Interferometry at different wavelengths: from radio to Cherenkov telescopes

Seminar of Experimental Techniques

Carolin Wunderlich

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Istituto Nazionale di Fisica Nucleare

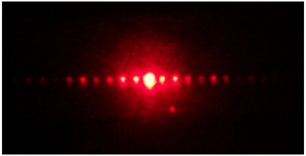
Università di Siena 1240

Overview

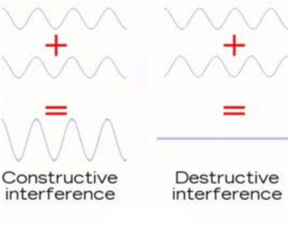
Introduction to interferometry

Principle of classical interference

A light beam is split into two or more beams, which take different paths and are then reunited and form a interference pattern.



https://www.researchgate.net/figure/Interference-pattern-produced-by-a-red-laser-light-traveling-through-a-Moire-grating_fig4_261382522



https://www.researchgate.net/figure/Constructive-and-Destructive-Interference-in-Wave-Patterns-Schematic-Woodford-C_fig76_343391907

Normalized first-order correlation function

Correlation between electromagnetic fields at two different locations $\vec{r_1}$, $\vec{r_1}$ and two different times t_1, t_2:

$$g^{(1)}(\vec{r_1}, t_1, \vec{r_2}, t_2) = \frac{\langle E^*(\vec{r_1}, t_1) E(\vec{r_2}, t_2) \rangle}{\left[\langle |E(\vec{r_1}, t_1)|^2 \rangle \langle |E(\vec{r_2}, t_2)|^2 \rangle \right]^{1/2}} \quad (1)$$

- Typical interferometers explore the first order correlation function $g^{(1)}$
- Coherent light: $|g^{(1)}|$ = 1
- Incoherent light $|g^{(1)}|$ = 0

Temporal coherence

$\vec{r_1} = \vec{r_1}$ and $t_1 \neq t_2$:

- average correlation between the value of the wave and itself delayed by τ
- **Weiner-Khinchin theorem:** The normalised value of the **temporal coherence function** is **equal to the Fourier transform** of the normalised **spectral energy distribution** of the source.

Spatial coherence

$\vec{r_1} \neq \vec{r_1}$ and $t_1 = t_2$:

- average correlation at different locations
- **Van Cittert-Zernike theorem:** For sources in the far field the normalized value of the **spatial coherence function** is **equal to the Fourier transform** of the normalised **sky brightness distribution**.

Visibility (fringe contrast)

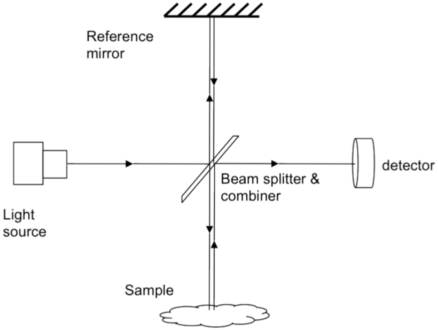
$$V = \frac{I_{min} - I_{max}}{I_{min} + I_{max}} = |g^{(1)}(\vec{r_1}, t_1, \vec{r_2}, t_2)|$$

Key elements of astronomical interferometry:

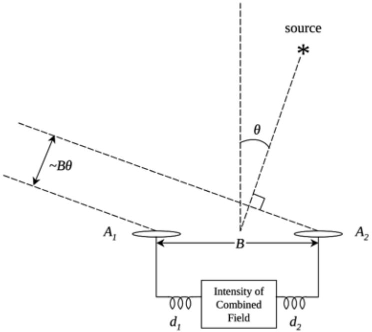
- Brightness distribution of a source can be represented as a Fourier decomposition
- Exploitation of the van Cittert-Zernike theorem
- Measurements at different sample points → visibility function at different baselines

Michelson Interferometer:

- An incident light beam is split by a beam splitter into two partial beams.
- The beams propagate along the interferometer arms and are reflected by the mirror/sample
- The are reunited by the combiner; after that they enter the observing telescope
- Interference vanishes when the arm difference exceeds the coherence length



https://www.researchgate.net/figure/Schematic-of-Michelson-Interferometer_fig2_258666630

