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A PROCEDURE FOR DETERMINING THE OPTICAL CHARACTERISTICS OF A DEVICE FOR MEASURING ILLUMINATION IN THE ATMOSPHERE OF VENUS

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A PROCEDURE FOR DETERMINING THE OPTICAL CHARACTERISTICS OF A DEVICE FOR MEASURING ILLUMINATION IN THE ATMOSPHERE OF VENUS

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INTRODUCTION /3*

On the space vehicles "Venera-9" and "Venera-10" the illuminance regime in the atmosphere of Venus was investigated on October 22 and 25, 1975. The measurements were made in five spectral intervals with respect to three directions. A description of the apparatus and the preliminary results of the measurements are presented in [1,2]. The quality of the processing of the measurement results and their interpretation depends on the accuracy with which the optical characteristics of the apparatus are determined. In the present paper we consider a procedure for obtaining the calibration, angular and spectral characteristics of the apparatus.

The apparatus is a broad band photometer. It has three identical groups of photoreceivers on which light falls through fiber light guides. Each group contains three cadmium sulfide photoresistors SF2-1 with light filters, a cadmium selenide photoresistor SF3-1 and a silicon photodiode KFDM. The temperature of the photoreceivers is measured by thermistors installed in series with the receivers.

* Numbers in margin indicate pagination of original foreign text.

1. General Aspects

The output signal of the photometer "U" is uniquely determined by the quantity "W" which is defined by the following expression:

$$W = \frac{\iiint_{\lambda \vartheta \varphi} J(\lambda, \vartheta, \varphi) \cdot S(\lambda) \cdot F(\vartheta, \varphi) \cdot \sin \vartheta \cdot d\lambda \cdot d\vartheta \cdot d\varphi}{\int_{\lambda} S(\lambda) d\lambda \cdot \iint_{\vartheta \varphi} F(\vartheta, \varphi) \sin \vartheta \cdot d\lambda \cdot d\vartheta \cdot d\varphi} \quad (1)$$

Here $J(\lambda, \vartheta, \varphi)$ – is the intensity of the atmospheric radiation in W/m^2 μ sterad; $S(\lambda)$, $F(\vartheta, \varphi)$ are, respectively the normed spectral characteristic and the beam pattern of the apparatus; ϑ and φ are, respectively, the polar and azimuthal angles in the spherical coordinate system, the axis of which coincides with the axis of the light guide of the apparatus; and λ is the wavelength in microns. /4

W is the intensity of the radiation, averaged with respect to the wavelength within the limits of the spectral sensitivity of the apparatus and the direction within the limits of the beam pattern.

To establish the relationship between the readings of the device "U" and the desired intensity, it is necessary to have a calibrated characteristic of the apparatus U = f(W), and also to know its angular and spectral characteristics $F(\vartheta, \varphi)$ and $S(\lambda)$.

The initial calibration data were as follows: The range of measurement of illumination is 10 - 270000 luxes for the spectral distribution of energy, corresponding to the solar range. The range of the temperature measurements of the photoreceivers is -20 - +80°C at intervals of 5 + 10°C. The spectral range is 0.4 - 1.2μ.

2. Calibrational Characteristics of the Apparatus

Calibration of the apparatus consisted in establishing the dependence of the output signal "U" per channel on the intensity W, as given by the formula (1). As light source providing a known radiation intensity $J(\lambda, \vartheta, \varphi)$, we used the ribbon lamp Sib-100. Here

$$J(\lambda,\tau,\varphi) = B(\lambda,T,\vartheta,\varphi) = \frac{\sigma}{\tau^2} K(\lambda)\,\varkappa(\lambda)\,\varepsilon(\lambda,T)\,\frac{C_1}{\pi}\,\lambda^{-5}\left(\exp\frac{C_2}{\lambda T}-1\right)^{-1}, \quad (2) \qquad (2)$$

where $B(\lambda,T,\vartheta,\varphi)$ (W/m^2 μ sterad) is the luminance of the lamp in the direction determined by the angles ϑ and φ, $\frac{\sigma}{\tau^2}$ (sterad) is the solid angle under which the lamp ribbon is visible; σ is the area of the lamp ribbon (m^2); τ [M] is the distance from the ribbon to the receiving end of light guide; $K(\lambda)$ is the factor which takes into account the spots of light from the support and the lamp bulb; $\varkappa(\lambda)$ is the transmission factor of the lamp bulb; $\varepsilon(\lambda,T)$ is the radiation factor of tungsten; T [K] is the temperature of the lamp ribbon; and C_1 and C_2 are radiation constants: /5

$$C_1 = 3{,}74 \cdot 10^5 \mu\ \mathrm{W/M^2}\ ; \quad C_2 = 1{,}438 \cdot 10^{-2}\ \mathrm{M \cdot deg}$$

The illumination which can be obtained during the use of the ribbon lamp Sib-100, however, is less than the required amount. Therefore, the calibration procedure was carried out in three stages. In the first stage, the appratus was calibrated in the photometric sphere at various temperatures of the photoreceivers. Here the function $U' = f_1(E_\Delta, T)$, was obtained, where E_Δ is the illumination in the photosphere. In the second stage, calibration was carried out in a parallel light beam at a fixed temperature of the photoreceivers. This provided the function

$$U = f_2(E_{II})$$

where E_{II} is the illuminance of the input end of the light guide. The source of light for these calibration stages was the xenon lamp DKSSh-1000. In the photometric sphere, a range of 10 - 60000 kilolux max was spanned; in the parallel beam, 10 - 300 kilolux. In the third stage, the calibration was accomplished in a parallel beam when the temperature of the photo receivers was fixed. The light source was the lamp Sib-100. This provided the function $U = f_3(W)$.

