Autocollimating compensator for controlling aspheric optical surfaces

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\textbf{ABSTRACT}
A compensator (null-corrector) for testing aspheric optical surfaces is proposed, which enables \textit{i}) independent verification of optical elements and assembling of the compensator itself, and \textit{ii}) ascertaining the compensator position in a control layout for a specified aspheric surface. The compensator consists of three spherical lenses made of the same glass. In this paper, the scope of the compensator expanded to a surface of revolution of a conic section of diameter \(D\). Having high enough optical power, a compensator must bring into a wavefront huge spherical aberration, moreover, of strictly specified value. Meanwhile, the conventional compensator cannot be verified and properly positioned without the use of extraneous optics. Thus, we must distinguish errors of the tested surface from those of the compensator and auxiliary devices. For this reason, leading optical workshops use a few compensators of different type, and only at coincidence of the analysis results the surface shape can be considered as ascertained.

\textbf{Key words:} telescopes

\section{INTRODUCTION}
As is known, it is easy to control a spherical surface during its making by examining the image of a point light source disposed at the center of curvature. If the sphere is perfect, we should see the diffraction Airy pattern; deviations from the desired surface shape can be evaluated either qualitatively, by using the Foucault knife-edge test, or quantitatively, by imposing a reference wavefront on the studied wave and analyzing the resulting interferogram.

On the contrary, testing of aspheric surfaces confronts opticians with a much more complicated problem. The point is that the spherical wave, being reflected from an aspheric surface, skews its original shape and does not form any reasonable image. Let us suppose, for example, that we have to control a surface of revolution of a conic section of diameter \(D\) with the paraxial curvature radius \(R_0\) and squared eccentricity \(\varepsilon^2\). Unlike the sphere, a bundle of normals to this surface do not converge in a single point; the distance \(N(y)\) between points of convergence of the paraxial normals and those to the \(y\)-zone -- an aberration of normals -- is defined by a simple expression:

\[ N(y) = \varepsilon^2 s(y), \]

where \(s(y)\) is sagitta for the \(y\)-zone (we assume, as usual, that the \(z\)-axis is directed along the system’s axis of symmetry). E.g., in the case of the nominal primary mirror of the Hubble Space Telescope (HST) we have \(D = 2400\) mm, \(R_0 = 11040\) mm, \(\varepsilon^2 = 1.002299\), so the marginal sagitta \(s(D/2) \approx 65.22\) mm, and the marginal normals aberration \(N(D/2) \approx 65.37\) mm. If we put a point light source in the paraxial curvature center, then the diameter of the reflected beam in the source vicinity exceeds 28 mm, and the image-based control of the mirror is simply out of the question.

Under these conditions, aspheric surfaces are usually controlled indirectly. Namely, a studied aspheric is included as a component into some more extent optical system in such a way that the wavefront emerging the whole system became spherical. The easiest way is to compensate the divergence of normals to aspheric surface. The corresponding methods, dating back to Maksutov (1924, 1932; see Maksutov 1984, p. 237) and Couder (1927), have now become basic at control of astronomical optics. The theory of compensators is discussed in detail in monographs of Wilson (1999, Sec. 1.3.4) and Geary (2002, Ch. 35), as well as in numerous papers mentioned there.

Clearly, tight tolerances are inherent to compensators, but not this feature lies in the heart of the problem; quite similar tolerances are inherent to some other optical systems. Having high enough optical power, a compensator must bring into a wavefront huge spherical aberration, moreover, of strictly specified value. Meanwhile, the conventional compensator cannot be verified and properly positioned without the use of extraneous optics. Thus, we must distinguish errors of the tested surface from those of the compensator and auxiliary devices. For this reason, leading optical workshops use a few compensators of different type, and only at coincidence of the analysis results the surface shape can be considered as ascertained.

Let us note in this regard that a known fault at figuring the HST primary mirror associated with wrong alignment of two-mirror compensator was essentially due to neglect-
than the paper that the compensator to a faster aspheric mirror recently given by Terebizh (2014). It was noted in the lat-
in CrAO optical workshop under the direction of N.V. Stesh-
(2014). This paper represents an autocollimating compensator, a device that meets requirements mentioned above.
As a consequence, one can definitely refer just to the as-
pheric surface all defects of the wavefront remaining visible after performance of specified procedures.

