

SUBSTANTIATION OF A UNIVERSITY NANOSATELLITE TELEVISION CAMERA PARAMETERS

V. Kolobrodov, V. Mykytenko, V. Sokurenko

In recent years, a tendency is established to reduce the size of orbital spacecrafts while preserving their functional capabilities. The modern element base allows to create inexpensive Earth-sensing satellites having 1U-2U form factor, which are capable to form images of the Earth's surface with the medium spatial resolution. To perform synthesis of such optoelectronic remote sensing equipment, a relatively simple calculation technique is required.

In this article, a technique has been developed to estimate an information system "Earth's surface – atmosphere – television camera". It allows to determine the basic parameters of a lens and a matrix detector of the television camera, based on harmonization of their resolution and providing a given spatial resolution on the surface of the Earth.

By using the proposed technique, a lens and a matrix detector have been selected. They provide geometric resolution of 25 m at the orbit with a height of 600 km. The resulting technical solution enables to fulfil applied tasks, for example, in agriculture, and can be implemented in a nanosatellite with the 1U-2U form factor.

Keywords: television camera, lens, nanosatellite, spatial resolution, modulation transfer function

1. Introduction

Optical-electronic surveillance systems (OESS) are widely used for remote sensing of the Earth from outer space. In the simplest version, such systems are designed as television transmitting cameras. In conditions of limited funding of Ukrainian universities, the most suitable space carrier is a nanosatellite located at a relatively low orbit. From 2017 to 2023, about 2400 nano- and microsatellites are planned to be launched worldwide [1]. A lot of technical universities in the world are successfully working in the field of developing small satellites [2, 3].

One of the important characteristics of the space OESS is spatial resolution threshold. It is determined by the minimum size of the element of the Earth's surface, which can be reproduced by the system [4, 5]. The spatial resolution properties define a list of tasks that can be solved with the OESS [6]. The main units of the space television camera are optical unit and radiation detector unit. Therefore, these blocks are the main research objects in calculations of the entire OESS. When solving practical problems, the actual task is to develop a simple calculation model, which will help to predict a real value of the spatial resolution of space optical-electronic systems in the visible range of the spectrum.

Hereafter, a choice of main components of an inexpensive space-based television camera is substantiated. Such camera can be installed on the university's satellite having the 1U–2U form factor and should potentially provide the moderate spatial resolution at low orbits for solving urgent problems of Ukraine.

2. Formulation of the problem

Inexpensive space OESS of the medium spatial resolution (from 10 m up to 100 m) are mostly used for land use planning, agricultural activity monitoring, forest inventory, as well as environmental monitoring [7, 8]. Ukraine has significant agricultural potential, and, therefore, these challenges are relevant for its implementation. Focusing on the minimum budget and mass-dimensional camera performances, it is advisable to consider inexpensive commercial digital television cameras with lens objectives. Due to a small size of nano- and micro-satellites, television transmitting cameras provide much worse spatial resolution than large-scale scanning systems. However, for certain tasks, for example, monitoring of farmland, a large group of inexpensive space-based low-sensitivity sensors can be more efficient than expensive submeter divisional systems [9].

In such systems, the geometric resolution on the Earth's surface is approximately 25 m. Similar characteristics are found, for example, in the space television camera of the Romanian project GOLIAT [10]. It uses commercial detector of radiation, but the lens is to be manufactured separately. For a significant reduction in cost, it is advisable to apply mass-made commercially-available lenses, especially in the case when it is planned to reduce further the size and value of a remote-monitoring complex by increasing a total number of sensors [11].

The most acceptable variant of the image formation by a small-sized space OESS is a frame-by-frame shooting with a matrix detector of radiation (MDR), which operates in a wide spectral range. To provide necessary spatial resolution, that is, the ability to distinguish between two closely spaced point sources of radiation having the same intensity [12], a number of calculation methods have been proposed already. However, many of them are based only on certain models of the lens and detector of radiation [13, 14]. A significant amount of research is devoted to the processing of satellite data to improve the accuracy and resolution of space images [15]. However, such methods cannot be used in the design of an OESS itself. A physical-and-mathematical modeling of signal transformation processes has been carried out at the stage of designing an objective in the project of the microwave satellite LAPAN A4 [16]. In this case, fundamental theories and generalized methods were applied. The authors [17] developed a digital remote monitoring camera based on the simulation of a signal modulation transformation in the optical path. In fact, a simplified engineering calculation method was applied, and the coordination of the parameters of the lens and the detector of radiation was not carried out. In paper [18], the analysis was performed for the alignment of the lens and the detector of radiation, taking into account the Nyquist criterion, but no methods were proposed to solve the inverse problem, namely, to synthesize the OOES.