During the calibration the spectral composition of the radiation of the lamps DKSSh-1000 and Sib-100 remained constant. In this case involving fixed input signals and temperature of the photo receivers, the following equations are satisfied:

$$W = A \cdot E_{\Delta}, \qquad (T = const,\ U = const) \tag{3}$$
$$E_{\Delta} = Б\, E_{II}, -$$

In formulas (3), A and Б are constants which can be found by comparing the curves

$$U = f_I(E_{\Delta}),\ U = f_2(E_{II}),\ U = f_3(W)$$

and by computational means:

$$A = \frac{\int_{\lambda} J_{xe}(\lambda)\, S(\lambda)\cdot d\lambda \cdot \iint_{\vartheta\varphi} F(\vartheta,\varphi)\cdot \sin\vartheta \cdot d\vartheta \cdot d\varphi}{\pi \cdot 683 \cdot \int_{\lambda} J_{xe}(\lambda)\cdot V(\lambda)\, d\lambda} \left[\frac{W}{м^2 лк}\right]. \tag{4}$$ /6

$$Б = \frac{\pi}{\iint_{\vartheta\varphi} F(\vartheta,\varphi)\cdot \sin\vartheta \cdot d\vartheta \cdot d\varphi}. \tag{5}$$

In formulas (4-5), $J_{xe}(\lambda)$ is the intensity of the radiation which the xenon lamp DKSSh-1000 creates in the photometric sphere; $V(\lambda)$ is the relative visibility of the eye, 683 lumen·w^{-1} -- the luminous equivalent of the radiation current.

It is preferable to obtain A and Б by comparing the curves, since during calculations the function $J_{xe}(\lambda)$, is used, which is known to lack accuracy.

During the acquisition of the function $U = f_I(E_{\Delta})$ all three receiving ends and the monitoring measuring apparatus, which had a logarithmic luminous characteristic with a 10^4 dynamic range, were introduced into the photometric range. The monitoring apparatus was a germanium photo diode which was contained in the idle running regime. Its thermal stabilization was achieved by an air current. Prior to calibration, the monitoring apparatus was calibrated by means of the luxmeter Yu-16. During the calibration, its stability was controlled with the help of a stabilized light source, installed in the photometric sphere. The precision of the transfer of the scale of the luxmeter to the monitoring apparatus was 3%, and its instability -- 5%. The relation of the output signals of the various channels of the apparatus to the illumination was recorded on the two-coordinate automatic recorders PDS-021. In Fig. 1 we present as an example a family of calibration curves for one of the channels of the apparatus.

Let us estimate the precision with which the spectral energy luminance of the tungsten ribbon lamp Sib-100 is determined. During the increase in $J(\lambda, \vartheta, \varphi)$ according to (2) it is customary to use published data regarding $\varepsilon(\lambda, T)$ /7
(cf., e.g., 4). We estimated indirectly the error in the quantity $\varepsilon(\lambda, T)$, after using data about the radiating capacity of tungsten employed by various authors [5]. Here it was proposed that not only different procedures be used in determining $\varepsilon(\lambda, T)$, but also different samples of tungsten. It turned out that in the interval $\Delta\lambda$ = 0.4 - 0.8 μ the scatter in $\varepsilon(\lambda, T)$ amounts on the average to ± 1% and does not exceed 1.2%.

The temperature of the lamp ribbon was measured by a luminance pirometer EOP-66. During the measurement the following relationships are satisfied:

$$\exp\left(-\frac{c_2}{0{,}65\cdot T_{я}}\right) = \varkappa_{0{,}65}\cdot\varepsilon_{0{,}65}\cdot\exp\left(-\frac{c_2}{0{,}65\cdot T_{и}}\right) = \varepsilon_{0{,}65}\cdot\exp\left(-\frac{c_2}{0{,}65\cdot T_{p}}\right), \quad (6)$$

where $T_{я}$ and $T_{и}$ are the luminance and the actual temperature of the lamp ribbon; λ = 0.65 μ is the wavelength at which the measurements are carried out; T_p is the computed value of the temperature of tungsten corresponding to the given $T_Я$ and $\mathcal{E}$. From (6) we obtain

$$T = \frac{C_2}{\frac{C_2}{T_p} + 0{,}65 \ln \mathcal{X}_{0{,}65}} . \qquad (7)$$

We assumed that $\mathcal{X}$ = 0.92 $\pm$ 0.01; here the error in the quantity

$$\mathcal{X} \cdot \exp(C_2/\lambda T_u)$$

where T_u from (7), is less than 1% for $\Delta\lambda$ = 0.5 - 1.2μ . The accuracy of the measurement of $T_Я$ by the pirometer ÈOP-66 amounts to $\pm$ 6°C at a level of 2000 - 3000°C; here T_u is determined with a precision of $\pm$ 8°C. The error arising here in $\mathcal{J}(\lambda, v, \varphi)$ (2) amounts to 2.5% for λ = 0.52μ and 1.4% for λ = 0.96 μ.

