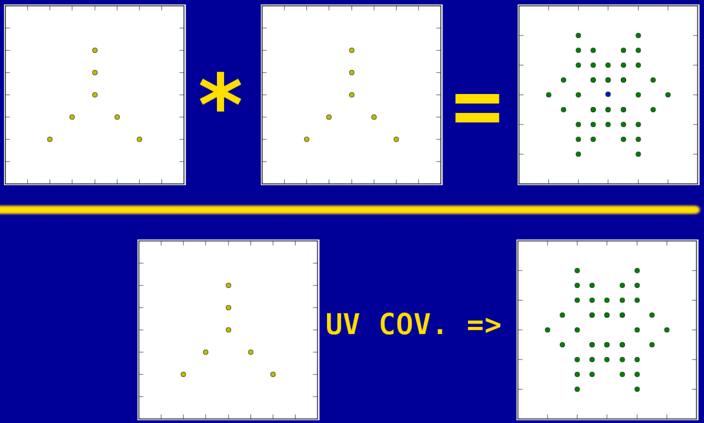


Synthesizing aperture. UV-coverage and PSF.



Synthesizing aperture. UV-coverage and array.

The UV coverage in a snapshot is equal to the autocorrelation of the array configuration as seen by the source (but removing the zero-spacing term)



Synthesizing aperture.
The interferometer seen as a single telescope

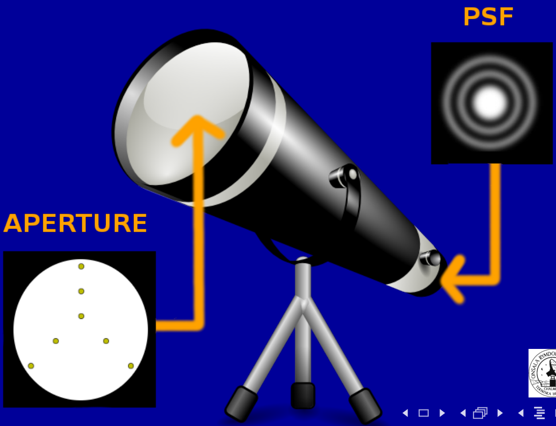
$$\mathrm{PSF} = \mathcal{F}(\mathrm{APERTURE} * \mathrm{APERTURE})$$

Synthesizing aperture. The interferometer seen as a single telescope

$\mathrm{PSF} = \mathcal{F}(\mathrm{APERTURE} * \mathrm{APERTURE})$

Aperture → Antenna distribution! Aperture autocorr. → UV Coverage!

PSF → PSF of interferometer!

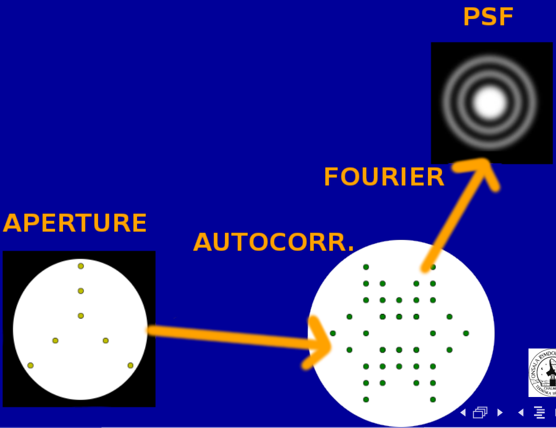


Synthesizing aperture.
The interferometer seen as a single telescope

$\mathrm{PSF} = \mathcal{F}(\mathrm{APERTURE} * \mathrm{APERTURE})$

Aperture $\rightarrow$ Antenna distribution! Aperture autocorr. $\rightarrow$ UV Coverage!

PSF $\rightarrow$ PSF of interferometer!

