Bulletin de la Société Royale des Sciences de Liège, Vol. 74, 5-6, 2005

Interferometric Arrays with a Wide Field-of-View

A. Quirrenbach

Sterrewacht Leiden, Postbus 9513, NL-2311XG Leiden, The Netherlands

Abstract: The useable field-of-view of optical and infrared interferometers can be limited by a number of effects: geometric vignetting, violation of the convolution relation between object and image in a Michelson interferometer, insufficient sampling of the *uv* plane, and imperfect coupling of off-axis light into single-mode fibers. This article provides an overview of techniques that have been proposed to overcome these limitations.

1 Introduction: Why is a Wide Field-of-View Useful?

The field-of-view of optical / near-infrared interferometers is usually much more restricted than that of traditional astronomical instruments. If no particular efforts are made, the useable field of an interferometer may not be larger than a few resolution elements in diameter. The term "wide field" has to be understood in this context; this article deals with the difficulties that need to be overcome if a useful field of order $1''$ is to be obtained. There are two possible reasons why one would want to achieve this. First, one may intend to observe objects that are extended with typical scales of several hundred milliarcseconds (mas), but possess substructure that require observations with interferometric resolution of a mas or less. Such measurements are actually very difficult, because the extended structure gives a low fringe contrast and thus a low signal-to-noise ratio, and because they pose stringent requirements on the coverage of the *uv* plane and on the calibration of the visibilities. These issues are rather well-understood (e.g., Perley et al. 1989), and will not be discussed further here. The second class of targets that call for a wide field-of-view consist of several point sources (normally stars), from binaries to clusters. In the case of multiple point sources, low visibilities are much less of an issue than for extended sources, and the requirements on the *uv* plane coverage are less severe. There are nonetheless a number of technical issues and limitations, which will be discussed in the subsequent sections.

There are three types of questions that one can address with interferometric observations:

- *Morphology.* Frequently most of the information is in the morphology of the target. Searches for faint companions, imaging of circumstellar matter, and studies of the geometry of dust tori and broad line regions in active galactic nuclei fall into this category.
- *Photometry or spectroscopy.* Sometimes the overall morphology of the observed object is known beforehand, but one wishes to obtain more detailed information on its physical

properties. In the case of a multiple stellar system, one may for example wish to obtain separate spectra for each component.

- *Astrometry.* In many cases the most interesting observables are source positions, and changes of these positions over time. Examples are the determination of binary orbits, astrometric searches for low-mass companions, and proper motions in dense stellar clusters.

Frequently there is no clear distinction between these categories of observations, but it is useful to consider them separately, because they set different requirements on the design and tolerances of interferometric instruments.

2 Beam Combination Schemes and Field-of-View

To understand the various factors that limit the field-of-view in astronomical interferometers, on first has to take a look at the different beam combination schemes that can be employed. These can be classified according to several criteria: the beam étendue (single-mode or multi-mode), the beam direction (co-axial or multi-axial), the combination plane (image plane or pupil plane), and the relation between input and output pupils (Michelson or Fizeau configuration).

In a Fizeau interferometer the output pupil is an exact replica of the input pupil, scaled only by a constant factor. This is also known as homothetic mapping between input and output pupil. In contrast, in a Michelson interferometer there is no homothetic relation between the input and output pupils[1]. This means that the object-image relationship can no longer be described as a convolution with a telescope transfer function, because the rearrangement of the apertures rearranges the high-spatial frequency part of the object spectrum in the Fourier plane (Tallon & Tallon-Bosc 1992). This has an important consequence for off-axis objects: the image position does not coincide with the white-light fringe position (see Fig. 1 in Tallon & Tallon-Bosc 1992). For a non-zero spectral bandwidth this means that the fringe contrast decreases with field angle and the field-of-view is limited; the maximum size of an image from a Michelson interferometer is $\sim R \equiv \lambda/\Delta\lambda$ resolution elements in diameter. This effect is known as "bandwidth smearing" in radio astronomy (Thompson et al 1986).

In the focal plane of a properly phased Fizeau interferometer one observes an image of the field, convolved with the point spread function (psf) of the array. The desired information can thus in principle be obtained rather easily by deconvolution. If the array is very dilute, however, this approach suffers from the fact that the psf has many rather high side lobes; this spreads the light from a point source over many pixels and reduces the SNR (Roddier & Ridgway 1999). To avoid this effect, one can magnify the output pupils of the individual telescopes with respect to the arrangement of their centers (Labeyrie 1996). Such a "conformal Michelson array" or "hyper-telescope" still forms a direct image, but only over a limited field; of order N^2 telescopes are needed to obtain a field N resolution elements across.

In most Michelson array concepts there is no similarity between the input and output pupil at all. These instruments measure the visibilities for all $N(N-1)/2$ baselines in a N-telescope array. The $N(N-1)/2$ visibilities can either be measured by pairwise beam combination, or by bringing the light from all telescopes together on one detector. In the latter "all-on-one" techniques the fringes from the different baselines have to be encoded either spatially (by

[1] This definition of Fizeau and Michelson interferometers is consistent with the one used by Quirrenbach (2001). However, some authors use these terms as synonyms for "image plane" and "pupil plane" interferometer, respectively. In the nomenclature used here, it makes sense for example to talk about an image plane Michelson interferometer.

using a non-redundant output pupil) or temporally (by using different dither frequencies for the beams from individual telescopes). In any case, the image is computed from the visibilities by a Fourier transform.