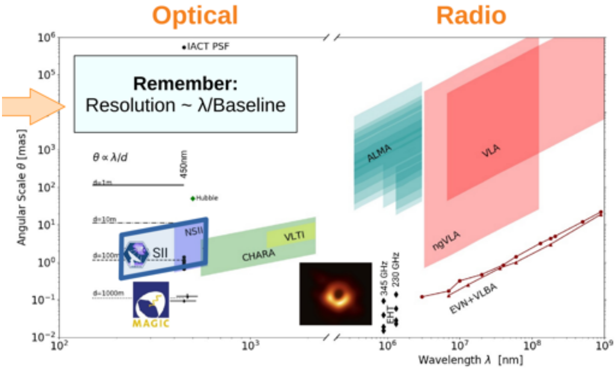


Frank Rotondo. "Imaging with Amplitude and Intensity Interferometers". In: (June 2004),p. 14.

Astronomical interferometer:

- A set of collectors, A_1 and A_2 to sample radiation from source
- Distance between collectors is baseline B
- Transport system for radiation to laboratory (optical path d_1 and d_2)
- Device to combine electric fields sampled by the collectors.
- Detector to sample combined fields.

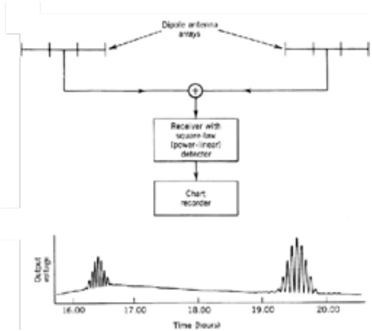
Radio interferometry



MAGIC Collaboration Meeting June 2021, Tarek Hassan

Brief history of radio interferometry:

- Michelson-Pease stellar interferometer in 1921
- First astronomical observation by a radio interferometer in 1946 by Ryle and Vonberg



Anthony Thompson, James Moran, and George Swenson Jr. Interferometry and Synthesis in Radio Astronomy. Vol. -1. Jan. 1991. ISBN : 978-3-319-44429-1. DOI :10.1007/978-3-319-44431-4.

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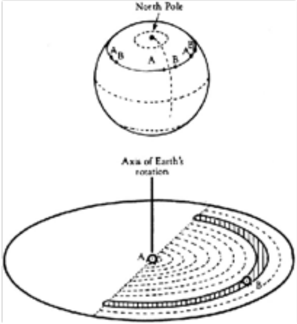

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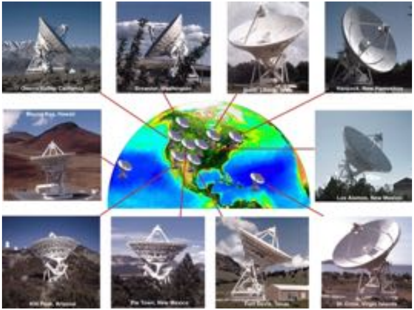
- Very-long-baseline interferometry (VLBI)



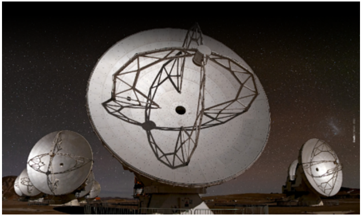
https://astronomy.swin.edu.au/cosmos/v/Very+Long+Baseline+Array

Atacama Large Millimeter/submillimeter Array (ALMA)

- Currently largest radio telescope in the world on the Chajnantor Plateau in the Atacama Desert in Chile since 2004
- 66 antennas: fifty-four 12-meter diameter antennas and twelve 7-meter diameter antennas
- Antennas can be moved between different pads (150 m - 16 km)

https://www.almaobservatory.org/en/outreach/downloads/

Structure of ALMA



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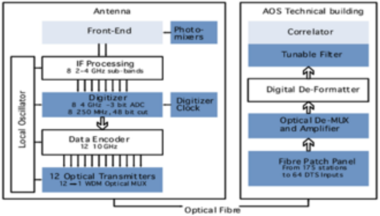


https://www.almaobservatory.org/en/about-alma/how-alma-works/technologies/optic-fiber-1000-km/

