Basic designs for optical systems with remote pupils

V. A. Zverev and A. G. Serebryakov

St. Petersburg State Institute of Precision Mechanics and Optics (Engineering University)
(Submitted May 31, 1999)
Opticheskiĭ Zhurnal **67**, 74–77 (June 2000)

The prospects for employing optical systems with remote pupils in optical devices of various sorts are examined. A number of different approaches to the composition of the basic arrangements of such systems are analyzed. Algorithms for the design of objectives with remote pupils are presented, and examples of optical systems with parameters calculated using these algorithms are given. © *2000 The Optical Society of America.* [S1070-9762(00)01406-8]

1. INTRODUCTION

Optical systems with remote pupils are very widely used units in the construction of modern optical devices. A distinguishing feature of such systems is that the pupil is situated a considerable distance from the optical system. This offset of the pupil can reach or exceed the focal length of the optical system. This asymmetry of construction complicates the calculation and aberration correction of remote-pupil systems, especially when there are strict requirements on the values of the angular field and relative aperture in connection with enlargement of the optical diameters of the lenses and vignetting of wide oblique beams. Meanwhile, the possibilities for application of remote-pupil optical systems are so vast that it raises the question of constructing certain basic designs of optical circuits incorporating the principles for the development of various sorts of optical systems of this class for different particular areas of application.

2. SOME POSSIBLE WAYS OF USING REMOTE-PUPIL OPTICAL SYSTEMS

2.1. Using a remote-pupil objective (RPO) in combination with an optical beam-deflecting element

Using RPOs in viewing devices (viewfinders, periscopes, etc.). The use of RPOs in systems of this kind can substantially reduce the overall dimensions of the head prism or mirror (Fig. 1). The specifics of this class of devices, in particular, their ability to operate with a variable magnification, requires that the objective have appreciable values of the angular field and relative aperture, and, furthermore, it is necessary to provide a high image quality over a wide spectral range with an objective of small size.

The use of RPOs in scanning devices. The fact that the use of RPOs can enable a substantial reduction in the overall size of the beam-deflecting element makes this use of RPOs particularly important, since decreasing the dimensions of the scanning element and optical diameters of the lenses makes it possible to improve the dynamic parameters of a system, to reduce its size, and to increase the scanning rate (Fig. 2). Since devices of this kind use lasers as the radiation sources, it is not necessary to correct for chromatic aberrations. However, since the given objectives typically have an appreciable angular field at a small relative aperture, correction of the field aberrations requires a special approach.

2.2. Using RPOs for the matching of pupils

In designing optical systems one often must solve the problem of matching the pupils when different optical units are switched. The conventional solution to this problem is to introduce a matching element (a collective) into the optical circuit of the device. However, the use of RPOs here would be helpful for decreasing the size of the elements (Fig. 3).

2.3. Ocular — a representative of a family of remote-pupil systems

In spite of the fact that the optimum design parameters have long since been found for the most common kinds of

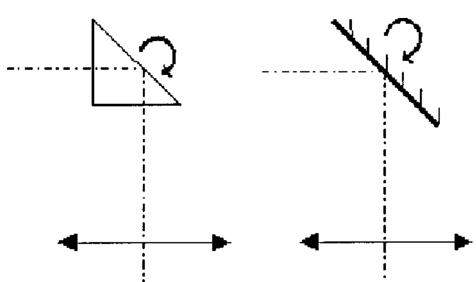

FIG. 1. RPO in a viewing device (viewfinder, periscope, etc.).

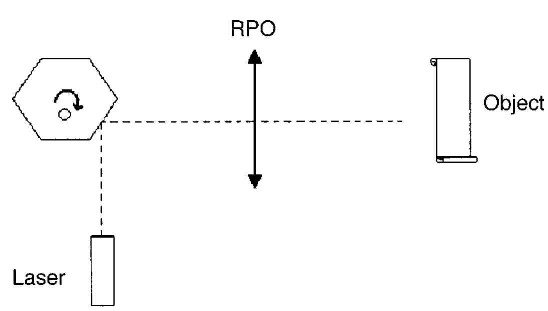

FIG. 2. RPO in a scanning device.

