OBTAINING SPECTRAL INFORMATION FROM AN ASTROMETRIC INTERFEROMETRY MISSION

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ABSTRACT

In this note given are few principles and designs aiming at getting spectral information on GAIA in parallel with getting astrometric information. One approach is to consider separated instrumental channels, another one is to modify the encoding of information so as to multiplex and then extract both spectral and astrometric data. In this latter, the goal is to introduce a third dimension dedicated to wavelength beside the two dimensions dedicated to field coverage and sampling. In this purpose, the reflexion is based on the principles of flat tint modulation, Fourier spectroscopy and channeled spectrum. It is clear that further investigation in terms of numerical figures is needed, but this is beyond the scope of this note.

Key words: space astrometry, GAIA

1. INTRODUCTION

This paper is an attempt to clarify the 'impromptu' thoughts about spectral information on GAIA, that I have briefly outlined during the workshop. To begin with, it is worth giving the guidelines along which the reflexion has been conducted. As I believe, the objective here is to find a way for getting spectral information without reducing the priority of the astrometric mission. Therefore the capabilities and operation mode of the present configuration (our baseline configuration, see Lindegren & Perryman 1994, 1995, is referred to as the LP-design in the following) must be preserved as far as possible. In particular, the various conceivable schemes must keep untouched the field sampling capabilities.

On another hand, it is worth looking at the motivations for spectral information. In this regard my feeling is that interferometry here is dedicated to accurate position sensing and not to astrophysics. This means for example that spectral information primarily aims at detecting multiplicity of sources or other peculiar morphological features (envelopes) so as to help in disentangling complex signals resulting from crowding in subfields. Actually those aspects are already taken into account by the LP-design, be it by means of a set of non redundant baselines and by using a set of filters. Nevertheless, using filters sequentially in time might be considered as a limitation since only a fraction of the collected spectrum is available at a time. A synthetic spectral information could then be an improvement inasmuch it could provide straightforward de-crowding and permanent use of all photons, and would not require high resolution.

2. BASIC GUIDELINES

A number of interferometers rely on dispersed fringes to encode spectral information and this is about to be a natural approach. On GAIA, since the two coordinates x and y in the focal plane are used for field sampling, it seems inappropriate to use any of them to accommodate a dispersed fringe pattern. Actually, with the grid modulation scheme, some idle pixels are available but they lie in a direction perpendicular to the fringes, so that dispersion should not take place along this direction, though it is possible to display several adjacent spectral channels each showing a fringe pattern.

In addition, as the source moves across the field, the fringes would rotate and this would introduce some supplementary complication in the analysis of the pattern. Therefore, it could be interesting to find another way to encode spectral information and this has been the starting point of my reflexion, at least regarding what could happen downward the Fizeau fringes.

Among others, there are two known methods for encoding spectral information in interferometers without using dispersed fringe-pattern in image plane. One is to record Michelson-Fourier interferograms (Gay & Mekarnia 1988; Mariotti & Ridgway 1988, Dyck & Benson 1988) the other is to display a channeled-spectrum (Traub & Lacasse 1988) which is but a dispersed version of the Michelson interferogram.

Now, it is possible to consider the problem before entering the Focal Plane Assembly and an approach could be to divide the incoming photons in two parts: the ones for astrometry and directed towards the LP-design and the ones for spectral information in a separate channel.

The use of non-homothetic output pupils (Michelson scheme as opposed to Fizeau scheme) has been mentioned during the workshop as something worth looking at. This case is well suited for the multiplexed encoding which is looked for. However the much reduced field of view when using Michelson interferometer is a serious drawback to be faced. At first sight this feature nearly eliminates such a scheme, unless some technical solution would be found to overcome this limitation.

In the following sections, some possible approaches are briefly described in terms of principle and possible set-up. Obviously some numerical figures should be attached in order to evaluate feasibility, but this is beyond the scope of this preliminary mental agitation.

