INTERFEROMETRY THEORY PRIMER

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Abstract. As an introduction to the following talks, this presentation reviews the theoretical background of interferometric measurements. Starting from a general formalism, I then emphasize the relationship between those measurements and the observed object properties.

Keywords: interferometry, theory, tutorial

1. Interferometric information

1.1. WAVEFRONT COHERENCE IN PUPIL PLANE

The distribution of the light intensity in the sky is commonly obtained in the optical and the near IR range, by collecting this light in a so-called *pupil plane*, focussing it and detecting the energy in the focal plane or *image plane*. Each position in this image plane is illuminated by the sources from a given direction in the sky, the scale being defined by the optic's focal length. The electric field propagation from the source to the optics and from the optics to their focal plane are respectively described by two successive Fourier transforms under the usual assumptions of Fraunhoffer diffraction theory:

$$E(\theta) \longrightarrow \hat{E}\left(\frac{\rho}{\lambda}\right) . Pupil\left(\frac{\rho}{\lambda}\right) . Atm\left(\frac{\rho}{\lambda}\right) \longrightarrow E_{det}(\theta)$$

where

- the conjugated variables are respectively i/ the direction in the sky θ and ii/ the vector distance in pupil plane, in wavelength units, given by ρ/λ;
- the optics are described by the $Pupil$ function: its modulus indicates the optical transmission and its phase indicates some delays of the light propagation, non homogeneous over the pupil (due to unperfectly flat mirrors for instance). Similarly, the effect of atmosphere (transmission but also and mainly non constant optical path length) can be described by a complex Atm function. This function is also highly time dependent.

Now, let us consider how is obtained the light intensity in the detector plane ($I_{det}(\theta)$), that is practically measured in the optical and IR range with quadratic detectors. In particular, how does it depend on the intensity in the source plane ($Obj(\theta)$), and how do the pupil and atmosphere modify it? This intensity $I_{det}(\theta)$ (resp. $Obj(\theta)$) is the average square modulus of the electric field $E_{det}(\theta)$ (resp.

Astrophysics and Space Science **286:** 3–15, 2003.

$E(\theta)$). Under assumptions that are reasonable in astronomy and that includes the previous assumptions for the Fraunhoffer diffraction (source of limited size, at large distance, and spatially incoherent), the Van Cittert-Zernike theorem ensures that the Fourier transform of the square modulus operation in one space translates into the autocorrelation of the conjugated fields. We derive the following relationships between the source and detector plane intensities on the one hand, and the autocorrelation of the pupil plane quantities on the other:

$$Obj(\theta) \longrightarrow \widehat{Obj}\left(\tfrac{\rho}{\lambda}\right)\ .\ MTF\left(\tfrac{\rho}{\lambda}\right) \longrightarrow I_{det}(\theta) = Obj(\theta) \star PSF(\theta),$$

where,

- $\widehat{Obj}\left(\frac{\rho}{\lambda}\right)$, the Fourier transform of the source plane intensity is not an intensity but an autocorrelation:

$$\widehat{Obj}\left(\frac{\rho}{\lambda}\right) = \hat{E}\left(\frac{\rho}{\lambda}\right)^{\star} * \hat{E}\left(\frac{\rho}{\lambda}\right) = \iint_{pupil} \hat{E}\left(\frac{r}{\lambda}\right)^{\star} \hat{E}\left(\frac{r-\rho}{\lambda}\right) dr$$

- the effect of the pupil and atmosphere is described by the *modulation transfer function*

$$MTF\left(\frac{\rho}{\lambda}\right) = \left\langle \text{Autocorrelation}\left\{ Pupil\left(\frac{\rho}{\lambda}\right)\ .\ Atm\left(\frac{\rho}{\lambda}\right)\right\} \right\rangle_{time}$$

- This filtering appears in the detector plane as a convolution of the intrinsic source image by the instrumental point spread function $PSF(\theta) = \widehat{MTF}\left(\frac{\rho}{\lambda}\right)$

In other words, the information defining the source image is described by this autocorrelation function of the electric field in the pupil plane. According to the previous formula, it is given by the relative values of the electric field on two points of the pupil separated by a given distance, averaged over the time and over the pupil (for all pairs of points with such a separation). This quantity is also called the *wavefront coherence* in the pupil plane. It is a function of the considered spatial frequency ρ/λ and may also depend on wavelength. Only part of the initial intrinsic information is selected and transmitted by the instrument and atmosphere, as described by the modulation transfer function.

