

Some Issues of Creation of Wide-Field Telescopes for Monitoring Satellites and Space Debris in High Earth Orbits

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Abstract. Presently, the catalogued GEO population of space objects numbers nearly 1500 payloads and space debris. The density of space objects continuously increases, the probability of dangerous approaches and collisions getting more and more. That means that regularly monitoring deep space with the help of optical sensors becomes more urgent every year. In this paper, the basic peculiarities of constructing the highly productive wide-angle telescope for survey of the GEO ring, detecting and getting metric measurements of space debris sized more than 25-30 cm are considered. The main attention is paid to the optical scheme of this telescope and agreement of the designed quality of a space object image and the CCD receiver parameters.

1. Introduction

The basic requirements laid to the space survey electro-optical detection systems are the following:

- as great as possible informative (productivity);
- high optical power.

The former one E is usually defined as the product of the effective telescope aperture area and the solid angle of the telescope field of view (FoV):

$$E = (\pi w D_m / 2)^2, \quad (1)$$

where w is an angular radius of FoV (deg.), D_m is a diameter of the telescope objective entrance pupil (m) (see, for example, [5]).

The sensitivity of the optical system M in terms of the telescope and detector parameters, and the observation conditions is defined as follows [2]:

$$M \approx \mu/2 + 2.5 \lg (D/\beta B) + 1.25 \lg (n_{0\lambda} \cdot T \cdot \Delta\lambda \cdot \tau \cdot q), \quad (2)$$

where

μ – sky background brightness in magnitudes from one arc second squared,

D - diameter of the telescope objective input pupil in cm,

β – angular diameter of the visible image of a star in arc seconds,

B – received value of the intelligent signal to noise ratio,

$n_{0\lambda}$ - light stream density from a star having zero magnitude:

$$n_{0\lambda} \approx 10^3 \text{ photons/s cm}^2 \text{ \AA},$$

T – signal accumulation time in seconds,

$\Delta\lambda$ – width of spectral band in \AA ,

τ – atmosphere and optics transparency factor,

q – photo-receiver quantum output (events/photon).

The quantities E and M, given by (1) and (2) are not independent. However, taken together they are very convenient for description of the survey class systems.

According to the formula (1), the survey information depends both on the aperture and the FoV size. So, one should try to increase both D and $2w$. This requirement is the main problem in designing the survey telescope: the attempts to increase the telescope diameter impact the difficulties for gaining a wide FoV. As for the limiting magnitude M, according to expression (2) the image quality is very important to increase its value. The image quality is characterized by the value of the β parameter, which is the angular diameter of the visible image of a star. In practice, the star image diameter provided by the optical system does not surpass the atmosphere quality that is $2'' - 3''$.

Thus, it is necessary to highlight the key points in respect to productivity/sensitivity before the development of survey optical systems.

It is the author's opinion that it is sufficient to have a telescope with the 75-cm entrance pupil for confident detection of space objects (SO) of sizes greater 25-30 cm ($18^m - 19^m$) in GEO.

At that, the effective FoV' area of 20-25 square degrees can be achieved. This FoV allows surveying the accessible GEO ring not less than 4-5 times over one observation night.

To observe the geostationary SO of sizes 5-20 cm ($19^m.5 - 21^m.0$) the telescope's aperture should be 3-5 times larger. Taking into account the requirements for the image quality, it will be difficult to achieve the indicated area of FoV. Most likely, this area will be 4-5 times less and adversely affect on systems productivity. The cost of such a telescope is a separate subject not discussed here.

Let us put a question: is there the barest necessity to GEO survey for search the small-sized space debris?

In our opinion, to provide safety for active spacecraft it is expedient to use the telescopes with 2-3 m aperture for a regular survey of the local zone near these spacecraft in GEO.

2. Substantiation of required telescope characteristics

For designing the wide-angle observation systems the following values of parameters, characterizing the observation condition and the radiation detector, were assumed:

- the sky background brightness $\mu \approx 21^m.0 - 22^m.0/\text{ang.s}^2$, which corresponds to the moonless night and absence of outside illumination;
- the angular diameter of a star image $\beta \approx 2'' - 3''$, which meets the expected atmospheric image quality;
- the acquisition interval $T \approx 1 - 5$ s, which is needed to provide the high system productivity ;
- the detector quantum output $q \approx 0.8 - 0.9$ events/photon;
- the region of visible band spectrum $\Delta\lambda = 3 \cdot 10^3 \text{ \AA}$;

- the resulting transparency coefficient $\tau \approx 0.3$.