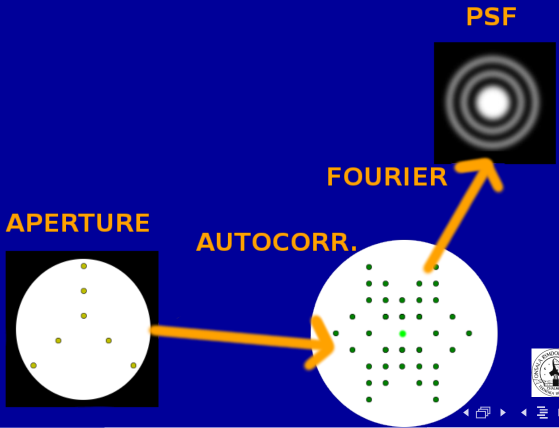


Synthesizing aperture.
The interferometer seen as a single telescope

$\mathrm{PSF} = \mathcal{F}(\mathrm{APERTURE} * \mathrm{APERTURE})$

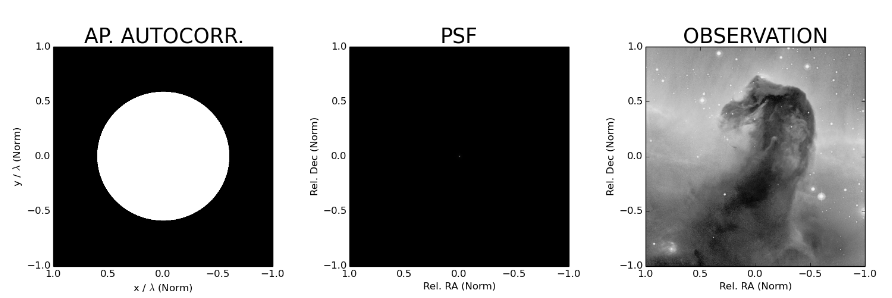
Aperture → Antenna distribution! Aperture autocorr. → UV Coverage!

PSF → PSF of interferometer! BUT BEWARE of the zero-spacing point!

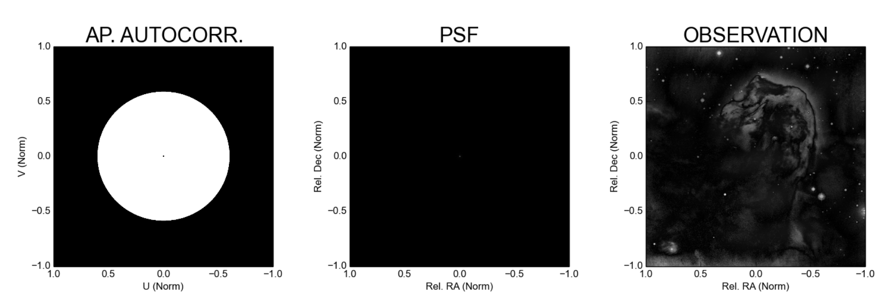


Synthesizing aperture.

