Multiple beam combination for faint objects

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ABSTRACT

The interference pattern of many beams includes multiple fringe sets, each for a corresponding pair of beams. These fringes must have a limited spectral band, so that they can extend far from the central, white-light fringe. It is possible instead to use a chromatic corrector in order to match the fringe spacing at different wave lengths. As a result, they will overlap over a much larger area, and thus improve the selectivity of the beam pairs.

Keywords: Stellar interferometry, beam combination, achromatic fringes.

1. INTRODUCTION

The problem how to combine beams in multiple-beam stellar interferometry has many solutions. A common way to solve this problem is to use a multiplicity of beam-splitters, fibre couplers, or wave-guide couplers, in the so-called Michelson approach. An array of beam-splitters is used to have full beams, arriving from different telescopes, interfere on a number of detectors. Fibre systems pick the whole stellar speckle pattern, or just a central speckle, filter it through its modes, and the beam splitting and combination are performed in fibre couplers, then leading again into a number of detectors (Figure 1). Instead of the fibre couplers, it is possible to use a planar wave guide, again feeding into a number of detectors. One can think of these options essentially as planar methods. Even if the beams or fibres stray a little off their plane, in the end they all end up lined up against an essentially linear multi-pixel detector. This approach is conceptually simpler, and has the added advantage of avoiding complex polarization issues arising from non-planar interferometers, also related to Berry's phase[1]. Its biggest disadvantage is the difficulty to expand it to a very large number of combined beams, as the system complexity becomes prohibitive.

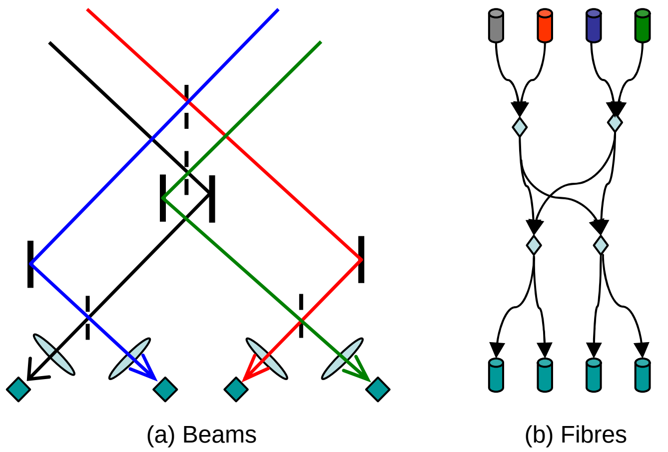

Figure 1: Michelson combination of (a) beams or (b) fibres using beam splitters or couplers. The Fibre option also requires accurate intensity calibration of each input, achieved with more splitters and detectors (not shown). These are essentially two-dimensional schemes.

We investigate here another approach, in which the beams propagate in free space, starting from an ordered planar pattern into another ordered planar pattern: the detector. These two planes are essentially parallel to each other. It

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is convenient if the output pattern maintains accurately the same shape as the original telescopes (the Fizeau approach), such as in masked aperture interferometry[2]. The hyper-telescope approach is similar, even if the beams themselves are magnified at a different rate from the original telescopes[3].

The free-space propagation does not require that the beams maintain their original order. It was proposed to line them in non-redundant spacings, so that on the facing detector every two beams form a fringe pattern of a unique frequency, non-redundant with the other ones. Fourier analysis can then separate the different pairs. This is still a one-dimensional approach, but now the fringes can be dispersed in an orthogonal direction, making use of the two-dimensional detector [refs for operating examples]. Alternatively, the beams can arrive from a two-dimensional non-redundant array, and the fringes will form on a two-dimensional detector (Figure 2)[4].

