All-spherical telescope with extremely wide field of view

V. Yu. Terebizh

1 Crimean Astrophysical Observatory, Nauchny, Crimea
2 Institute of Astronomy RAN, Moscow 119017, Russian Federation

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An all-spherical catadioptric telescope with the angular field of view of several tens of degrees in diameter and spherical focal surface is proposed for the monitoring of large sky areas. We provide a few examples of such a system with the apertures up to 800 mm and the field of view 30° and 40° in diameter. The curvature of the focal surface is repaid by high performance of the telescope. In particular, the diameter of a circle that includes 80% of energy in the polychromatic image of a star is in the range 1′′4–1′′9 across the field of 30° size and 2′′2–2′′9 for the field of 40° size. Some ways of working with curved focal surfaces are discussed.

1 Introduction

There are two primary modes in surveying of large areas of the sky: 1) we need to cover sequentially the area in the reasonable time; 2) the sky area we are interested in should be under continuous watching, as is the case when we look for the fast transient objects. To some extent, problems of the first kind can be solved with the help of wide-field telescopes with a flat field of view, such as those discussed by Wilson (1996) and Terebizh (2011). It is easily seen that problems of the second kind require too many flat-field telescopes, so it seems that the better way in this case is the creation of a single telescope with an extremely wide angular field, even at a spherical focal surface.

Just this way was chosen in the second half of the last century, when the Baker-Nunn (Henize 1957; Baker 1962), Hawkins & Linfoot (1945), and Maksutov-Sosnina (1950s, unpublished) cameras were put into operation. Their angular field attained 20°–30°, whereas the shielding of light and curvature of the focal surface were taken into account by application of a narrow emulsion tape. The main disadvantages of these cameras were as follows: 1) Some lens surfaces were substantially aspheric; 2) the demanding sorts of glass were used in the correctors; 3) nevertheless, the image quality was inadequate. For example, four surfaces of the Baker-Nunn camera were aspheres of 4th and 8th orders, the Schott KzFS2 and SK14 glasses were applied, but the rated image of a point-like source of light was nearly 100 μm (40″) in diameter (Carter et al. 1992). Later modification of the Baker-Nunn camera with aspheric surfaces of the same order but larger aperture provides 1″ resolution in a narrow spectral band (Sasaki et al. 2002).

1 In the calculations, we used the Zemax optical program (ZEMAX Development Corporation, U.S.A.).
The system is provided by the mirror, while the four-lens design. To a good approximation, the same is also true for our system. The point symmetry both of the fundamental form of a polychromatic image of a star, varies from 5.4 µm (1′′4) on the optical axis to 7.3 µm (1′′9) on the edge of the field. The complete description of the system is given in Table 1.

The proposed system proceeds from the two generic versions of the Bernhard Schmidt (1931) camera that were then developed by A. Bouwers (1941, 1946), D. D. Maksutov (1944), D. G. Hawkins and E. H. Linfoot (1945), C. G. Wynne (1947), and J. G. Baker (1945, 1962). Our current goal is to get rid completely of aspheric surfaces. This is partly achieved by introduction the modified double meniscus of Wynne (1947), i.e., the first and forth lenses in Fig. 1; the two inner lenses were inserted both to minimize coma and spherochromatic aberration. The double-meniscus corrector was applied by Baker in his super-Schmidt design, but he placed inside a highly aspheric correction plate such as that introduced by Schmidt. Meanwhile, the only possibility to achieve the true point symmetry about the center of the entrance pupil is to use a purely spherical optics.

The point symmetry both of the fundamental form of a wide-field telescope consisting of an idle stop at the center of curvature of a spherical mirror (J. Petzval, H. Vogel, K. Strehi) and the basic Schmidt’s model is closely related to the fact that the entrance pupil coincides with the aperture stop. To a good approximation, the same is also true for our design.

Another important feature is that the optical power of the system is provided by the mirror, while the four-lens corrector working at f/44 is nearly afocal. Just that should be the case to prevent the chromaticity at reducing spherical aberration inherent to the spherical mirror. The resulting width of the chromatic focal shift curve is 10.5 µm, whereas it should be less than ~9 µm for an ideal, diffraction-limited system. Besides, a small optical power of the lens corrector greatly contributes – along with the spherical shape of surfaces – to the mitigation of general tolerances.