3. USE OF DEDICATED & SEPARATED CHANNELS

Here the working principle of the focal plane assembly of the LP-design is maintained, but not preserved in terms of available flux, except for one solution relevant to the case of an amplitude grid which would avoid this limitation. This latter choice is but mentioned, because it seems quite uneasy to implement and/or to accommodate, according to the present design of the telescope. In addition using a phase grid prevents this choice.

3.1 Off-axis Reflective Amplitude Grid

As far as it would be technically achievable, a grid with opaque parts made reflective for incoming photons is a way to recover photons otherwise lost. They would be then directed to a suitable optical system providing dispersed fringes or another encoding. It is also possible to imagine a substrate shaped as an off-axis mirror instead of a flat one, so that the images of the pupils could be formed at the entrance of the optical system, but here aberrations induced on transmitted light by the substrate could be prohibitive, and bias on position could result from inserting non uniform pathlengths across the field (though removable with proper calibration).

3.2. Amplitude Division Before the Grid

Slightly less unrealistic is the case shown in Fig. 1 below, where a field lens in focal plane images the entrance pupils onto a lens which collimates the beams. Then a beamsplitter plate or cube directs a selected fraction of the flux perpendicular to the axis, towards some optical system managing for 'spectral information', for example in forming fringes somewhere and dispersing in the appropriate direction.

Figure 1. Separation of photons for dedicated channels

The remaining part of the flux follows the original direction in parallel beams which again meet a lens forming images of the source in a new image plane where the LP-design can work. This lens also forms backward a virtual image of the pupils in order to maintain the 'Fizeaubility' of the configuration. Using parallel beams is in principle not mandatory, but this choice is likely to minimize aberrations. If the use of a unique polarisation ends up being cleaner for interferences at the focal plane assesmbly, it is possible to use a polarizing cube, so that photons rejected by the astrometric channel are used by the spectral channel.

4. MULTIPLEXED ENCODING

4.1. Interferograms and Channeled Spectrum in Optical Path Difference Space

The basic idea comes from what is sometimes called flat-tint modulation commonly met in various interferometers (Mackay & Baldwin 1988; Carleton 1988; Shao 1988) associated to the temporal coherence variation versus optical path difference between the collecting apertures (Gay & Mekarnia 1988; Mariotti & Ridgway 1988; Dyck & Benson 1988). It can be viewed as the limiting case of the Young's slit (Rabbia 1988), where the separation of the holes is virtually made zero, then the fringe's period is made infinite and the image of superimposed pupils shows a uniform illumination (flat tint). The intensity of illumination depends on the optical path difference between the two pupils. As the optical path difference varies linearly, the intensity oscillates at a given period around an average intensity.

Now as the optical path difference increases, the amplitude of oscillations varies. This variation is governed by the temporal coherence of the radiation: nearly constant for monochromatic light, rapidly decreasing for a large bandwidth. Moreover, the shape of this variation (envelope of oscillations) is linked by a Fourier Transform to the spectrum of the radiation. So that recording the variation of the envelope versus the optical path difference, gives a mean to recover the spectrum (resolution is linked by inverse-law to the maximum optical path difference excursion) a method called Fourier spectroscopy (Connes 1970).

If images of superimposed pupils are formed through a dispersive system, we find a sequence of adjacent flat tints at various levels of illumination. Those levels oscillate with an amplitude determined both by the optical path difference and by the spatial coherence of the source at the working baseline. For a point like source with an optical path difference near zero, intensity oscillates between (nearly) zero and twice the collected intensity. At a given optical path difference, the intensity is modulated along the direction of dispersion (Fig. 3), and there appears a sequence of alternating bright and dark stripes, the channeled spectrum (Traub & Lacasse 1988).

