Observational Astrophysics
23. Optical Interferometry

Rodolfo Smiljanic
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Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences
ul. Bartycka 18
00-716 Warsaw, PL

E-mail: rsmiljanic@camk.edu.pl
Office: 115

`http://users.camk.edu.pl/rsmiljanic`

1 Introduction

Interferometry is the technique that allows astronomers to measure angular sizes with highest possible resolution by using arrays of telescopes. While the angular resolution of a single telescope of diameter D is limited by its diffraction limit, $\Delta\theta \propto \lambda/D$, the resolution of a combination of telescopes is related to its baseline B, the distance between the telescopes, $\Delta\theta \propto \lambda/B$. By disconnecting the angular resolution from the collecting area, measurements could be improved by a few orders of magnitude. Notice however, that measuring the angular size of a source is different from imaging that source.

Optical interferometry, however, at least from my point of view, remains one of the hardest observing techniques to master and to use effectively. In the context of our lectures, what I can do, in the limited time we have available, is indeed to give only a short and qualitative introduction to the subject and point to additional material where you can find more details.

When I refer to "optical" interferometry here, I do not mean using the visible part of the spectrum only. I mean the extended region from the bluest wavelengths observable from the ground up to the mid-infrared. The spectral region for which photons are detected in similar ways (using incoherent, "photo counting" detectors). This is needed to make a particular distinction with radio interferometry. In radio, light detection is coherent and phase information is saved. This gives the possibility of combining the signal detected by two different dishes later, using a computer. In optical interferometry, because we do not detect the phase, only the power, the beams have to be combined before the signal is detected and recorded.

2 Read these texts

For an introduction (albeit long) to optical interferometry, I recommend reading Chapters 1 to 4 of the book "An Introduction to Optical Stellar Interferometry" by Labeyrie et al. (2014). These Chapters start presenting the ideas qualitatively, before reviewing some basic concepts (some that we have already looked at, like interference, diffraction, etc), and finally introducing more advanced topics until reaching the idea of aperture synthesis.

The second text to read, is “Radio and Optical Interferometry: Basic Observing Techniques and Data Analysis” by Monnier & Allen (2013)[1]. This one includes discussions about writing proposals for interferometric observations, performing those observations, and also about data analysis methods.

3 Summary of concepts

- We discussed interference before, when looking at diffraction. You might want to go back to the notes on spectroscopy for that. The first key concept to remember is the fringe pattern created by constructive and destructive interference of the light rays that emerge from the system with different phase. Having a mental picture of the interference happening because of slits is useful to get the basic concepts of interference in the signal going through different telescopes (exchanging the slits by the primary mirrors).

- The fringe pattern of a point source emitting monochromatic light is the simplest one. If we have two such sources, then we will have two overlapping fringe patterns. In case of multiple sources, then there will be several overlapping patterns. The key is that the structure of the combined fringe pattern holds information about the spatial structure of the distribution of sources, and that spatial structure can then be studied to a scale that is smaller than what is possible to achieve with conventional imaging. Modern instrumentation allows measurements at the milliarcsecond scale.

- If light emitted from all points of an extended source oscillate with the same frequency and known phases, then the source is said to be spatially coherent. If emission is stable over a certain time, in the sense that the relative phases at each points does not change, then the source is said to have temporal coherence.

- Light emitted by most astronomical sources is spatially incoherent (apart from masers and pulsars). The different spatial regions of a source are independent and the processes of photon emission have very short timescales. However, it is possible to show that from a large enough distance the wavefronts will spread-out, overlap, and merge in a way that they acquire a degree of spatial coherence over a certain time frame. This is the Van Cittert-Zernike theorem[2].

- The time frame over which a series of waves arriving at Earth remain coherent is the so-called “coherence timescale”. That is true, of course, above the atmosphere. While crossing the atmosphere, the turbulence processes that we discussed before will add propagation delays and decoherence. Because of that, the coherence time of the wavefront reaching a telescope will be even shorter.

- Only coherent waves can interfere, because the phase difference between them remains relatively stable. The fringe pattern will only be stable during the coherence time of the incoming waves. The measurements have to be made faster than that timescale. That timescale in optical interferometry is of the order of milliseconds.

- So let us consider the case where we have two optical telescopes and want to bring their light together to interfere (as in Fig. 1, imagine they are telescopes and not antennas as they look

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[1] `https://link.springer.com/referenceworkentry/10.1007/978-94-007-5618-2_7`

[2] Named after the Dutch physicists Pieter Hendrik van Cittert and Frits Zernike.

like). Because the telescopes are separated by a certain distance, at a given moment each telescope is actually measuring a different wavefront. If the signal was completely coherent, this would not matter. However, as we discussed above, that is not the case. To recover the coherence, the beam combiner has to introduce a phase delay (by compensating the difference in the optical path) so that the signal from the same wavefront, observed by each telescope, is combined. For radio, all that is done electronically (as implied in the figure). In the optical, there is a whole system of mirrors to create the added path length.