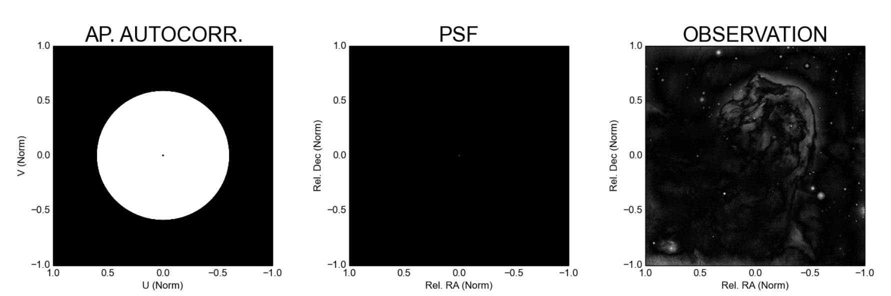
The zero-spacing hole



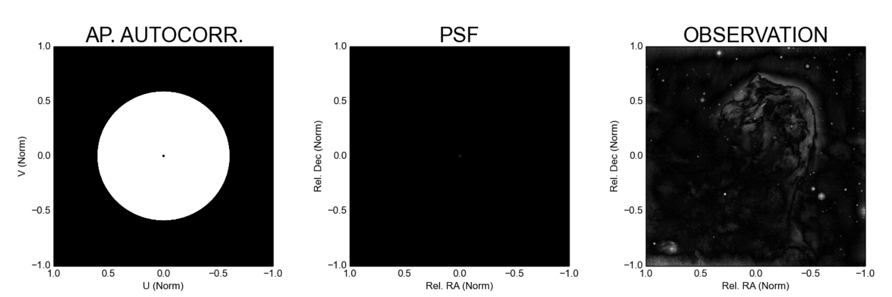
The zero-spacing hole



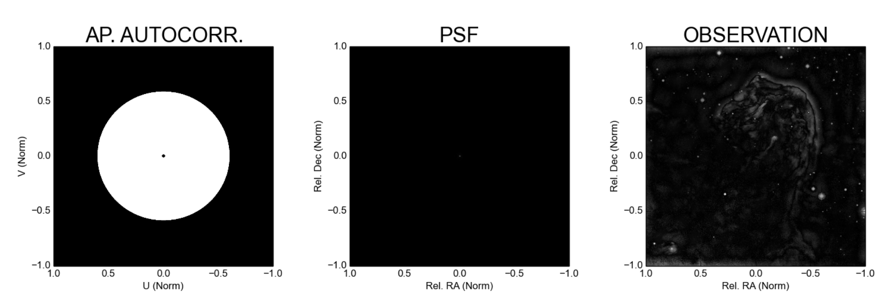
The zero-spacing hole



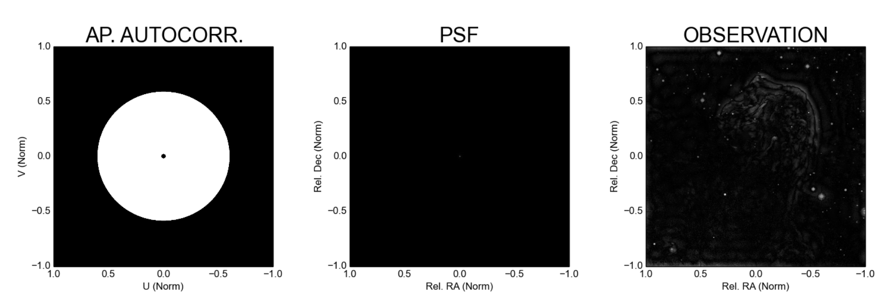
The zero-spacing hole



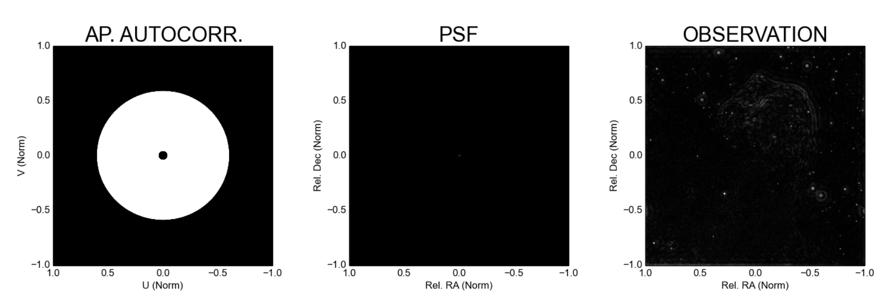
The zero-spacing hole



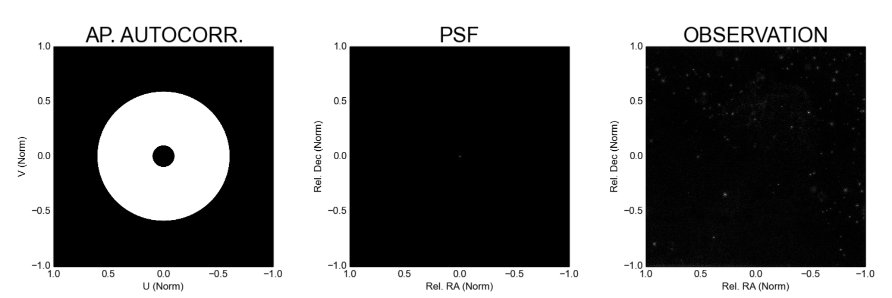
The zero-spacing hole



The zero-spacing hole



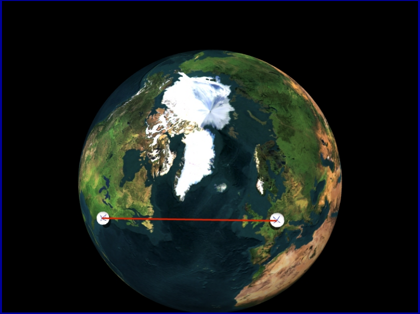
The zero-spacing hole

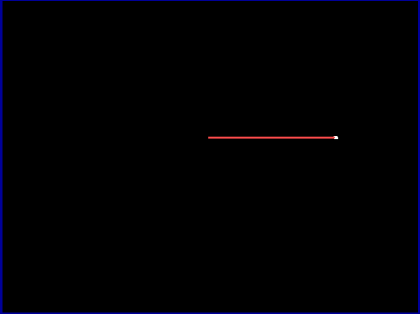


Multi-element interferometers II:

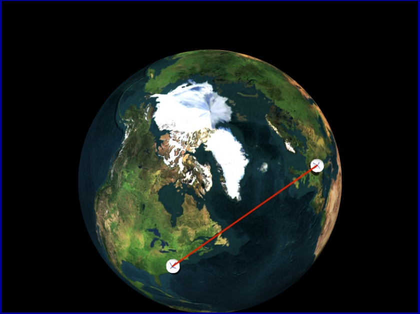
Earth rotation

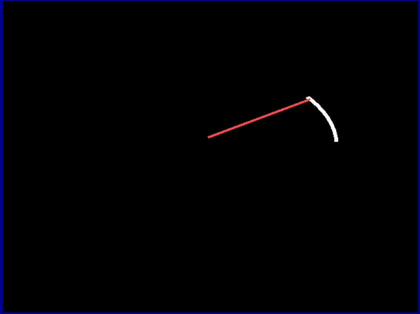
Aperture Synthesis



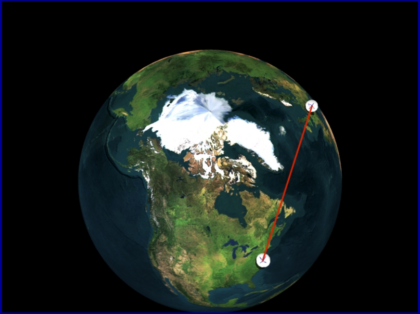


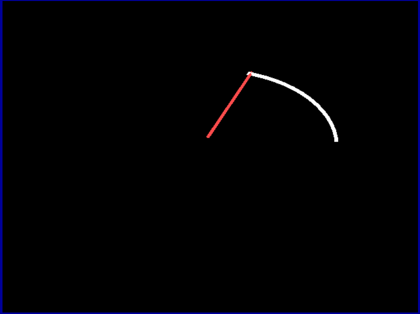
Aperture Synthesis



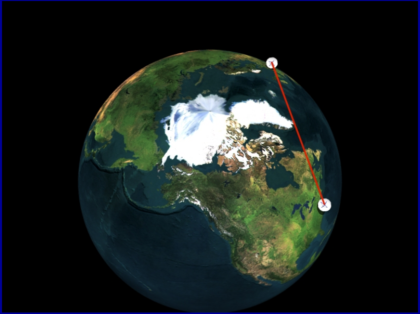


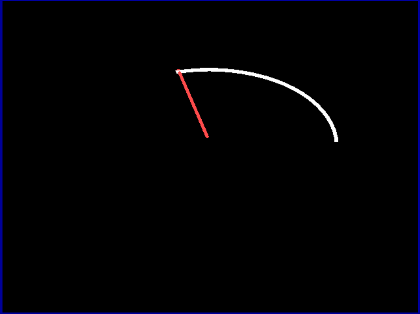
Aperture Synthesis



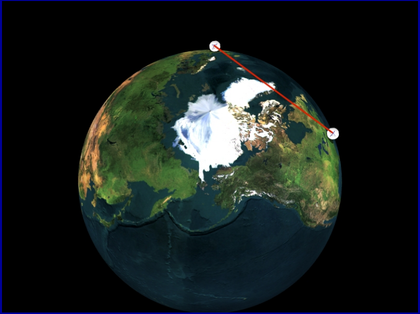


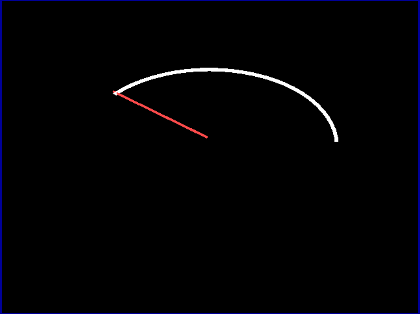
Aperture Synthesis



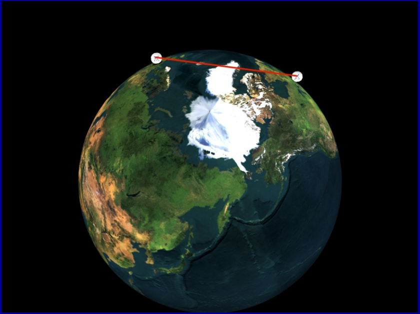


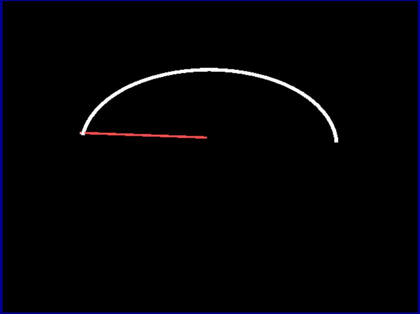
