AN ULTRAVIOLET OPTION FOR A FUTURE ASTROMETRIC SATELLITE

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ABSTRACT

Ultraviolet operation is discussed as an option for a future astrometric satellite. Using the ultraviolet one may achieve much higher accuracy in comparison with the visual waveband, either for an interferometer or for a single-aperture telescope. Besides, a single aperture UV-telescope with an elongated 60–80 cm aperture is equivalent in accuracy to a small visual interferometer of 2–2.5 m base. The spectral band is proposed to be extended down to the 912Å absorption limit of interstellar hydrogen. Microchannel plates (MCP) with opaque photocathodes deposited directly on the inner inclined faces of the MCP pores are considered as suitable detectors for the ultraviolet option. Two photocathodes, (CsI and TeCs) have been tested by computer simulations.

Key words: space astrometry, ultraviolet, microchannel plates, interferometry

1. INTRODUCTION

One may increase the resolution of a telescope either by using large entrance pupils (particularly, by using an interferometer) or by working at shorter wavelengths, for example, in the ultraviolet (UV). In the latter case the telescope becomes more compact, the link and calibration of the telescope optical elements becomes easier. Besides, moving to the UV allows one to achieve higher quantum efficiency detectors because of the higher energy photons. On the other hand, the UV-observations themselves are of importance to astronomy—they may bring new information about hot stars, stellar atmospheres, evolution of stars, interstellar medium and so on. That is why the ultraviolet option is worth discussion while designing a future astrometric satellite, be it the GAIA interferometer or the future Russian satellite, *Struve*. The latter is assumed to have two on-board telescopes, one of which might be devoted to the UV survey.

2. OPTICS

With a 50 cm single aperture telescope one may expect at least 65000 visual photons coming from a 14 mag star during its 24 sec transit over the field of view, and one may estimate the accuracy of the observation to be ≈ 0.4 mas. Using a 2.5 m-base interferometer one may improve the accuracy to 15–20 microarcsec.

Figure 1: Diffraction images for the 2.5 m baseline interferometer ($\lambda_{\rm eff} = 600$ nm, the solid line) and for the single 0.6 m aperture at $\lambda_{\rm eff} = 150$ nm (the dashed line). The width of the waveband for both cases corresponds to $\Delta\lambda/\lambda = 0.67$.

Similar results may be achieved with a single-aperture telescope operating at essentially shorter wavelengths. For example, with $\lambda_{\rm eff} = 150$ nm the accuracy is expected to be ≈ 40 microarcsec for a single 60 cm aperture. As an illustration, two diffraction images of a point source are shown on Fig. 1, where the dashed line presents the diffraction pattern for a single aperture telescope at $\lambda_{\rm eff} = 150$ nm and the solid line represents the fringes for a 2.5 m interferometer (assuming $\lambda_{\rm eff} = 600$ nm).

As one can see, the width of the Airy disk at $\lambda = 150$ nm approximately corresponds to that of the 600 nm interferometry fringe, except that the concentration of energy in the central fringe should be higher for the single-aperture mode. Figure 2 demonstrates the potential accuracy both of interferometers and of single-aperture telescopes. The estimations have been made for the two wavelengths using the formulae given by Lindegren (1978). The flux from a star has been calculated by the formula $N_V = 2.8\frac{\pi D^2}{4} \cdot 10^{-0.4V+6}$, which takes into account the relative width of the waveband $\Delta\lambda/\lambda = 0.67$ and loss of photons due to division of the entrance pupil by a beam combiner and due to reflection losses.

Figure 2: Estimations of the theoretical accuracy of observations (in microarcsec) for an interferometer and for a single aperture telescope. The abscissae gives the distances between two apertures for the case of an interferometer. In the case of a single-aperture telescope they are the diameters of the entrance pupil. The integration time is 24 sec which corresponds to the time of a single transit of an image over the field of view. The estimations have been made for a star of A0 spectral class and visual magnitude $V = 14$ mag.

Table 1: Necessary accuracy of the detector (in μm) and the parameters of the focal plane assembly for the different focal lengths F.

F	Single		Interf.		V	L	t_r	N
(m)	Vis	UV	Vis	UV	$\frac{mm}{s}$	cm	μs	CCD
3	0.5	0.1	0.07	0.01	2.2	5.2	5.4	51
6	1	0.2	0.14	0.03	4.4	10	2.7	245
12	2	0.4	0.27	0.06	8.7	21	1.4	980
24	4	1.0	0.55	0.11	17	42	0.7	$4 \cdot 10^3$
48	8	1.8	1.1	0.23	35	84	0.3	$1 \cdot 10^4$
96	16	3.6	2.2	0.46	70	168	0.17	$6 \cdot 10^4$
192	32	7.2	4.4	0.93	140	335	0.08	$2 \cdot 10^5$
384	64	14	8.7	1.86	279	670	0.04	$1 \cdot 10^6$

3. SCALE

The optical diffraction resolution could be lost due to limited resolution of the applied photodetector. For example, the typical resolution of a CCD is 12–16 μm, and the smallest known size of either CCD pixels or MCP pores is 6 μm (Timothy 1992). New technology which is being developed by the Vavilov's State Optical Institute (Saint-Petersburg) allows one to reduce the MCP pore size down to 1–2 μm. Increasing the resolution allows one to apply smaller telescope focal lengths and, hence, to reduce dimensions and masses of the instrument units.