The temperature along the length of the lamp ribbon is variable. On the edges it is higher than at the center. For lamps used to calibrate the apparatus, the temperature drop amounted to 100°C (Fig. 2). In computing $\mathcal{J}(\lambda, v, \varphi)$ /8
we used the quantity $T_{эф}$, determined from the relation

$$\int_\lambda S(\lambda) \cdot \mathcal{E}(\lambda, T_{эф}) \cdot \lambda^{-5} \cdot \exp\left(-\frac{C_2}{\lambda T_{эф}}\right) d\lambda = \qquad (8)$$

$$= \frac{1}{L} \int_0^L \int_\lambda S(\lambda) \cdot \mathcal{E}(\lambda, T_u) \cdot \lambda^{-5} \cdot \exp\left(-\frac{C_2}{\lambda T_u(\ell)}\right) d\ell \cdot d\lambda ,$$

where L - is the length of the lamp ribbon. It turned out that it is possible to compute T_{cp} with an error less than 1%, where

$$T_{cp} = \frac{1}{L} \int_0^\ell T(\ell)\, d\ell . \qquad (9)$$

During the calibration, the current across the lamp was maintained with a precision of 0.3%; here the change in $\mathcal{I}(\lambda, \vartheta, \varphi)$ amounted to 2% for λ = 0.52 and 1% for λ = 0.96.

The geometric dimensions of the lamp were determined with an accuracy of 2%. The light spots from the support and the lamp bulb amounted to 10 ± 2% of the basic signal. Assuming that the indicated errors are independent, we find that during calibration the quantity $\mathcal{I}(\lambda, \vartheta, \varphi)$ was determined with an accuracy of 4.5% for λ = 0.52μ and 3.7% for λ = 0.96 μ.

The transition from calibration in units of luminance to absolute calibration with respect to a model ribbon lamp was accomplished by means of the coefficient A (3). In determining A, the instability of the photo receivers was taken into account. Investigation of the photo receivers has shown that the photo resistors, in particular SF2-1 and SF3-1, change their sensitivity during illumination. The photo diode KFDM turned out to be stable. It is recommended that the optical characteristics of the the photo resistors be measured after they have been illuminated for 1 hour [6]. However, as our measurements showed, this is insufficient. Although the sensitivity of the photo resistors is stabilized, the stabilization is not complete. The change in the sensitivity of the photo resistors with time and level of illumination is shown in Fig. 3. The parameter in the graph is the level of the output signal. The ribbon lamp Sib-100 with /9
T_{μ} = 2900°K was the source of light during the measurements. In the first cycle of illumination, the luminance of the light-sensitive area in the photo receivers was 1000 lux; in the second -- 3000 lux. From Fig. 3, it is evident that:

a) the instability of the photo resistors is lower, the higher the level of the output signal;

b) the instability is reduced in proportion to the increase in the illumination time, although it does not entirely disappear.

Therefore, A (3) was determined for the maximum levels of the output signal obtained during calibration by the lamp Sib-100. The error in A, due to the instability of the photo receivers, amounted to $\pm$ 5%. Moreover, when processing the measurements made in the atmosphere of Venus, a correction for the instability of the photo resistors was introduced into the data obtained. In order to obtain the correction, the conditions relative to time and luminance for measurements in the atmosphere of Venus and for calibration in the photosphere were imitated in one apparatus.

Aside from the components mentioned above, the following were taken into account when calculating the precision of the calibration: the precision with which the output signal was recorded; the precision in the measurement of the distance from the lamp ribbon to the light-receiving area of the apparatus; the non-coaxiality of the apparatus and the lamp; the influence of extraneous light; the precision of the luxmeter Yu-16 which, according to certification, was 10%. The mean square error in the calibration for the first two stages amounted to $\pm$ 12%. The mean square error in calibration by the lamp Sib-100 was $\pm$ 7.5%. The overall error in the calibration was 14%.

3. The Spectral Characteristics of the Apparatus

At the present time several definitions of the spectral sensitivity of photoelectric devices are in use. In [7] a resume of these definitions is given. In the general case when the /10 luminance characteristic of a photo receiver is nonlinear, the definitions are not equivalent. As a result, the spectral characteristics of the photo receivers of a given type obtained by different authors sometimes differ substantially from each other [8-11]. In [7] it is justified theoretically that the most correct calculations of spectral sensitivity are those made according to the formula:

$$S(\lambda) \sim \frac{1}{\Phi(\lambda)}, \qquad \text{when I = const} \tag{10}$$

Here $\Phi(\lambda)$ (w/μ) is the spectral density of the radiation current; I is the reaction of the photo receiver, e.g., the photo current (a). In case the luminance characteristic is linear (the photo diode in the short-circuit regime; a photo resistor when the reaction level is low), formula (10) is equivalent to the following:

$$S(\lambda) = \frac{\Delta I(\lambda)}{\Delta \Phi(\lambda)} . \tag{11}$$

It is well-known [3, 8] that the conductivity and the photo current of photo resistors is connected to the irradiance of the photo receiving area E by the following function:

$$I = a \cdot E^{b} . \tag{12}$$

which is satisfied in a large irradiance interval. Here a and b. are constants for a given photo resistor, and depend on the structure of the semiconductor, the character and number of impurities in it, the type of contacts, etc. [3]. Moreover, $\frac{1}{2} \leq b \leq 1$. The expression (12) was obtained for white light; however, it is to be expected that it is valid for monochromatic radiation, while the quantities a and b depend on the wavelength.