Receiver:

- Three-stage cryo-refrigator
- 10 frequency bands from 8.6 mm - 0.32 mm wavelength
- Water vapor radiometer

Optic fiber:

- 192 antenna pads
- two local oscillators for each antenna
- antenna pads and correlator connected by optic fiber

Correlator:

- Installed in AOS Technical Building
- Process data from up to 504 antenna pairs

Optical/IR interferometry

Interferometer design

Relay optics:

- After light collection, light must be transported from telescope to central beam combining
- If propagating in air, significant dispersion
- High reflectivity needed

Delay line:

- movable delay line to compensate for changing geometrical delay

Fringe tracking

- white-light fringe is actively tracked

Very Large Telescope Interferometer (VLTI)

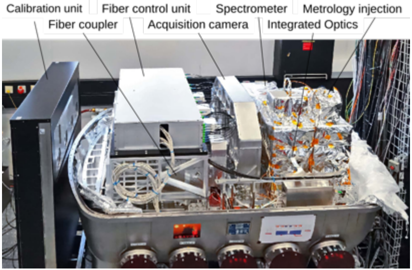
- Four Unit Telescopes (UT) with main mirrors of 8.2 m diameter and four movable 1.8 m diameter Auxiliary Telescopes (AT) at ESO's Paranal Observatory, Chile
- At present baselines up top 140 meters
- Light from different telescopes is combined by using a complex system of mirrors in underground tunnels

https://www.eso.org/public/images/_DSC7227-CC/

GRAVITY

- second-generation instrument of VLTI observing since 2016
- Combines light of four VLT telescopes
- Can be operated as two interferometers: one observes bright star, second observe object with long exposure time

https://www.eso.org/public/images/gravity-cc/



Gravity Collaboration. "First light for GRAVITY: Phase referencing optical interferometry for the Very Large Telescope Interferometer". In: 602, A94 (June 2017), A94. DOI :10.1051/0004-6361/201730838. arXiv: 1705.02345 [astro-ph.IM].

Intensity Interferometry

Amplitude interferometry

- first-order measurement
- correlation between electromagnetic fields in two different locations

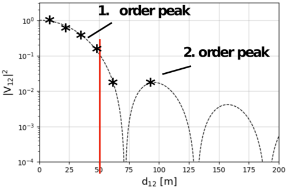
$\Longleftrightarrow$

Intensity interferometry

- second-order measurement
- correlation between pairs of point sources
- exploit correlation and anti-correlation effects in intensity (Hanbury Brown and Twiss effect)

Observed interference pattern can be described by visibility:

$$g^{(2)} = 1 + |g^{(1)}|^2 = \frac{< I_1 \cdot I_2 >}{< I_1 > \cdot < I_2 >}$$



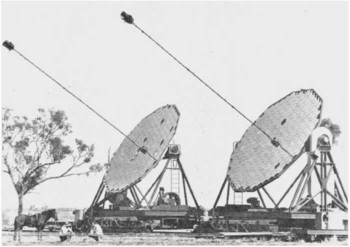
MAGIC Collaboration Meeting June 2021, Thomas Schweizer

Intensity Interferometer

- Correlation does not depend on the phase difference of the light → less stringent requirements on mechanics and optics
- Poor sensitivity (second order effect) → need of large light collectors

Narrabi intensity interferometer:

- First optical intensity interferometer in 1963 in Narrabi, Australia
- First measurement of star diameter at optical wavelengths
- After first success this technique was abandoned



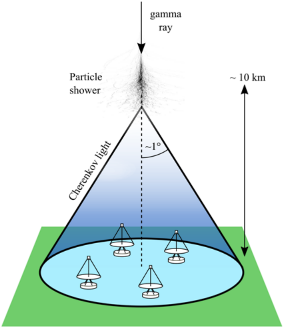
BROWN, R. Stellar Interferometer at Narrabri Observatory. Nature 218, 637–641 (1968)

