ON THE ADVANTAGES OF DISPERSED FRINGES

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ABSTRACT

This paper summarises some of the considerations which entered the design of the Michelson interferometer proposed by ESA's Space Interferometry Study Team, and which may have some relevance to the designs of an astrometric interferometer following the lines of the GAIA concept. Particular emphasis is given to the question of the dispersion of the interferometric fringes, and it is shown how spectral dispersion leads to a significant improvement in the overall mission efficiency. Some preliminary ideas about how such fringe disperion could be implemented are presented.

Key words: GAIA, space astrometry, interferometry

1. INTRODUCTION

It has become clear that the ESA scientific programme will not accomodate a large *imaging* interferometer in space in the foreseeable future. Therefore, some members of the imaging community have begun to investigate whether some of their ideas might be useful for an interferometric *astrometry* mission like GAIA, which appears to have a much better chance of being realised within their lifetime.

The present author has been involved with ESA's activities in the area of optical interferometry in space since 1981, including the ESA Space Interferometry Study Team in 1988-90. In its report (SIST, 1990), it outlines two concepts for a multi-element imaging interferometer in space, a Michelson and a Fizeau. The Michelson concept was preferred because it allows baselines longer than about 10 meters.

The SIST report provides some details about a possible design for such a Michelson interferometer, which was mainly based on the OASIS concept (Noordam et al. 1987). In this paper, a summary will be given of the relevant parts of the design. It is followed by a discussion of how one of these, i.e., dispersed fringes, could be applied to GAIA. Other aspects might also be of interest.

2. ASPECTS OF THE SIST DESIGN

The SIST design for an imaging Michelson interferometer in space consists of a two-dimensional array of 10–15 optical telescopes, each with a diameter of 30–50 cm. They are mounted on a 'weak' inflatable structure with dimensions of about 100 m. The field of view is split into three subfields, which are separated by up to 0.5°: an on-axis 'science' subfield, and two subfields with off-axis reference stars. Each subfield has the size of the diffraction limit of an individual telescope, which is 0.2 arsec for a diameter of 50 cm. The 3×10–15 beams are combined in three separate beam combining units, one for each subfield. The reference stars have to be bright enough (< 11 mag) to provide feedback information every 10 msec or so, for controlling the telescope pointing and the optical delay lines. The 'science field' is calibrated by coupling its delay lines to those of the reference star fields.

The SIST design is really a worst-case analysis of how much the stablity requirements can be relaxed, in terms of attitude control and structural deformations. It turns out that the numbers are quite acceptable. The pointing accuracy of the overall (100 m) structure only has to be about 1 arcsec. Structural deformations of up to 1 cm/s can be tolerated, as long as their power spectrum does not contain frequencies above 1 Hz.

2.1 Fringe Detection

In the SIST design (and many other Michelson designs), fringes are produced by combining the incoming light from different telescopes under a small angle on a 2D detector, while dispersing the light in a direction parallel to the fringes at the same time. Each combination of two beams then produces a fan-shaped fringe pattern as shown in Fig. 1.

Figure 1. A fan-shaped fringe pattern formed by beam-combinination with dispersion. Note that one of the axes is frequency. The fringe period increases with wavelength. The white-light fringe is the vertical one.

Such a fan-shaped pattern of dispersed fringes has the following properties:

- the fringe spacing is determined by the beam combining angle, and by the wavelength. The latter causes the fan-shape, with the fringe period increasing towards longer wavelengths.
- the fringe contrast is a measure of the visibility amplitude. An extended source will have lower contrast than a point source. The contrast is strongly influenced by various instrumental imperfections, and thus not always easy to measure.
- the position of the central 'white-light fringe' of the fringe fan is determined by the 'optical pathlength difference' through the two arms of an interferometer. This is the sum of the (wanted) visibility phase, and a host of instrumental optical pathlength differences which have to be calibrated out.
- the number of discernable fringes (i.e., the width of the fan) is determined by the coherence length $\lambda^2/\delta\lambda$, where $\delta\lambda$ is the bandwidth of a frequency channel, i.e., the bandwidth covered by a detector pixel in the frequency direction.
- the ('horizontal') movement of the fan over the detector is caused by residual optical pathlength difference variations, i.e., those that are not compensated by the delay lines. (The optical pathlength of each beam is compensated smoothly and continuously by its own individual optical delay line). These movements play an important role in fringe detection.
- any distortion of the nominal fan-shape is caused by frequency-dependent source structure (e.g. a red and a blue star, at different positions in the field), and by instrumental dispersion.

It is recommended to use single-mode optical fibres at the input of the beam combining units. Their small diameter allows close packing and good control over the beam combining angles, resulting in a well-defined shape of the fringe-patterns. Fibres also improve the fringe contrast (at the price of throwing away useless photons) by only allowing one mode to propagate.

