A SUPERCONDUCTING DETECTOR FOR A FUTURE SPACE ASTROMETRY MISSION

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ABSTRACT

Within the last two years, an entirely novel optical detector concept, based on superconducting phenomena, has been developed and demonstrated in ESTEC. In principle, such a device could provide the basis of a photon counting detector having high spatial resolution (10–30 microns), high quantum efficiency (approaching unity) over a broad wavelength region (from the UV into the near IR), with high time resolution (below 10 microsec), high dynamic range, and providing energy resolution (at around 10 nm for a niobium device). Such attributes would essentially combine the merits of a CCD-based system with those of a photon-counting detector. Use of such a system within the proposed GAIA concept would allow direct measurement of the photon arrival times and position, and would thus provide a direct measurement of the light modulation without the need for the 'integrate-and-shift' approach considered so far for a CCD-based system. The intrinsic energy resolution of the device could benefit both the interferometric and incoherent modes, providing low-resolution spectroscopy in parallel with the astrometric measurements. The disadvantages of such a detector concept, in addition to its technological immaturity, are the requirements for cryogenic operation (below 1 K), the development complexity of a large detector area, and the resulting data rate.

Key words: space astrometry, GAIA, optical detectors

1. INTRODUCTION

The GAIA concept for an interferometric space astrometry mission (Lindegren & Perryman 1994a, 1994b, 1995) provides orders of magnitude improvement, with respect to Hipparcos, in terms of accuracy, number of objects, and limiting magnitude. Optimisation of the GAIA photometric system defined by the baseline interferometric mode could lead not only to a profound improvement in the study of stellar variability, but also to spectral classification through intermediate-band multi-colour observations at the instrument's focal surface. In addition, consideration is being given to the parallel determination of the sixth astrometric parameter, the radial velocity (Favata & Perryman 1995). Improved determination of spectral type, luminosity class, metallicity, and spectral peculiarities may be feasible, and this would lead to GAIA performing the most dramatic census of the galactic stellar population contemplated to date.

One of the reasons for the considerable improvement in performance expected from GAIA, compared with Hipparcos, is the proposed detection system: for Hipparcos, a (photon-counting) image-dissector tube was employed, with the sensitive area of the detector being pointed sequentially to the object being observed. Although CCD's were investigated as a possible detection element for Hipparcos during the early Phase B studies in around 1982, they were excluded on the grounds of techological immaturity—aspects such as cooling, charge-transfer efficiency, and response stability were considered inadequately advanced. The technology has, of course, now advanced considerably, and the possibility of treating the CCD as the baseline detector for an interferometric astrometry mission results in improved detection efficiency, as well as improved observational efficiency since all objects in the focal surface can be observed in parallel, rather than sequentially.

The practical implementation of a CCD-based detection system has recently been considered in further detail by Høg (1995). The need for careful assessment of the effect of charge traps on the performances resulting from repeated forward and backward clocking, especially for the case of radiation-damaged CCDs, has been noted by Lumb (1995).

In the original accuracy estimates, Lindegren & Perryman (1994a) discussed a 'baseline option', based on the use of modulating phase grids, and a 'direct fringe detection' system, based on the existence of a hypothetical detector with sufficient spatial resolution to replace the modulating grid. The potential availability of a high-efficiency photon-counting detector underlies the consideration of the possibility of direct fringe detection, as considered in the original GAIA proposal. As an indication, the baseline option was expected to lead to accuracies on parallaxes and annual proper motions, at $V = 15$ mag, in the range 6–12 μas, while direct fringe detection was expected to lead to corresponding accuracies in the range 2–3 μas. This further increase in the astrometric performances, and also in the expected limiting magnitudes (of about 20 mag), motivates the requirement to look into alternative detector concepts.

2. OPERATIONAL PRINCIPLES OF THE STJ

Whereas a CCD relies on the excitation of an electron to the conduction band, separated by a band-gap of the order of 1 eV, the superconducting ground state (Cooper pairs) is separated from its excited (quasiparticle) state by an energy gap some three orders of magnitude smaller (around 1.5 meV for niobium). A single photon impact can thus create thousands of free charge carriers, depending on the actual photon energy. Extraction of the free charge before relaxation to the ground state (which occurs on a time-scale of order 100 ns), employing a superconducting tunnel juntion (STJ), can therefore, in principle, lead to a panoramic photon counting detector having high spatial resolution (10–30 microns), high quantum efficiency (approaching unity) over a broad wavelength region (from the UV into the near IR), with high time resolution (below 10 microsec), high dynamic range, absence of dark current and readout noise, and providing energy resolution (at around 10 nm for a niobium device).