Aperture Synthesis



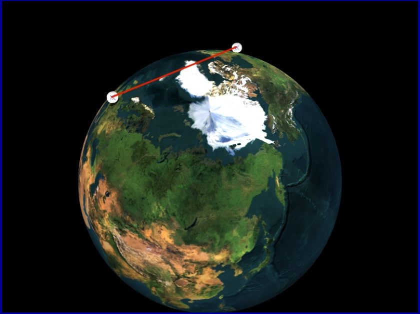


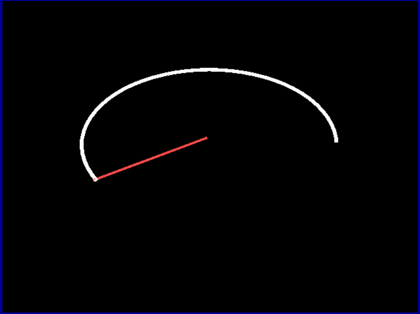
Aperture Synthesis



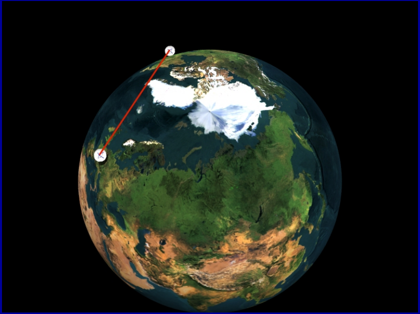


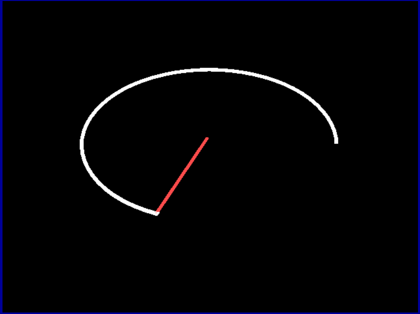
Aperture Synthesis



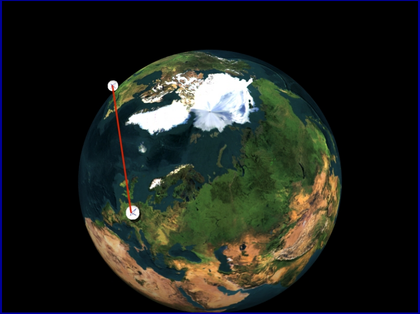


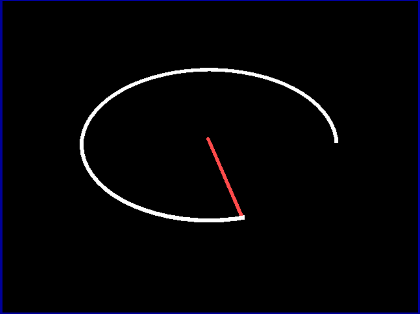
Aperture Synthesis



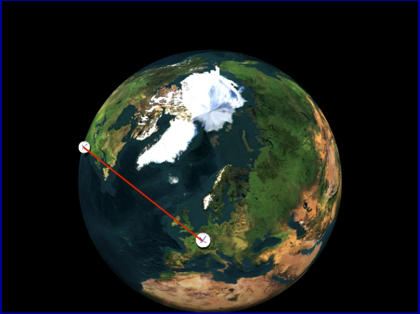


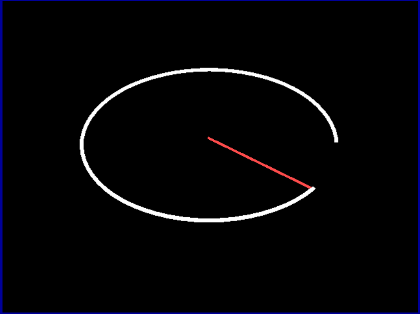
Aperture Synthesis



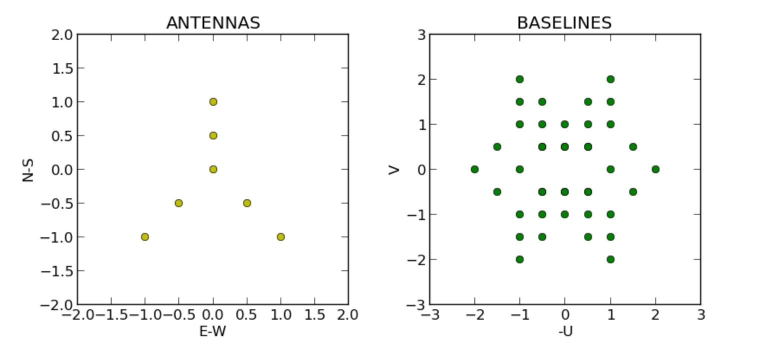


Aperture Synthesis

