SOME PROBLEMS OF WIDE-FIELD ASTROMETRY WITH A SHORT-FOCUS CCD-ASTROGRAPH

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ABSTRACT: The worldwide application of CCDs in astronomy is concerned mainly with the problems of photometry and spectrophotometry. Astrometry with CCDs is limited by the small fields of view and now is used to solve some special tasks such as parallax determination of faint stars, observations of QSOs, etc. Very interesting results were obtained using a CCD with a meridian circle in a drift scanning mode to solve the problem of the extension of the reference system to stars of 16^{th} - 17^{th} mag and the linkage between radio and optical reference frames (Stone 1994).

Based on the preliminary results of our observations, some proposals on astrometry with CCDs are discussed in the paper. The aim is to show the use of short-focus telescopes with CCDs in the mode of traditional astrographs. Numerous tasks may be solved with such instruments more simply and correctly than with meridian instruments in a drift scanning mode.

The problems of the application of CCDs with short-focus optics are also discussed. Some effects of CCD properties on the accuracy of astrometric and photometric measurements are also considered.

1. INTRODUCTION

Since the early 1980s numerous results on the application of CCDs for different tasks in astrometry have been obtained. The majority of observations was made with large telescopes and, therefore, with small fields of view. It appears that the application of CCDs allows one to solve some very interesting new astrometric problems, but seriously limits the traditional tasks of these instruments in a photographic mode.

A general way to extend the possibilities of telescopes with CCDs is to create new, large CCDs or to use a mosaic of CCDs. It is very promising, but is an expensive and complicated way with numerous technical problems. On the other hand it may be shown that from the point of view of "rational sufficiency" it is enough to use rather small short-focus instruments with available CCDs to solve numerous traditional astrometric problems. The main reason for this approach is that the internal precision of such an instrument is quite comparable with the accuracy of reference systems, and the resulting accuracy of astrometric measurements cannot be improved significantly by improvement of the instrument. It may be shown that such instruments allows us to solve a wide class of traditional and modern astrometric problems.

This approach is based on the experience of CCD-observations, made in 1990, in context

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with the work on the REGATTA-ASTRO space project, and on the results of observations made at Pulkovo in 1993 - 1994 with a small short-focus astrograph, which can be regarded as a prototype of a desirable instrument.

2. EXPERIMENTS OF CCD-ASTROMETRY WITH SHORT-FOCUS INSTRUMENTS.

We started CCD observations in 1990. It was a part of the work on the REGATTA-ASTRO space project, developed by the Space Research Institute (Moscow) and Pulkovo observatory (St Petersburg). The project was aimed at creating a catalogue of 400,000 stars, including positions, proper motions, parallaxes (with accuracy of 0.01 arcsec) and WBVR-photometry (with accuracy of 0.01 mag). In the summer of 1990 we made a series of experimental observations with a very small prototype of our onboard CCD-telescope operated in the mode of the space project: fast routine reading of direct images of the sky areas crossing the field of view at a diurnal rate. The precision of the astrometric measurements (for a single exposure) was evaluated as 0.01 - 0.02 of the pixel size (with a complicated algorithm of the image center) and 0.02 - 0.04 (with a simple centroid method) for all stars in the range of V magnitudes 6 - 11. The precision of the photometric measurements was 0.02 - 0.11 mag for the same range (Alexeeva et al. 1993). In addition, the CCD-observations with the Pulkovo Large Transit Instrument were made during night and day time. In the day time we obtained direct images of stars (up to V = 7), Mars, Venus and the Sun. It allows us to conclude that traditional day-time fundamental astrometric observations are quite possible with CCDs.