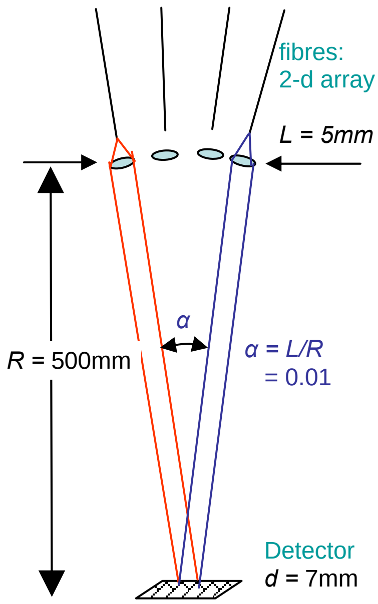

Figure 2: Non-redundant, two dimensional beam combination in three-dimensional space. The *f*-ratio of the fibres is extended by lenslets to be nearly collimated. The fibres and lenslets are inside a square of size $L \times L$ at a large distance R from the detector. The number of monochromatic fringes is $\approx R / L$. Typical dimensions are given.

When the achromatising optics are inserted in the free space between the lenslets and the detector, the fringes become polychromatic (Figure 5).

Yet another three-dimensional approach is to line the beams densely, and to interfere them with a copy of the same line of beams, now rotated at a right angle, as if in a table. In order that each beam interferes with every other beam, they are first expanded anamorphically into lines in the normal direction. In this scheme, as in the Michelson approach, detection of the fringes from each beam pair is unique, and is not swamped by fringes from other pairs[5]. This approach needs a special optical design because of the high anamorphic ratio ($1{:}N_{beams}$) and the 90^0 shear interferometer between the anamorphic beam array and its rotated copy. Because of the pseudo-Michelson combination, white light fringes are formed naturally (Figure 3).

Thus it can summarised in general that the two main approaches to beam combinations, as presented here, are either a linear array of beams and a linear detector, or a planar array of beams and a planar detector. The first is simpler, the second extendible to many beams.

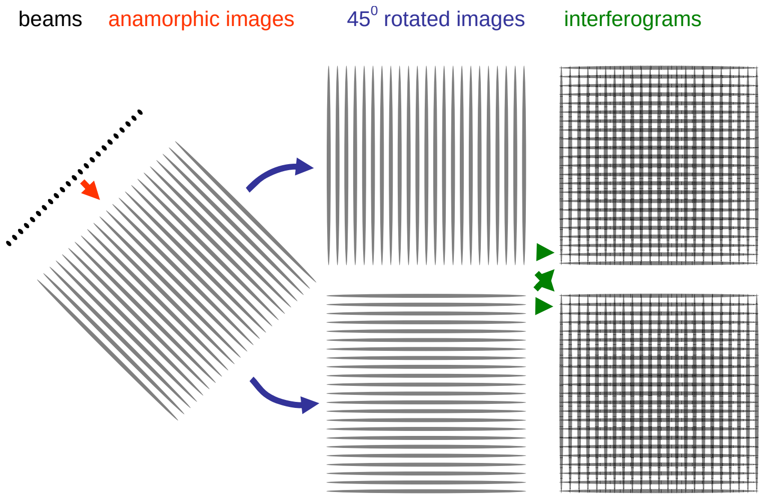

Figure 3: First the N beams are stretched anamorphically to N times their size. Then they are interfered with their rotated copy. As a result, we obtain white-light fringes between each beam and all the other ones.

2. THE COLOUR PROBLEM

In general, when two beams interfere, as in Young's experiment, we have a central white-light fringe, with a few colour fringes on each side, smearing into grayness after a few cycles, depending on the band-width of the system: the wider the band, the narrower the fringe pattern. When more beams are added, we get additional fringe sets, whose density and direction depend on the source beams. If we now want to separate these sets of fringes, we employ a Fourier transform to the combined pattern. In the transform, each fringe pattern is represented as a spot, whose amplitude and phase represent the complex visibility of that beam pair. However, the size of the spot depends inversely on the length of the fringe pattern, so the longer the fringes are, the tighter the Fourier spot is (Figure 4).