The functions $I = f(\Phi)$ were obtained for the photo resistors SF2-1 and SF3-1 (Figs. 4, 5). It turned out that:

1) not only the parameter a_i, but also b_i depend on the wavelength; 2) the function (12) is satisfied when Φ varies, at least for two orders. The values of a and b for concrete resistors are given in Table 1.

TABLE 1 /11

SF2-1 With the Light Filter SES-9			SF-1		
λ	a	b	λ	a	b
0.42	0.87	0.70	0.70	1.45	0.94
0.46	1.90	0.62	0.74	7.25	0.80
0.50	11.0	0.56	0.78	4.35	0.84
0.54	2.50	0.58	0.82	2.45	0.87
0.60	0.96	0.70			

In this case the spectral sensitivity of a photo receiver (10) is written in the form

$$S(\lambda) = \frac{a_\lambda^{\frac{1}{b_\lambda}}}{a_{\lambda max}^{\frac{1}{b_{\lambda max}}}} \cdot I^{\frac{b_{\lambda max} - b_\lambda}{b_{\lambda max} \cdot b_\lambda}} \tag{13}$$

Here λ_{max}, is the wavelength at the maximum spectral sensitivity. Then (1) is expressed in the form

$$W = K \cdot \int_0^\infty \frac{a_\lambda^{\frac{1}{b_\lambda}}}{a_\lambda^{\frac{1}{b_{\lambda max}}}} \cdot I^{\frac{b_{\lambda max} - b_\lambda}{b_{\lambda max} \cdot b_\lambda}} \cdot \varphi(\lambda)\, d\lambda = K \int_0^\infty A(\lambda) \cdot \varphi^{B(\lambda)}\, d\lambda; \tag{14}$$

From this two conclusions follow: 1) the spectral sensitivity of the photo resistors depends on the energy level of the illumination; 2) the slope of the luminance characteristic of a photo resistor $dW/d\Phi$ depends on the spectral composition of the radiation.

The first conclusion is easily proven from the data of Figs. 4 and 5. For example, in Fig. 4 it is clear that for $I = 25$, $S_{0.46}/S_{0.50} = 0.076$, and for $I = 100$, $S_{0.46}/S_{0.50} = 0.091$. In order to test the second conclusion, the following experiments were performed.

Experiment 1. For a fixed wavelength λ_1 the current $\Phi_{\lambda 1}$, incident on the photo receiver was fixed by regulating the magnitude of the input slot of the monochromator DMR-4. To this current corresponded the photo current $I_{\lambda 1}$. Then the size of the slot was changed by 20%, which corresponds to /12 the change in $\Phi_{\lambda 1}$ of 20% also. Here the increment in the photo current amounted to $\Delta I_{\lambda 1}$. For the monochromator, the wavelength λ_2. was specified. The size of the output slot of the monochromator was regulated in such a way that $I_{\lambda 1} = I_{\lambda 2}$. Then the quantity $\Phi_{\lambda 2}$ was changed by 20% by means of the slot and the increment in the photocurrent was measured. It turned out that $\Delta I_{\lambda 1}$, $I_{\lambda 2}$ differ from each other by 17% for certain wavelengths corresponding to a level of approximately 0.3 on the opposite borders of the spectral characteristic.

Experiment 2. Two sources were used with radiation of drastically different composition -- an incandescent lamp with a light filter and one without a filter. A photo resistor was installed at a fixed distance ℓ_1 from the source of radiation. By regulating the lamp current, we caused the signal of the photo receiver to remain the same when the spectral composition changed. Then the photo receiver was shifted to a new position ℓ_2 and for these same points of the lamp the signal of the photo resistor was fixed. The difference in the readings amounted to 20% when $\ell_I = 2\ell_2$.

The photo resistors possess the properties described above, but the photo diodes do not. When obtaining the spectral characteristics of the various channels of the photometer, the spectral sensitivity of the photo diode channels was calculated by formula (11). For the photo resistor channels $S(\lambda)$ with low levels $\Phi(\lambda)$ was determined by (10); moreover, the functions $I=f(\Phi_\lambda)$ were obtained with a set of interference light filters. A ribbon lamp served as a source of light. $\Phi(\lambda)$ was calculated by formula (2).

The form of the spectral characteristic depends on the temperature of the photo receiver. This function was studied in [7] for cadmium sulfite photo resistors. It turned out that in the interval 20-200°C, $S(\lambda)$ depends weakly on the temperature. The form of the curve $S(\lambda)$ remains practically constant during temperature changes. When the temperature increased, the curve $S(\lambda)$ was displaced to the side of the shorter wavelengths by the amount $\Delta\lambda/\lambda \approx 0{,}03$ /13

4. The Beam Pattern of the Apparatus

The beam pattern is determined in the same way as the spectral sensitivity of the photo receivers:

$$F(\vartheta,\varphi) \sim \frac{1}{\Phi(\vartheta,\varphi)} \text{ . when I = const} \tag{14}$$

In the case of linear photo receivers, in particular in the case of photo resistors when the energy levels of illumination are low, (14) reduces to the form

$$F(\vartheta,\varphi) = \frac{I}{\Phi(\vartheta,\varphi)} \text{ .} \tag{15}$$

The beam patterns of the apparatus were calculated by this formula.

The beam pattern was measured in the unit in which the light-receiving area of the apparatus was rotated relative to the light source -- the lamp Sib-100.