- Let us consider now Fig. 2. For a single point source and two slits, a certain interference pattern is obtained with fringe spacing equal to λ/b, where b is the distance between the center of the two slits. If there was a second point source, at an angular distance equal to half the fringe spacing from the first source, they illumination patterns will be out of phase by 180 degrees. The interference is destructive. The "visibility" is the contrast between peaks and valleys in the interference pattern. For the single source, the contrast is perfect and the visibility is one. When there is destructive interference, there is no contrast left, and the visibility is zero. For intermediate cases, the visibility will be a function of the angular separation of the sources, such as in Figure 3. The contrast of the fringes is related to a unique Fourier component of the incident brightness distribution of the source.

- The fringe pattern, or the 2D Fourier transform of the source brightness on the sky, obtained using a given interferometer baseline, is the "complex visibility function" which can be written as something like: $\tilde{\mathcal{V}} = |\mathcal{V}|\,\mathrm{e}^{i\phi_{\mathcal{V}}}$. The fringe amplitude, $|\mathcal{V}|$ (or visibility, as we called above) is one argument of the complex visibility function. The other component is the fringe phase, $\phi_{\mathcal{V}}$.

- Although the fringe pattern sounds relatively simple for the case of two sources, the situation can get quickly complex when there are multiple sources, with various strengths, a general uniform background, and/or an extended source, with size comparable to or bigger than the fringe separation. It becomes impossible to distinguish between the multiple possibilities by analyzing a single fringe pattern.

- The way to solve this is to connect more than two dishes or telescopes in an "interferometric array". Qualitatively, the effect is the same as when we discussed the interference pattern from a grating of N slits or grooves. For monochromatic light, we have a series of peaks of the interference pattern, modulated by the pattern of one single telescope. The more telescopes that are connected, the narrower the peaks become, increasing the angular resolution. In radio astronomy, we can link many dishes/antennas in arrays spread over several km. Occasionally, dishes on different continents are also linked, creating baselines of the order of the Earth radius, in what is known as Very Long Baseline Interferometry (VLBI).

- However, if we want to recover the two dimensional distribution of brightness of a source. One line (or configuration) of dishes is not enough. One actually needs baselines that can observe at different projected angles at the sky, to explore the 2D spatial distribution of the source. This can be achieved with the rotation of Earth, which naturally changes the projection of the grid of dishes, creating different baselines and azimuthal angles. The analysis to invert the measurements becomes much more reliable. This method of mixing the signals to invert the measurements and estimate the image proprties is known as "aperture synthesis"[3].

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[3] The English radio astronomer Martin Ryle was awarded the Nobel prize of physics in 1974 for his contributions to radio astronomy, in particular the invention of the aperture synthesis technique.

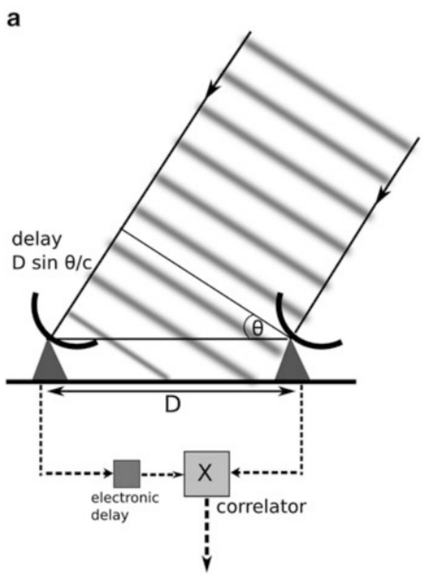

Figure 1: An illustration of a two-telescope (two-dish actually) interferometer. Credit: Figure 3.16 from Lawrence (2013).

- The baseline vector, of coordinates (x, y), connecting two telescopes projects a vector r on the sky. In astronomy it is common to use the spatial vector r normalized to wavelength, r/λ, where this normalized vector has coordinates (u, v). They are the Fourier conjugate to angular position in the sky.

- To be able to invert the image, one has to make enough measurements to cover the (u, v) plane as well as possible, hoping that there is no strong contribution left out by any of the projections that are missing.

- Once we have obtained the data covering the (u, v) plane as well as possible, we would like to invert the image by a Fourier transform. That of course assumes we got a good understanding of the fringe amplitude and phase. The visibility is straightforward from the recorded data, giving $|\mathcal{V}|$. Finding the phase, however, is a bigger problem. The fringes are continually displaced in random ways because of differential atmospheric phase changes affecting the light at each aperture.

- Some science can be done with visibilities only. Such applications usually rely on models, assuming certain symmetry, such as a circular or elliptical star, and a certain well behaved intensity distribution (like uniform brightness or a certain law of limb darkening).