This formalism is general and appropriate for both classical imaging or interferometry. In interferometry, the pupil shape may be of any type and the way of measuring the signal may differ from the direct detection of an image in the focal plane. In this context, the coherence properties of the electric field in pupil plane is widely used; the simplicity of the impact of instrumental effects as a multiplication of the object intrinsic signal depending on its spatial frequency, rather than an image convolution, makes also the discussion of the signal in the pupil plane very convenient.

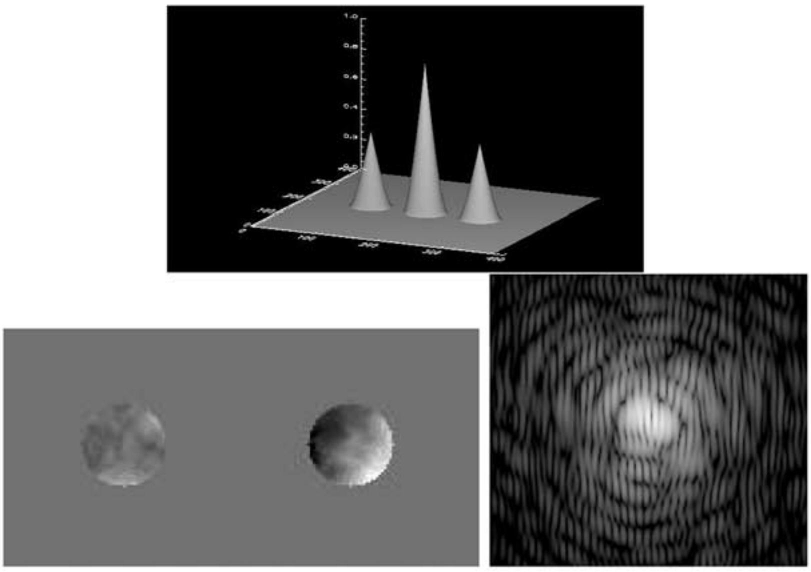

Figure 1. Top: example of transfer function corresponding to a pupil constituted of two circular apertures. On top of the low frequency peak transmitted by each individual aperture with a cut-off frequency defined by the individual aperture diameter D/λ, the system transmits the information at higher frequency (secondary peaks) centered around the frequency defined by the apertures separation or baseline B/λ. Bottom: image in log scale of a point-like source through this system (right), affected by random turbulent phase delays over the pupil, represented on the left.

1.2. MEASURING THE VISIBILITIES

1.2.1. *Coding the interferometric information*

The problem is to measure the correlation of the electric field taken in 2 positions of the pupil plane: $< E(P_1, t) \, . \, E^\star(P_2, t) >$ (normalized to the target flux). In the optical range, the use of heterodyne techniques (that make it possible to numerically compute such correlations) dramatically limits the spectral bandpass, and consequently the sensitivity, of the system (the frequency bandpass is directly defined by the electronics sampling frequency, which remains very small compared to the electric field frequency, typically 10^{14-15}Hz).

Alternatively, this quantity can be derived from the more easily obtained intensity after the beam combination,

$$I_{12} = < \left\| E(P_1, t) + E^\star(P_2, t + \tau) \right\|^2 >$$

where the delay τ should be controlled and modulated by the instrument set-up. This modulation can be i/ temporal (a rapidly moving element in the path modulates the optical length of one arm, such as a Michelson set-up) or ii/ spatial (as in the Young experiment: depending on the pixel position in the detector plane, the optical length from collected points P_1 and P_2 is not identical; this optical path difference, OPD, can be translated into a delay: $\tau = OPD/c$).