The following group of parameters gives the survey characteristics which are desirable to be provided in the designed system:

- signal to noise ratio $B \approx 5 \dots 7$, which corresponds to reliable detection of a space object under the typical noise level for the contemporary CCD detectors;
- the limiting magnitude $M \approx 18^m.0 - 19^m.0$, which corresponds to space debris sized 25–30 cm under the mean phase angles of illumination, not more than 80–85 deg;
- the angular diameter of FoV $2w \approx 7^\circ$;

The above set of parameters, together with expression (2), allows to estimate the needed telescope entrance pupil diameter as $D \approx 60\text{--}80$ cm.

For gaining the required observation efficiency the size of the light receiver resolution element should be agreed with the atmospheric quality of image. The adopted value of the receiver quantum output $q \approx 0.8\text{--}0.9$ appreciably restricts the choice of feasible CCD matrices in serial production. In terms of correlation between “cost and quality” the most attractable seems the CCD matrix issued by the Great Britain Corporation E2V CCD 60-90, for which the quantum output is 0.90–0.92, the readout noise is about $6e^-$, and the pixel size is $13.5 \times 13.5 \mu\text{m}$.

For the equivalent telescope focal length F_{mm} the pixel angular size equals

$$p'' \approx 206 \cdot p_{mcm} / F_{mm} \text{ (ang. s)}, \quad (3)$$

where p_{mcm} is a linear pixel size in microns. If in accordance to above we accept in (3) the pixel angular size as $2''$, then for its linear size $13.5 \mu\text{m}$ we should provide the effective focal distance of about 1390 mm.

Taking into account the obtained estimate, F_{mm} , and confining to a rather high value of lens aperture, about 1:2, we come to refining the telescope aperture diameter – not more than 75 cm. With a further increase of aperture the difficulties grow hard in terms of attaining the required image quality in high aperture optics and the cost of telescope increases, too.

3. A design of the wide-angle telescope for detecting space objects in GEO and HEO

3.1 Initial data for a design

For development of the survey telescope system the following characteristics substantiated above were accepted:

- entrance pupil diameter $D = 750$ mm;
- FoV angular diameter $2w = 7^\circ$;
- effective observational spectral band $0.45\text{--}0.85 \mu\text{m}$;
- as a light receiver an array of CCD matrices with pixel size $13.5 \times 13.5 \mu\text{m}$ is used;
- FoV linear diameter – about 170 mm;
- RMS image diameter for a point light source in integral light should not exceed $2^2\text{--}3^2 \gg 15 - 20 \mu\text{m}$ within the whole FoV.

Besides the above requirements it is desirable that

- the system be compact;
- optical elements have the simple surface form;
- the lenses be made from simple and reliable sorts of glass.

3.2 The optical scheme and the basic telescope characteristics

The optical scheme of the telescope under design (Fig. 1) presents the further upgrading of the scheme developed in [4]. The latter in its turn originated from the Richter-Slefogt scheme [1, 3, 6]. Let's remember that the original Richter-Slefogt scheme FoV angular size is about 0.5 m, whereas that of its modifications is much more, and it can be increased up to 10° [4].

The merits of the scheme are a rather soft tolerance for its parameter values and simplicity of the optical surfaces.

Let's note that in the design a significant rear segment (100 mm) is envisioned necessary for accommodation of the construction elements. As is generally known, the increase of the rear segment appreciably deteriorates the image. But in this case a compromise solution was attained. The similar result was attained as to the sorts of glass used: application of some simple sorts of glass for the two-lens output corrector allows improving the image quality; however, the acceptable quality is attained by using the single most reliable and cheap sort of glass for all telescope lenses.