Figure 2. An array of N telescopes produces $N(N-1)/2$ different fan-shaped fringe patterns on the same detector. They can be distinguished from each other, partly because they have different fringe spacings, but most of all because each fan moves 'horizontally' over the detector with a different velocity.

For an imaging interferometer, the 10–15 incoming lightbeams have to be combined *simultaneously* on the same detector (see Fig. 2), in order to take advantage of 'closure phase' techniques. This means, that for N telescopes, there will be $N(N-1)/2$ separate 'fringe fans' on the same detector. These 45–105 fans will have to be distinguished from each other. It helps of course that the fringe spacing can be made different for many (but not all) fans, by choosing the beam combining angles carefully.

But the most helpful aspect is that all fans move over the detector continuously with different speeds. This is due to the inevitable slow temperature deformations in the overall structure, which cannot be completely compensated by the optical delay lines. Each individual fringe-fan can be detected separately by weighting the (x, y, t) coordinates of all detected photon events with a software mask, which is (adaptively) matched to its particular shape and movement. Such a mask acts like a single spatial frequency in a specialised Fourier Transform: it will be very sensitive to photons belonging to 'its own' fringe-fan, but the effects of photons belonging to other fans will rapidly average out to a background of white noise.

Thus, the SIST design reaches its goal of $\lambda/10$ optical pathlength stabilisation in two steps. The first step is the optical delay lines, which keep the optical pathlength differences well within the coherence length which can be as large as tens of microns if the channel bandwidth is narrow enough. The second step is moving fringe detection in conjunction with closure phase, which determines the remaining optical pathlength errors per telescope.

2.2 Fizeau versus Michelson

The SIST decided to prefer the Michelson concept to the Fizeau mainly because the magnification of a Fizeau is *very* sensitive to variations in the relative position of the primary and secondary mirrors. Even for a reletively small baseline of 6 m, the required accuracy was 0.1 μm, which was considered problematic. Moreover, a Fizeau mission seemed inappropriate because the concept does not seem to be extendable to baselines of 100–10 000 m.

3. RELEVANCE TO GAIA

It is clear that the SIST concept oulined above (and described in more detail in the SIST report) cannot be applied directly to an astrometry mission like GAIA. The latter requires a very wide field, and should preferably not have any moving parts. However, as an example of how some of the ideas can be relevant, we will treat the case of dispersed fringes. We will emphasize their advantages over the modulating grid method that is used in the GAIA 'baseline design' (Lindegren & Perryman, 1995), which will be called the LP-design from here on. We will then investigate whether there are possibilities to include them in the GAIA design.

The advantages of direct detection of dispersed fringes are the following: (a) they allow a 10× higher sensitivity because of larger total bandwidth (2×), direct fringe detection (3×) and higher fringe contrast per channel (2×); (b) all wavelengths are measured simultaneously, which has advantages for science and calibration; (c) they offer a better grip on non-point sources; (d) they allow longer baselines without loss of sensitivity; (e) there may be possibilities for a larger field size; (f) they offer a large coherence length, which is important for Michelson solutions; (g) last but not least, a high spectral resolution increases the scope for interesting auxiliary programmes.

However, it is not trivial to reconcile the requirement of dispersed fringes with the requirement of a wide field. The latter is difficult enough in itself. Several authors at this workshop have addressed the problem that existing detectors do not have a pixel size that is small enough for a 3 m baseline and a field of one square degree. And even if such a detector could be made in the future, only one pixel in 10^4 would be usefully occupied at any one time.

The design proposed by Lindegren & Perryman (1995) cleverly solves this problem by *exchanging spatial (pixel) resolution for time resolution.* The modulating grid produces a single time-modulated output signal for an entire subfield of several hundred square arcsec, which is received by a single pixel of the detector. The only requirement is that the time-resolution of the detector is high enough to sample the time modulation which is caused by the fringed star image(s) travelling over the grid.

Even if dispersed fringes could be produced in the design proposed by Lindegren & Perryman, for instance by means of a objective prism, it does not seem possible to devise a modulating grid to match them. For the sake of discussion, two rather immature ideas for alternative approaches (i.e., without modulating grid) will be outlined below.

Figure 3. Exchange of spatial (pixel) resolution for time resolution in the case of dispersed fringes. This method is used in the LP-design of GAIA, but for a single wavelength band defined by a filter. Note that the fringe pattern looks the same as in Fig. 1, but that the horizontal axis now represents time. For each sub-field on the sky, all the photons of a particular frequency are detected by a single pixel. The fringe pattern moves 'horizontally' at a constant speed, because the optical pathlength difference for a particular star changes smoothly as a result of the rotation of the satellite. The 'time-position' of the row of detectors (one per frequency channel) is indicated. The necessary time resolution (μsec) to sample the fringe pattern properly is achieved more easily than smaller detector pixels.