In December, 1992 we began regular experimental CCD-observations at Pulkovo. The first aim was to make a complete meteorological investigation of our CCD and optical system. We use a very small refractor (Double Short-focus Astrograph) with D = 100 mm and F = 712 mm. Our CCD-camera was created in the Space Research Institute using the virtual-phase CCD ISD015A produced by "Electron" (St Petersburg, Russia) (Khmelevitskij et al. 1991). The parameters of the CCD are: 520 x 580 pixels (18 x 24 microns), sensitive area 9.4 x 13.9 mm, spectral band 0.2 - 1.0 micron. The Quantum Efficiency (QE) at different wavelengths is as follows: 15% at 0.2 microns, 28% at 0.4, 58% at 0.7 and 12% at 1 micron. The full well capacity is 220,0000 e^- and the real (working) dynamic range is 6 to 7 mag. The readout noise (nominal) is 10 e^- with high speed amplifier and 7 e^- with low noise amplifier. We use the CCD placed in a gas-filled housing equipped with a thermoelectric (Peltier) cooler, which provides a temperature difference between the CCD and that of the environment of about 40° - 50° C. The dark current (nominal at -40° C) is 12 e^-/pixel/s. Our CCD-camera was designed to be used onboard the spacecraft and works without any shutter. An 11-grade analog-digital converter is used (2048 cu, one cu $\sim$ 100 e^-); every frame takes 603 Kbytes. A very short readout time (1.5 sec) allows the camera to work without a shutter, but this creates additional problems to be solved. The observation routine is as follows: a fast reading (1.5 s), exposure (from 0.1 s to 30 minutes), a fast reading, display on the PC/AT monitor and a store (if necessary). The focal length of our astrograph provides an angular field of 45 x 67 arcmin (the angular scale is 5.2 x 7 arcsec/pixel). Thus, the expected accuracy at the level of 0.02 of the pixel size should be 0.10 arcsec in declination and 0.15 arcsec in right ascension.

The first observations were made to evaluate the accuracy of our positional and photometric measurements. The Pleiades cluster and some other standard fields were chosen for this purpose. We have made a series of observations of the same fields with different exposure times. For the first evaluations we have used a simple and rough centroid method to determine the star image center. The internal precision of the positions obtained appears to be four to five times better than in the case of photography and varies from 0.10 to 0.35arcsec (for a single observation) for a wide range of magnitudes. By use of different exposure times (from 0.1 seconds to 10 - 20 minutes) we can observe all stars from the brightest to the stars of 16^{th} - 17^{th} mag with our small instrument. The precision of a single magnitude determination varies from 0.03 to 0.15 mag over the whole range. It means that from a series of 5 - 10 frames it is possible to obtain positions (with an accuracy 0.05 - 0.15 arcsec) and magnitudes (with an accuracy 0.01 - 0.05 mag) for a set of 500 - 700 stars. To realize this opportunity it is necessary to make a special investigation of possible quasi-systematic errors of the instrument at the same level of accuracy. We have made the "upper" evaluation of our accuracy by a comparison with the Pleiades catalogue by Vasilevskis et al. (1979). The mean deviations of our star positions from that by Vasilevskis do not exceed 0.2 arcsec and, thus our systematic errors are not large. A detailed investigation of all possible sources of error has been made and methods of appropriate corrections are now developed. After the completion of these investigations it will be possible to begin a wide program of observations. We are planning to observe some selected areas on the sky, minor planets and QSOs, which can be observed at Pulkovo with our small instrument. We are planning also to create an instrument with better optics and CCD, more suitable for our tasks.

3. POTENTIAL OF ASTROMETRY WITH SHORT-FOCUS CCD-ASTROGRAPHS

An important problem of modern ground-based astrometry is to extend the best reference systems, HIPPARCOS and TYCHO, to the faint stars of 15^{th} - 17^{th} mag. Two ways are known to solve this task: astrophotography with large telescopes and differential observations with meridian instruments equipped with CCDs. It may be shown that an optimal variant of the instrument can be created for this task and numerous other applications, when we take into account all the aspects of situation.

