the composite material and that the accuracy is sufficiently high.

Figure 3 shows a nomogram of the process which expresses the relationship $\Delta_1=\Delta_1(\tau)$ determined by the combination of criteria in (2) for various values of α and R.

An analysis of the results of the calculation shows that when α_1 = 15 (free convection, air) the thickness of the "sandwich" Δ_1 for the briquet radii investigated is a monotonic function of the compaction time $\hat{\tau}$, and reaches values $\Delta_1 \gg$ R at large values of $\hat{\tau}$. At the values of $\hat{\tau}$ being considered, the criterion which governs the behavior of Δ_1 is the condition $(2)_3$. On increasing the heat transfer coefficient to α_2 = 100 (forced convection, air) a "plateau" appears on the curve $\Delta_1=\Delta_1(\hat{\tau})$ at the level of 70-80 mm. The effect of the criterion $(2)_3$ becomes smaller as R increases, and the criteria $(2)_1$ and $(2)_2$ begin to have an effect, and for $25 \leqslant R \leqslant 50$, the behavior of Δ_1 is determined exclusively by the criterion $(2)_2$. It should be noted that $\Delta_1(\alpha_1) \gg \Delta_1(\alpha_2)$ in all cases when $\hat{\tau} \geqslant$ 15 seconds. A further increase of the heat transfer coefficient to α_3 = 250 (forced convection, water) leads to an increase in the effect of criterion $(2)_1$ for $10 \leqslant R \leqslant 25$, and when $R \geqslant 25$ mm the effect of criterion $(2)_2$ becomes smaller. The trend towards an increased thickness of the shell is simplified for briquets of small dimensions at quite large holding times. It can therefore be concluded that the role of the effectiveness criteria shifts in the direction $(2)_3 \to (2)_1$ as α increases, and that in the working range of $\hat{\tau}$

$$\Delta_1(\alpha_1) \gg \Delta_1(\alpha_2) \gg \Delta_1(\alpha_3).$$

The results which have been obtained make it possible to provide practical recommendations for the construction of the heat-protective shells. From Fig. 4, which represents the thickness Δ_1 as a function of α for various radii and holding times, it follows that there is an optimum (but not a very sharply marked one) in the conditions of cooling at which a sufficiently small thickness of the "sandwich" is reached.

LITERATURE CITED

1. A. A. Samarskii, The Theory of Difference Schemes [in Russian], Moscow (1983).
2. A. A. Samarskii and E. S. Nikolaev, Methods of Solving Finite-Difference Equations [in Russian], Moscow (1978).
3. N. N. Kalitkin, Numerical Methods [in Russian], Moscow (1978).

THERMOOPTICAL PROCESSES IN MIRROR–LENS OBJECTIVES. I. SCHEME FOR SYNTHESIS OF A THERMOSTABLE TELESCOPE

G. N. Dul'nev, E. D. Ushakovskaya, and G. I. Tsukanova

UDC 535.813:536.24

Special features of the designing of a thermostable telescope are discussed on the example of the objective for the narrow-angle television camera of the Vega spacecraft.

A new scientific discipline, which can be called thermooptics for short, has taken shape in recent years. The sphere of consideration of the latter includes the joint analysis of thermal and optical phenomena arising in the passage of light through condensed and uncondensed media. Up to now these phenomena have been studied in sufficient detail in gaseous lenses, controlling strong fluxes of laser radiation [1], as well as in the active elements of solid lasers, in resonators, etc. [2-4]. Relatively long ago, opticians turned attention to the influence of thermal processes on the quality of the image produced by an optical system [5-7]. In the investigation of optical systems, however, there has been insufficiently full allowance for the mutual thermal influence of the construction elements on each other, the thermooptical models have not been adequate to the object being studied, as a rule, and the

Leningrad Institute of Precision Mechanics and Optics. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 52, No. 5, pp. 827-833, May, 1987. Original article submitted March 24, 1986.

0022-0841/87/5205-0607$12.50

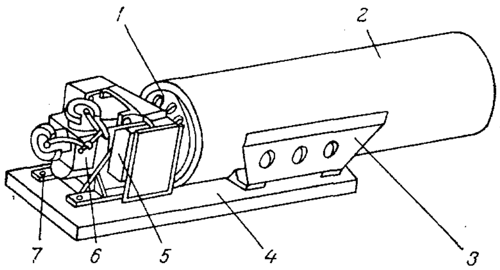

Fig. 1. Construction of the telescope.

process of synthesis of the construction has not been traced sufficiently clearly.