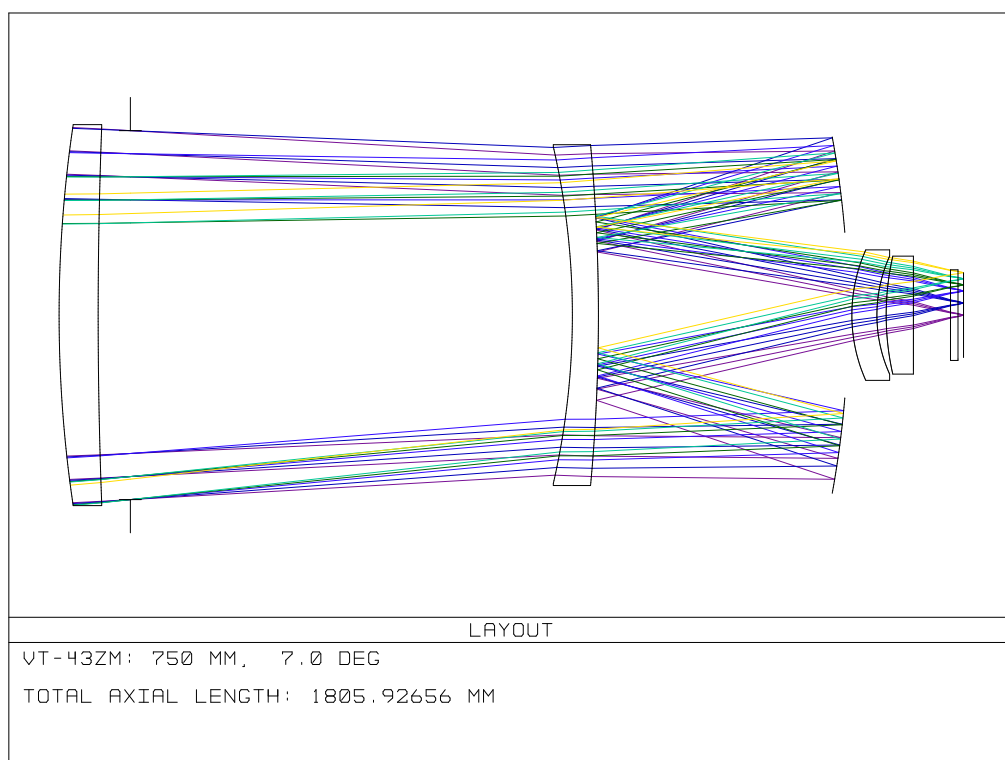


Fig 1. The telescope optical scheme

The basic characteristics of the telescope optical scheme are given in Table 1.

Table 1. Basic telescope characteristics

| A characteristic | Value |
|---------------------------|--------------|
| Entrance pupil diameter | 750.0 mm |
| Equivalent focal distance | 1380.5 mm |
| Lens aperture | 1:1.84 |
| Spectral band | 0.45–0.85 μm |

| | |
|---|--|
| FoV angular diameter | 7°.0 |
| FoV linear diameter | 169.1 mm |
| Length of the rear segment | 100 mm |
| Optical surfaces type | All spheres |
| Sorts of glass for lenses | All Schott N-BK7 |
| RMS image diameter of a point light source in integral light over the whole FoV | 10.5 – 15.6 μm , 1".6 – 2".3 |
| D ₈₀ , diameter of a circle containing 80% of the image energy for a point source in integral light over the whole FoV | 16.0 – 23.3 μm , 2".4 – 3".5 |
| Maximum distortion at wavelength 0.65 μm | 0.12 % |
| Total mass of optical elements | ~ 170 kg |
| Total mass of telescope | ~ 550 kg |
| Length of optical system | 1706 mm |

3.3 The rated quality of image

The quality of a point light source image in the integral band of light for this optical scheme is illustrated by Figs 2 and 3. The values of the RMS image diameter and the frequently used parameter D₈₀ are given in Table 1.