The application of CCDs allows one not only to reach much fainter stellar magnitudes with the same telescope in comparison with photography, but also to increase significantly the precision of positional and photometric measurements. With comparatively small CCD-astrographs one can solve the same problems as with a large photographic telescope, with a great advantage in the data processing. The optimal variant of CCD-telescope can be chosen if one takes the internal precision of positional measurements and the accuracy of reference catalogue to be equal. For ground-based observations the TYCHO catalogue will become the reference frame of choice due to the dense set of stars with precise positions. This catalogue will provide us with 25 stars per square degree (in the average) with a mean positional accuracy of 30 mas. Thus, correct differential astrometry will be possible within small enough field of view, and the main limitation will be imposed by atmospheric turbulence. It is very important that differential observations were made for all stars within the field of view simultaneously, in a mode of classical astrographs. Observations in a drift scanning mode are affected by the long-period variation of refraction and extinction, variation of the instrument position, variation of detector parameters and so on. Moreover, in this variant of observations the star image is affected by all the cosmetic defects of the CCD and variations of the distortion "gathered" through the path of charge transfer (in the case of so-called "stare mode" these errors can be detected and correctly taken into account for every pixel separately). It causes some difficulties in the data reduction and leads to a worse external accuracy of such observations in comparison with very high precision of the internal errors.

The common experience of astrometric CCD-observations shows that it is quite possible to obtain a precision of star image location of 0.02 of one pixel and better. With a telescope having a focal length of one meter and a CCD of 1k x 1k pixels (15 x 15 microns) one could obtain a field of view of one square degree, a scale of 3.1 arcsec/pixel and a precision of a single observation of 60 mas. The series of five to ten frames allows us to achieve a position accuracy of 20 - 30 mas. It is about ten times better than the accuracy of the best existing reference catalogue, PPM, and quite comparable with the accuracy of the future best reference catalogue, TYCHO. A telescope with a focal length of two meters and a CCD of 2k x 2k pixels (15 x 15 microns) provides about the same field of view and the precision of single observation of 30 mas; that is about the limiting precision for the ground-based observations in the presence of atmospheric turbulence within the field of view of one square degree.

The resolving power of short-focus telescopes is the main problem. To illustrate this problem we compiled Table 1 (on the basis of "Astrophysical Quantities" by Allen (1973). We suppose here that the minimum useful variant is F = 1000 mm, CCD 1k x 1k pixels, that provides for one square minute a set of 20 x 20 pixels of size three arcsec. We suppose also that star images occupy 3 x 3 pixels with the FWHM of approximately 1.5 - 2 pixels.

TABLE 1

Mean density of stars per one square minute (20 x 20 pixels) with magnitudes less than "m" as a function of galactic latitude "b" (Allen 1973).

m\b	0	20	40	60	90
15	0.73	0.25	0.11	0.07	0.05
16	1.67	0.55	0.23	0.13	0.10
17	3.75	1.11	0.43	0.24	0.17
18	8.78	2.36	0.77	0.41	0.29
19	17.5	4.40	1.39	0.70	0.44
20	27.8	8.8	2.2	1.1	0.7

It is easy to see that the problem of resolving close stars arises only for 17^{th} - 18^{th} mag near the galactic equator and is practically absent up to 20^{th} - 21^{st} mag at mean and high galactic latitudes (it is especially important for observations QSOs). Certainly, these are only the statistical evaluations and the real distribution of stars on the sky is irregular. But it may be shown that if two stars are located on the CCD with a separation of more than one pixel, the resolving of stars is not a problem. On the other hand, the seeing for ground-based telescopes often exceeds two arcsec, and all the stars which are "closer" than three seconds cannot be resolved. In any case, there exist some regions on the sky which cannot be resolved with any telescope (for example, globular clusters) and for every instrument the proper "resolving" limit should be accepted and kept in mind. That is why the idea to use short-focus CCD-telescopes for such work seems to be reasonable.

Numerous astronomical problems may be solved by use of such instruments. Among them are:

a) Creation of large catalogues of positions, proper motions and photometric values of stars up to 16^{th} - 17^{th} mag.
b) Observations of solar system bodies: planets (with their satellites), minor planets, comets, asteroids etc.
c) Observations of QSOs and the establishment of a precise link between radio and optical reference frames.
d) Ground-based supplements of space projects, for example, searching for peculiar objects and their monitoring, etc.
e) Different astrophysical problems, such as investigation of variable stars, investigation of star clusters, etc.