An attempt to outline a scheme of solution in this direction for an extensive class of opticoelectronic instruments and to propose a method of analyzing the temperature fields of complicated optical instruments is contained in [8, 9]. On the basis of the results of these papers, we shall consider special features of the designing of a thermostable telescope on the example of a television camera for the Vega spacecraft. And we shall attempt not only to analyze the thermal and optical processes of the telescope but also to outline a scheme for the synthesis of such instruments.

The telescope is designed to obtain black-and-white and spectrozonal images of the nucleus of Halley's comet, as well as to control the rotating platform, assuring that the scientific instruments are aimed at the comet's nucleus. The construction of the instrument contains the optical system 1 and the surrounding blind 2, which is fastened by a bracket 3 to the platform 4. The optical system, together with the electronic units 5 and the detector unit 6, is mounted on a bracket 7 (Fig. 1). Let us give the main parameters of the optical system. Focal length f' = 1200 mm, aperture ratio 1:5, angular field 2ω = 48', diameter of the primary mirror 240 mm. The telescope operates in open space, the background temperature of which is −269°C. The instrument is mounted on a platform, the temperature of which varies in the range of (−20 to +40)°C. For protection from the action of the ambient medium, the television camera is covered on the outside by a metallic shield and vacuum-shield thermal insulation (VSTI).

The comet is observed over four days. On the first two days solar radiation falls on the inner surface of the blind at a 60° angle to the optical axis. On the next two days solar radiation does not enter the instrument.

The low temperature of the ambient medium and the high density of the solar radiation (2300 $W \cdot m^{-2}$) can be causes of a considerable range of variation of the temperature of the optical system, a temperature drop between its elements, and a temperature gradient in the optical elements. These factors, in turn, lead to the appearance of thermooptical aberrations, mainly defocusing. Therefore, one of the important problems connected with designing the telescope for the VEGA television system was to assure its normal operation in different regimes, in which the sizes of the thermooptical aberrations do not exceed the allowable values.

The solution of this problem requires a joint analysis of the thermal and optical characteristics of the instrument, which allows us to proceed to the next main problem — the synthesis of the construction. The synthesis problem (designing a thermostable optical system) was solved in three stages. In the first stage we chose the basic construction of the instrument and the materials of the optical and structural elements and determined the thermoaberrations for equal temperatures of all the structural elements. We also made a preliminary estimate of the allowable temperature differences between the main elements of the optical system.

In the second design stage, simultaneously with the construction analysis, we made a thermal calculation to determine the temperatures of the structural elements and assured a stable thermal regime for the instrument.

In the third stage we made a final calculation of the temperature fields for the construction developed and determined the sizes of the thermooptical aberrations corresponding to them.

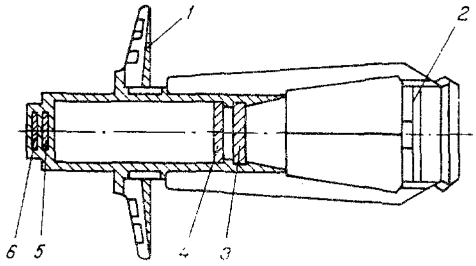

Fig. 2. Optical system of the telescope.

The designing begins (first stage) with the choice of the basic construction. Here we must immediately reject the use of active systems of temperature regulation because of the rigid demands on the mass of the instrument and the power consumption.

Omitting the procedure for choosing the basic construction, in Fig. 2 we give its general scheme, consisting of a primary mirror 1, a secondary mirror 2, and compensator lenses 3-6.

Then it was necessary to determine the materials for the fabrication of the mirrors, the lens amounts, and the housings of the objective and the detector unit. In choosing the materials we allowed for the fact that thermooptical aberrations are determined by three factors: the variation of the overall temperature level of the optical system, the temperature drops between optical elements, and the temperature gradients in the elements. Starting from this, different ways of solving the problem are possible. In this case the mirrors should be made of quartz, Pyrex, or pyroceramic, while the structural elements and the detector unit should be made of Invar.

A second way of solving it is to fabricate the mirrors, structural elements, and detector unit from the same material, such as titanium. In this case, if there are no lens elements in the system, defocusing due to a change in the overall temperature is compensated for by displacement of the receiver. The temperature drops in the optical system and the temperature gradients in the mirrors will be lower than in the preceding case (because of the higher thermal conductivity of the material), but the degree of their influence on the image quality is higher. Therefore, the demands increase for a uniform temperature distribution in the optical system. In this case the weight of the objective is considerably lower than in the first variant. As a result, we chose the second way of solving the problem.