In order to measure properly coordinates of a diffraction image or those of a fringe pattern one should project this image over a few pixels. At least two pixels should be covered by the image. With the desirable number of pixels covered by the diffraction fringe one may calculate the necessary focal length of the telescope. For example, with 10-μm pixels of a CCD ($\lambda_{\rm eff} = 700$ nm) and the circular entrance pupil of $D = 0.4$ m (the parameters of the Struve instrument), one should use the 2.3 m focal length of the telescope. In the case of UV-operation, the focal length is to be enlarged up to ≈ 17 m. With this focal length, the linear sizes of the detector proves to be rather big (30×30 cm^2), and it is very desirable that the pixel size of the detector were 1–2 μm. The dispersion of photons for a single-aperture telescope is ≈ 34.3 mas for $\lambda_{\rm eff}$=600 nm and ≈ 7.7 mas for $\lambda_{\rm eff}$=150 nm. The corresponding values for a 2.5 m interferometer are 4.7 and 1.0 mas, respectively. Choosing proper focal length of the telescope one may calculate the necessary accuracy of the micrometer (Table 1).

The table gives also linear velocities of images, V, (assuming that the satellite makes 10 revolutions per day), the linear size of the field of view, L, the available time for reading out the signal, t_r (which corresponds to the pixel size 6×30 μm^2), and the necessary number of detectors to cover the field of view (assuming the CCD has 500×500 pixels).

With a reasonable accuracy of the micrometer (≈ 1 μm) one should use rather large values of the telescope focal length: about 50 m for the visual GAIA interferometer or 200 m for the ultraviolet interferometer. Realizing that the focal length of the space instrument is limited to values of about 6–12 m (due to dramatically increasing sizes of the micrometer and the linear velocity of the image) one should conclude that the precision of a single measurement is to be rather high (0.14–0.27 μm per detectable event in the case of the visual interferometer or 0.03–0.06 μm for the UV). Besides, the number of detectors becomes very large.

4. DETECTORS

Two types of the detectors are to be discussed: the solid state detectors (CCDs, tunnel diodes, etc.) and the photoemission devices (such as photomultipliers or microchannel plates). The solid state detectors (CCDs) have a very high quantum efficiency (up to 90%) in the visual waveband. With a special technological means (so called flash gate and antireflection coatings) their quantum efficiency in the UV might also might be increased up to 20%–30% (Janesick et al. 1987).

When detecting the moving images with the use of a CCD one should shift the accumulated charges synchronously with the image in order to increase the integration time. This causes convolution of the diffraction image with the periodic structure of the CCD, and limits the resolution to the level of two pixels. One may restore the resolution by wobbling the accumulated charges around the image during its transit (Yershov 1993). But wobbling splits the image and decreases the signal to noise ratio. Such a technique is hardly to be applicable for faint star observations. Modulation of the signal by a special grid placed in front of the CCD results in similar degradation. Therefore, the best way of increasing the resolution is the use of larger telescope focal lengths. This leads to a higher linear velocity of the image, and decreases the time for the signal readout. For example, if a 500×500 pixel CCD has 6×30 square micron pixels, and the satellite rotates with a frequency of 10 revolutions per day, then the readout time will not exceed 1.4 microsec for the moderate focal length 12 m. If one uses a larger CCD, the readout time becomes absolutely unacceptable. Therefore, the use of CCDs for a space astrometric telescope is problematic both for the interferometer and for the UV single-aperture telescope.

The use of detectors with a random readout (charge injection devices, MCPs, arrays of superconducting tunnel junctions, etc.) is much more suitable for the scanning satellite. But arrays of superconducting tunnel junctions (having very high quantum efficiency, Perryman et al. 1992) are at the initial stage of their development and need cryogenic temperatures for their operation.

Photomultipliers and microchannel plates are well known detectors for astronomical applications (bernacca et al. 1994, Bianchi & Christofer 1994, Viotti 1994). They have rather high spatial resolution and large sizes of photocathodes (up to 70 mm or more). MCP detectors have lower quantum efficiency in comparison with CCDs (not higher than 30% at $\lambda = 400$ nm.) Other disadvantages of MCPs are: low geometrical transparency, significant structural noise, low dynamic range which is caused by saturation of channels (a bright object may degrade the characteristics of the detector, and the channels might be periodically blinded).

Despite of these disadvantages MCPs are very promising devices for space astrometry. Their quantum efficiency may be increased by using opaque UV-photocathodes (in the UV higher photon energy causes higher photoyield). For example the TeCs + Cs opaque photocathode has $\approx 35\%$ quantum efficiency at $\lambda_{\rm eff} = 200$ nm (Nikonov 1973), and the CsI photocathode has 70% photoyield at $\lambda_{\rm eff} = 100$ nm (Meaburn 1979). The pores blinded by a bright object might work as reducers of the image dynamic range.