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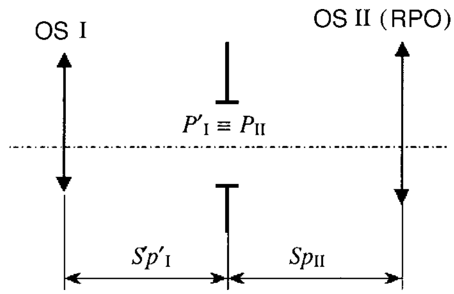

FIG. 3. RPO for the matching of pupils.

oculars, in nonstandard situations (large angular field, appreciable offset of the pupil) the designer must solve the problem of constructing a new optical circuit. In this connection the experience gained in the design of remote-pupil systems is altogether relevant.

Here we have considered only a small fraction of the possible applications of remote-pupil systems, but it is nevertheless clear that the problem of devising a technique for making design calculations for such systems is quite urgent. However, a bibliographic search turns up only an extremely limited number of publications devoted to this problem,[1–3] and they do not give the solution of the problem in general form and cannot take care of all the problems that face the designer. For example, one encounters the problem of considering the possible basic layouts of optical systems and of devising a computational algorithm for the most commonly used designs for remote-pupil systems.

3. DETERMINATION OF THE PARAMETERS OF POSSIBLE BASIC LAYOUTS FOR REMOTE-PUPIL OPTICAL SYSTEMS

It is obvious that the initial solution of the problem of constructing basic layouts should be sought in the area of correcting the third-order aberrations.

3.1. Construction of RPOs on the basis of a two-lens objective

It turns out that the simplest RPO design with satisfactory image quality can be based on a two-lens objective, for which the calculations do not present any difficulties. It is advisable to use the free parameters in the calculation for correcting the spherical aberration, coma, and meridional curvature (Fig. 4).

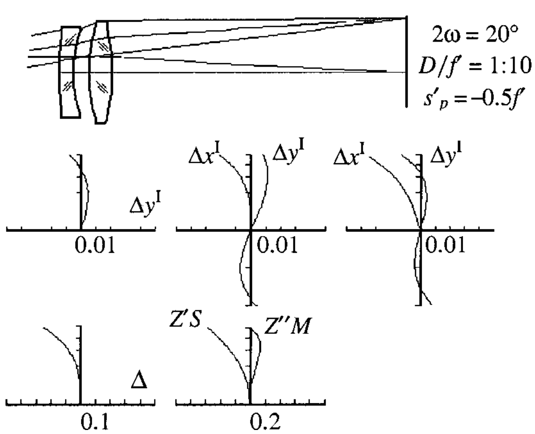

FIG. 4. RPO based on a two-lens objective.

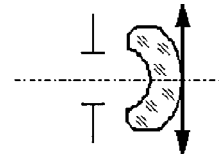
FIG. 5. RPO layout based on a meniscus concentric with the entrance pupil.

3.2. Construction of RPOs on the basis of a meniscus concentric with the entrance pupil

A patent search and an analysis of the existing designs for RPOs suggests that many of them are constructed on the basis of a thick negative meniscus concentric with the pupil (e.g., Refs. 5–8). Therefore, as the initial basic layout it is advisable to take a construction consisting of a thick meniscus concentric with the pupil — a compensator of the curvature of the field — and a power component, which to a first approximation can be considered thin (Fig. 5). This computational object can have the following variants of the basic design (Fig. 6a–e). The computational algorithm reduces to the following:

1) Specify the initial data: s_p — the offset of the pupil, and n — the refractive index of the meniscus.

2) Devies a system of equations for solving the problem of calculating the overall dimensions:

$$\left.\begin{aligned} &r_1=s_p,\\ &\varphi_1=(n-1)\left(\frac{1}{r_1}-\frac{1}{r_2}\right)+\frac{(n-1)^2d}{nr_1r_2}=\frac{(n-1)(r_2-r_1)}{nr_1r_2},\\ &\varphi_1+\varphi_2h_2=\varphi_1+\varphi_2+\varphi_1\varphi_2r_2=1,\\ &S_{\mathrm{IV}}=-\sum_{i=1}^{i=N}\frac{1}{r_i}\Delta\frac{1}{n_i}\approx\varphi_1+\varphi_2\pi=0. \end{aligned}\right\} \tag{1}$$

The first two equations derive from the condition that the meniscus is concentric with the entrance pupil, the third from the normalization condition, and the fourth from the Petzval condition. After solving the system of equations (1) we obtain the following parameters of the optical system: φ_1,φ_2 — the optical powers of the meniscus and thin component, r_1,r_2,d — the structure parameters of the thick meniscus.