3. The purpose and objectives of the study

The purpose of this work is to substantiate selection among lenses and TV units with matrix detectors available on the market of Ukraine, which will provide the given quality of space images. The transmitting television camera should have the dimensions acceptable for placing it within the dimensions of a 1U-2U nanosatellite.

To achieve this goal, the following tasks were set:

1. To develop a mathematical model of the information transformation in the system "Earth surface – lens – matrix detector of radiation";
2. To propose a method for matching the main parameters of the lens and MDR, based on the developed model. The matching is to be fulfilled by using the modulation transfer functions of the lens and the MDR at level of 50% contrast.
3. To choose real-life samples of the matched lens and MDR, which will potentially provide the geometric resolution of 25 m for the Earth's orbit with a 600-kilometer altitude.

4. Estimated model of information transformations in the system "Earth surface - lens - matrix detector of radiation"

Let us consider a simplified model, which describes process of signal formation in the space OESS. By using it, we will choose underneath the lens and the transmitting television camera.

After reflection from the Earth's surface, on which an observation object is located, the solar radiation (including a visible range of the spectrum) passes through the atmosphere and enters the lens of the television camera. The lens creates an image of both the object and background in the plane of the MDR. This detector converts the distribution of light into an electrical signal, which, forms a video signal.

The object is placed on the Earth's surface background, which is characterized by albedo ρ_b . The object has the reflection coefficient ρ_t , exceeding the albedo by a relative value $\Delta\rho$ defined as

$$\Delta\rho = \frac{\rho_t - \rho_b}{\rho_b}. \quad (1)$$

Let us suppose that both the object and the background reflect solar radiation in accordance with the law of Lambert. The Sun creates spectral illumination $E_{0\lambda}$ on the Earth's surface. Then the brightness values of the object and the background in the working spectral range ($\lambda_1 - \lambda_2$) will be equal to

$$L_t = \frac{1}{\pi} \int_{\lambda_1}^{\lambda_2} \rho_t(\lambda) E_{0\lambda}(\lambda) d\lambda; \quad L_b = \frac{1}{\pi} \int_{\lambda_1}^{\lambda_2} \rho_b(\lambda) E_{0\lambda}(\lambda) d\lambda. \quad (2)$$

In this case, a useful signal is formed due to a difference in reflecting abilities of the object and the background surfaces, i.e. due to an absolute contrast of brightness

$$\Delta L_e = \frac{1}{\pi} \int_{\lambda_1}^{\lambda_2} [\rho_t(\lambda) - \rho_b(\lambda)] E_{0\lambda}(\lambda) d\lambda. \quad (3)$$

Because of the atmosphere's absorption and dispersion, the parameters of radiation spreading from the object and the background to the television camera are obviously changed. The atmosphere is characterized by the spectral $\tau_A(\lambda)$ and the integral τ_A transmission coefficients. Moreover, $\tau_A = E_0 / E_s$, where $E_s = 4.8 \times 10^{-2}$ W/cm² is the integral illumination created by the Sun in the working spectral range at the upper boundary of the atmosphere; $E_0 = 2.4 \cdot 10^{-2}$ W/cm² is the known integral illumination of the Earth's surface. In a simplified model, one can assume that the integral coefficient of transmission $\tau_A = 0.5$.

The optical system consists of two elements: the primary lens and the light filter (optional). The main features of the lens are as follows:

- the focal length f'_o ;
- the relative aperture D_p / f'_o (or the effective diaphragm number $k_{eff} = f'_o / D_p$, called also as a F-number), where D_p is the diameter of the entrance pupil;
- the field of view: an angular value $2\omega_0$, or a linear value in space objects (on the surface of the Earth) $X \times Y$ or in the image space (in the plane of the MDR) $X' \times Y'$;
- the modulation transfer function (MTF); $M_o(\nu_x, \nu_y)$;
- the working spectral range ($\lambda_1 - \lambda_2$), taking into account transmitting properties of the light filter;
- the spectral $\tau_o(\lambda)$ and the integral τ_o transmission coefficients.