5. MODELLING THE DETECTOR

A detector on MCPs is considered with the pores as small as 1 μm and with 1.5 μm centre-to-centre separation between the pores. The UV-photocathode is assumed to be deposited directly on the open inner faces of the pores. In order to achieve higher accuracy, it is desirable to choose the working spectral band as short as possible. The shortest wavelength might be close to the 912Å absorption limit of interstellar hydrogen. The CsI photocathode is suitable for this waveband, and it is sensitive in a rather narrow waveband ($\approx$ 200 nm), that makes it solar blind.

Observations have been simulated for the 60 cm single-aperture UV-telescope. A three-mirror optical scheme for such a telescope has been designed by the Vavilov's State Optical Institute for the Struve project. The 5 m-focus telescope has near-diffraction limited images within its $1^\circ \times 1^\circ$ field of view. Two such telescopes are folded into a 3 m diameter and 1 m height cylinder with a beam combiner installed at the centre of the inner volume of the instrument. Options with larger focal lengths (10–15 m) are also considered, when the telescopes are folded into a slightly higher body of the instrument.

Computer simulations assumed the flux from a star of a given spectral class has been convolved with the spectral response of the photocathode, and the diffraction image of a star has been simulated projecting (and moving) to the above described structure of a MCP. Coordinates of each photon have been considered lost within the microchannel circle. In addition, a registration error has been introduced imitating the measurement of the centre of the electron avalanche. The error has been accepted equal to the pore radius. The results of the simulations for a TeCs + Cs photocathode and a 14 mag star (visual magnitude, spectral class A0) are presented in Table 2.

Table 2: Accuracy of registration (in mas) with the TeCs + Cs photocathode as a function of $\lambda_{\rm eff}$ and the width of the spectral waveband $\Delta\lambda$ (in nanometers). Observations of a 14 mag star (V) of spectral class A0. The integration time is 5 sec

$\Delta\lambda$	$\lambda_{\rm eff}$, nm					
(nm)	200	300	400	500	600	700
190	2.7	2.5	2.2	5.5	5.7	8.2
150	3.2	2.6	3.0	4.7	5.7	8.9
100	4.1	3.8	4.7	5.0	8.3	9.2
50	4.4	6.4	5.5	7.7	9.9	11.8
25	6.4	7.1	6.5	12.3	16.4	21.1

Results of simulation for the CsI-photocathode are shown in Fig. 3 for two spectral classes of stars. It can be seen that sub-milliarcsec accuracy is achievable for hot stars (spectral class B0) down to the limiting magnitude $V = 20$ mag.

Figure 3: Error of a single transit for stars of two spectral classes.

An MCP detector with open inclined pores gives also the possibility of measuring polarization due to the vectorial photoeffect (Fraser et al 1989). The UV-polarimetric observations would bring important information on geometrical properties of stars (asymmetry of their shape, presence of stellar coronae, gas jets, accretion disks, and so on) and on chemical properties of matter.

6. OBJECTS OF OBSERVATION

The limiting magnitudes achievable with the CsI detector are presented in Table 3 as a function of spectral classes of stars. Hot stars are observable down to $V = 21$ mag because almost all their energy is emitted in the UV.

The distribution of stars as a function of their colour and the number of available stars for each colour are also given in the table. The number of available stars will be smaller for the later spectral classes, and the total number of the

Table 3: Limiting magnitudes (visual), the fraction of stars in the Galaxy (Q_{Sp}) and the number of available stars for different spectral classes.

Sp	$(B-V)$ range (mag)	V lim (mag)	Q_{Sp}	Available stars
O		21.0		
B	< -0.02	19.4	5%	$34.5 \cdot 10^6$
A	-0.02 - 0.30	16.6	16%	$12.8 \cdot 10^6$
F	0.30 - 0.55	13.5	17%	$1.2 \cdot 10^6$
G	0.55 - 0.95	10.7	30%	$0.3 \cdot 10^6$
K	0.95 - 1.50	7.8	27%	$0.01 \cdot 10^6$
M	> 1.5	4.9	5%	$0.02 \cdot 10^4$

UV program stars might be about 50 million. The UV telescope could also explore a large number of quasars and galaxies with active nuclei. Up to 1 million quasars and a similar number of spiral galaxies might be discovered. More than 300 000 hot white dwarfs and subdwarfs will be explored.

7. CONCLUSION

The UV astrometric and photometric survey will yield new fundamental information on the nature of the energy source in quasars, the evolutionary history of stars, their luminosity function and so on. A complete 3-dimensional distribution of dust and hot interstellar medium in the Galaxy will be obtained, the ionization of the intergalactic medium will also be explored. Many other scientific problems may also be solved with the use of a UV astrometric satellite. Operation in the UV promises to be a fruitful additional scientific instrument both for the GAIA interferometer (where one may place the UV-detectors within the incoherent part of the field of view) and for a single-aperture telescope. For the latter case, the accuracy is expected not to be very far from that of a moderate-size visual interferometer.

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