3 Technical Limitations of the Field-of-View

Since there are different effects that can potentially limit the useful field in an interferometer, it is useful to introduce names for the fields corresponding to each one of them. One can thus distinguish between:

- *The unvignetted field-of-view.* If the starlight is transferred by bulk optics from the telescopes through the delay lines to the beam combiner, the diameters of the beam transfer optics have to be sufficiently large to transmit the desired field. Compression of the beams by a factor of m magnifies angles by the same amount; therefore rather large optics are needed to avoid vignetting especially for large telescope diameters and long baselines.

- *The coherent field-of-view.* In a Michelson interferometer, bandwidth smearing leads to a loss of coherence, as explained in the previous section. For a each baseline, the coherent field-of-view is a strip on the sky $\sim R \equiv \lambda/\Delta\lambda$ resolution elements wide, perpendicular to the baseline direction.

- *The synthesized field-of-view.* When observations on different baselines and at different times are combined to form a synthesized image, the data are usually re-binned to a grid of uv cells. The cell size has to be inversely proportional to the desired field, according to the Nyquist sampling theorem. Since a non-zero bandwidth means that each visibility measurement constitutes an average over a radial range of uv coordinates, the synthesized field can never be larger than the coherent field. In addition, one has to limit the integration time for each data point, since otherwise Earth rotation leads to further smearing in the uv plane.

- *The single-mode field-of-view.* Many interferometers employ single-mode fibers, wave guides, or pinholes in the beam relay or beam combiner. Such filters improve the stability of the visibility calibration, but affect the fringe contrast of off-axis objects (Dyer & Christensen 1999). Since only a single mode is transmitted (beam étendue of λ^2), the field-of-view is limited to one single-telescope Airy disk.

The useable field-of-view of the interferometer is obviously the intersection of these fields. One has to keep in mind, however, that none of them has a clearly defined hard edge. Vignetting leaves the central field unaffected, then introduces a soft edge; all other effects lead to a degradation for all off-axis objects, which increases with distance from the field center.

4 Strategies to Achieve a Wide Field-of-View

The most obvious technique for obtaining a wide field is Fizeau interferometry, or homothetic mapping, but this approach implies very tight tolerances on the optical alignment (Beckers 1990, van der Avoort et al. 2004). For ground-based observations, the changes of the input pupil due to Earth rotation have to be tracked precisely by the output pupil; special mechanisms have been designed for this purpose (van Brug et al. 2004). An alternative beam combiner design employs a staircase mirror in an image plane to correct the field-dependent delay in an approximate way (Montilla et al. 2005). It appears that with state-of-the-art control of precise mechanisms and with one or the other of these techniques it should be possible to build a wide-field beam combiner for a large interferometric array.

A Michelson interferometer can also have a large field-of-view, provided that the bandwidth of each spectral channel is kept sufficiently narrow. In the mid-infrared, where background noise dominates over detector noise, the penalty of dividing the observing band in many narrow spectral channels is small; the data from the individual channels can then be reassembled easily (taking into account the dependence of the *uv* radius on wavelength for each observation), if one does not require high spectral resolution. A variation on this approach combines imaging of a field much larger than the single-telescope Airy disk with double Fourier spectroscopy (Rinehart et al. 2004).

Because of the high cost of building bulk-optics beam relay systems for arrays with kilometric baselines, beam transport and delay compensation with single-mode fibers appears very attractive (e.g., Quirrenbach 2004). In such systems, achieving a field-of-view larger than the single-telescope Airy disk seems possible if each telescope beam is coupled into multiple fibers (Guyon 2002).

Beam combiners employing the hyper-telescope concept appear to have the most severe field-of-view restrictions, but even for this class of instruments wide-field extensions based on an array of pupil densifiers working in parallel could be considered (Lardière et al. 2003).

5 Conclusions

There are very good reasons why one would like to obtain a large field-of-view in an interferometer; perhaps the most important one is that observations of multiple stellar systems or in crowded stellar fields are much less efficient or even impossible if the field has a diameter of only a few resolution elements. This issue has received some attention in design studies of interferometric facilities and instruments, but at present no instruments designed specifically for wide-field interferometry are operational. Consequently, there is little practical experience with any of the concepts that have been considered.

For future arrays with kilometric baselines there will be additional complications, from the need to transmit a large field over long distances to the number of detector pixels required for proper sampling at the Nyquist frequency. The ratio of baseline length to telescope diameter will be of order 1,000 or even more, which will make Fizeau-type beam combination schemes very inefficient. (Each single-telescope Airy disk would be crossed by 1,000 fringes!) On the other hand, none of the pupil densification or Michelson concepts proposed thus far seems to allow a convenient extension of the field by such a large factor, unless the bandwidth of each spectral channel is kept very small. As a compromise, one should perhaps design a next-generation general-purpose interferometer with variable baseline length, and provide a wide-field option only for the more compact configurations.

Finally, additional work will be needed to investigate the relation between the tolerances in a wide-field interferometric system, and the resulting precision of the astronomically relevant measurements. Most analyses have considered the loss of fringe contrast and derived admissible instrumental tolerances on the basis of requirements on the visibility amplitude. For practical astronomical applications similar studies have to be carried out for the photometric and astrometric integrity, taking the calibration strategy into account.

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