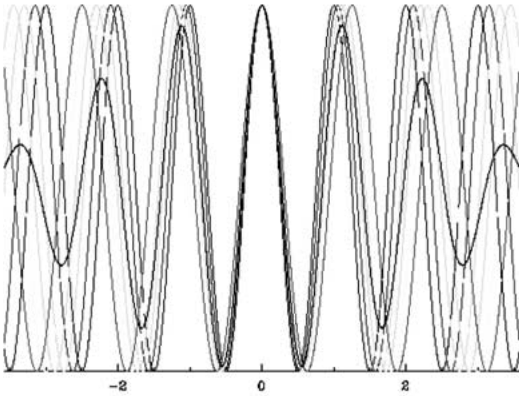

Figure 2. Illustration of the fringe pattern formed in the Young experiment. The fringe separation is defined by the wavelength and the separation of the 'Young holes' (or output pupil) that form the fringe pattern (independently from the entrance pupil or baseline for which it measures the visibility). Each individual thin curve corresponds to a given wavelength. Their average (in thick line) shows the expected fringe pattern for a broad band observation: the fringe contrast decreases on a typical scale OPD $\simeq R.\lambda$, where R is the spectral resolution.

If (at least partially) coherent, the electric fields $E(P_1)$ and $E(P_2)$ will interfere constructively or destructively, depending on τ: $I_{12}(\tau)$ shows then a fringe pattern.

$$I_{12} = I_1 + I_2 + 2\mathcal{R}e\left\{ < \ E\,(P_1, t)\ \ .\ E^{\star}\,(P_2, t + \tau)\ \ > \right\},$$

where I_1 and I_2 refer to the intensity of the electric field propagated from P_1 and P_2 respectively down to the detector (see Figure 2).

Around the zero OPD position (or white fringe), the fringe contrast measures the visibility modulus and its position the visibility phase (an offset of one fringe corresponds to a source offset of λ/B and a phase shift of 2π). Due to the chromaticity of the fringe separation, a broad band fringe pattern gets blurred far from the white fringe. In other words, we compare electric fields which get temporally de-correlated: $|< \ E\,(P_1, t)\ \ .\ E^{\star}\,(P_2, t + \tau)\ \ >|$ gets significantly smaller than $|< \ E\,(P_1, t)\ \ .\ E^{\star}\,(P_2, t)\ \ >|$. The number of fringes of the pattern is limited to spectral resolution R=$\lambda/\Delta\lambda$ (the coherence length of the electric field is $R.\lambda$). Finally, this number of fringes may also be limited (for a given source) to the windowed field (B/D fringes for a monomode instrument).

The principle mentioned above makes it possible to derive the mutual coherence of two points in the entrance pupil from the contrast of the fringe pattern obtained after beam combination. This principle can be extended to more than 2 apertures, with dedicated pixels for each pair of apertures. When using a spatial coding of the fringe patterns, the patterns related to different pairs of apertures may be detected on a single line of pixels as long as the corresponding fringe separations are non redundant in order to be able to associate the measurement of each fringe pattern with the relevant pair of apertures. This condition is ensured

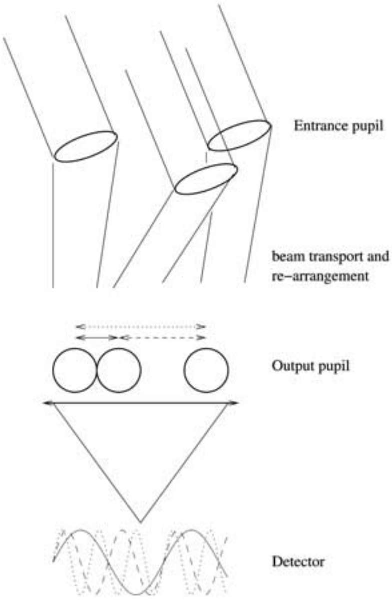

Figure 3. Illustration of the spatial coding of 3 fringe patterns on a single line of pixels with non-redundant fringe separation. The fringe separation of each fringe pattern is defined by the separation each corresponding pair of apertures in the output pupil. The corresponding measured visibility is related to the source image spatial frequency defined by the separation of telescopes (in the entrance pupil).

when the configuration of the pupil used to recombine the various apertures (or output pupil) is non-redundant.