Large light collectors

less accuracy in controlling optical path

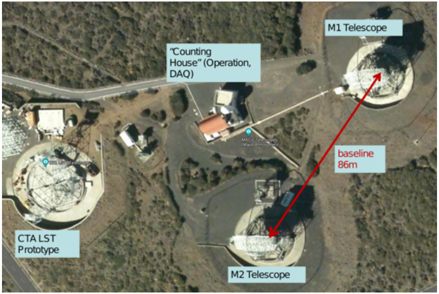
atmospheric turbulence/some background ok

- Use Imaging Atmospheric Cherenkov Telescopes (IACT) for intensity interferometers
- Actually to detect Cherenkov light emitted by particle showers
- Cherenkov telescopes have huge light collectors
- Interferometry observation can be done during full moon periods



MAGIC interferometer:

- Two IACTs with 17 m diameter mirror dishes at the Roque de los Muchachos on La Palma Observatory, Spain
- Two pixels in telescope MAGIC 1 and MAGIC 2
- One pixel to measure nightsky background (moonlight); Star light is focussed to second pixel
- Correlation within a telescope / Zero-baseline correlation



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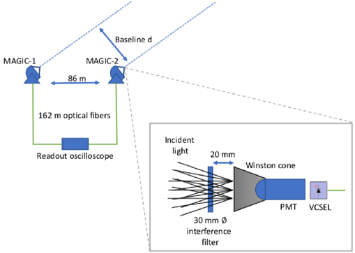
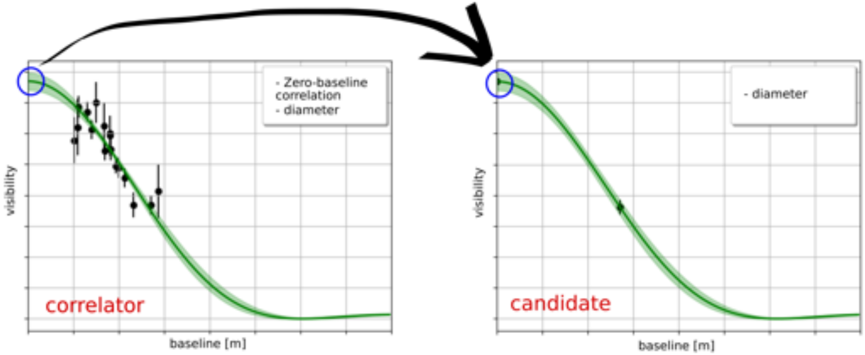


Optical intensity interferometry observations using MAGIC imaging atmospheric Cherenkov telescopes. MAGIC collaboration. 2019

Data analysis - Visibility function



Summary

- Interferometers provide best resolution of all telescope types
- Astronomical interferometry: exploit Van Cittert-Zernike theorem
- Synthesis arrays: array of telescopes work as one giant telescope
- Two kinds of interferometry: amplitude (first order) and intensity interferometry (second order)
- Interferometry in optical regime very challenging (therefore intensity interferometry promising)
- Cherenkov telescope array have potential as optical interferometers

Thank you :D

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Chris Haniff. "An introduction to the theory of interferometry". In: *New Astronomy Reviews* 51.8 (2007). Observation and Data Reduction with the VLT Interferometer, pp. 565–575. ISSN: 1387-6473. DOI: https://doi.org/10.1016/j.newar.2007.06.002. URL: https://www.sciencedirect.com/science/article/pii/S1387647307000619.

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Vakili F. Lai O. et al. Rivet JP. “Optical long baseline intensity interferometry: prospects for stellar physics”. In: *Exp Astron* 46 (2018), 531–542. URL: https://doi.org/10.1007/s10686-018-9595-0.