3) Determine the basic parameters P, W, and C of the thin component by proceeding from the following considerations:

a) If one is designing an objective with a small relative aperture, then the values of the basic parameters can be determined from the condition for the correction of the coma, astigmatism, and chromatism of position, $S_{\mathrm{II}}=S_{\mathrm{III}}=S_i^{\mathrm{chr}}=0$:

$$P_2=\frac{1-\varphi_1}{r_2^2}, \tag{2}$$

$$W_2=-P_2r_2, \tag{3}$$

$$C_2=\frac{1}{\nu\varphi_2(1+r_2\varphi_1)^2}\left(\varphi_1-\frac{(n-1)d}{nr_1}\varphi_1+\frac{(n-1)^2}{n^2r_1^2}\right); \tag{4}$$

b) If the objective has an appreciable relative aperture, the main parameters are determined from the conditions for correcting the spherical aberration, coma, and chromatism of position, $S_{\mathrm{I}}=S_{\mathrm{II}}=S_{\mathrm{I}}^{\mathrm{chr}}=0$:

$$P_2=-\left(\frac{n-1}{nr_1}-\varphi_1\right)^2\left(\sigma_1n^2-\frac{n-1}{nr_1}\right)-\frac{(n-1)^3}{r_1^3n^2(1+\varphi_1r_2)}, \tag{5}$$

$$W_2=-P_2r_2, \tag{6}$$

$$C_2=\frac{1}{\nu\varphi_2(1+r_2\varphi_1)^2}\left(\varphi_1-\frac{(n-1)d}{nr_1}\varphi_1+\frac{(n-1)^2}{n^2r_1^2}\right). \tag{7}$$

Further, from the known relations (see, e.g., Ref. 4) we find the main parameters of the thin component $\mathbf{P}_2$ and $\mathbf{W}_2$.

4) Calculate the structure parameters of the thin component from the known values of $\mathbf{P}_2$, $\mathbf{W}_2$, and $\mathbf{C}_2$. Performing this operation does not present any difficulties, since it can be done automatically on a computer by available means. Depending on the specified image quality and considerations as to the fabrication of the objective and other constructional matters, one may choose any of the variants illustrated in Fig. 6a–e as the main part. One can do a parallel calculation for several variants of the main part of the objective and then choose the best solution.

5) Use a computer to automatically correct the basic design obtained. If the required image quality is not achieved at this stage, it will be necessary to introduce corrective elements into the basic design. Depending on the character of the dominant aberrations, these could be coma compensators, Smith lenses, ''chromatic'' radii, etc.

As an example, let us give the characteristics of the objectives in Figs. 7 and 8, calculated on the basis of the basic designs with $S_{\mathrm{I}}=S_{\mathrm{II}}=S_{\mathrm{IV}}=S_{\mathrm{I}}^{\mathrm{chr}}=0$ (input data $s_p=-0.5f'$ and $n=1.6476$) and with $S_{\mathrm{II}}=S_{\mathrm{III}}=S_{\mathrm{IV}}=S_{\mathrm{I}}^{\mathrm{chr}}=0$ ($s_p=-0.5f'$ and $n=1.6476$). It is seen from the examples given that the most acceptable design of the main part of the objective is the two-lens uncemented objective, which has the maximum number of free parameters for correction of aberrations. If the requirements on the speed of the objective are more stringent, the optimum for the basic unit is a combination of a two-lens cemented objective and a simple thin lens.

With the proposed method of calculation one can create basic designs for objectives with the parameters:

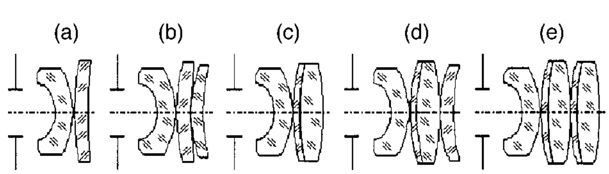

FIG. 6. Variants of the basic design for RPOs based on a concentric meniscus.