Finally, in the particular case where the output pupil, that determines the configuration of the fringe pattern on the detector, is homothetic to the entrance pupil (telescope array configuration), the obtained fringe pattern is a direct image of the observed source, in the sense that it is the convolution of the source by the instrument PSF.

In principle, a number of methods for the interferometric signal coding are ideally equivalent. In practice, the choice is not trivial and should be optimized according to the array configuration and to the main astrophysical goals. They indeed do not imply the same number of physical pixels, or pixel read-outs (and corresponding noise). Also, a temporal modulation of the fringes assumes that the MTF remains stable during the fringe scan: the atmosphere consequently impose very short exposure times. Alternativelly, when using a spatial modulation of the fringe (the complete fringe pattern being simultaneously detected on different pixels), the various beams are not transmitted through same optics: the system transmission for each beam down to the detector has to be well calibrated and stable for an accurate visibility measurement.

1.2.2. *Effect of atmospheric turbulence*

Instantaneously, for 2 pupil points, the propagation through the atmosphere induces a random delay for one point compared to the other (differential piston). As a consequence, the instantaneous fringe pattern is translated: the corresponding visibility phase is shifted by a random value. If averaged over time (with an integration time longer than the atmospheric coherent time, which is typically a few ms in visible and scales as $\lambda^{6/5}$), the random phase delay varies significantly: the fringe pattern is blurred; in the complex plane, the visibility vector rotates and is attenuated after the average. Not only the visibility phase is modified but also the modulus is attenuated. In other words again, the transfer function is attenuated.

In case of extended sub-apertures (larger than the turbulent coherent length, that is typically a few 10 cm in visible), the visibility measurement for a given spatial frequency results (even instantaneously) from the spatial average over each pair of pupil points with the appropriate separation. This spatial average induces a similar degradation on the transfer function[⋆]. In the general case, both spatial and temporal averages degrade the signal: it reduces the transfer function and makes it difficult to calibrate accurately.

Dealing with the atmospheric perturbation is very difficult and remains often the main limitation in various observing modes. This limitation motivates the use of various specific devices or observing procedures:

- *short exposure times* within an atmosphere coherent time to freeze the turbulence: this is critical for accurate visibility measurements when scanning a fringe pattern (temporal coding); this is also important when using a spatial coding of the fringe in order to preserve a high fringe contrast, but this reduces the limiting magnitude
- *real-time correction* of the atmosphere perturbation: fringe tracker and/or adaptive optics. For extended apertures, the adaptive optics acts with a fast deformable mirror and aims at correcting for the wavefront perturbation over each aperture. The fringe tracker, for each baseline (or pair of apertures), adjusts the OPD and aims at stabilizing the corresponding fringe pattern. Those corrections in fast servo-loop also require bright stars (typically H or $K \simeq 11$–13) to acquire high signal-to-noise measurements but they make possible much longer interferometric integrations, which may be very valuable in particular to get higher spectral resolution.
- *spatial filtering* through monomode fibers may reject the residuals from adaptive optics: only the coherent part of the incoming flux on each aperture is transmitted. The atmospheric variations of the incoming wavefronts are then translated into calibrable photometric variations. This method which makes possible more accurate visibility measurements limits the field of view to the resolution of a single aperture.

[⋆] This degradation due to the spatial average has motivated pupil masking techniques in order to create a non redundant pupil.

- *differential measurements*: the atmospheric OPD is (in first approximation) achromatic. The relative visibility (modulus and phase) obtained simultaneously at 2 distinct wavelengths can be measured much more accurately than each individual visibility. This mode requires an appropriate instrument for such simultaneous measurements; it is well suited for spectrally dependent target structures more than for continuum measurements.