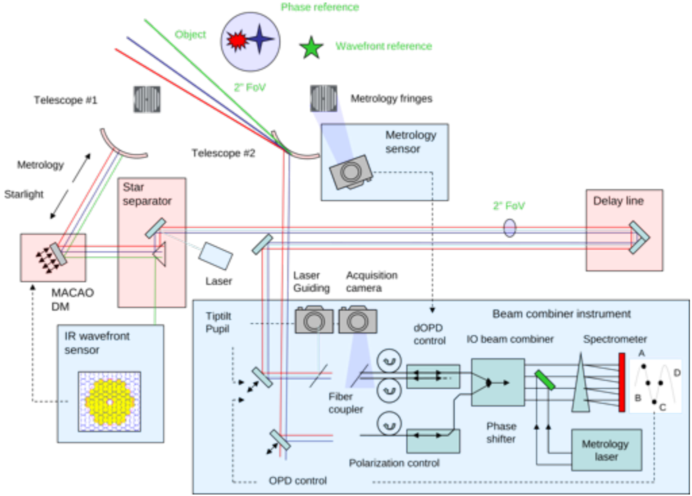
V. A. Acciari et al. “Optical intensity interferometry observations using the MAGIC imaging atmospheric Cherenkov telescopes”. In: *Mon. Not. Roy. Astron. Soc.* 491.2 (2020), pp. 1540–1547. DOI: 10.1093/mnras/stz3171. arXiv: 1911.06029 [astro-ph.IM].

About ALMA. https://www.almaobservatory.org/en/about-alma/origins/. Accessed: 2021-06-15.

GRAVITY. https://www.eso.org/public/teles-instr/paranal-observatory/vlt/vlt-instr/gravity/. Accessed: 2021-12-03.

VLA Basics & Tech. https://public.nrao.edu/telescopes/vla/. Accessed: 2021-06-15.

What is an Interferometer?
https://www.ligo.caltech.edu/page/what-is-interferometer. Accessed: 2021-06-15.



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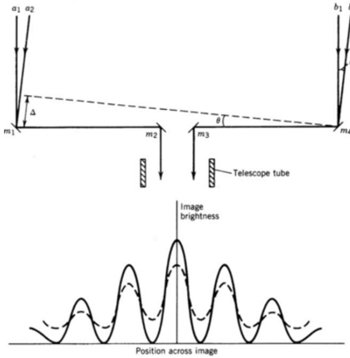

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Interferometric observables

fringe contrast:

$$V = \frac{I_{min} - I_{max}}{I_{min} + I_{max}} = |g^{(1)}(\vec{r_1}, t_1, \vec{r_2}, t_2)| \quad (2)$$

fringe phase:

Position of central fringe with respect to zero optical path difference

Key elements of astronomical interferometry:

- Brightness distribution of a source can be represented as a Fourier decomposition
- Exploitation of the van Cittert-Zernike theorem
- Measurements at different sample points → visibility function at different baselines
- Fourier inversion to recover source brightness distribution

https://public.nrao.edu/telescopes/vla/

Very Large Array (VLA)

- Inaugurated in 1980 in New Mexico, USA
- 28 antennas with 25 m diameter (27 in use)
- antennas arranged in "Y"-shape to have many different and long baselines
- telescopes are on rails

Dave Finley, courtesy NRAO and Associated Universities, Inc.

Receiver:

- Each antenna use 10 receivers depending on wavelength band
- Receivers are supercooled

Array:

- Three times a year telecopes are moved
- Baselines between 1.0-36.4 km

Correlator:

- Incoming radio waves are amplified and digitized
- Data is processed by supercomputer

Interferometer design

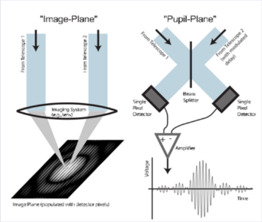
Relay optics:

- After light collection, light must be transported from telescope to central beam combining
- If propagating in air, significant dispersion
- High reflectivity needed

Delay line:

- sidereal motion due to earth's rotation
- movable delay line ro compensate for changing geometrical delay

Beam combination:



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Fringe tracking

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Cherenkov Telescops as Interferometers

MAGIC:

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- Parabolic mirrors
- Active mirror controll

https://www.researchgate.net/figure/A-picture-of-the-two-MAGIC-telescopes-at-the-Roque-de-los-Muchachos-observatory_fig4_228467537

VERITAS:

- Four IACTs with 12 m diameter mirror dishes at the Fred Lawrence Whipple Observatory inn Amado, USA
- Davies Cotton design

https://astro.desy.de/gamma_astronomy/veritas/index_eng.html