A particular scheme of the autocollimating compensator has been proposed several years ago (Terebizh 2009) in connection with the prospective renovation of the G.A. Shain 2.6-m telescope in the Crimean Astrophysical Observatory (CrAO, Ukraine). Then the compensator was manufactured in CrAO optical workshop under the direction of N.V. Steshenko. A more detailed description of that layout has been recently given by Terebizh (2014). It was noted in the latter paper that the compensator to a faster aspheric mirror than the f/3.85 G.A. Shain primary is of considerable interest. Just this case is discussed below on an example of the f/2.3 HST nominal primary. Apparently, the most extensive use of fast compensators can be expected in the domain of wide-field survey telescopes (Terebizh 2011).

2 AUTOCOLLIMATING MODE

The compensator consists of three spherical lenses made, for the sake of simplicity, of the same material (Fig. 1). Choice of glass type is a secondary issue; in particular, the compensator for the G.A. Shain mirror has been made of LZOS K8, equal to Schott N-BK7 and Ohara S-BSL7. An imaginary compensator for the HST primary discussed here is assumed to be made of fused silica, which is more stable to temperature variations. The light diameter of the largest lens is 111 mm. The rear surface of the third lens is intentionally made flat.

Fig. 1 and Table 1 give a complete description of the HST compensator in a test, autocollimating mode (for brevity, let us call it ‘A’). If we place a point light source S at a certain distance L from the vertex of the first compensator’s surface (in our case, L = 379.062 mm), then, after reflection from the flat surface, light passes the compensator in back direction, forming the image in the same place S where the source is located. To increase the brightness of reflected light, one can leave the flat surface uncoated, or it can be temporarily done specular. By one of usual ways the image is put aside; its quality speaks about an acceptability of a particular sample of the compensator.

Obviously, we can reach highest sensitivity at testing by providing the diffraction image quality. This requirement is fulfilled for the designed HST compensator (Fig. 2); the RMS wavefront error at wavelength \( \lambda = 0.6328 \mu\text{m} \) of He-Ne laser is \( \lambda/46 \).

Table 1. Compensator in autocollimation mode A.

<table>
<thead>
<tr>
<th>Element</th>
<th>( R_0 ) (mm)</th>
<th>( T ) (mm)</th>
<th>Glass</th>
<th>( D ) (mm)</th>
<th>Conic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>( \infty )</td>
<td>379.062</td>
<td>–</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>L1</td>
<td>–1200.0</td>
<td>16.0</td>
<td>FS</td>
<td>110.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>–121.449</td>
<td>0</td>
<td>–</td>
<td>110.9</td>
<td>0</td>
</tr>
<tr>
<td>L2</td>
<td>918.520</td>
<td>12.0</td>
<td>FS</td>
<td>109.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>–245.465</td>
<td>6.831</td>
<td>–</td>
<td>108.4</td>
<td>0</td>
</tr>
<tr>
<td>L3</td>
<td>–139.005</td>
<td>12.0</td>
<td>FS</td>
<td>107.6</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>( \infty )</td>
<td>0</td>
<td>–</td>
<td>107.6</td>
<td>0</td>
</tr>
<tr>
<td>Flat</td>
<td>( \infty )</td>
<td>0</td>
<td>Mirror</td>
<td>107.6</td>
<td>0</td>
</tr>
</tbody>
</table>

Designations: \( R_0 \) – curvature radius, \( T \) – distance to next surface, \( D \) – light diameter, Conic = \( -z^2 \). FS – fused silica.

![Figure 1](image1.png)

Figure 1. Verification the HST compensator in autocollimating mode.

![Figure 2](image2.png)

Figure 2. Spot diagram for the HST compensator in autocolli-
mating mode. Scale bar corresponds to 10 \( \mu\text{m} \), the circle of diam-
eter 5.4 \( \mu\text{m} \) – to Airy disc at 0.6328 \( \mu\text{m} \).

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\[ \delta z \simeq 0.2/u^2, \]  
where \( u \) is measured in radians and \( \delta z \) in microns. We have for the HST sample \( u = 9.4^\circ \simeq 0.16 \text{ radian}, \) so \( \delta z \simeq 8 \mu \text{m}; \) this value is within the tolerances.

3 CONTROL OF ASPHERIC SURFACE

The basic mode (let us call it ‘C’) corresponds to controlling a specified aspheric surface (Fig. 3). Table 2 gives a complete description of the particular example for the HST primary mirror. Since characteristics of the compensator itself remain identical in both the modes A and C, the differences between the Table 1 and Table 2 are concerned only with distances from the light source, diameters of light beams and inserting of examinee mirror into the scheme.