4. SOME PROBLEMS OF CCD-ASTROMETRY WITH SHORT-FOCUS OPTICS

Numerous effects appear to be significant in CCD-observations with a short-focus astrograph, because small linear errors in the focal plane correspond to large angular errors. Additional problems for us are connected with the properties of our CCD-camera and the conditions of observations.

Some specific problems at Pulkovo observatory are lighting and electromagnetic pollution. We are surrounded by luminous St Petersburg and neighboring towns. But the worst effect is connected with a powerful radio (or TV) broadcast interference, because the half period of these waves exactly corresponds to the image diameter of stars, and a faint star may increase its image size, vanish or shift in both directions. At present some improvements in the construction of the CCD-camera have been made which reduce this effect. On the other hand a method of mathematical filtration has been developed to diminish the errors caused by this interference.

The next problem is that we are working with a thermoelectric (Peltier) cooler without stabilization of the CCD temperature. Nominally this cooler should maintain the temperature difference between the CCD and the environment of 60° - 65° C. We have this difference varying from 41° C (at an air temperature of -20° C) to 51° C (at an air temperature of +20° C). Partially it may be explained by the construction of our special CCD-camera, by the shortcoming of the concrete CCD sample. The variation of the CCD temperature during the night creates an additional problem for the reduction of the data. Fortunately, we can measure the CCD temperature anytime by use of a thermistor. The dependence of the dark current on the temperature appears to be very stable and for every observation frame we can calculate the dark current frame, including the separate response of every pixel on the temperature variation.

The investigation of the spectral sensitivity of our chip shows that it has significant irregularities. There are large variations of the spectral response from pixel to pixel and variations with CCD temperature which need a careful flatfield study and to determine the corrections.

An important problem is connected with cosmic ray events and their accidental impact on the star images, and their effect on the precision of positions and photometry. The problem is specific for each type of CCD. We have investigated the characteristics of our chip on the basis of a series of dark current frames. We have extracted only the events with energy greater than 1000 e^- to be sure that these are real events. The results are presented in Table 2 and on the Figures. In the table one can see the statistics of five dark current frames (events, which affect

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one pixel, two adjacent pixels and so on with a signal exceeding 1000 e^-).

TABLE 2

The number of events "n", which affect "m" adjacent pixels with a signal exceeding 1000 e^- (from five dark current frames obtained with a ten minute exposure)

m (pixels)	1	2	3	4	5	6	7	8	17
n (events)	161	59	22	11	7	5	2	1	01

On the average there are 100 "bad" pixels in each frame for a ten minute exposure with false signals, that exceed the noise by approximately a factor of ten. The distribution of these events with energy is shown in Fig. 1. Moreover, we can suppose the presence of a large number of false signals (events) with smaller energy. Very often we can find on dark current frames star-like images and tracks (like the moving NEOs). An example of such a track is shown on Fig. 2. Some conclusions follow from these results: a) it is not worthwhile to use very long exposures, because a majority of star images will be affected by radiation events; b) it is necessary to take some frames (no less than three) of the same sky area to exclude possible accidental errors caused by radiation events.

One of the important sources of error in position and brightness determinations is connected with the complicated structure of pixels. In every case the CCD pixel consists of parts with different sensitivity. Especially it is important for front-illuminated CCDs, in which a large part of a pixel may be entirely insensitive. The measured positions and photometric values depend on the location of the star image center within the pixel. The result is that periodic errors are created with a main spatial period equal to the pixel size. It may be shown that this effect depends significantly on the subpixel sensitivity, on the shape of image (point spread function, quality of guiding and atmospheric conditions) and on the method of image center determination. The errors of the position determination can reach 0.1 of the pixel size and should be taken into account, as well as the errors of photometry.