The lens creates an image of the object and the background in the detector's plane with the contrast of illumination

$$\Delta E' = \frac{1}{4} \left(\frac{D_p}{f'_o} \right)^2 \int_{\lambda_1}^{\lambda_2} \tau_A(\lambda) \tau_o(\lambda) E_{0\lambda}(\lambda) [\rho_t(\lambda) - \rho_b(\lambda)] d\lambda. \quad (4)$$

The MTF of the lens can be estimated based on the following considerations. For an ideal lens, the size of the resolved element on the Earth's surface is determined by a geometric size of the pixel (Fig. 1)

$$\delta V = V'_D = \frac{V_D h_f}{f'_o}; \quad \delta W = W'_D = \frac{W_D h_f}{f'_o}, \quad (5)$$

where $V'_D \times W'_D$ are dimensions of the pixel projection onto the Earth's surface.

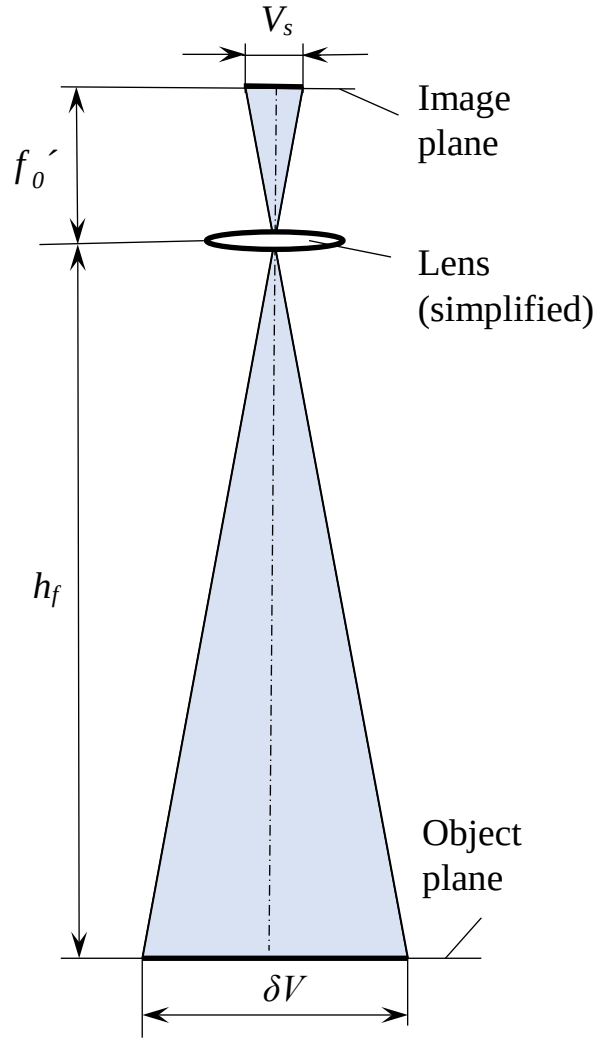


Fig. 1. Geometrical resolution of the space OESS:

V_s is the size of the resolution element of the system “lens – MDR” (television camera), f_o' is the focal length of the lens, h_f is the orbit height of the satellite and δV is the size of the resolution element on the Earth's surface

If the OESS is characterized by a one-dimensional MTF $M_s(v_x)$, then the spatial resolution of the system can be defined:

1. By the specified reduction of the image contrast $C_0 = M_s(v_{x0})$. In this case, the resolution element on the Earth's surface is determined by the expression:

$$\delta V = \frac{h_f}{2v_{x0}}, \quad (6)$$

where v_{x0} is the angular spatial frequency corresponding to the contrast C_0 , rad^{-1} .