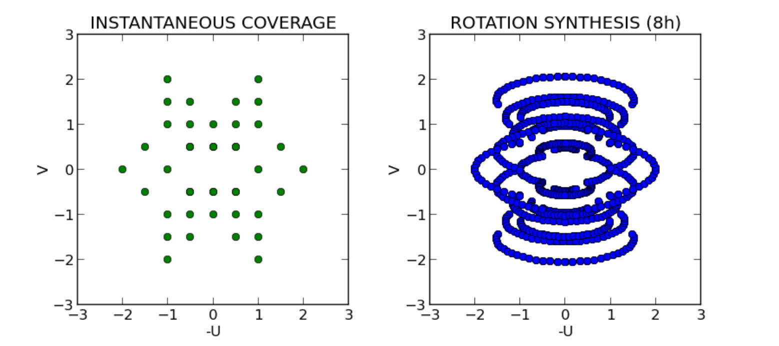




Aperture Synthesis

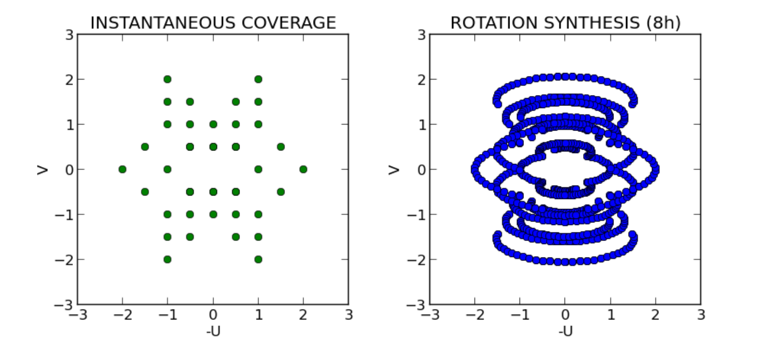


Aperture Synthesis



When the Earth rotates, the positions of the telescopes change as seen from the source. We can use the Earth rotation to *synthesize* UV coverage (a.k.a. aperture)!

Aperture Synthesis

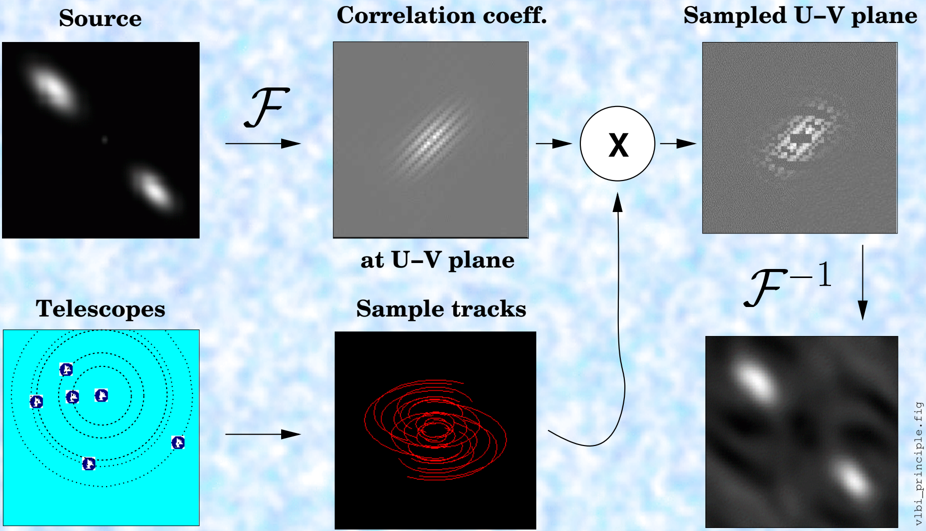


However, there will always be *holes* in the UV plane with no observations. These holes will limit the quality and fidelity of our images: contrast (a.k.a. dynamic-range) limit.