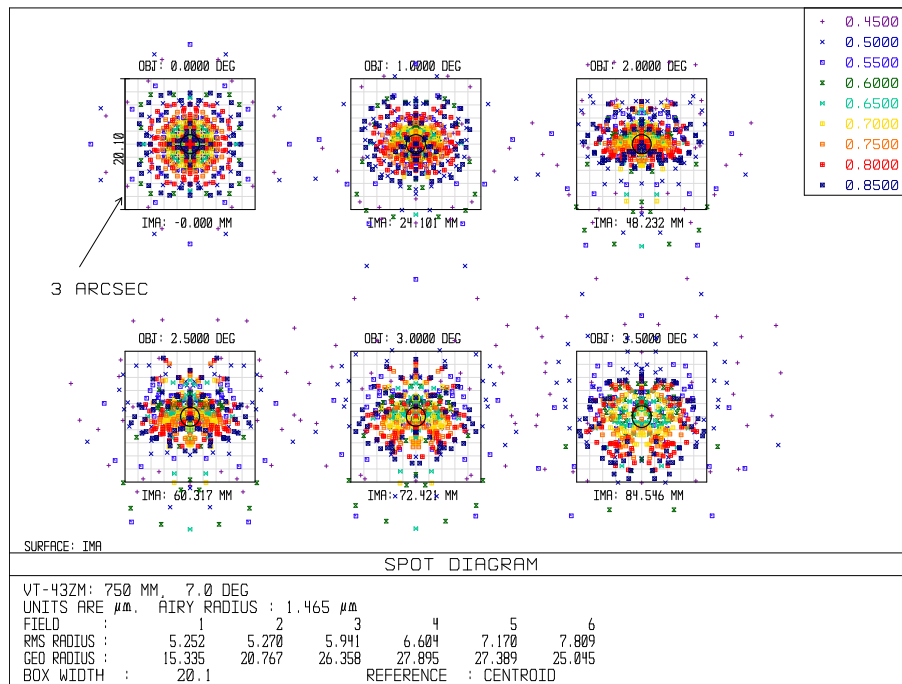


Fig 2. Point diagrams along the FoV in integral light

The square side corresponds to 20.1 μm (3"), the values of FoV angle are indicated at the top of squares, the distances from the sight axis are at the bottom of the squares. At the bottom of Figure 2 the RMS image radius is given.

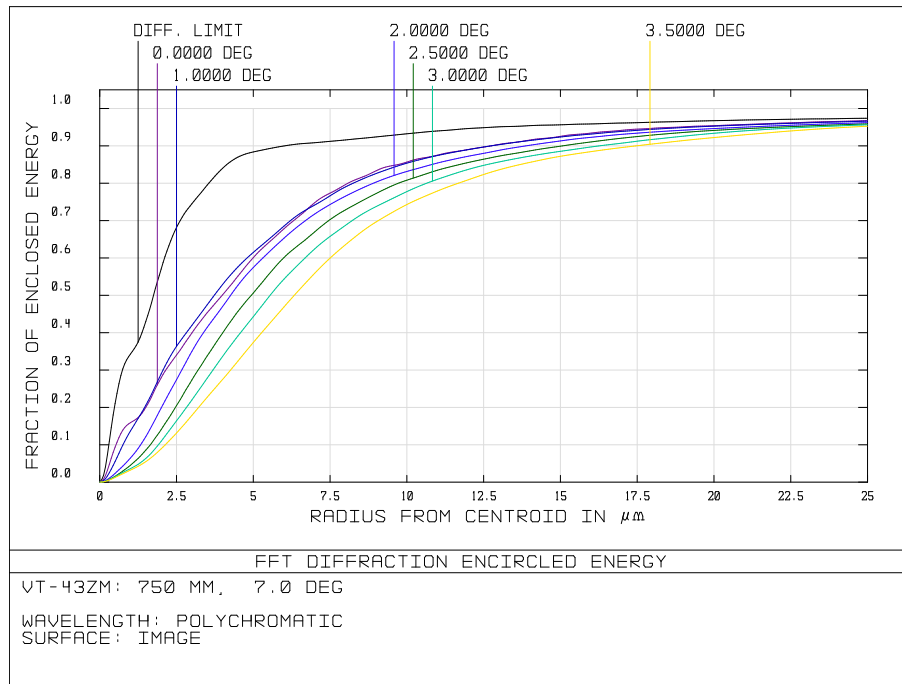


Fig 3. Energy concentration in polychromatic image of the point light source (fraction of enclosed energy in the circle (centroid) against its radius). The diffraction limit is given in black.

3.4 Distortion and light-transmission factor

Distortion of an extended image for a wavelength of $0.65 \mu\text{m}$ is a maximum value 0.12%, which is reached at the edge of the FoV. For alternative wavelengths the data are similar.

Take notice that using up-to-date methods of processing optical image distortion is no problem: its character within the field of view does not change in time and it can be corrected in the course of primary data analysis.