3.1 A Massively Parallel Michelson

If it would be possible to couple all the light from a subfield of, say, 10×10 arcsec^2 with reasonable efficiency into a single-mode optical fibre, the following approach might be an interesting alternative design for GAIA.

Each telescope would be a Schmidt telescope, with a diffraction-limited field of 1°. Their focal planes would be covered with the closely packed inputs to single-mode fibres, each of which would define one subfield on the sky. Each fibre would form a zero-angle Michelson interferometer with its counterpart from the other telescope, perhaps using some kind of 'fibre directional coupler'. The combined output would then be dispersed, and fed into a single detector per frequency channel. As a star travels across a subfield through the rotation of the satellite, the optical pathlength difference changes smoothly, and the detector would alternatingly see light and dark (see Fig. 3).

Some numbers: a focal ratio of $f/D = 10$ gives an image scale of 25μm/arcsec. So a 10 arcsec subfield would have a size of $250\mu m$. For a telescope diameter $D = 50$ cm, an Airy disk would have a diameter of 0.2 arcsec, or $5\mu m$. The length of each fibre is chosen in such a way that the optical pathlength difference is zero when it is in the middle of the subfield that the fibre represents. Thus, the fibre length will depend on the position of its subfield in the field of view, and has to be accurate to about $10\mu m$ (the actual length error must be *known* to a much greater accuracy, of course). Since the optical pathlength difference of a star changes by about $150\mu m$ (or 300 fringes at $\lambda = 500$ nm) when moving across a subfield of 10 arcsec, the coherence length has to be at least that large. This means a frequency resolution of at least $R = 300$. Detectors must be of the 'time-tagging' type, with high quantum efficiency, and a time resolution of μs.

Fringe detection would be done with an adaptable software mask, like in the SIST design. This method can handle multiple fringe patterns if there is more than one star in a subfield, as long their white-light fringes do not coincide. Unfortunately, their fringe fans will always move with the same velocity, and will introduce systematic errors if the white-light fringes are within a few fringes from each other. It may help a bit to reduce the size of the subfield, but that does not remove the effect of faint background stars.

Obviously, the number of subfields, and thus the number of separate Michelson interferometers, will be rather large: 10^5 in our example. Each fiber will have to be positioned carefully in the field of view, and cut to the right length to give the correct optical delay. However, note that the number of detector pixels is not particularly large, especially if a frequency-discriminating detector (see Perryman & Peacock, 1995) could be used. Moreover, since there is on average at least one (≤ 20 mag) star in a subfield at all times, all pixels would be usefully occupied.

Other problems are presented by the properties of optical fibres, particularly their temperature-dependence. It would be necessary to reduce the number of independent parameters as much as possible by putting the fibres in close temperature contact, and to increase temperature time constants by good insulation. Active temperature control is not recommended.

However, it is probably impossible in the first place to meet the basic condition mentioned at the beginning of this section. This can be easily veryfied by reversing the direction of the light. However, since the present workshop is supposed to have the character of a brainstorm, others may know of a way to construct a Massively Parallel Michelson that *would* work.

3.2 Fizeau with Objective Prism

Le Poole (1995) has suggested the following way to produce dispersed fringes with a Fizeau. A short outline is reproduced here, although it probably does not do the concept full justice.

Firstly, the need for a modulating grid is removed by a combination of methods that have been proposed in various forms by other authors at this workshop. The wavelength is increased to a few microns. The image scale is increased to increase the fringe spacing. Then new software techniques are used to sample the fringes 'properly' with pixels with a size as large as 2λ.

Secondly, dispersed fringes are produced by means of an objective prism or a (reflective) aperture grating. These devices convert the image of a star image into a spectrum. Obviously, the dispersion should be parallel to the fringe direction, i.e., perpendicular to the scanning direction. It should also be shorter than the average separation between stars, in order to avoid confusion. By making the image scale in the scanning direction different from that in the dispersion direction, and given the expected size of detector pixels, it should be possible to split up the total bandwidth in about 10 channels.

Obviously, this approach has drawbacks. But it has the advantage that it does not violate the 'Second Law' like the fibre idea above, and it seems technologically feasible. Most of all, it brings into reach the coveted prize of direct detection of dispersed fringes.

4. CONCLUSION

The conclusion is that the existing 'LP-design' design for GAIA will certainly work, and probably meet its specifications. However, finding a way to use dispersed fringes instead of a modulating grid offers so many potential rewards that it should have a high priority. The same may be true for some other ideas from the field of imaging interferometry.

But in terms of workable solutions for the next step in global astrometry in space, the 'official' LP-design of GAIA remains the best one available for the moment.

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