The accuracy of the measurements is limited by the following errors: the error due to the finite width of the light beam incident on the apparatus; the instability of the lamp current; the error in the measurement of the angle of rotation; the instability of the photo receivers during the measurements; the nonlinearity of the luminance characteristic of the photo receivers; the error in the measuring apparatus; the influence of extraneous light. The accuracy in the measurements of the beam pattern amounted to 12%.

Conclusions

a) The procedure for determining the energy characteristics when the light currents are large, using two light sources -- a high-pressure xenon lamp and a ribbon incandescent lamp -- is valid.

b) A procedure has been developed for determining the spectral characteristics of photo resistors, and the dependence of a spectral characteristic on energy and the spectral composition of the light incident on the photo resistor has been established. /14

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Figure Captions /16

Fig. 1 The calibration characteristics of one of the channels of a broad band photometer for measuring luminance in the atmosphere of Venus.

Fig. 2 The temperature distribution along the length of the ribbon lamp Sib-100.

Fig. 3 Measurement of the sensitivity of photo resistors when they are illuminated by white light.

СФ2-1 SF2-1 — СФ3-1 SF3-1

Fig. 4 Luminance characteristics of the photo resistor SF2-1, covered by the light filter SES-9, when it is illuminated by monochromatic radiation.

Fig. 5. Luminance characteristics of the photo resistor SF3-1 when it is illuminated by monochromatic radiation.

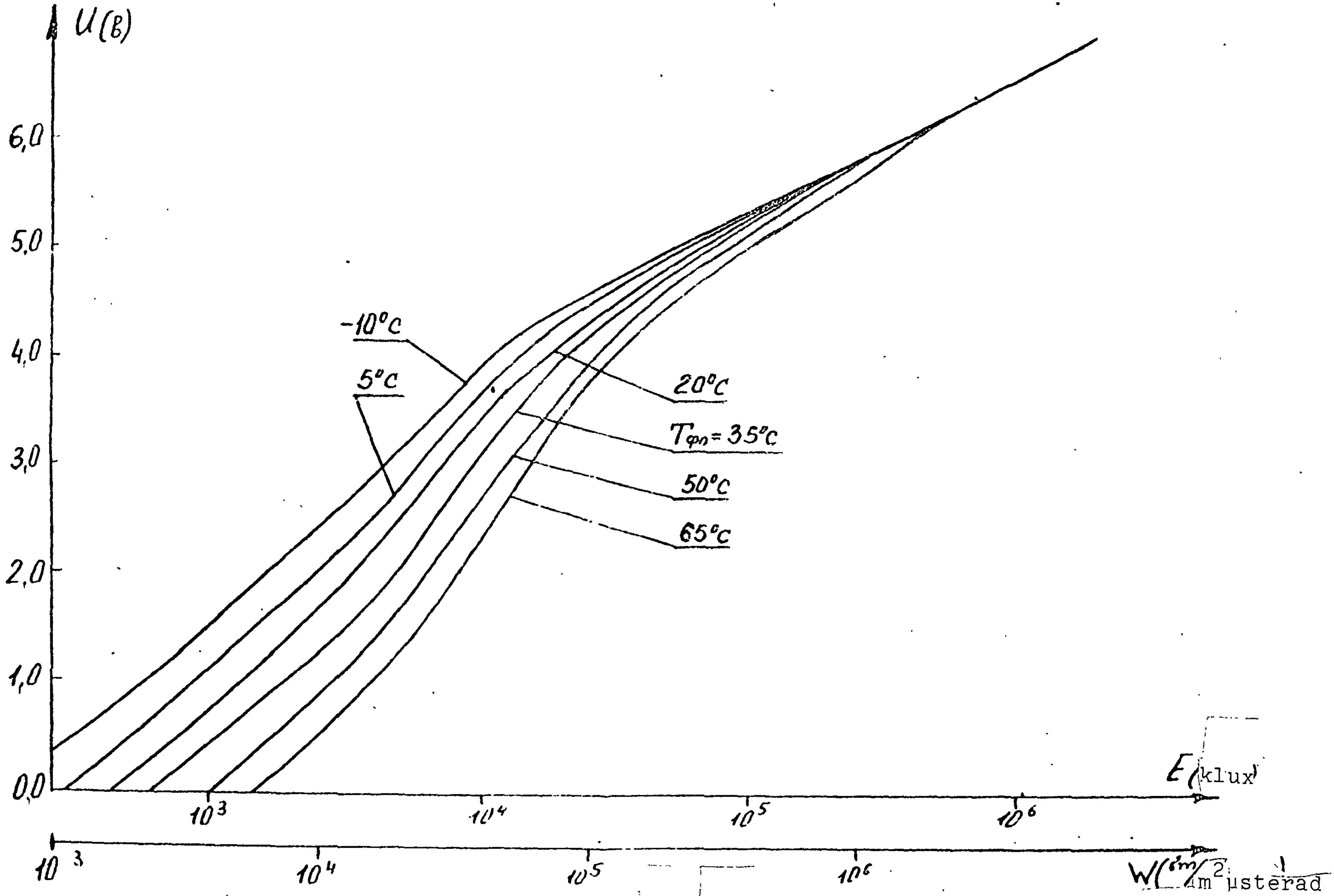

U(B)
6,0
5,0
4,0
3,0
2,0
1,0
0,0
-10°C
5°C
20°C
$T_{фп}$ = 35°C
50°C
65°C
E (klux)
10^3
10^4
10^5
10^6
W (lm/m² μsterad)
10^3
10^4
10^5
10^6