In the first stage of designing we estimated the thermoaberrations for two values of the uniform temperature field, equal to the extreme values of the platform temperatures, +40°C and −20°C. Here the radii r_t, the thicknesses and the air gaps d_t, and the indices of refraction n_t were determined from the formulas

$$r_t = r_{20}(1+\alpha\Delta T), \quad d_t = d_{20}(1+\alpha\Delta T), \quad n_t = n_{20}+\beta\Delta T. \tag{1}$$

The calculations showed that the amount of defocusing in a uniform temperature field does not exceed 0.001 mm, i.e., it is practically absent. We also made a preliminary estimate of the allowable temperature drop between the first and second mirrors of the optical system.

Let us find an expression for the thermooptical aberration of the position of the image for a two-mirror system. The invariant of paraxial optics for the mirror surface has the form [6]

$$S'^{-1} + S^{-1} = 2r^{-1}, \tag{2}$$

where S and S' are the distances from the mirror to the object and the image; r is the radius of curvature of surface. The quantities S, S', and r are functions of temperature. After differentiating (2), we obtain

$$\Delta S'/S'^2 + \Delta S/S^2 = 2\Delta r/r^2. \tag{3}$$

For mirror surface number k, after multiplying (3) by h_k^2 and a transformation, we have

$$\Delta S_k (\tan \alpha_k'^*)^2 + \Delta S_k (\tan \alpha_k^*)^2 = 2h_k^2 \Delta r_k / r_k^2. \quad (4)$$

Here h_k denotes the height of the zero ray at the k-th surface, while tan $\alpha_k'^* = h_k/S_k'$ and tan $\alpha_k^* = h_k/S_k$ are tangents of the angles between the zero ray and the optical axis.

In a two-mirror system with a distance d_1 between mirrors, we have

$$S_1' = S_2 + d_1, \quad \Delta S_1' = \Delta S_2 + \Delta d_1. \quad (5)$$

Taking (4) and (5) into account, we have

$$\Delta S_2' = -2\Delta r_1/r_1^2 + 2h_2^2/r_2^2 \Delta r_2 + \Delta d_1 (\tan \alpha_2^*). \quad (6)$$

The thermooptical aberration of the image position in (6) is given for f' = 1. To obtain its true value, one must multiply the quantity $\Delta S_2'$ by the focal length of the objective.

Substituting the values $h_2 = 0.5$ and $\tan \alpha_2^* = -2$ for the telescope into (6), we obtain

$$\Delta S_2' = -2\Delta r_1/r_1^2 + 0{,}5\Delta r_2/r_2^2 + 4\Delta d_1. \quad (7)$$

The changes in the radii of curvature r_1 and r_2 and in the distance d_1 between the mirrors are, in accordance with (1),

$$\Delta r_{1,2} = r_{1,2}\alpha_{1,2}\Delta T_{1,2}; \quad \Delta d_1 = d_1 \alpha_d \Delta T_d. \quad (8)$$

Substituting (8) into (7), we find

$$\Delta S_2' = -2\alpha_1 \Delta T_1/r_1 + 0{,}5\alpha_2 \Delta T_2/r_2 + 4\alpha_d d_1 \Delta T_d. \quad (9)$$

The displacement Δa of the image receiver due to a change in the temperature of the housing in which it is mounted will be

$$\Delta a = \alpha_{re} h_2 \Delta T_{re}. \quad (10)$$

The defocusing Δ arising in this case is determined from the equation

$$\Delta = \Delta S_2' - \Delta a = -2\alpha_1 \Delta T_1/r_1 + 0{,}5\alpha_2 \Delta T_2/r_2 + 4\alpha_d \Delta T_d d_1 - \alpha_{re} \Delta T_{re} h_2. \quad (11)$$

The amount of this defocusing will be zero if the coefficients of linear expansion of the materials of the mirrors, the housing, and the receiver unit are close to zero or the thermo-optical aberration of the image position is compensated for by a displacement of the receiver.

With uniform heating or cooling of the instrument, i.e., with $\Delta T_i = \Delta T = \text{const}$ (i = 1, 2, d_1, re), and with the same coefficient of linear expansion for all the elements, i.e., with $\alpha_i = \alpha = \text{const}$ (i = 1, 2, d_1, re), the amount of defocusing, determined by Eq. (11), is

$$\Delta = \Delta S_2' - \Delta a = \alpha \Delta T (-2/r_1 + 0{,}5/r_2 + 4d_1 - h_2). \quad (12)$$

Substituting the telescope parameters $r_1 = -1$, $r_2 = -1$, $d_1 = -0.25$, and $h_2 = 0.5$ into (12), we obtain the defocusing Δ, equal to zero for all values of α and ΔT.