The theoretical possibilities for optical photon-counting were considered by Perryman, Foden & Peacock (1992, 1993). First experimental results, obtained at ESTEC, were very encouraging, demonstrating the expected response to monochromatic light in the range 250–1100 nm (Rando et al. 1995). Recent experiments have successfully achieved photon counting performance, with high QE and modest energy resolution (Peacock et al. 1995).

3. FUTURE PROSPECTS

The laboratory development of the optical STJ detector is proceeding rapidly, with the following prospects relevant to the possibility of a space-based detector:

(a) pixel size: in its simplest realisation the pixel size of the superconducting detector is defined by the size of the superconducting tunnel junction deposited on a substrate. Each junction has its own read-out electronics, leading to the determination of the photon's time of arrival, energy, and position. In this approach, the positional resolution is determined simply by the junction size; presently, junctions can be manufactured in the size range $10 \times 10\mu m^2$ to $50 \times 50\mu m^2$. Smaller junctions are easier to manufacture than larger junctions (the control of the barrier uniformity being one of the present limiting factors in the detector performance).

(b) the energy resolution is determined by the number of free charge carriers tunneling as a result of each photon absorption event. The number of quasiparticles per photon event is primarily determined by the superconducting material: the number of excess charge carriers created being of order $h\nu/\Delta$, where $h\nu$ is the photon energy, and 2Δ is the (temperature and magnetic field dependent) energy gap, which is of order meV. Δ decreases linearly with the superconductor's critical temperature, T_c, ($\Delta \sim 3kT_c$ from BCS theory), so that improved energy (spectral) resolution can be obtained with lower T_c devices. Thus theoretical expectations are for $\Delta\lambda = 13$nm for Nb, 8 nm for Sn, and 4 nm for Al at 400 nm. The number of measurable charge carriers per photon event is also influenced by the junction composition, band-gap engineering leading to the possibility of multi-tunneling, and a larger number of charge carriers per incident photon for any given superconducting material.

(c) with a relaxation time of order 100 ns, non-linearity becomes theoretically problematic at count rates of order 10^5 photons per pixel per second, although practical implementation will probably impose a trade-off between energy resolution and achievable count-rate. At high count rates, an analogue rather than a photon-counting detection scheme is possible, in principle, at the expense of energy resolution.

(d) the requirement that each junction has its own associated readout electronics imposes complications for the construction and operation of a junction array. Presently, the development underway in ESTEC is expected to lead to an array of 6×6 junctions, each of $20 \times 20\mu m^2$, and a packing density of around 90 per cent, towards the end of 1995.

(e) the possibility of a device with large active area and a realtively small number of junctions was proposed by Perryman, Foden & Peacock (1993). In this approach, four junctions are placed at the corners of a superconducting substrate. Using concepts similar to those used for resistive anode arrays, the event location (in temporal, spatial, and energy coordinates) could be estimated in real-time by signal digitisation and look-up tables onbaord. A substantial reduction in the number of junctions (junctions separated by 1 mm could provide a spatial resolution of order 20 μm) would be at the expense of energy resolution and maximum event counting rate.

4. CONCLUSIONS

Depending on the time-scale on which an interferometric astrometry mission is to be devloped, the CCD-based option provides an excellent baseline detecion system, fulfilling the scientific objectives considered by the Horizon 2000+ Survey Committee. Nevertheless, the prospects for an advanced photon-counting detector appear promising, and developments over the next couple of years should provide a clearer indication of whether these possibilities might become a reality.

Evidently the consequences on the payload design will be considerable, both concerning the cryogenic operation, lifetime requirement, and the data handling (both on-board, and telemetry requirements). Operation of an acceptable cryogenic system may also result in unacceptable vibrational consequences resulting from first-stage mechanical coolers. ESA may nevertheless investigate the possibilities of a space-based superconducting optical detector for an HST-2002 advanced camera, and such parallel studies should clarify whether such a detector system may indeed provide a possible option for one or more of the detection systems within an interferometric astrometry satellite.

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