As the optical path difference changes, the spacing of the stripes changes accordingly and they globally slide along the dispersion axis, unmasking every spectral channel at its turn (near zero optical path difference no masking occurs), so that a spectrum can be reconstructed. Let us recall that primarily only a rough shape of the spectrum (or the detection of a double spectrum) is looked for, not a well calibrated spectrum for astrophysical purpose.

What is attractive with these approaches in the case of GAIA is that we have a continuous and linear variation of the optical path difference between the two apertures and that spectral information could be recovered without affecting the field sampling, since spectral information has been transferred to the optical path difference space. Now, the problem with GAIA is to find a design able to provide a superimposition of collecting apertures, and then to find accommodation for a channeled spectrum.

4.2. Applications to GAIA

It must be noted than if the flat tint modulation is naturally used in pupil plane (hence a terminology confusion sometimes met) it works also in image plane (this kind of a drawback, here), but in any case requires a superimposition of pupils. We can imagine to install before the focal plane assembly a Michelson spectral interferometer with beam splitter and mirrors, providing superimposed images of the source or of the pupils. The corresponding set-up has something to see with the one presented in Section 3.2, Fig. 1, and will be seen later on.

But things could be made simpler, if we notice that behind the grid we do have superimposed pupils: orders 0 and 1 (also 0 and -1) of the diffracting grid, (Lindegren & Perryman 1994). As soon as the light modulation would be interpretable as the result of the optical path difference variation between the two apertures, our interferogram is already here (Fig. 2.).

Figure 2. Representation of the use of Michelson interferograms from the modulation of superimposed pupils.

The point is that since the spectral bandwidth is limited and the optical path difference excursion within a subfield as well. Therefore the envelope of oscillations might show no significant variation. Limited bandwidth put the need for a large excursion, if not, the resolution of the expectable spectrum is made so poor that no spectral information can be extracted. A solution could be to increase the bandwidth and/or to enlarge the subfields. Algebraic derivation shows that an upper limit exists for the bandwidth, and enlarging the subfields increases crowding, what is not desirable.

Conversely, if enlarging the bandwidth is made possible, it results in a narrowing of the envelope of oscillations. Then the interferogram might reduce to (nearly) a single pulse superimposed to a uniform intensity. Hence the ability of determining phase is reduced (no oscillation available), and so is the ability of recovering any envelope for spectrum. However, this effect might be compensated by a better signal to noise ratio provided by larger bandwidth. On another hand, the narrowing of the envelope allows to clearly detect multiple objects in the subfield (without help of spectral information).

Further analysis, out of the scope of this note (and over available time) must be made in this regards, as far as such an approach would remain under consideration.

Now we can consider the use of channeled spectrum (Fig. 3). Since idle pixels might be used besides the area of superimposition (made free from extra light thanks to masks) it is possible to insert a dispersive component before the final imaging of pupils onto the detector, and to have two twin spectra (0/1 and 0/-1). Here again numerical figures would be necessary to evaluate feasibility, but the principle is there.

Let us note that in addition to making available the spectral information, the sliding of dark fringes might be taken advantage of, for example to monitor the scanning rate, and other information to extract from autocorrelation, cross correlation and so on. However, caution must be taken that the intensity variation is periodic only when it is displayed versus the spectral wavenumber $\sigma = 1/\lambda$.

Figure 3. An idealized representation channeled spectrum applied to images of superimposed pupils behind the grid.

Now let us come back to the Michelson interferogram. There still remains the problem of fast passing and limited optical path difference excursion, so it could be nice to slow the interferogram and to increase the optical path difference excursion. For example, if we can explore the interferogram during a time corresponding to the crossing of the whole field instead of a subfield, there would be a nice slowing factor.

The set-up shown in Fig. 4 might give an answer to this problem. Basically the idea is to artificially introduce a supplementary optical path difference variable with the source's position (astronomical and artificial optical path difference would be of opposite sign). Similarly as in Fig. 1, a beamsplitter cube is used but now it is used as a Michelson interferometer, in making the appropriate faces reflective. As the star crosses the field, the beam moves within the cube's reflecting faces, at constant separation.