The dependence of the light-transmission factor (the telescope optics light passing capacity coefficient) versus wavelength was analyzed under the condition when the special MgF2 clarifying coating is put on the telescope optics surfaces. The thickness of the coating layer is $\lambda/4$ ($\lambda = 0.65 \mu\text{m}$). When the wavelength changes from $0.45 \mu\text{m}$ to $0.85 \mu\text{m}$ (the basic spectral band), the light-transmission factor varies in the range 0.70...0.76. These values are acceptable because the modern multilayer coatings count on a wide spectral band reaching much more light-transmission.

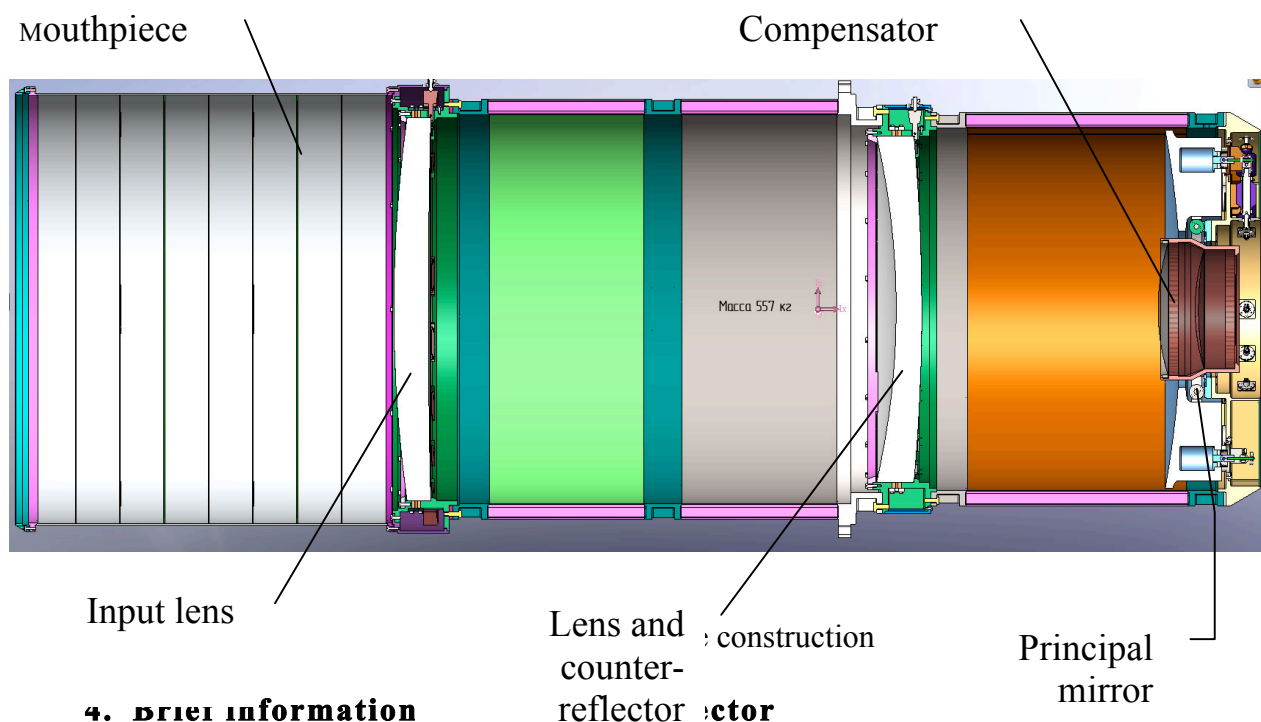
3.5 Construction of the telescope

The main elements of the telescope construction are shown in Fig 4.

The two-lens output corrector, together with its drive, is formed as a separate assembly. This allows its independent adjustment and tuning. For total elimination of a thermal misalignment, this corrector can move along the visual axis.

For removal of the possibility for direct stray lighting of the receiver, the telescope is equipped with an input blind. Elimination of the flare light and diminution of light diffusion inside the tube is attained by a special corrugation of the inner surfaces of tubes and rings of telescope.

All the air cavities in the telescope can be blown through with dry air. For this, special drain openings are envisioned.