Let the temperatures at the primary and secondary mirrors be different. Let us determine the defocusing for this case, assuming that the temperature of the housing connecting the primary and secondary mirrors equals the arithmetic mean of their temperatures, while the rest of the housing has the temperature of the primary mirror.

Substituting the values of ΔT_1 and ΔT_2 into (11), we obtain

$$\Delta = 1{,}125\alpha (\Delta T_1 - \Delta T_2). \quad (13)$$

Equation (13) is very approximate, since the housing near the detector unit and the detector unit have different temperatures from the temperature of the primary mirror.

In order that the circle of confusion due to defocusing not exceed the size of a receiver element (18 × 24 μm), it is necessary that the temperature difference between the mirrors to be no more than 8°K, i.e., $\Delta T \leqslant 8°K$.

In the second stage, simultaneously with working out the construction, on the basis of thermal calculations we solved the problem of assuring an allowable thermal regime (the temperature level of the optical system and the temperature drops between its elements).

An analysis of the thermal regime of the television camera showed that the temperature level of the optical system is determined mainly by its heat exchange with outer space, with the blind, and with the platform. Heat exchange with the detector and electronic units influences the temperature drops in the optical system and hardly affects its temperature level.

For an approximate estimate, we can take the temperature fields of all the regions as uniform and estimate them from the formula

$$T_o = (T_p\sigma_{op} + T_b\sigma_{ob} + T_s\sigma_{os})/(\sigma_{op} + \sigma_{ob} + \sigma_{os}). \tag{14}$$

The thermal conductivities between the optical system (OS) and the platform (σ_{op}), the OS and the blind (σ_{ob}), and the OS and the outer space (σ_{os}) can be calculated from formulas given in [10].

As was noted earlier, the temperature of the platform varies in the range of (−20 to +40)°C while the background temperature of space is −269°C. The temperature of the blind is determined by its heat exchange with outer space and by the solar radiation absorbed by it and, as estimates showed, can vary in the range of (−70 to +100)°C.

The temperature of the optical system is determined by the ratios between the thermal conductivities σ_{op}, σ_{ob}, and σ_{os}.

To reduce heat exchange between the objective and space, the entire instrument is covered on the outside by vacuum-shield thermal insulation. In outer space the heat is transferred by radiation through the entrance opening of the blind. The conductivity σ_{os} is determined by the sizes and mutual arrangement of the optical system and the blind, as well as by their emissivities. These parameters are chosen on the basis of the optical demands, so that regulation of the thermal regime by varying the conductivity σ_{os} is very limited.

The wide range of temperature variation (−70 to +100)°C of the blind and its thermal coupling with the optical system can lead to considerable fluctuations in the temperature of the latter. In this connection it is expedient to reduce the thermal coupling between the optical system and the blind, i.e., to "uncouple" them structurally. At the same time, it is not possible to fully eliminate the influence of the blind on the temperature of the optical system because of the presence of radiative heat exchange. This influence can be reduced considerably, however, by narrowing the range of variation of the blind temperature, which is achieved by thermally insulating the surface of the last diaphragm of the blind, facing toward space, and by increasing the thermal conductivity σ_{bp} between the blind and the platform. In Fig. 3 we give the dependence of the temperature drop ΔT between the objective and the platform on the value of σ_{bp}.

The temperature drops between the optical system and the blind and between the optical system and outer space are considerable, causing large heat fluxes between them even when the conductivities are relatively low. Therefore, if the values of all the conductivities appearing in Eq. (14) are comparable with each other, a slight change in even one of the conductivities (due to a change in the external conditions or the construction parameters) leads to a considerable change in one or several heat fluxes and ultimately to a considerable change in the temperature of the optical system, i.e., the thermal regime of the instrument becomes unstable. The stability can be increased by considerably increasing one of the thermal conductivities. It is most convenient to do this for the conductivity σ_{op} between the optical system and the platform. Then the heat flux between these regions increases and becomes several times higher than the other heat fluxes appearing in Eq. (14). In this case, even upon a considerable change in the thermal conductivities σ_{os}, σ_{ob}, and σ_{op}, the temperature T_o of the optical system hardly changes and remains close to the platform temperature.