Figure 4. Introduction of a supplementary optical path difference variable with the source's position

At the output face an optical element (as in Fig. 1) focuses images of the source at the entry of the LP-design. No light is lost as soon as a 50/50 splitting is achieved, and 'Fizeaubility' is maintained as in Fig. 1. Now, in order to insert a variable optical path difference, and before aluminizing the reflecting faces, glass plates are installed as shown in Fig. 4. One is a plate of suitable thickness, the other is a composite plate, made of two glass wedges of unequal optical indexes. This configuration has something to see with the Girard interferometer (Girard 1970) used in the past for astronomical Fourier spectroscopy, but here instead of regular plane wedges, we use parabolic wedges (Fig. 5). Indeed, if plane wedges were used the optical path difference between the two apertures will remain constant. In order to have a linearly variable optical path difference a square law profile is needed.

Figure 5. Schematic representation of the composite plate.

Let us denote by $l(\alpha)$ the optical path difference induced by the crossing of such a composite wedge, α being the location of the beam's impact on the reflecting face. We have:

$$l(\alpha) = ne(a) + n'(e_0 - e(\alpha))$$

where e_0 is the total thickness of the composite plate, and n and n' the optical indexes. The optical path difference inserted between the two apertures (moving with a constant separation of $\Delta\alpha$) is:

$$\begin{aligned} \mathrm{OPD}(\alpha) &= 2(l(\alpha + \Delta\alpha) - l(\alpha)) \\ &= 2(n - n')(e(\alpha + \Delta\alpha) - e(\alpha)) \end{aligned}$$

where the factor 2 traces the back and forth crossing (due to reflexion on the upper face). If $e(\alpha)$ is linear versus α, OPD(α) depends on $\Delta\alpha$ but not on α itself. If $e(\alpha)$ is parabolic, $e(\alpha) = g\alpha^2$ we find:

$$\mathrm{OPD}(\alpha) = 2(n - n')g\Delta\alpha^2 + 4(n - n')\Delta\alpha g\alpha$$

The constant term is compensated by the other plate. By proper selection of n, n' and g (related to the mean slope of the wedge) the rate of variation is controlled. Consider a pixel area reading the modulated light from the grid. Since the average optical path difference within the subfield is now changed from one subfield to the next, we will have a corresponding change in amplitude, according to the shape of the envelope.

Thus the envelope of the interferogram can be recovered by pieces with a total excursion displayed over the whole field (and not a subfield) and with a selected total excursion. Recording the sequence of amplitude A_k of each subfield k, we recover a sampled envelope. A Fourier transform provides then a sampled spectrum at the end of the source's transit (Fig. 6).

Note that this scheme can be implemented behind a field lens array, thus limiting the angular excursion within the cube, but not the total excursion of the optical path difference. As a matter of fact, many variations around this basic scheme can be conceived, in order to overcome some technical difficulties (as for example the problem of manufacturing and properly assembling the composite plate) or in order to add some capabilities (as for example a virtual grid matched to every wavelength or the use of rotation shearing). Obviously, allowing observation time for oscillation of reduced amplitude (down to zero sometimes) is somehow a limitation of performances, but we cannot pretend to have everything and pay nothing. As usual, the problem is to carefully evaluate expected gain before viewing any suggestion as an answer.

Figure 6. Reconstructing envelope and spectrum from amplitudes at various optical path difference.

5. CONCLUSIONS

The various schemes presented in this note have been devised having in mind some working conditions to maintain (mainly the field coverage) in order to keep on using the LP-design (Lindegren & Perryman 1994, 1995) other conditions would have generated other concepts. They do not pretend to be more than mental agitation on a fascinating topic, in the framework of the technical session of the workshop. As they are based more on spontaneous intuition than on engineering computation, it is clear that further investigation is needed regarding relevance, feasibility and reasonably expectable performances, in terms of numerical figures.

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