Fig. 1

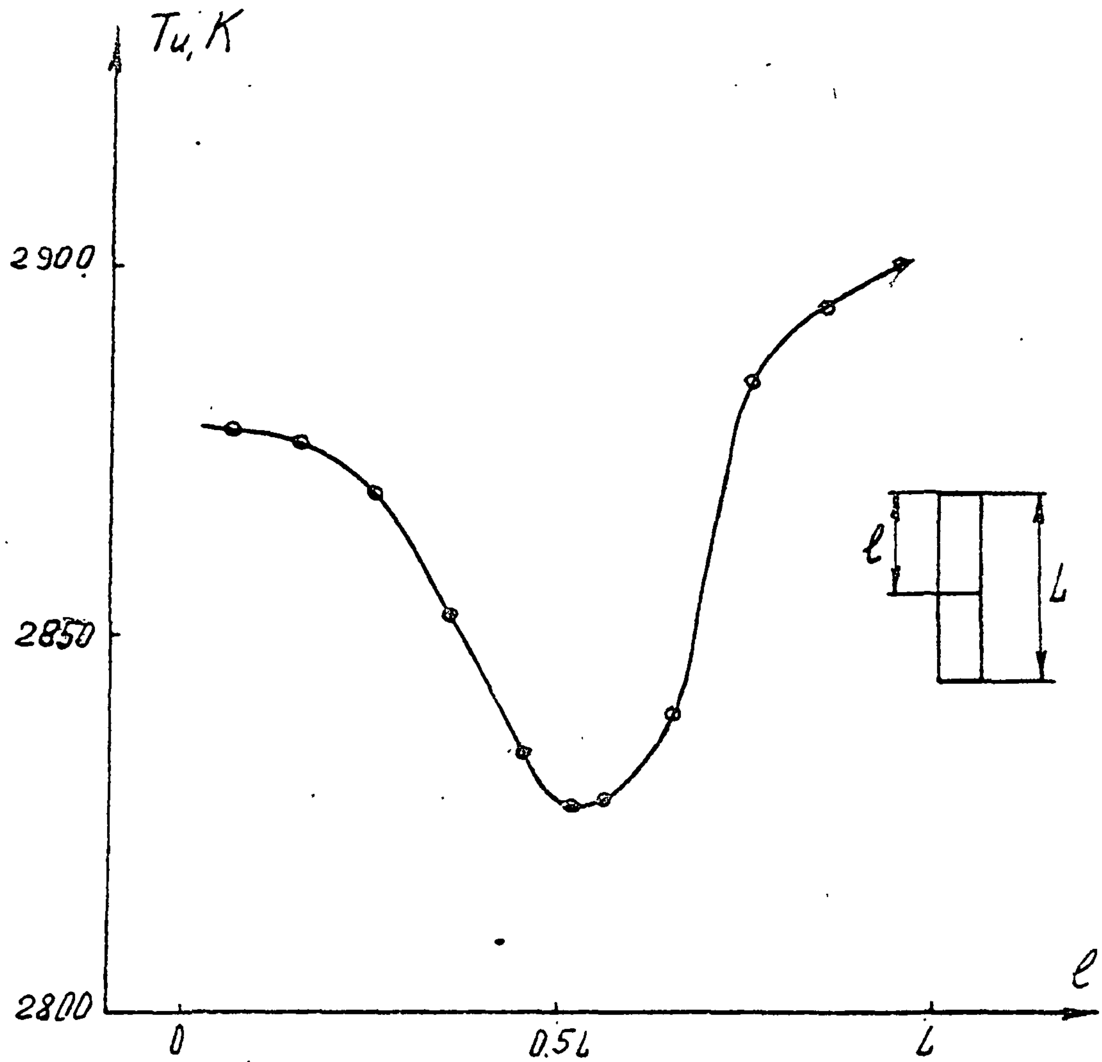
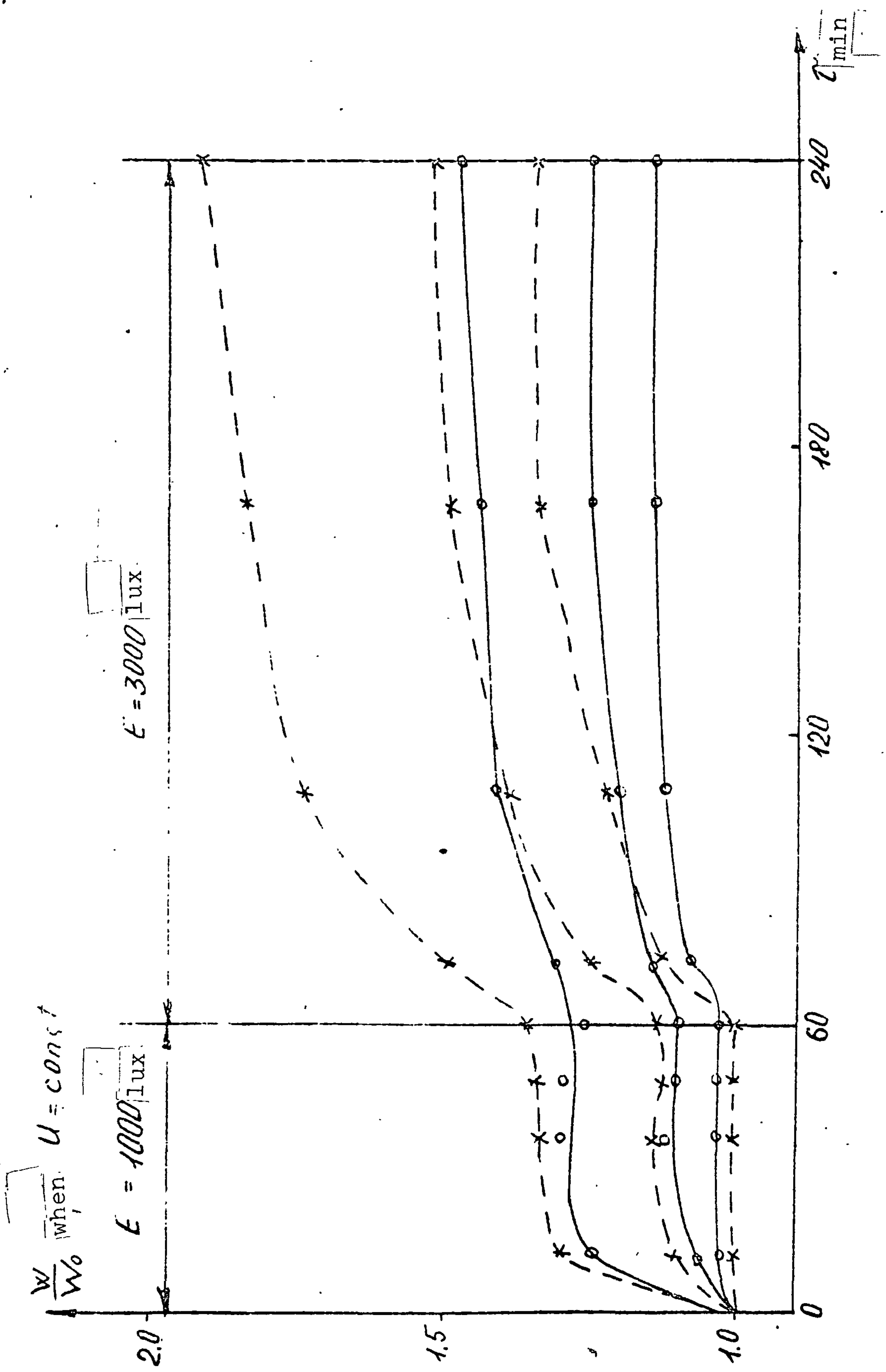