As regards losses of light, a strip-like detector of size 30′×5′ (39 cm × 6.5 cm) shields less than 7% of the flux.

Obviously, individual light detectors may be arranged freely, both continuously and discretely. An optimum way is to arrange them in accordance with the shape of the observed sky area.

3 All-spherical telescope with a 40° field

To illustrate the capabilities of the optical layout under discussion, we give in Fig. 3 and Table 2 an example of a 40°-design VT-119c, which spherical lenses are made of fused silica and simplest glasses Schott N-F2 and N-BK7. A similar system that uses only fused silica provides just a little inferior image quality, but is more expensive.

The effective focal length of VT-119c is still equal to 800 mm, the design waveband remained 0.45–0.85 µm. As before, the image quality is nearly fixed across the field: the diameter $D_{90}$ of a star image varies in the range 8.5–11.1 µm (2′′2–2′′9). The width of the chromatic curve, 27.8 µm, is not far from that for the diffraction-limited system, 10.2 µm.

4 Survey speed and limiting magnitude

When working with wide-field telescopes, most important characteristics are the survey speed $S$ (deg²/s) and limiting magnitude $m_{lim}$ given the exposure time $T$. Let us consider in this context the VT-119g design with the rectangular field of view of, say, 30′×5′, giving the observed sky area

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**Table 1** VT-119g design with an aperture of 400 mm and 30° field of view. The effective focal length is 800 mm.

| No. | Comments | $R_0$ (mm) | $T$ (mm) | Glass | $D$ (mm) |
|-----|----------|------------|---------|-------|----------|
| 1   | L1       | 1141.913   | 47.0    | FS    | 511.8    |
| 2   |          | 1241.285   | 165.714 | –     | 490.1    |
| 3   | L2       | -1060.80   | 51.871  | FS    | 422.5    |
| 4   |          | -997.351   | 0.0     | –     | 410.1    |
| 5   | Stop     | ∞          | 304.135 | –     | 397.9    |
| 6   | L3       | -530.106   | 50.0    | FS    | 518.3    |
| 7   |          | -436.465   | 23.871  | –     | 536.0    |
| 8   | L4       | -438.102   | 62.0    | FS    | 543.4    |
| 9   |          | -653.243   | 1065.44 | –     | 601.2    |
| 10  | M1       | -1656.21   | -855.191| Mirror | 1169.6   |
| 11  | Image    | -781.790   | –       | –     | 413.8    |

**Notes:** $R_0$ – paraxial curvature radius, $T$ – distance to the next surface, $D$ – diameter, FS – fused silica. All surfaces are spheres.
and dead time.

The "dead time" is the sum of read-out and telescope redirection time. It was assumed that the noise obeys the Poisson distribution. Assuming also that the telescope image seeing $\omega = 30\arcsec$, the sky background is $20\mu m$, the atmosphere effective aperture diameter is 5 s, and the threshold signal-to-noise ratio $S/N = 8$, we come to results shown in Fig. 4. Our estimates of limiting magnitude were performed by standard methods, they are in a good agreement with those according to the SIGNAL package created by the team of the Isaac Newton Group of Telescopes (http://catserver.ing.iac.es/signal/). The survey speed is simply the field area divided by the sum of the exposure time and dead time.

$\Omega = 150 \text{deg}^2$ (the diameter of the equivalent circular field $2\omega = 13.8\arcmin$). It was assumed that the noise obeys the Poisson distribution. Assuming also that the telescope image quality $D_{\text{iso}} = 1\arcsec/7$, its transparency is 0.85, the fraction of unvignetted rays $U = 0.90$, the quantum efficiency of detector is 0.85 counts/photon, pixel size is 9 $\mu m$, the atmosphere effective aperture diameter is $150\arcsec$, the sky background is 20 $\mu m$/arcsec$^2$, the optical thickness of the atmosphere in zenith is 0.30, the object zenith angle is $40^\circ$, the dead time is 5 s, and the threshold signal-to-noise ratio $S/N = 8$, we come to results shown in Fig. 4. Our estimates of limiting magnitude were performed by standard methods, they are in a good agreement with those according to the SIGNAL package created by the team of the Isaac Newton Group of Telescopes (http://catserver.ing.iac.es/signal/). The survey speed is simply the field area divided by the sum of the exposure time and dead time.

