A compact imaging hyperspectrometer

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Abstract. The paper describes the design of a compact hyperspectrometer equipped with a transmission phase diffraction grating, which is used as a dispersing element. The calculation of the microrelief parameters of the dispersing element is given. The spectral characteristics of the developed device are investigated. The possibility of determining the normalized vegetation index is demonstrated. The weight and dimensions of the compact imaging hyperspectrometer are given.

1. Introduction

Methods of hyperspectral analysis are widely used in solving various applied problems associated with the rational use of natural resources [1, 2], forestry and agriculture [3, 4], and geology [5]. Among these application areas can be identified class vegetation monitoring problem that require rapid response, e.g., fire hazard assessment forest condition [4]. Therefore, hyperspectral images are often obtained not from Earth remote sensing satellites, but from small aircraft. There is a need to minimize hyperspectral equipment. The spectral range of such equipment is in the range of 400-1000 nm.

There are compact designs based on a diffractive lens [6–8] and a hybrid lens [9, 10]. Obtaining information in such structures is associated with high complexity of processing algorithms and it is often impossible to obtain sufficient spectral resolution.

In [11], the design of an aerospace hyperspectral camera is presented in which reflective diffractive optical elements (DOE) are used as a dispersing element. This device is characterized by a high spectral resolution (3 nm), however, this design has high requirements for the accuracy of forming the diffraction microrelief, which increases the cost of devices.

This paper presents the design of a compact imaging spectrometer that uses transmission phase diffraction grating as dispersing element.

2. Hyperspectrometer design

The working principle of a compact imaging hyperspectrometer is to register at each instant of time a spectral pattern of narrow strip image of the test object. Hypercube formation of a full object image is carried out by scanning the surrounding space by circular rotation or linear movement of the hyperspectral camera along the object under study.

The optical scheme of the developed device is shown in Figure 1. The object image I is built in the inner plane, where, in accordance with the optical scheme, there is a slit diaphragm 3, cutting out a full
image of a narrow section. After the collimating lens 4, the cut out image falls on the diffractive optical element 5, where the formation of the spectral pattern takes place, which is projected by the lens 6 on the photomatrix 7.

![Figure 1. Optical scheme of the hyperspectral camera: 1 – object of observation; 2, 4, 6 – lenses; 3 – slit diaphragm; 5 – DOE (diffractive optical element); 7 – photomatrix.](image)

DOE is a quartz plate coated with a binary microrelief with a period of 6 μm. The microrelief height of the binary grating \( h \) is determined by the wavelength \( \lambda \) and is calculated by the formula:

\[
h = \frac{\lambda}{2(n - 1)},
\]

where \( n \) – refractive index.

To obtain the optimum signal-to-noise value over the entire spectral range of the compact imaging spectrometer a wavelength of 700 nm was chosen for calculating DOE [12]. Using formula (1) with a quartz refractive index of 1.47 gives a height value \( h = 750 \) nm. The characteristics of the matrix spectral sensitivity and the features of solar radiation were taken into account.

The diffraction grating was manufactured by plasma chemical etching. The protective mask was formed by direct laser recording technology on chrome. Figure 2 presents the results of measurements of the relief parameters obtained using a scanning probe microscope.

![Figure 2. SPM image of the surface microrelief on the diffraction grating a) and its profile b).](image)

The difference in the measured microrelief height from the calculated value is 20 nm, which is equivalent to the value of the relative error in the microrelief formation of less than 3%.

3. Results and Discussion
The spectral resolution of the hyperspectral camera was determined as follows. The screen was illuminated by extended laser radiation with a wavelength of 532 nm. The specified wavelength is the middle of the spectral range. Additionally, a fluorescent lamp with characteristic spectral peaks was projected onto the screen. The position of these peaks was used to calibrate the spectral channels by wavelength. The spectral image of the screen and the corresponding profile are shown in Figure 3. The measured width of the spectral peak corresponding to a wavelength of 532 at a level of 0.5 was 5 nm.

To compare the quality of the obtained hyperspectral data, a hyperspectrometer was used based on the Offner scheme [12, 13], the image from which we will consider the reference. For this, an image
was collected over three spectral channels ($\lambda_1=480\text{nm}$, $\lambda_2=532\text{nm}$, $\lambda_3=640\text{nm}$). Synthesized RGB images of both spectrometers are presented in Figure 4.

**Figure 3.** Spectral image of a laser beam (532 nm) with a background from a fluorescent lamp a) and the corresponding spectral profile b).

**Figure 4.** Synthesized RGB images obtained using hyperspectrometers: a) compact hyperspectrometer; b) Offner hyperspectrometer.

The image from the compact hyperspectrometer is expectedly worse, however, it is enough to obtain vegetation indices. Figure 5 shows a comparison of the distribution of the normalized vegetation index (NDVI) on images of Eucharis leaves with different degrees of drying obtained from both devices. The average values of the NDVI indices determined using the ENVI software package differ by no more than 8%.

**Figure 5.** Distribution of the normalized vegetation index (NDVI) on images of Eucharis sheets with different degrees of drying obtained from both devices: a) compact hyperspectrometer; b) Offner hyperspectrometer.

**Figure 6.** Appearance of the hyperspectral camera.
4. Conclusions
The design of a compact imaging hyperspectrometer has been developed, the spectral range of which is 400–1000 nm when using the Sony IMX 249 matrix. The spectral resolution was 5 nm. Dimensions of the prototype are 250x40 mm. Weight 400 g. The appearance of the compact hyperspectrometer is shown in Figure 6.

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