Fig. 2



W/W0 when U = const
E = 1000 lux
E = 3000 lux
τ min
2.0
1.5
1.0
0
60
120
180
240

Fig. 3

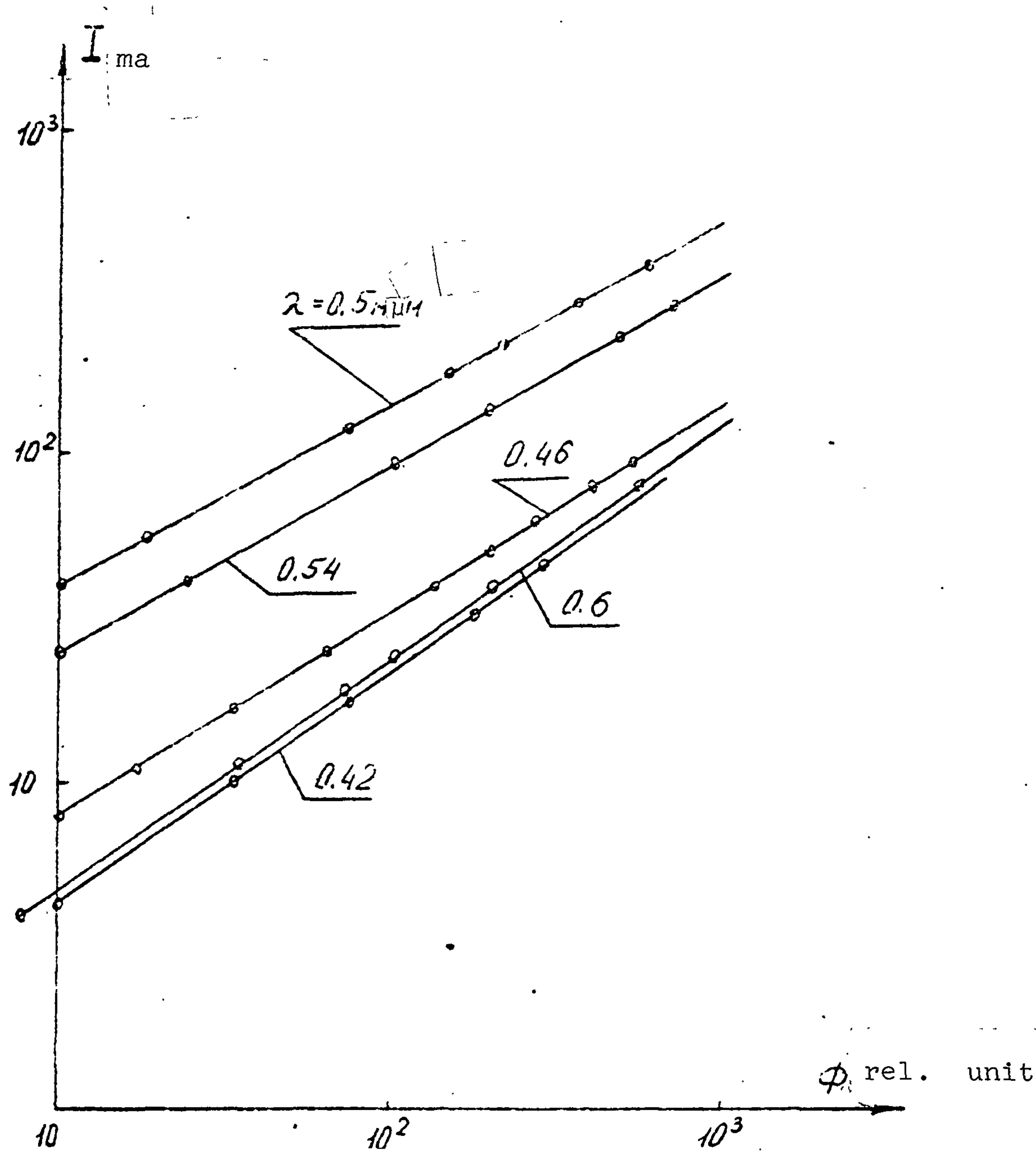