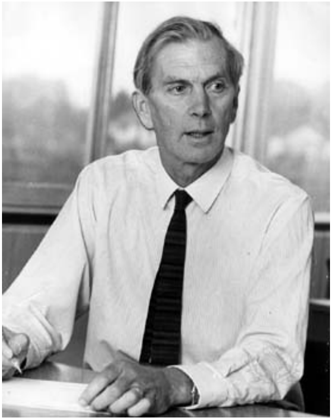
Summary

- An interferometer made of many elements (antennas) can be understood as a set of many two-element interferometers (as many as antenna pairs can be formed).
- The different antenna pairs sample different points of the UV plane.
- The Earth rotation changes the baseline projections into the source plane, hence synthesizing a more complete sampling of the UV plane (UV coverage).
- There are, however, remaining holes in the UV plane with no observations, and this will limit the quality and fidelity of our images (dynamic-range limit).
- Special care must be taken with the hole at the center of the UV plane, since it limits our sensitivity to extended structures.

VLBI (Very Long Baseline Interferometry)



How it all begun (here and there)



Sir Martin Ryle (1918 - 1984) (G3CY)

Jorma J. Riihimaa (1933 - 2011) (OH2PX,OH8PX)

A new radio interferometer and its application to the observation of weak radio stars

By M. Ryle

(*Communicated by Sir Lawrence Bragg, F.R.S.—Received* 19 *June* 1951—*Revised* 10 *October* 1951)

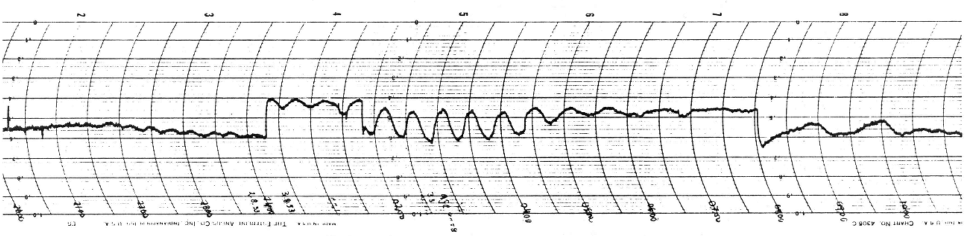
A new type of radio interferometer has been developed which has a number of important advantages over earlier systems. Its use enables the radiation from a weak 'point' source such as a radio star to be recorded independently of the radiation of much greater intensity from an extended source. It is therefore possible to use a very much greater recorder sensitivity than with earlier methods. It is, in addition, possible to use pre-amplifiers at the aerials, and the resolving power which may be used is therefore not restricted by attenuation in the aerial cables.

Besides improved sensitivity, the new system has a number of other advantages, particularly for the accurate determination of the position of a radio source. Unlike earlier systems the accuracy of position finding is not seriously affected by rapid variations in the intensity of the radiation. It also has important applications to the measurement of the angular diameter and polarization of a weak source of radiation.

The new system has been used on wave-lengths of 1·4, 3·7, 6·7 and 8 m for the detection and accurate location of radio stars, and for the investigation of the scintillation of radio stars. It has also been used in a number of special experiments on the radiation from the sun. The results which have been obtained in these experiments have confirmed the advantages predicted analytically.

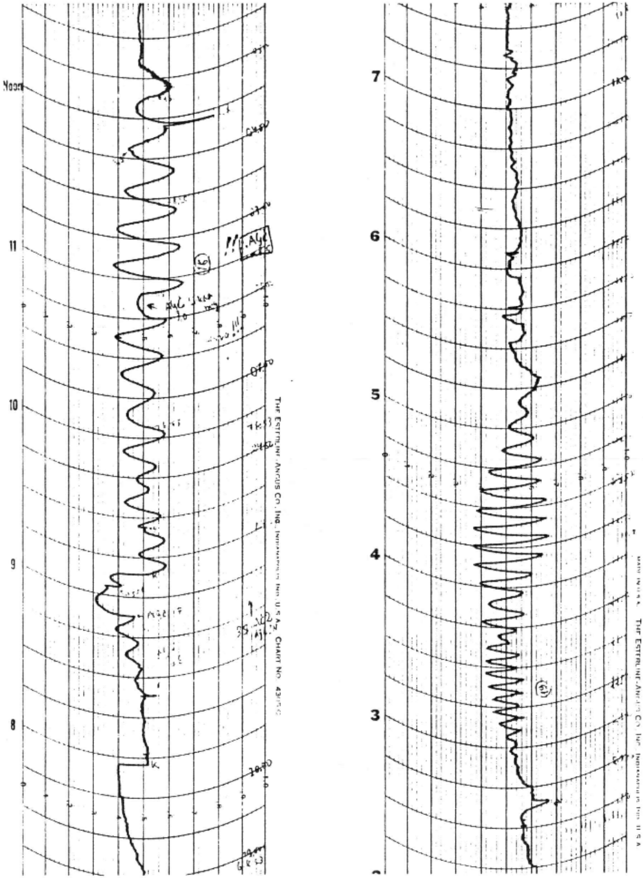
K.39. Teekkari J.J. Riihimaa etuvahvistinta virittämässä.

