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Multispectral Imagery and Interference Filter Effects

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The multispectral photography of the earth surface provides for useful information both to science and practice and is applied in remote aero- and space sensing. The multizonal camera MKF-6 was elaborated for this purpose. The separation of the spectral ranges in it is effected through specially designed interference filters (IF) combined with coloured glasses. They are of steep slopes and large luminous transmittance. Imagery of objects studied with the MKF-6 is rectangular. The long side of the frame corresponds to an angle of sight $2\sigma_{e}=36°$ and the short side — to $2\sigma_{s}=25°$ [2]. It is assumed that such an angle of taking the image does not affect significantly the spectral brightness, related to the increase of the angle θ between the vertical and the picture direction [1]. The changes resulting from the fact that IF operate with relatively large light beams are not yet evaluated. We assume that such an evaluation should be performed. Therefore, we are looking for the IF effects on the frame image in a given spectral range using data from previous studies of other IF. This is based on the similarity between the angle characteristics of the IF of common principle of operation. The spectral coefficient of IF transmission is described by the function [3]

$$\tau(\lambda,\theta)=\frac{I^{(t)}}{I^{(i)}}=\left(1-\frac{A}{1-R}\right)\frac{1}{1+F\sin^2\frac{\delta(\lambda,\theta)}{2}}, \tag{1}$$

where

$$\delta(\lambda,\theta)=\frac{4\pi}{\lambda}\,nh\sqrt{1-\frac{\sin^2\theta}{n^2}}+2\varphi, \tag{2}$$

$$\lambda_m(\theta)=\frac{2nh}{m-\varphi/\pi}\sqrt{1-\frac{\sin^2\theta}{n^2}},\quad m=1,2,\ldots, \tag{3}$$

with the following denominations: λ — wavelength in vacuum; θ — slope of falling light; n — refraction index of the filter intermediate layer; h — thickness of the same layer; φ — phase shift; A — light losses from the filter reflective cover; R — cover reflective capacity and $F=\frac{4R}{(1-R)^2}$.

Both the wave length λ_m for which $\tau = \max$ and the semiwidth $\Delta\lambda$ of the transmission band and the value of maximal transmission, are functions of the beam slope θ. Therefore, the IF effects on imagery would be revealed in two directions:

a) redistribution of illumination $E(\theta)$ on the frame;

b) spectral range shift in which the object brightness is studied.

The illumination at one frame point at a distance r from its centre ($r = f \operatorname{tg} \theta$, where f is the objective focal distance) may be represented as

$$E(\theta) = \varphi(\theta) \int_0^\infty B(\lambda)\tau_\theta(\lambda)d\lambda, \tag{4}$$

where $\varphi(\theta)$ is the specific function of a given optical instrument showing the light distribution along the field of sight; $B(\lambda)$ is the spectral brightness of the studied object; $\tau_\theta(\lambda)$ — spectral coefficient of IF transmission in the case of parallel light beam at angle θ. At equal exposure time, the negative density is defined from $E(\theta)$ at a given point. Therefore, the IF effect is expressed through the function $\theta_\theta(\lambda)$. We have examined the experimental data for $\tau_\theta(\lambda)$ of several IF [4]. It was defined there that the dependence $\tau_m(\theta)$ for $\theta \leq 20°$ is well approximated with the function $\cos(k\theta)$, where k is a constant typical for a particular filter. For the samples studied $k \sim$ 1.15—2,65. The semiwidth $\Delta\lambda$ of the curves $\tau_\theta(\lambda)$ slightly increases with the θ slope increase differently from τ_m.

Let us examine two boundary cases determined by the function $B(\lambda)$ type:

1) the brightness of the object $B(\lambda)$ slightly changes within the resolution range of a given IF. $\lambda_1(\theta)$ and $\lambda_2(\theta)$ limit this range for a given θ. According to the theorem for the average values, from (4) we have

$$E(\theta) = \varphi(\theta) B_\theta(\bar{\lambda}) \int_{\lambda_1(\theta)}^{\lambda_2(\theta)} \tau_\theta(\lambda)d\lambda = \varphi(\theta) B_\theta(\bar{\lambda}) I_1(\theta). \tag{5}$$

From the function $I_1(\theta)$ with which we have denominated

$$I_1(\theta) = \int_{\lambda_1(\theta)}^{\lambda_2(\theta)} \tau_\theta(\lambda)d\lambda \tag{6}$$

and which may be considered as integral IF transmission for slope θ, the redistribution of energy over the frame is determined. The determination of the dependence of the integral IF transmission on the incident light angle is a very interesting fact in itself. It can be performed in different ways, for example through measurement of the light energy transmitted by the IF for various θ with nonselective receiver of given sensitivity or by calculating the integral $I_1(\theta)$. We shall examine the second case, as the calculation of $I_1(\theta)$ is performed through geometric calculation of areas surrounded by the experimental curves $\tau_\theta(\lambda)$ available. For the areas $S(\theta)$ under the curves $\tau_\theta(\lambda)$ the results presented in Table 1 were obtained. The maximum relative area variation under the curves $\tau_\theta(\lambda)$ for the two IF (i. e. of $I_1(\theta)$) is 3.3 and 1.5%, respectively. Therefore, we may consider with sufficiently good approximation that the integral transmittance of IF is constant by θ.