- There are some approaches to try to recover the phase information. “Phase referencing” uses observations of a brighter calibration object to stabilize the fringes. “Fringe tracking” separates the light in two channels, where one will be used for measuring the effects of the atmosphere and the second is used for the science. “Closure phase” makes use of three baselines. With three telescopes, we can create three interference patterns (combining signal from telescopes 1–2, 2–3, and 1–3). If some turbulence causes a phase shift in the signal of telescope 2, two fringe patterns (1–2 and 2–3) will be affected with shifts of the same absolute value but in different directions (with opposite sign). Because of that, the sum of

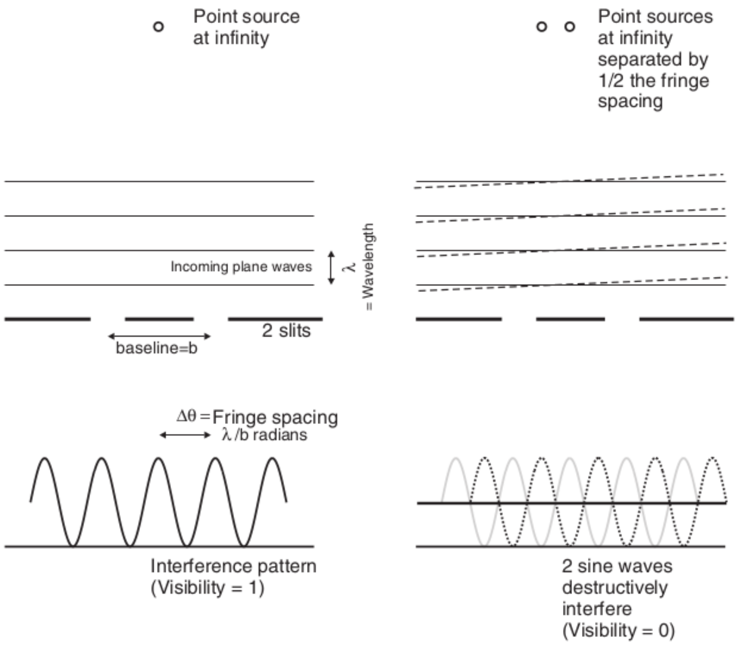

Figure 2: Extremes of visibility, one single source and two sources separated by an angular distance equal to half the fringe spacing. Credit: Figure 1 of Monnier (2003).

the three fringe phases (1–2, 2–3, and 1–3) is insensitive to the phase delay above telescope 2. More generally, the sum of three phases over such a triangle of baselines is independent of telescope-specific phase shifts caused by the atmosphere. Adaptive optics is very useful for optical interferometry, as it effectively increase the coherence time by correcting for the atmospheric turbulence.

- One issue that limits the applications of interferometric observations in the optical is the number of reflections needed to control the path difference of the beams. This can easily get to 10 or even 20 mirrors in the optical path. If each mirror has 97% efficiency in reflecting light, after 10 reflections we lost ∼25% of the light (after 20, almost 50% is lost).
- Moreover, the path difference is not constant. As the source moves across the sky, the path length difference will be constantly changing. Consequently, the fringe pattern will be moving. Because of that, the mirrors inside the beam combiner have also to continually move to correct for the changing path difference.

4 Additional reading

The lecture notes on “Principles of Long Baseline Stellar Interferometry” edited by Lawson (2000)[4] is often cited as a very useful resource to start on the topic of interferometry (despite having 350 pages...). Another resource usually recommended for beginners is the review by Monnier (2003)[5].

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[4] https://ecommons.cornell.edu/handle/1813/41240

[5] https://ui.adsabs.harvard.edu/abs/2003RPPh...66..789M/abstract

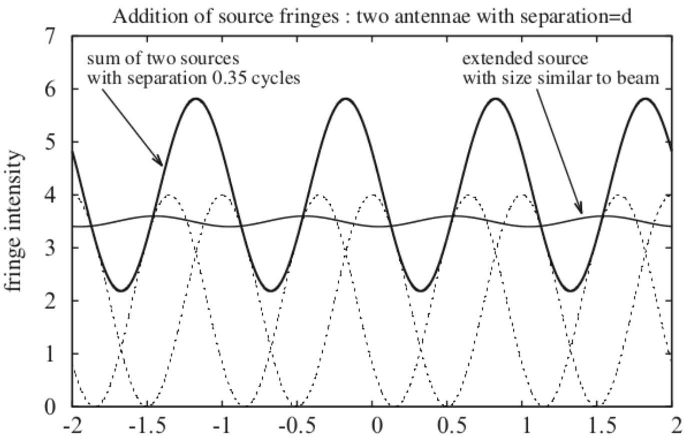

Figure 3: An intermediate case of the visibility of the pattern created by two sources. Credit: Figure 3.17 from Lawrence (2013).

There are several techniques that can be used to construct images at very high angular resolution and I can not provide a comprehensive overview of all of them. One place to look for information of such methods and their scientific application is the "Astronomy at High Angular Resolution: A Compendium of Techniques in the Visible and Near-Infrared" edited by Boffin et al. (2016)[6], which results from a workshop held at ESO in 2014.

Just like any other VLT instruments, the instruments used for interferometry also have their manuals which you should check when you consider using the VLTI for your science. In addition to those, there is also a more general VLTI User Manual. You can find the version for P108 and P109 proposals here.

References

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[6] https://link.springer.com/book/10.1007/978-3-319-39739-9