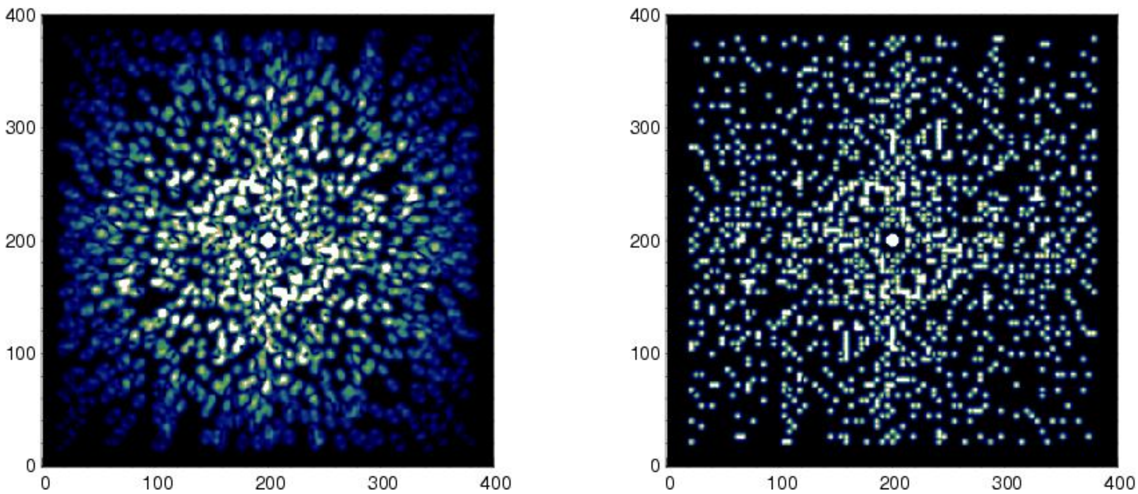

Figure 4: Fourier transforms of the fringe patterns between 36 beams in a non-redundant spacing (pseudo colour scale representing intensity). Even thought the relative bandwidth is rather narrow (left, 620-640 nm) there is smearing of the Fourier frequencies compared to monochromatic fringes (right). Actually, the fringes on the right were achromatised to within 5% for the much wider band of 600-700

Thus the length of the fringe pattern affects the signal in two ways: with a tighter spot the signal-to-noise ratio is improved. In parallel, the spots can now be denser in the Fourier domain without overlapping. Hence the Fourier domain can be smaller, and because of this, the detector can be smaller – the two domains have the same number of elements. And a smaller detector means that the light is concentrated in fewer pixels, with lower additive read-out or thermal noise.

To have a longer fringe pattern usually means to have a narrower band, again losing precious stellar light. Here we propose a different solution: achromatisation of the fringes.

3. THE COLOUR SOLUTION

Since fringes at different wave lengths have different spacing, they do not overlap and as the distance from the central fringe grows, this mismatch blurs the sum of the different fringes. It is possible to stretch the narrower fringes or squeeze the wider fringes according to their colour, so that they now match each other over a larger region. This way, when they add up, they do not smear until very far from the centre (Figure 5).