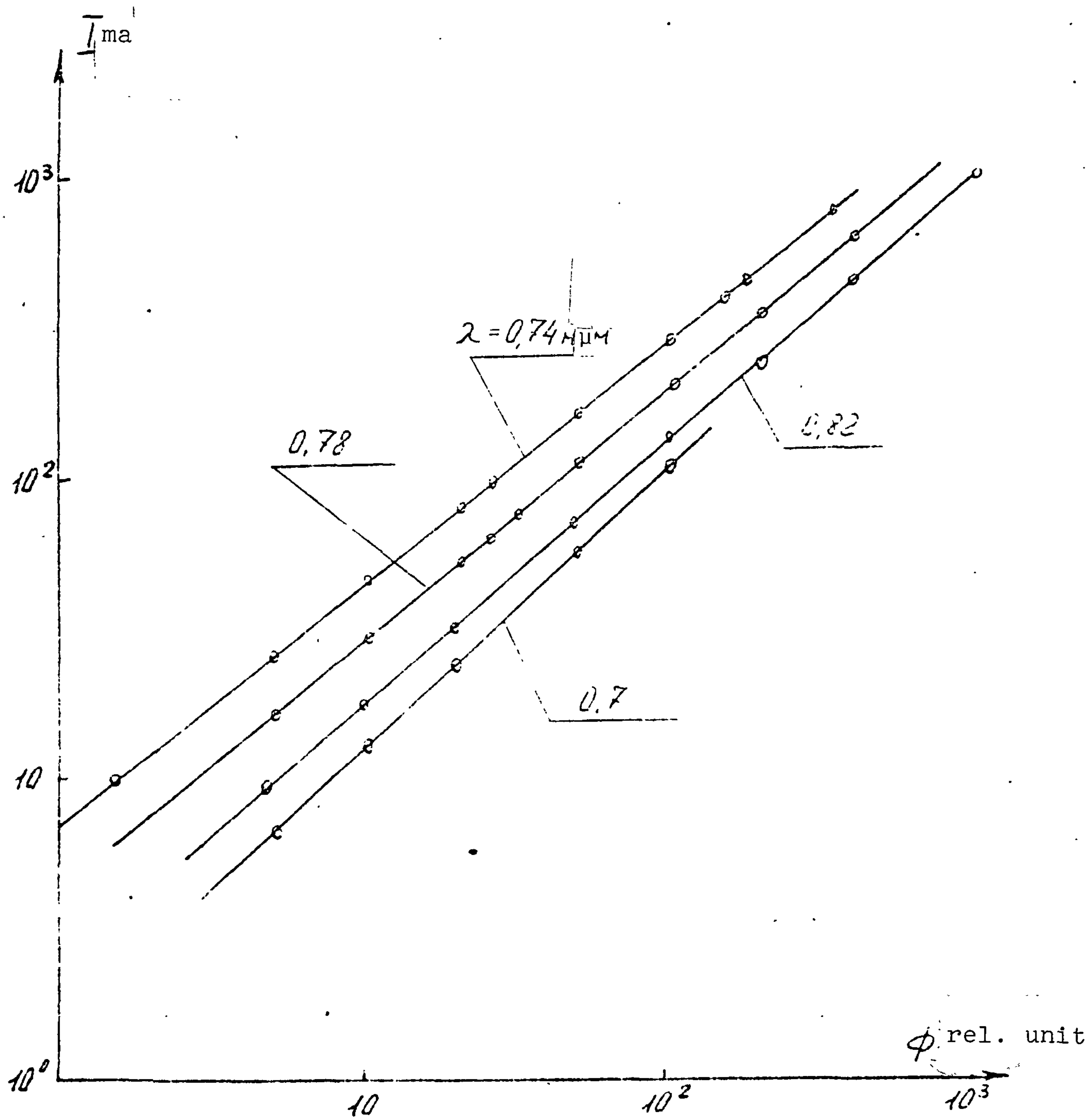


Fig. 4



$\bar{I}$ ma
10^3
10^2
10
10^0
$\lambda = 0{,}74$ мкм
0,78
0,82
0,7
ϕ rel. unit
10
10^2
10^3

Fig. 5