2. By the geometric noise bandwidth GB being a more universal resolution criterion:

$$GB = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} M_o^2(v_x, v_y) dv_x dv_y.$$

According to this criterion, the spatial resolution of the OESS is defined as

$$\delta V = \sqrt{\frac{GB}{\pi}}.$$

Finally, for a one-dimensional case, one can get

$$\delta V = \frac{h_f}{\int_{-\infty}^{\infty} |M_s(v_x)|^2 dv_x}. \quad (7)$$

For small fields of view, the OESS is often considered as a linear invariant system with the MTF

$$M_s(v_x) = M_o(v_x) M_D(v_x), \quad (8)$$

where $M_o(v_x)$ and $M_D(v_x)$ are the MTF of the lens and the MTF of the MDR, respectively. It is supposed that the electronic unit does not introduce additional distortions into the image.

The MTF of the diffraction-limited lens is described by the well-known approximation function

$$M_o(v_x') = \begin{cases} \frac{2}{\pi} \left(\arccos x - x\sqrt{1-x^2} \right), & \text{when } 0 \leq x \leq 1; \\ 0, & \text{when } x > 1, \end{cases} \quad (9)$$

where $x = \lambda \frac{f_o'}{D_p} \left(1 - \frac{\beta'}{\beta_p} \right) v_x'$, D_p is a diameter of the entrance pupil, β' is linear (transverse) magnification of the image, β_p is linear magnification in pupils and v_x' is spatial frequency in the image plane.

In a simplified model, the two-dimensional MTF $M_o(v_x, v_y)$ of the lens presented in the expression (9), is often replaced with a one-dimensional one. For high-quality lenses, it is convenient to approximate the MTF with analytical expressions like, for example,

$$M_o(v_x') = 1 - 1.218 k_{eff} \lambda \frac{v_x'}{\eta_{di}}, \quad (10)$$

where $\eta_{di} = \frac{v_{xr}'}{v_{xd}'}$ is the approximation parameter that determines a difference, at the certain contrast, between the MTF of the real lens and the MTF of the diffraction-limited lens. In the presence of small aberrations $\eta_{di} < 1$.

It is assumed underneath that the MDR has following basic parameters:

- readout frequency f_d ;
- exposure H_n , equivalent to the root-mean-square (RMS) noise value;
- saturation exposure H_m ;
- pixel size $V_D \times W_D$;
- the distance between origins of pixels Δl_D ;

- number of pixels in the row NX_D and in the column NY_D ;
- sensitivity R_D ;
- maximum dynamic range.

The MTF of the MDR is described by a product of two functions, namely, the spatial MTF M_{Ds} determined by the geometric shape of its sensitive area, and the time-dependent MTF M_{Dt} , determined by the detector's inertia. Thus, an overall MTF of the MDR can be written as

$$M_D = M_{Ds} \cdot M_{Dt}. \quad (11)$$

For a single-element detector, with the uniform sensitivity within the rectangular area $V_D \times W_D$, the spatial MTF is determined by the function

$$M_{Ds}(v_x', v_y') = \frac{\sin(\pi V_D v_x')}{\pi V_D v_x'} \frac{\sin(\pi W_D v_y')}{\pi W_D v_y'}. \quad (12)$$

This function has the first zero value at $v_{x01}' = 1/V_D$ and $v_{y01}' = 1/W_D$.

At higher spatial frequencies, the value of this approximation MTF becomes negative, that indicates onto the contrast reversal. When designing the OESS, the size of the MDR's sensitive area must meet the condition:

$$\begin{pmatrix} V_D \\ W_D \end{pmatrix} \leq \begin{pmatrix} 1/v_{x,\max}' \\ 1/v_{y,\max}' \end{pmatrix}, \quad (13)$$

where $v_{x,\max}'$ i $v_{y,\max}'$ are the maximum spatial frequencies of the formed image in the plane of the MDR along the corresponding coordinates.

In practice, more strict conditions are often to be fulfilled:

$$\begin{pmatrix} v_{x,\max}' \\ v_{y,\max}' \end{pmatrix} \leq \begin{pmatrix} v_{Nx} = 1/2V_D \\ v_{Ny} = 1/2W_D \end{pmatrix}, \quad (14)$$

where v_N is the Nyquist frequency.

The most typical time-based MTF is the MTF of a low-frequency filter is

$$M_{Dt}(f) = \left[1 + (2\pi t_D f)^2 \right]^{-0.5}, \quad (15)$$

where f is the time frequency.