2. Generic Interferometer Purposes

Generally speaking, the interferometer will aim at collecting the light over a pupil of any shape (this pupil plane is also called the frequency plane or u-v plane as common notation for the frequency coordinates) and at estimating the wavefront coherence over this pupil for each possible available spatial frequency (i.e. for each possible pair of points separation available within this pupil). Not going into the discussion of practical problems with this instrumentation (see M. Schoeller, this volume), I draw hereafter in general terms a non-exhaustive list of limitations or challenges for interferometers that conditions their design or discussions:

- *u-v coverage or selection of transmitted spatial frequencies of the target:* Unlike connected pupils (in classical imaging) that provide the complete image information up to the cut-off frequency (or resolution) defined by the aperture diameter, a diluted pupil may provide information for much higher frequencies (defined by the largest baseline), but this information is generally incomplete. The usual way to represent the frequency plane or u-v coverage, is to plot the pupil autocorrelation (optical transfer function). It is possible to improve a sparse u-v coverage in different ways.
  i/ a large number of apertures provides simultaneously a large number of baselines ($n(n-1)/2$), each of them independent if the array geometry is non redundant.
  ii/ alternatively (or additionally), it may be possible to move such apertures so as to modify the array and measure sequentially more and more frequencies
  iii/ finally, for a given array geometry, the earth rotation itself modifies the projected baselines (or aperture separations as seen from the source).
  In each case, the light will have to be propagated to the combination laboratory, and the optical path length to be accurately controlled and equalized: this implies possibly long delay-lines (up to a significant fraction of the baselines).
- *transfer function:* on the available frequency window defined by the array geometry, any instrumental defects (such as non constant phase delays in time or spatially over the pupil, non homogeneous polarization effects, vibrations…) induces a coherence loss, i.e. an attenuation of the transfer function. The ideal instrument will have
  - a high transfer function (measured as the fringe contrast in case of an unresolved source for which the wavefront is intrinsically perfectly coherent)

not to loose the interesting signal down to the noise level; this requirement sets very severe specifications on the quality of the whole interferometric opto-mechanics,

  - and known to a very accurate level, that will drive the final accuracy of the measured target visibility. This implies accurate calibration procedures of this transfer function (which is a complete issue by itself, see Percheron, this volume) and a high instrumental stability between these calibrations.

- *sensitivity and speed:* other sources of noise (detector and photon noise) definitely also limit the signal quality. This sensitivity issue is often critical due to the number of relay optics involved in the complete interferometer. Also, the small structures of the targets (close binaries, stellar surfaces, circumstellar ejecta, ...) may often involve a small fraction only of the total flux and be variable on short timescales. The sensitivity on moderate exposure times for a single array configuration is in many cases a critical issue. This need drives the motivation for the interferometry of large coherent apertures, i.e large telescopes equipped with adaptive optics
- *spectral coverage and resolution:* as for any other instrument, the target interferometric information may be interesting and complementary in various spectral ranges and up to high spectral resolution (see Petrov and Przygodda, this volume). Additionally, one will note that the observing wavelength directly impacts the measured spatial frequency B/λ for a given geometric baseline. For instance, for an achromatic source, the simultaneous observations at various wavelengths may replace advantageously some time consuming array re-configurations in order to complete the u-v coverage. On contrary, in the cases of object geometries that strongly depend on wavelengths (for instance a point-like object in continuum that is extended in an excited emission line), simultaneous observations may provide very accurate self calibration.
- *polarization:* here again, the interest for measurements in various polarization states of the target light may be interesting in interferometry also. And here also, if theoretically possible, the number of optics usually involved here make this measurements very delicate and involve specific calibration procedures

This list is very general: a single instrument may probably not be optimized for all of these items. After a generation of pioneering instruments that have explored a number of instrumental capabilities and that have provided interesting astrophysical results, the up-coming instruments dedicated to a wide community will significantly improve some of the mentioned goals. The case of VLTI is a good example. The common infrastructure itself is very powerful and designed for *a wide range of use* (see Glindemann, this volume): from the visible to mid-IR, combining either medium-sized or large telescopes, with an increasing number of delay-lines. The instrument plan aims at covering various astronomical purposes with complementary instruments. Each focal instrument is focussed on a specific observational niche.