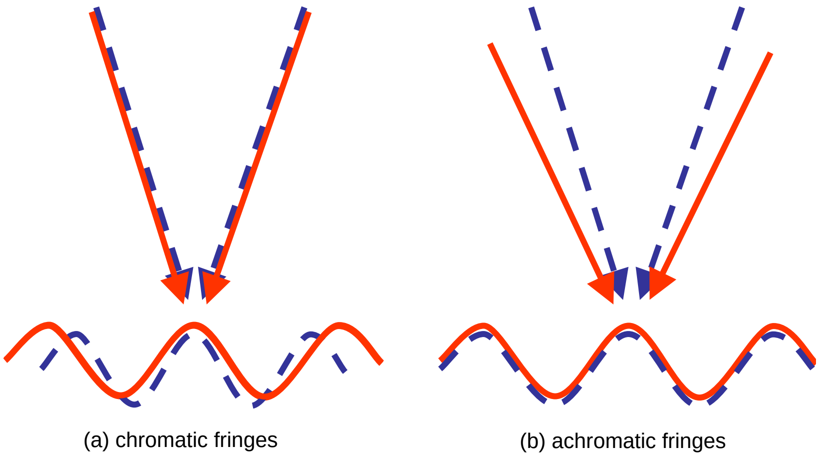

Figure 5: (a) When the two white-light interfering beams create fringes, the side fringes in red (full line)and blue (broken line) do not overlap and, upon addition, smear into gray. (b) When the interfering beams are magnified linearly with colour, the fringes now overlap at all colours. The colours have been shifted slightly for display purposes.

There are two well known ways to have different light paths for different colours. Colour dispersion is natural with gratings and prisms, and indeed they were utilised exactly for this purpose in the past[6]. However, this solution is limited to linear fringes, since the dispersion is in one dimension only. The same effect can also be achieved in two-dimensional patterns, by using combinations of either holographic or Fresnel lenses. While they can indeed produce magnification which is exactly linear with wave length, they have a limited diffraction efficiency, usually below 80%. This means that some of the light will not be focused, causing degradation of the signal and contributing to background noise. Alternatively, the non-diffracted light can be shunted into a simple intensity detector, which is essential for fibre beam interferometry.

It is possible to achieve the same fit with standard glass lenses. Such devices have been proposed in the past for speckle interferometry[7], and indeed applied for the dark speckle method[8]. Two other realizations of the device were constructed in conjunction with rotational-shear interferometry[9,10]. Even though the linear dependence of magnification on wave length is limited (around 5%), they produce indeed many fringes in white light. Their main deficiency is the very limited field of view, only seconds of arc.

The chromatic magnifiers are made from two complex lenses, each with a strong chromatic aberration (Figure 6). These are flat glass slabs made from glasses with different dispersion. The first lens has not effect on the central wave length, which has the same refractive index for all glasses, but at longer wave lengths it opens up the beam and at shorter wave lengths it focuses them slightly. This is because of the slight difference between the indices of glasses above and below the central wave length. After propagating at different angles for the different colours, a similar lens corrects the directions of the beams to the original ones, so that the blue is now parallel to the red. There are two main options: an afocal one and a focal one. In the afocal version, collimated beams remain collimated, but with a wider red cylinder of light as compared to a narrower blue cylinder of light. In the focal system, the lenses are placed symmetrically before and after the focus, where the cones of light are now at angles according to the wave length. Full design details are given by Wynne[7], with slight modification by D. Kohler[8] (in their Fig. 2, radii should have had opposite signs in the second triplet). The principle is given in Roddier et al.[9] The accuracy is limited by the matching between the dispersion curves.

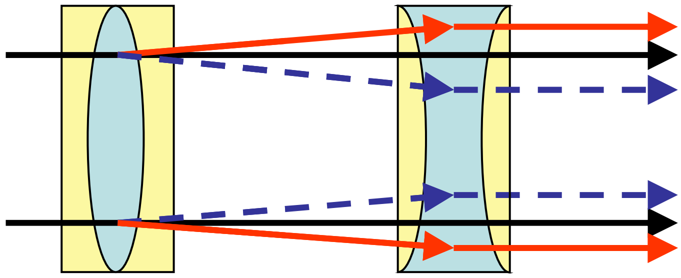

Figure 6: Achromatic fringes using triplets of crown-flint-crown inside parallel slabs. A ray at a wave length where the indices are equal is not deflected. A ray at shorter wave length (broken line) is deflected twice to create a narrower beam, and a ray at longer wave length is deflected twice in the opposite directions to create a wider beam. The distance between the triplets is so adjusted to get a beam width linear with wave length.