Taking into account that $ft_o = v_x' V_D$, the one-dimensional of MTF the MDR can be written as

$$M_D(f) = \frac{\sin(\pi ft_o)}{\pi ft_o \sqrt{1 + (2\pi t_D f)^2}}, \quad (16)$$

where t_o is the time interval required to scan one image element. It can be evaluated by the equation

$$t_o = \frac{\eta_{sc}}{f_f \cdot N_a}.$$

where η_{sc} the scan efficiency factor, f_f is the frame rate, N_a is the number of active elements of the image decomposition.

The effectiveness of a scanning system is determined by the scan factor, which is equal to a product of the efficiency of the frame and line scan.

When designing the OESS, it is important to match the time interval t_o and the time constant t_D of the MDR. The condition for matching these parameters may be

$$f_D \geq f_{\max},$$

where f_D is the relaxation frequency defined as

$$f_D = \frac{1}{2\pi t_D},$$

and $f_{\max}$ is the maximum frequency of the video signal at the output of the MDR, which can be evaluated as

$$\Delta f = f_{\max} - f_{\min} \approx \frac{1}{2t_o}.$$

Finally, we have

$$t_D \leq \frac{t_o}{\pi}.$$

The MTF of the MDR can be conveniently presented as a product of two functions, namely, the MTF $M_{Ds1}(v_x, v_y)$ of a sensitive pixel area and the MTF $M_{Dsd}(v_x, v_y)$, that takes into account the spatial sampling process performed by the MDR. For a rectangular shape of the sensitive area having the size $V_D \times W_D$, the MTF $M_{Ds1}(v_x, v_y)$ has a view similar to the expression (12).

The function $M_{Dsd}(v_x, v_y)$ is determined by the sampling period. If the sample period of the matrix structure is $V_D \times W_D$, then the function $M_{Dsd}(v_x, v_y)$ is equal to

$$M_{Dsd}(v_x, v_y) = V_D W_D \text{sinc}(V_D v_x) \text{sinc}(W_D v_y). \quad (17)$$

The principle of the MDR's action also effects onto its MTF. This impact is specific and can be taken into account by additional transfer functions, if necessary.

The consideration of the function M_{Dt} in real-life conditions of the OESS operation requires more detailed research and goes beyond the scope of this study. Here, we will assume that $M_{Dt} \approx 1$ and

$$M_D(v'_x) = \frac{\sin(\pi V_D v'_x)}{\pi V_D v'_x}, \quad (18)$$

where spatial frequency v'_x is measured in mm^{-1} .

To transfer a value from the linear spatial frequency v'_x to the angular spatial frequency v_x , which is measured in mrad^{-1} , we use the ratio

$$v'_x = v_x \frac{1000}{f_o},$$

where f'_o is the focal length of the lens, measured in mm.

This model allows to carry out preliminary first-order (dimensional) and energetic calculations of the input unit of the OESS. The spatial resolution of the image is influenced simultaneously by two MTF (of the lens and of the MDR). For linear invariant systems, the MTF of the “lens – MDR” system has a form of the product

$$M_s(v'_x) = M_o(v'_x) M_D(v'_x). \quad (19)$$

Taking into account the expressions (10) and (18), one can get

$$M_s(v'_x) = \left(1 - 1.218 k_{eff} \lambda \frac{v'_x}{\eta_{di}} \right) \frac{\sin(\pi V_D v'_x)}{\pi V_D v'_x}. \quad (20)$$

To match the resolution properties of the lens and the MDR, it is often supposed that they should have the same MTF values at a certain spatial frequency v'_{x1} . Mostly, the equality $M_{o1} = M_{D1} = 0.5$ is chosen (Fig. 2). In this case

$$M_{o1}(v'_{x1}) = 1 - 1.218 k_{eff} \lambda \frac{v'_{x1}}{\eta_{di}} = \frac{1}{2};$$

$$M_{D1}(v'_{x1}) = \frac{\sin(\pi V_D v'_{x1})}{\pi V_D v'_{x1}} = \frac{1}{2}.$$

Then

$$v'_{x1} = \frac{\eta_{di}}{2.436 k_{eff} \lambda}; \quad v'_{x1} = \frac{0.6}{V_D}. \quad (21)$$