$$I_1(\theta) = \text{const} = I. \tag{7}$$

Table 1

Filter	$S(\theta)$	θ°				$\left(\frac{\Delta S}{S}\right)_{max}$, %
		0	10	15	20	
1	$S_1(\theta)$	425	425	411	412	3.3
2	$S_2(\theta)$	471	475	478	472	1.5

Table 2

θ°	r, mm	λ_m, nm						$\Delta\lambda$, nm	
0	0	480	540	600	660	720	840	40	100
5	11.5	479	539	599	659	719	839	40.6	101.5
10	20.0	477	536	596	656	715	834	42.6	106.5
15	33.5	473	532	591	650	709	827	46.2	115.5
18	40.5	470	528	587	646	705	822	49.5	123.6

This means that IF would not introduce additional redistribution of energy on the frame. In the case where the spectral characteristic of the object slightly changes within the operation range of IF, its effect is experssed by the constant I, i. e. quantitatively the filter weakens the light energy passed through it equally for all waves regardless of the angle of their propagation. In addition, the IF changes the spectral range in which the averaging of the measured brightness $\overline{B_\theta(\lambda)}$ is performed in dependence on the slope θ. Let us assume that the IF of the MKF-6 camera have $k=2$ and accept the following appproximation (which often happens in practice) — that the $\tau_\theta(\lambda)$ are П-shaped curves whose width equals the semiwidth $\Delta\lambda$ for the slope 0, and the height is equal to the maximal transmittance for the same slope. Then, it follows from (6) and (7)

(8)
$$\int\limits_{\lambda_1(\theta)}^{\lambda_2(\theta)} \tau_\theta(\lambda)d\lambda = \tau_m(\theta)\Delta\lambda(\theta) = \tau_m(0)\Delta\lambda(0)$$

as $\tau_m(0)$ and $\Delta\lambda(0)$ are data from the filter passport. In addition, if we consider (3), we shall have an approximate picture of the variation in the spectral ranges introduced by the IF at different points of the MKF-6 frame. The results from these approximate calculations are given in Table 2 and plotted in Fig. 1, where the operation ranges of the MKF-6 camera are presented together with their shift in dependence of the distance r.

2) The brightness largely varies within the range of $\lambda_1(\theta)$—$\lambda_2(\theta)$. We shall consider the boundary case for such large variation, where $B(\lambda)$ changes in steps

$$B(\lambda) = \begin{cases} B, & \lambda \leq \lambda_c \\ 0, & \lambda > \lambda_c \end{cases}.$$

Let $\lambda_c \in [\lambda_1(\theta), \lambda_2(\theta)]$ for some of the filters. The illumination distribution over the frame from (4) is

(9)
$$E(\theta) = \varphi(\theta)B \int\limits_{\lambda_1(\theta)}^{\lambda_c} \tau_\theta(\lambda)d\lambda.$$

The IF effect on the illumination distributions in this case is defined by the term

$$I_2(\theta)=\int_{\lambda_1(\theta)}^{\lambda_c}\tau_\theta(\lambda)d\lambda$$

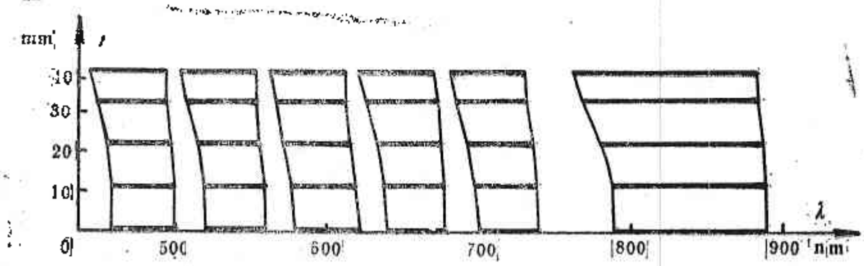

Fig. 1

and can easily be calculated if we consider again the IF characteristics as П-shaped, with reference to (7) then we have

$$I_2(\theta)=\tau_m(\theta)\,[\lambda_c-\lambda_g(\theta)],$$

λ_g is the left end of the П-shaped characteristic.