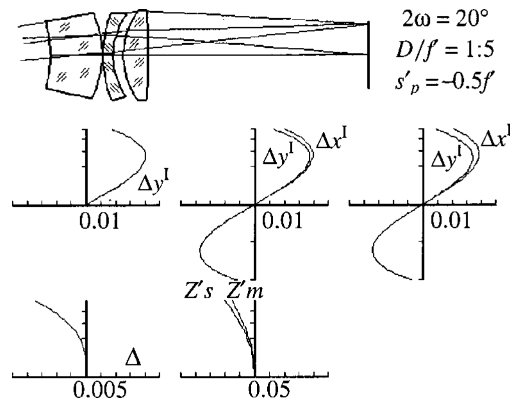

FIG. 7. Objective designed using the basic layout with $S_{\mathrm{I}}=S_{\mathrm{II}}=S_{\mathrm{IV}}=S_{\mathrm{I}}^{\mathrm{chr}}=0$.

— for $S_{\mathrm{I}}=S_{\mathrm{II}}=S_{\mathrm{I}}^{\mathrm{chr}}=0$, with $-s_p<0.5f'$, $D_p/f'<1{:}4$, $2\omega<30°$, with an image quality close to photographic;

— for $S_{\mathrm{II}}=S_{\mathrm{III}}=S_{\mathrm{I}}^{\mathrm{chr}}=0$, with $-s_p<0.15f'$, $D_p/f'<1{:}20$, $2\omega<15^{circ}$, with an image quality close to diffractional.

More stringent requirements on the speed and field of view of the RPO will force the designer to go beyond the region of solution of the problem set by the third-order aberrations. The higher-order aberrations that arise will make it necessary to introduce additional corrective elements into the basic design.

3.3. Construction of RPOs based on a confocal lens

Analysis of the existing designs shows that many RPOs are constructed on the basis of a thin power component and a negative confocal meniscus.[9–11] Such a design (Fig. 9) has the advantage that in the aplanatic correction of the power component the astigmatism and field curvature of the image do not depend on the position of the pupil, and for $S_{\mathrm{I}}=S_{\mathrm{II}}=0$ they are given by the expressions

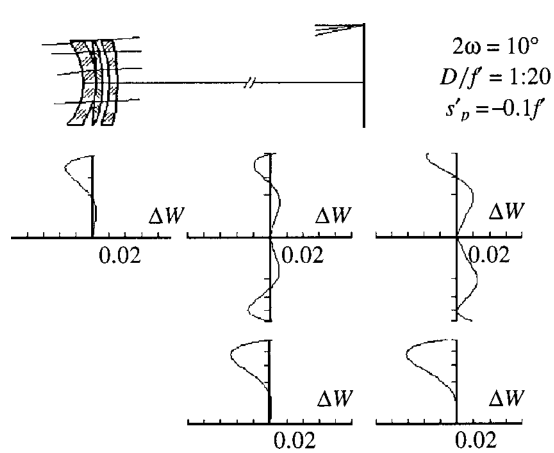

FIG. 8. Objective designed using the basic layout with $S_{\mathrm{II}}=S_{\mathrm{III}}=S_{\mathrm{IV}}=S_{\mathrm{I}}^{\mathrm{chr}}=0$.

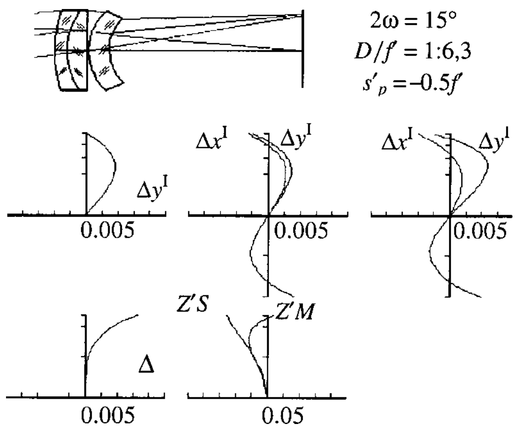

FIG. 9. RPO based on a confocal lens.

$$\left.\begin{aligned} z'_m &\approx -1.85 f \tan^2\omega, \\ z'_s &\approx -0.85 f \tan^2\omega, \\ z'_m - z'_s &\approx -f \tan^2\omega \end{aligned}\right\}. \tag{8}$$

The design calculations for the objective reduce to a calculation for an aplanatic two-lens cemented objective and determination of the parameters of the confocal meniscus. In comparison with the single two-lens cemented objective, the introduction of a confocal meniscus in the optical circuit makes it possible to correct the meridional curvature and to reduce the astigmatic difference $z'_m - z'_s$ to a minimum; the diameter of the circle of confusion along the field can be decreased by 50%.

In summary, the proposed approaches to the composition of basic layouts of optical systems with remote pupils can eliminate many of the problems of designing such systems.

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