In order to maximize the return from such instruments, to validate some program feasibility and finally to optimize the use of the interferometer, the observer himself definitely needs to identify *which part* of the general interferometric signal is critical to constrain his target, what specific accuracy and calibration are required. The generic approach is to model the target properties, and simulate the expected interferometric signal (at various frequencies). Varying the model parameters makes possible to discuss the optimal frequency range where to constrain them, the amplitude of the effect and required SNR. These requirements will be compared to the available instrument capabilities and configurations. The following sections illustrate in some examples such an approach, as a basic reference frame, discussing in particular the relation between the object information and the observed visibility modulus and phase.

3. Which Visibilities Tell Me What Object Properties?

3.1. VISIBILITY MODULUS

The visibility modulus at a given spatial frequency indicates the fraction of the object image involved in flux variations on the typical λ/B angular scales. This baseline, that does not replace more complete numerical simulations, explains easily as a first approach what are the relevant baselines in order to characterize the object properties (see examples in Fig. 4). From such measurements, it will in particular be possible to derive the information relative to the *object structure*: whether most of the object intensity is extended or not, on what scale, with what orientation and aspect ratio (if it is more extended in one direction than in another), whether sharp edges are present (implying non-zero visibilities up to high frequencies, much larger than the global object typical size)...

I will not illustrate here, in a general paper, many cases of such information content, but I will only point out a few remarks:

- *number of measurements:* very often, the interesting astrophysical information is not only a ‘typical size’ of the source in a given direction. This means that a single measurement with one baseline B will very often not be enough and will certainly not provide a complete image at the resolution λ/B ! This statement is already clear to most of the readers but has to be emphasized: even in the case of relatively simple models, the structure will require probably various appropriate configurations to be unambiguously identified, and will imply a priori information (with at least as many measurements as parameters to be constrained)
- *accuracy of the measurements:* here again, obviously, the ability to distinguish between similar models, or in other words the propagated uncertainties onto the determination of the model parameters, is determined directly from the visibility measurements accuracy. This accuracy comes from the source