Some different ways may be proposed to determine the necessary corrections to the measured positions and brightness. The first is to measure directly the sensitivity inside a pixel in the laboratory with complicated enough equipment and to use these data in the process of image reconstruction. The second way is to use the information on the geometry of pixel structure, to create a model of the subpixel response and to reconstruct the parameters of this model on the basis of real observations. And the third way is to obtain the necessary corrections statistically on the base of a large enough series of observations of the same field on the sky with a great number of stars. It may be done if we use many frames taken with small different shifts of the CCD field of view with respect to the stars observed. This way seems to be most useful, because all the above-mentioned obstacles appear to be taken into account automatically. The preliminary and rough results of the application of this method (with a small statistics - only three frames) are shown in Fig. 3 (positions) and Fig. 4 (photometry).

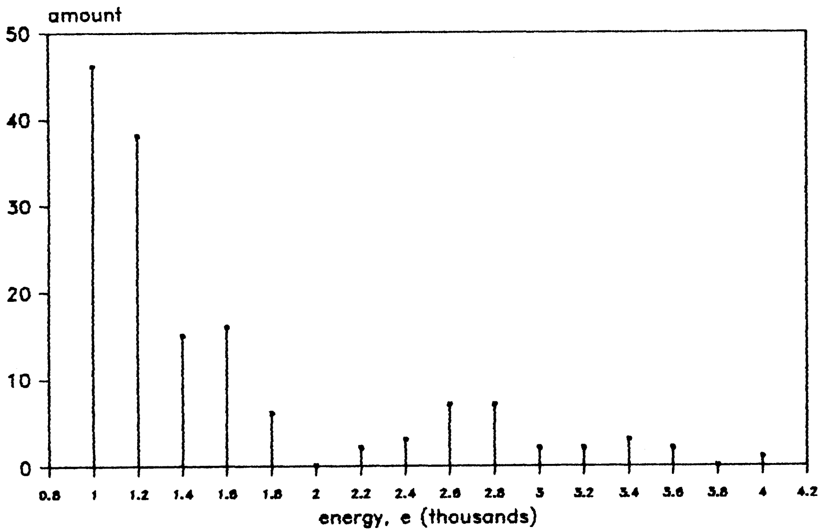

Fig. 1. Radiation events (for ten minutes) - the energy distribution.

8	5	-1	1	3	-1	3	5	2	-1	1	4	1	1
0	7	4	1	5	4	6	2	5	3	3	2	11	-1
2	-1	4	-1	3	1	7	1	7	6	1	4	23	7
3	1	2	0	0	2	2	2	1	3	0	20	5	2
5	5	3	-2	1	2	2	10	13	3	23	22	4	5
1	1	0	4	4	3	-1	1	3	15	27	7	5	-2
1	3	3	1	0	1	3	8	5	19	10	1	2	1
4	2	3	2	3	-2	5	6	16	11	2	1	1	5
2	2	0	0	3	4	6	9	18	9	1	4	5	0
5	6	0	8	2	5	4	12	11	1	3	5	3	7
1	5	4	-1	-1	2	14	11	5	5	7	-1	1	3
5	3	0	3	4	10	14	7	2	0	2	2	1	-1
1	0	7	4	5	21	7	1	3	1	5	6	-1	1
0	0	3	2	10	15	6	0	3	6	8	1	-2	1
1	3	5	14	30	6	5	2	2	2	-1	0	-1	3
5	-1	1	38	9	5	4	2	4	2	0	2	4	-3
4	2	25	8	8	1	0	0	3	4	4	7	2	0
2	13	15	9	3	3	3	4	7	0	3	3	-2	2
4	18	1	2	3	6	4	3	-2	1	0	4	0	6
1	2	6	8	3	0	-3	-3	3	4	2	0	1	-1

Fig. 2. An example of a particle track.