One of the essential compensator’s features is that the front surface of the first lens is concave, and its curvature radius is equal in absolute value to a new distance from the light source, diameters of light beams and inserting of examinee mirror into the scheme.

In the C mode, the aperture angle \( u = 5.3^\circ = 0.093 \text{ radian}, \) and equation (2) estimates the longitudinal accuracy of setting the light source as \( \delta z \simeq 23 \mu \text{m}, \) which is also within tolerances for the complete control scheme.

As one can see from Fig. 4, at appropriate placing of the compensator it provides the diffraction image quality of a point light source. In the C mode, the RMS error of the wavefront is \( \lambda/78 \) for \( \lambda = 0.6328 \mu \text{m}. \) Therefore, a possible imperfection of the image should be attributed only to errors of the tested aspheric surface. The specific distribution of errors according to types of aberrations is defined by the expansion of the wavefront into Zernike polynomials, orthogonal at the annular aperture [Noll 1976, Mahajan 1981].

4 TOLERANCES

Since the HST compensator is considered here only as an illustrative example, it is inappropriate to discuss a complete set of tolerances on its parameters, especially as their list includes 66 items. We will confine ourselves by pointing the order of magnitude and comparison of tolerances with those for the traditional Offner compensator.

As expected, tolerances of the autocollimating compensator are tight but common to all compensator types. If we limit the wavefront RMS error by value \( \lambda/20, \) then radius tolerances are within \( \pm(0.05 – 0.30) \mu \text{m}; \) thickness and surface decenter tolerances lie within \( \pm(0.01 – 0.10) \mu \text{m}, \) while the elements decenter tolerances are tighter, of the order of several microns. Tolerances on the transverse displacement of the compensator as a whole are also tight, \( \pm 7 \mu \text{m}. \) On the other hand, tolerances on the index of refraction and Abbe number are not too hard, \( \pm 0.0001 \) and \( \pm 0.3, \) respectively.

As a conventional Offner compensator to the HST primary, we have designed the system consisting of two singlet lenses of light diameters 93 mm and 31 mm, both made of fused silica. At the previous upper limit for the RMS wavefront error, all tolerances have the same order of magnitude as the specified above, except the noticeably tighter tolerances for radii of curvature and refractive index. Perhaps,
the reason for more strict tolerances is that Offner lenses have higher optical power.

Certainly, an advanced compensator can be used as well, e.g., the two-mirror Offner null-corrector with an additional field lens that was actually used for the HST. But, as Wilson (1999, p. 83) noted, “Such a 2-mirror Offner compensator may be considered as the ultimate in null system technology. However, the problems of manufacture and, above all, adjustment to correct position remain.”

Let us note that in the course of a compensator design one can adjust values of all radii to a standard grid of test plates, so the implementation of this part of requirements will not be too awkward.

Generally speaking, the control with a compensator is possible even beyond prescribed tolerances, but in that case we need to know the actual values of the compensator’s parameters and its actual position in order to account this information at analysis of interferogram as the inverse problem (Terebizh 2005).

5 CONCLUDING REMARKS

As we see, the proposed three-lens compensator has two core features:

- There is a position of a point light source, at which light twice passes through all lenses and forms a diffraction image at the source position. It allows us to find small deviations from nominal characteristics not only of the lenses, but also their mutual positions.
- The radius of curvature of the first compensator’s surface is equal in the absolute value to the distance of the compensator from the light source in a control mode. This feature allows us to set correctly both the light source and compensator.

It is worthy to mention, as an additional feature, that all the lenses are rather small, so one can choose a homogeneous piece of glass of which lenses will be made. Besides the specified, there are some other features of individual samples. In particular, due to moderate speed of G.A. Shain primary mirror, \(f/3.85\), it was possible to reduce the compensator diameter to 70 mm and make some of its curvature radii identical.

The autocollimating compensator can be considered as the development of a three-lens design by Puryaev (1976) intended for the control of the 6-m BTA primary mirror. In the Puryaev’s compensator, the ‘setting’ reflection of light occurs not from the first surface, as in our design, but from the front surface of the second lens; this feature brings an evident uncertainty, because the error in distance of the light source can be balanced by the deviation of geometrical parameters of first two lenses or by the refraction index of the first lens. Eventually, the basic difference of these two schemes is that our design allows the self-test both in the assembled and control states.

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