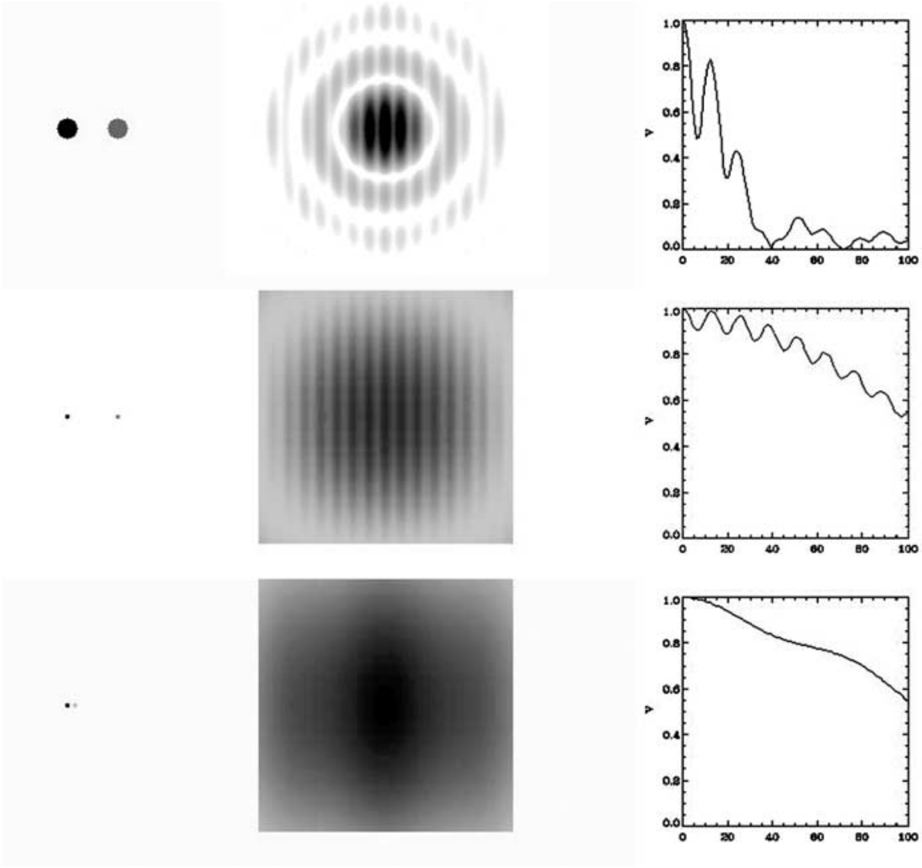

Figure 4. Examples of visibility modulus corresponding to the image of binaries, with arbitrary spatial scale units. Left: assumed object image (with various stellar radius, binary separation and contrast); middle: the Fourier transform of the image provide the expected visibility modulus, on each point for the corresponding baseline; right: extracted visibility curve for baselines aligned with the binary separation. The 3 examples from top to bottom illustrate the impact of the each star diameter (general decrease of visibilities), the binary separation (the closer the separation – bottom –, the larger the fringe separation), and binary flux ratio (from 3 for the top example to 20 for the two others) as the amplitude of the visibility oscillation.

brightness, the collecting surface, but also very importantly from the instrument transfer function stability and calibration accuracy. The requirement for a very high accuracy is in particular obvious in the case of high dynamic range detections (for instance a binary with a high brightness ratio, but also small spots on a stellar surface, or gap/inhomogeneities over a disk...): as a rule of thumb, the amplitude of the visibility modulus signature of a structure is roughly (at the appropriate frequency) the fraction of the flux involved in this structure.

- *measurement of low visibilities:* the performance of an interferometer (sensitivity, accuracy) are usually given for unresolved sources (high visibility). Observations of resolved sources with low visibilities are more difficult to i/ detect and track the fringes, and ii/ estimate the visibility (SNR $\propto V^2$). Such observations may however be interesting in some cases (to maximize the variation of visibility according to the model parameters, as in the case of constraining a stellar diameter) or even unavoidable in other cases (to detect and characterize small structures of a larger source). When observing with more than two apertures and when an interesting but very low visibility is expected with the largest baseline, 'bootstraping' techniques may be very useful. It consists of using an array configuration where the apertures creating the largest baseline are also involved in shorter baselines. On the shorter baselines, the fringes are more easily detected, the optical path can be efficiently monitored so as to make possible longer and coherent integrations for the low visibility measurement. A similar technique can also be applied with a single baseline but simultaneous observations at different wavelengths.
- complementary observations: finally, as for any instruments, the measurements of the visibility modulus may be astrophysically interesting for various wavelengths, polarizations and at different time.

3.2. VISIBILITY PHASE

Information on the visibility modulus only (even for a large number of baselines and high SNR) is not enough to reconstruct the target image. The information on the visibility phase is critical for such reconstruction; such a reconstruction is possible when this information is obtained for many spatial frequencies (to be compared to the target complexity), as demonstrated with radio observations.

For a given spatial frequency (or a given baseline), the visibility phase is relative to the position of this frequency component of the target image: a 2π shift corresponds to a source offset of λ/B compared to the instrument axis. This offset induces the incoming wavefront to be slightly tilted so that the optical path length is slightly longer (by a wavelength) on one arm compared to the other. Note that any other source of OPD will produce the exactly similar measurement as an instrumental or atmospheric visibility phase, in addition to the intrinsic astrophysical signature. It is very difficult, in practice, to control accurately the complete optical path in the interferometer and to manage the random delays due to the turbulent atmosphere so that the critical issue is to find a relevant phase reference (or in other words to control/calibrate the phase of the turbulent and instrumental transfer function).