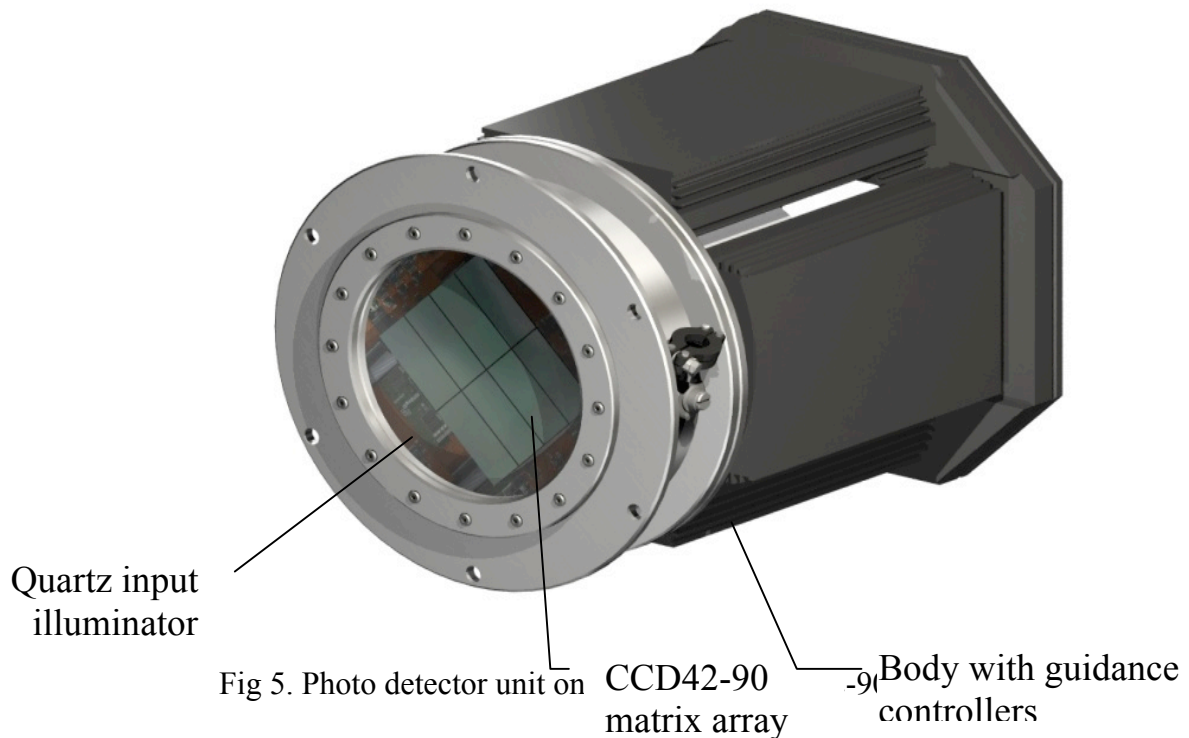


4. BRIEF INFORMATION

As a photo detector for operation with the telescope a special unit is envisaged. It is implemented on the base of an array of CCD matrices, CCD42-90, produced by the E2V Technologies. This array has the total format 8192×9216 pixels, the pixel size being $13.5 \mu\text{m} \times 13.5 \mu\text{m}$. The total size of the light sensing surface of the assembly equals $125 \text{ mm} \times 113 \text{ mm}$. The detector quantum output in the visible band of wavelength is 0.89-0.92. The outward appearance of the camera is shown in Fig 5.

The matrix assembly is placed inside the vacuum cavity and is cooled down up to the operational temperatures from -100°C to -120°C .

Especially for this camera an electromechanical shutter of the blind type was developed. It provides the necessary range of exposures. The time of full opening/shutting of the light sensing surface of the matrix array is less than 0.1 s.



5. Concluding remarks

The main features of the presented optical scheme are connected with carrying out the image of Cassegrain type, essential increase of distance between the input corrector lenses (which helps suppressing the image coma), and introduction of the two-lens output corrector. All this allows attaining the diameter of FoV, 7° , the telescope aperture being 750 mm. Earlier that was attainable only for a Schmidt camera (the known telescopes of this system - in Palomar and Bjurokan – have the diameters of their FoV of 6.5° and 5.5° , respectively). However, the correction plate of Schmidt camera is an aspheric element with the surface of four orders, while the presented scheme has only spherical surfaces. This circumstance essentially brings down technological difficulties of manufacturing the system as well as provides high smoothness of optical surfaces. The latter diminishes the light diffusion level and thereby increases the contrast of image.

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