$$\lambda_g=\lambda_m(\theta)-\frac{1}{2}\,\Delta\lambda(\theta)$$

$$I_2(\theta)=\tau_m(0)\lambda_c\cos(k\theta)-\tau_m(0)\lambda_m(0)\cos(k\theta)\sqrt{1-\frac{\sin^2\theta}{n^2}}+\frac{1}{2}\,\tau_m(0)\Delta\lambda(0)=$$

$$=a\cos(k\theta)-b\cos(k\theta)\sqrt{1-\frac{\sin^2\theta}{n^2}}+c,$$

where

$$a=\lambda_c\tau_m(0),$$

$$b=\tau_m(0)\lambda_m(0),$$

$$c=\frac{1}{2}\,\tau_m(0)\Delta\lambda(0).$$

Similarly, if $B=\begin{cases}B, & \lambda\geq\lambda_c\\ 0, & \lambda<\lambda_c\end{cases}$ and $\lambda_c\in[\lambda_1(\theta),\ \lambda_2(\theta)]$,

$$I_2(\theta)=-a\cos(k\theta)+b\cos(k\theta)\sqrt{1-\frac{\sin^2\theta}{n^2}}+c.$$

Let a diffusively reflecting object (which often occurs in nature) with a step-like spectral characteristic fill up the entire field of sight of the MKF-6 objective. Then, in dependence on the values of λ_c, we shall obtain different pictures.

a) $\lambda_c<\lambda_g(0)$. Such an object would not be centered in the frame. It could be seen for distances greater than r for which $\lambda_c=\lambda_g(\theta)$, $r=f\,\mathrm{tg}\,\theta$, and with the increase of r the negative density will augment gradually. The frame would

Table 3

Parameters	Channel 2					Channel 5				
r, mm	4.3	12.6	18.2	21.1	27	4.3	9.4	12.0	21.1	27
$d(r)$	1.00	0.96	0.92	0.83	0.86	1.00	0.97	0.95	0.93	0.96

look as if two objects were photographed: one round shape, which does not emit within the filter range, and the second surrounding the first one with brightness gradually increasing in radial direction.

b) let λ_c be close to $\lambda_2(0)$ and the spectral brightness of the object filling up the objective field of sight be of the second type, i. e, limited from below. Such an object would appear on the frame as two objects: one in the centre with decreasing brightness and around it another one with zero spectral brightness in this range.

Thus the effect of IF over the frame image is the stronger the less smooth the spectral characteristic of the studied object is. For example, the spectral characteristic of grass permits to follow the decrease of its spectral brightness with the increase of the distance r from the frame centre for the 2nd and 5th channel of the MKF-6 camera for $\lambda = 540$ and $\lambda = 720$ nm, respectively. For the purpose, the densities of negatives representing grass (D_T) and white tissue (D_M) are measured with microdensity meter at different places of the frame. Pictures are taken with the MKF-6 camera on board the airplane laboratory AN-30 over a research field in Bulgaria. For the white tissue we obtain from (5) and (7)

(10) $$D_M(\theta) \sim E_M(\theta) = \varphi(\theta) B_M I. \; B_M I = \text{const}$$

and for the grass we obtain from (5) and (10)

(11) $$D_T(\theta) \sim E_T(\theta) = \varphi(\theta) d(\theta) \sim D_M d(\theta)$$

or as

$$\theta = \text{arctg}\,(r/f),$$

$$D(r) \sim D_M(r) d(r),$$

from where we obtain the function $d(r)$ normalized by its maximum value (Table 3). With the increase of r the value of $d(r)$ decreases due to spectral range shift, where the measured spectral brightness is averaged. This illustrates the effect of IF.

What type of practical conclusions may be drawn from this study. Certainly to the end of the frame the spectral range shifts to shorter wavelengths and expands. This effect is larger for the long-wave channels. The graphical presentation of this shift is sufficiently clear. It is seen that changes introduced by IF can be entirely neglected in the frame centre. The size of their area is specific for the instrument applying the IF and depend on the characteristics of the filters themselves. For the examined case, the IF do not change the picture in a circle with radius of about 22 mm centrally located ($\theta = 10°$). The approximate calculations performed may be considered as a pattern of evaluating the effect of IF used in the multispectral photographic images obtained and also in designing instruments similar to the MKF-6 camera.

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Влияние интерференционных фильтров на получаемые с их помощью многоспектральные изображения

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(Резюме)

В данной работе рассматривается влияние интерференционных фильтров на многоспектральные изображения, полученные камерой МКФ-6. Показано, что влияние проявляется в смещении спектральных диапазонов работы камеры с увеличением расстояния r от центра к краю поля изображения. В качестве примера рассмотрено уменьшение спектральной яркости определенного объекта (люцерина) к краю кадра для второго ($\lambda=540$ nm) и пятого ($\lambda=720$ nm) каналов многоспектральной фотокамеры МКФ-6.