Various options can be explored (and are actually considered in the VLTI: see Delplancke, and Petrov, this volume) in order to retrieve the astrophysical visibility phase information:

- *external star as a phase reference:* by observing simultaneously and through the same optical path (as far as possible) an external astrophysical source, it may be possible to detect and measure any phase shifts suffered by the target of interest. In other words, the external source is used as a reference. The method requires the presence of such a bright phase reference source in the vicinity of the target (within the piston isoplanetic patch, which is typically in units of 10 arcsec, depending on the wavelength); the exact simultaneity is strictly necessary for the calibration of turbulent effects; additionally, the required field of view implies dual-beam optics (and differential delay lines so as to monitor the optical path lengths for both targets) but the instrumental phase should be very similar and calibrated for both beams. In order to measure absolutely the separation of both sources, an internal metrology of the 2 paths is necessary.
- *differential measurements at various wavelengths:* in case that only one target is observed, the visibility in one wavelength, where the object structure is known a priori, can be used as a reference for other wavelengths. Here again, this method requires the simultaneity; it relaxes interestingly the problem of phase delays to 'only' their chromatic part (which still are to be calibrated accurately). It applies efficiently to objects with a variable position or structure with wavelength (variation of photo-center with wavelength, structure in an emission line...)
- *closure phase:* in the case of simultaneous observations with 3 (or more) apertures, the addition of each visibility phase corresponding to the 3 baselines forming a closed loop of telescopes cancels out the optical path lengths variations affecting any individual aperture (such a variation affects 2 baselines, with opposite signs). The resulting value, the closure phase, is a quantity that is intrinsic to the astrophysical source, and is in particular non zero for non centro-symmetrical sources.

This information on the phase is the basis of *astrometry* at the resolution of the interferometer. In such context, the visibility modulus may or may not be simultaneously used. In a pure astrometric instrument, the specification on the modulus of the transfer function (or instrument contrast) is very much relaxed: it may even vary in some range as long it remains high enough to make possible the fringe detection with a good SNR.

As mentionned in the introduction of this section, the visibility phases, when obtained for a large number of baselines and combined with visibility modulus measurements, make possible to reconstruct a high angular resolution *image* of the target. As for radio interferometry, the reconstruction is directly conditioned by the obtained u-v coverage (see sect 2, first item), and by the measurements SNR; it also takes benefit from any a priori information on the target to regularize the inverse problem (see for instance the presentations of C. Haniff and E. Thiébault, this volume).

3.3. THE CASE OF NULLING INTERFEROMETRY

Nulling interferometry is an observing mode with specific objectives and instrumental requirements. Its interests and instrumental requirements correspond closely to those of coronography and the frontier between them is not well defined. The purpose is not to measure a visibility phase or modulus but to produce an interferometric pattern that is destructive for an on-axis source and constructive for a much fainter interesting target. The discrimination between the extinguished and transmitted source is obtained on the scale of the interferometer resolution λ/B. This capability is primarily motivated by the search for extrasolar planets but also concerns a number of other high dynamic range observations.

We already mentioned that measuring the signature associated to a high dynamic source requires very accurate visibility measurements (with an accuracy better than the brightness ratio between the faint structure of interest and the total flux). A specific requirement for this mode is to obtain a transfer function which is not only very stable and/or calibrated to that accuracy but also that this function is very high (close to unity). In other words, the coherent part only of the incoming on-axis light will be rejected: a rejection rate of a factor 20 would for instance require a instrumental visibility of > 0.95. This requirement is very severe.

The specific interest for this mode is to strongly reduce the photon noise associated with the bright on-axis source, which is a fundamental limit otherwise. Eventually, if other sources of noise are well controlled and reduced (in particular in space without the problems related to atmosphere), the photon noise will be the dominant limitation and such a mode will improve the high dynamic detection capabilities (see Fridlund, this volume).

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