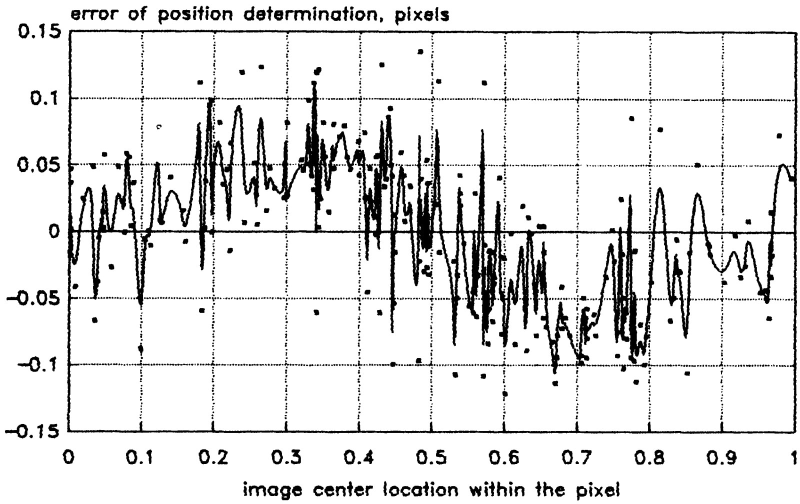

Fig. 3. Effect of the pixel structure on the position determination.

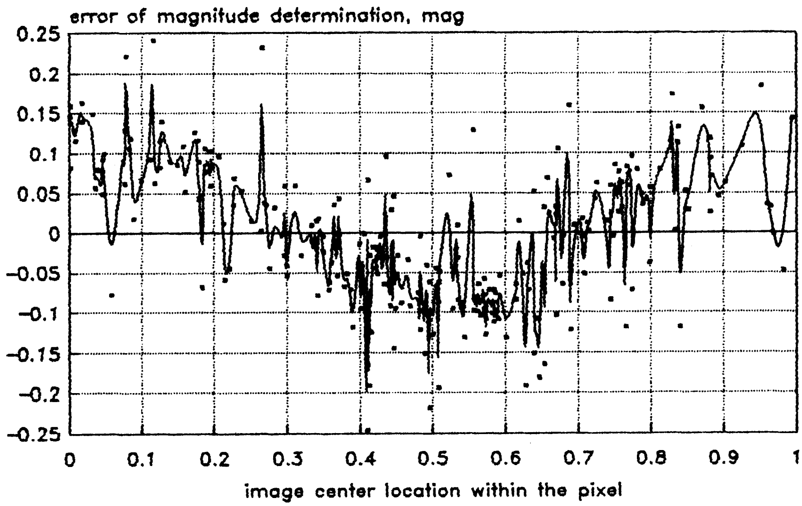

Fig. 4. Effect of the pixel structure on the magnitude determination.

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The next important effect is connected with the Charge Transfer Efficiency (CTE) which can cause an error in position measurements, depending on the stellar magnitude. It is similar to the well-known "brightness equation", but this effect is quite linear, depends on the readout time and the CTE, is significantly greater along CCD columns than along rows, depends only on the star magnitude and does not depend on the position of star image with respect to the optical center of the frame. This effect may be found in two ways: by the statistical evaluation of a great number of stars with well-known coordinates and on the basis of observations of the same star field with different orientation of the CCD - direct and inverse. In the last case a difference in the positions of the same star with respect to the center of field gives a double correction to be used for data reduction. In our case (fast readout) this error is about 1 micron/mag and has to be taken into account in any case.

A very important problem is the general distortion of the instrument, which includes both the optical distortion and the distortion of the CCD. As in a previous case, the same procedure may be used to obtain the correction, but it is more useful to take many frames with different orientations of the instrumental frame with respect to the sky area. It may be done effectively if we use the North Pole region for this purpose, because a majority of instruments is able to take images of this field with any position of the instrument.

All the effects mentioned are to be carefully investigated and will be taken into account to obtain high precision positions and photometry with a CCD-telescope.

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DISCUSSION

PENNY: You seem to have already been studying the problem I talked about yesterday, half pixels which only have half sensitive areas. What range of magnitudes can you measure on one exposure?

GUSEVA: We can measure a range (6 - 7) magnitudes on a single exposure.