K. 36. "Jätepuuantenni". Toinen kahdesta neljän kokoaaltodipolin ryhmästä Viikin koetilan alueella. Taustalla "työnjohtajan koppi". (Heinäkuu 1953)



1953

K.43. Ensimmäinen rekisteröinti Cass A:n ohikulusta
2-3.8.1953. (81.5 MHz)



K.44. Kojeiston parantelua. Oikealla näkyvät Cyg A:n ja Cass A:n perättäiset ohikulut (pienemmällä rek.pap. nopeudella).

Interferometry in Finland

- First fringes by Riihimaa in 1953
- 1973 Riihimaa started decametric observations with a two-LPDA interferometer in Oulu
- 1979 First tests in Metsähovi with 13.7m telescope at 5 GHz
- 1991 First observations at 22 GHz with Finnish-built equipment
- 1995 First mm-VLBI at 86 GHz
- 2001 First 2mm (150 GHz) observations
- Fast development of eVLBI (`www.metsahovi.fi`)

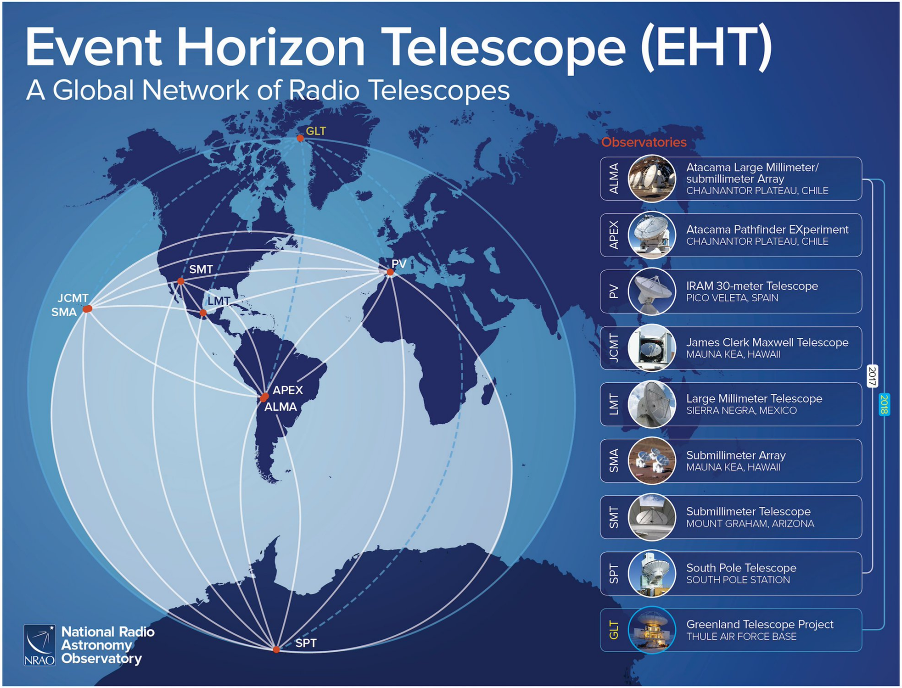
e- VLBI:

connecting remote telescopes in real- time

Huib Jan van Langevelde

Joint Institute for VLBI in Europe

Sterrewacht Leiden


Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes
GLT
SMT
PV
JCMT
SMA
LMT
APEX
ALMA
SPT
Observatories
ALMA
Atacama Large Millimeter/ submillimeter Array
CHAJNANTOR PLATEAU, CHILE
APEX
Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE
PV
IRAM 30-meter Telescope
PICO VELETA, SPAIN
JCMT
James Clerk Maxwell Telescope
MAUNA KEA, HAWAII
LMT
Large Millimeter Telescope
SIERRA NEGRA, MEXICO
SMA
Submillimeter Array
MAUNA KEA, HAWAII
SMT
Submillimeter Telescope
MOUNT GRAHAM, ARIZONA
SPT
South Pole Telescope
SOUTH POLE STATION
GLT
Greenland Telescope Project
THULE AIR FORCE BASE
2017
2018
National Radio Astronomy Observatory
NRAO