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Evidently, the large field of view entails high survey speed of the system. It is enough to say that at the exposure time 4 s the survey speed of 11 $\text{deg}^2$/s is attained, so the objects brighter than $\sim 19^m$ can be registered in the sky area of $10^4 \text{deg}^2$ in 15 min.

As regards limiting magnitude, it is difficult to expect its high value for a telescope of relatively small size. We see that for short exposures, which are specific to fast transients, the objects not fainter than about $19.5^m$ are attainable. The limit is increased to $20^m$ at the exposure time of 20 s. To reach more faint sources, the proposed optical system can be scaled up, the more that the image quality is very weakly dependent on the size of the system (see the next section).

It seems quite evident that the significant survey efficiency, including both the deep limit and high speed, can be achieved by creating a hierarchical system, consisting of different types of telescopes.

Let us also estimate the “sky survey rate” $\Gamma$ that was defined in the review of Terebizh (2011) by Eq. (A2). It is simply the product of the observed sky area $\Omega$ (deg$^2$) and effective aperture area of the telescope $A = \pi D^2/4$ (m$^2$), divided by the squared image quality $\Delta$ (arcsecond):

$$\Gamma \equiv \Omega \times A/\Delta^2 \quad \text{Herschel,}$$

where, by definition, the measurement unit is Herschel $\equiv 1 \text{ m}^2 \text{deg}^2/\text{arcsec}^2$ (shortly denoted by H). For the fraction of unvignetted rays, $U = 0.90$, and the delivered image quality $\Delta = 3\arcsec$, we obtain the effective aperture diameter $D_e \approx 0.38 \text{ m}$ and the survey rate $\Gamma \approx 1.5 \text{ H}$. Even with such a small part of the available field, this is a significant value.

As was mentioned, detectors may be positioned arbitrarily in the field of view. In this connection, Tonry (2015) noted that some optimal summary area of detectors to maximize $\Gamma$ should exist because by expanding the operating area we increase $\Omega$ but reduce the effective aperture of the
of larger size. The proposed design as the core of some light-gathering system is promising for the lenses. For example, replacement of fused silica in the system VT-119f with acrylic reduces the weight of the lens corrector twice at the same image quality and transparency in a wide spectral range. Perhaps, further reduction of the lens corrector is possible only for not too wide angular field, say, not larger than 10°. Behind this approximate boundary, it is difficult to account for the curvature of the focal surface.

Of course, large curved light detectors, the production of which has just begun, will be used in future. This field is developing rapidly. The principal issues and real examples are discussed by Iwert & Delabre (2010) and Iwert et al. (2012); the first paper includes a photograph of curved detector with size of 60 mm × 60 mm and curvature radius 500 mm. There are also working devices of this type. In particular, a curved detector has been implemented in the DARPA 3.5 m Space Surveillance Telescope (Blake et al. 2013).

Besides, one need to keep in mind the long-known technology based on a plurality of delicate waveguides with a curved in aggregate input faced to the focal surface.

The method of working with the spherical focal surface applicable currently is the using of small flat detectors each of which is equipped with a flattening lens. This way has been implemented, e.g., in the Kepler space telescope that has a 95 cm aperture and an equivalent field diameter of 11°.6. Its detector consists of 21 pairs of ordinary 59 mm × 28 mm CCDs covered by sapphire field-flattening lenses. As to the VT-119g design, the curvature radius of its focal surface is 782 mm, so with a small flat detector of size, say, 25 mm the edge images are blurred up to 50 mm. Our preliminary consideration shows that the image quality can be improved considerably even by a single lenslet made of fused silica, and is fully recovered by the doublet of the same material. The problem becomes much simpler for larger telescopes similar to VT-119g. (The doubling of diameter gives only 2 m, which is already not far from the size of which has just begun, will be used in future. This field is developing rapidly. The principal issues and real examples are discussed by Iwert & Delabre (2010) and Iwert et al. (2012); the first paper includes a photograph of curved detector with size of 60 mm × 60 mm and curvature radius 500 mm. There are also working devices of this type. In particular, a curved detector has been implemented in the DARPA 3.5 m Space Surveillance Telescope (Blake et al. 2013).

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It seems likely that further research will expand the scope of the proposed optical layout. In particular, applications in the spectroscopy, physics of cosmic rays, geophysics and tomography are especially promising.
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