To determine the value of the conductivity σ_{op} required to assure stable operation of the telescope in a thermal respect, we carried out a statistical analysis, the algorithm for which is given in [3]. For this the deviations of the thermal conductivities were modeled randomly in accordance with a uniform law in an interval of ±20% of the nominal values. From the results of the statistical analysis we constructed the dependence between the relative size of the confidence interval Δ and the thermal conductivity σ_{op} (Fig. 4) and found the

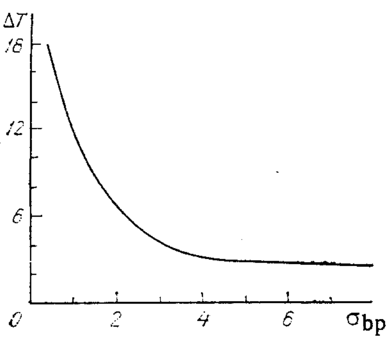

Fig. 3

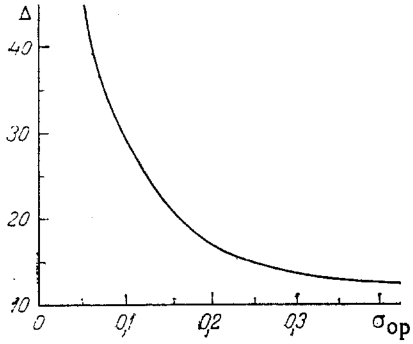

Fig. 4

Fig. 3. Dependence of the temperature drop ΔT (°K) between the objective and the platform on the thermal conductivity σ_{bp} (W·°K^{-1}) between the blind and the platform.

Fig. 4. Size of the confidence interval Δ (%) for the temperature of the optical system, normalized to the nominal value of this temperature, as a function of the thermal conductivity σ_{op} (W·°K^{-1}) between the objective and the platform.

region of stable thermal regime for the telescope.

As was noted earlier, the operation of the optical system is influenced not only by its temperature level but also by the temperature drops between the optical elements, primarily between the mirrors. The estimate given in [9] shows that the temperature drop ΔT is the larger, the greater the differences between the thermal conductivities between the mirrors and outer space, the blind, the electronic and detector units, etc., and the contribution to the temperature drop is larger for regions whose temperatures T_j differ more strongly from the temperature T_o of the optical system. On the basis of such an analysis, measures could be proposed for reducing the temperature drop between the mirrors. But our investigation of the thermal regime of the telescope is still insufficient for an estimate of the image quality in different regimes of operation. These questions comprise the content of the third stage of designing and will be discussed in the future.

NOTATION

r_{20}, d_{20}, n_{20}, radius of curvature, air gap, and index of refraction at 20°C; α, coefficient of linear expansion of the material; ΔT, temperature drop of the optical system relative to 20°C; β, temperature coefficient of the index of refraction; α_{re}, coefficient of linear expansion of the material of the receiver housing; ΔT_{re}, variation of the temperature of the receiver housing relative to 20°C; T_p, T_o, T_s, T_b, temperatures of the platform, the optical system, outer space, and the blind, respectively.

LITERATURE CITED

1. O. G. Martynenko, P. M. Kolesnikov, and V. L. Kolpashchikov, Introduction to the Theory of Convective Gaseous Lenses [in Russian], Minsk (1972).
2. W. Koechner, Appl. Opt., 9, No. 11, 2548-2553 (1970).
3. G. N. Dul'nev, B. A. Ermakov, and S. I. Khankov, Inzh.-Fiz. Zh. 42, No. 2, 307-313 (1982).
4. Yu. É. Kamach, V. M. Ovchinnikov, and V. G. Parfenov, Opt.-Mekh. Promst., No. 2, 54-57 (1984).
5. D. S. Volosov, Opt. Spektrosk., 4, No. 5, 663-669; No. 6, 772-778 (1958).
6. G. G. Slyusarev, Methods of Calculation of Optical Systems [in Russian], Moscow (1969).
7. H. Koehler and F. Strehl, Space Optics [Russian translation], Moscow (1980), pp. 80-100.
8. G. N. Dul'nev and E. D. Ushakovskaya, Inzh.-Fiz. Zh. 45, No. 4, 659-666 (1984).
9. G. N. Dul'nev, V. I. Kostenko, E. V. Sakhova, and E. D. Ushakovskaya, "Thermal regime of the Vega television camera," Preprint, Inst. Kosm. Issled., Akad. Nauk SSSR, Moscow (1984).
10. G. N. Dul'nev, Heat and Mass Transfer in Radio-Electronic Apparatus [in Russian], Moscow (1984).