4. COLOUR BEAM COMBINATION

The fibred beam combination is a test case for the idea. In this method, light is collected from the pupil plane of a telescope, after correction of the wave front based on infra red measurements of its aberrations. The residual wave front is now corrected so as to have larger isoplanatic patch and lower Greenwood frequency[11]. In this way, the lenses focus light from larger areas of the aperture and for longer integration times onto fibres[12,13,4]. On the other side of the fibres, the light is collimated by lenslets into (nearly) parallel beams, then focused on a common detector to form fringes. The beams are spread non-redundantly in two dimensions, so that each fringe pattern is unique and can be separated by Fourier transforming the full image.

In both of these applications, the fringes will suffer strong colour mixing, and hence only the central few fringes will be visible. If now we insert the afocal colour corrector in the region where the beams are fully or nearly collimated, the fibres will look as if having spacing linear with the wave length. Thus the resulting fringes will have spacing independent of wave length. For the band width we are interested in, of 300 nm, the quality of correction can be such that tens of white-light fringes will be visible. To avoid spatial frequency smearing it is possible to insert another such corrector before the image of the aperture. Thus each mask will transmit a single spatial frequency.

Previous experience with the afocal colour corrector[10] showed us that it is extremely sensitive to direction, and can only correct within a very narrow field of view[8]. Thus it is essential that the beams are indeed well collimated and line up with the colour corrector. In the case that the beams converge onto the detector (Figure 2), the corrector has to be designed for the specific convergence angle.

To test the validity of the idea, we ran a simulation, combining 36 beams into fringe patterns on the detector. The number of fringes between them is $(36\times35)/2=630$. Upon transformation, we received 630×2 spots in the Fourier domain, where each spot has a mirror hermitian image because of the real data. At the band width chosen, 620-640 nm, the fringe frequency of each beam pair changed enough to cause radial smearing of the Fourier spot (Figure 4a). Upon extension of the band width to the range of 600-700 nm the spots actually merged and achromatisation was a necessity. Assuming a Wynne corrector with a non-linear portion of 5%, the spots tightened again to be distinguishable (Figure 4b).

5. LINEAR FRINGE BENEFIT

The design described above is valid for the three dimensional propagation from a planar set of fibres to a planar detector. However, it is also useful for the simpler case of a linear set of fibres, again at non-redundant spacing, now interfering on a linear detector[5]. While a diffractive element, a prism or grating combination, could be used for this simpler case, the fringe achromatiser described here will also be effective. In addition, the fringes can be dispersed in the orthogonal direction (channeled spectra) to provide information about the colour content of the astronomical object (Figure 7). Without chromatic correction, the fringes will open up with the wave length. With chromatic correction, the fringes will line up normal to the fibre direction. The main result will be that the required number of pixels for full sampling of the fringes can be reduced. In addition, the data processing will be simpler and comparison of different wave lengths trivial. For example, any differential dispersion between the two beams will show up as a deviation from this linearity. Any optical path difference will hinge the whole set of fringes.

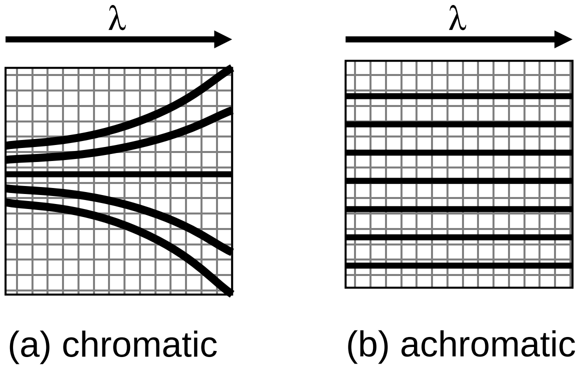

Figure 7: (a) Channelled spectra, chromatic fringes (only one set shown, between two beams). The fringes' spacing varies with wave length and requires more pixels and complex processing. (b) When the fringes are achromatised, the fringes become linear and make detection and calculation simpler.

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