By comparing two previous expressions, one can find the formula for matching the lens and the MDR parameters, namely,

$$\frac{D_p}{f'_o} = 1.46 \frac{\lambda}{\eta_{di} V_D}. \quad (22)$$

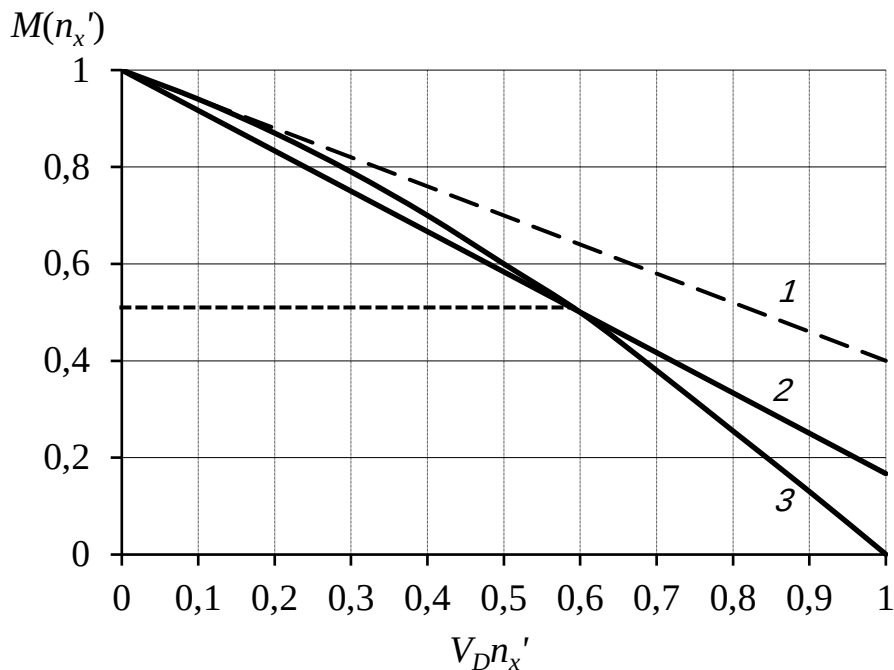


Fig.2. The lens and the MDR parameters matching: 1 is the MTF of a diffraction-limited lens, 2 is the MTF of a lens when $\eta_{di} = 0.8$ that is matched with the MDR and 3 is the MTF of the MDR with pixel size V_D

Typically, a shape of the pixel in a low-cost MDR is rectangular. Therefore, we will approximate the element of resolution of the "lens-MDR" system at the detector's plane by the rectangle $V_s \times W_s$. The one-dimensional MTF of such a system has the well-known form

$$M_s^a(v'_x) = \frac{\sin(\pi V_s v'_x)}{\pi V_s v'_x}. \quad (23)$$

From the condition of an intersection of functions (20) and (23) at the level of 0.5, we obtain a system of equations

$$M_s(v'_x) = 0.5; \quad M_s^a(v'_x) = 0.5.$$

From the second equation, similarly to expressions (21) we have

$$v'_{x2} = \frac{0.6}{V_s}. \quad (24)$$

Then, taking into account expressions (22) and (24), the first equation can be written as

$$\left(1 - \frac{V_D}{2V_s}\right) \frac{\sin\left(\pi V_D \frac{0.6}{V_s}\right)}{\pi V_D \frac{0.6}{V_s}} = \frac{1}{2}.$$

The solution of this transcendental equation is as follows

$$V_s = 1.49V_D. \quad (25)$$

The focal length of the lens is determined by the similarity of the triangles (Fig. 1)

$$f'_o = h_f \frac{V_s}{\delta V}, \quad (26)$$

where V_s is the size of the spatial resolution element of the "lens-MDR" system in the detector's plane, h_f is the satellite's orbit height and δV is the size of the spatial resolution element on the Earth's surface.

By using (26), one can determine in the simplest form the geometric resolution δV of the transmission camera on the Earth's surface in the nadir. For a square shape of the MDR pixel ($V_D = W_D$), this value is the same both along and across the spacecraft track. To calculate dimensions of the resolution element when the sighting axis is inclined from the direction of the local vertical (Fig. 3), one can use the equations

$$\delta V = V'_D = \frac{V_s h_f}{f'_o \cos^2 \omega}; \quad \delta W = W'_D = \frac{W_s h_f}{f'_o \cos \omega}, \quad (27)$$

where ω is the angle of inclination of the sighting axis relative to the local vertical.

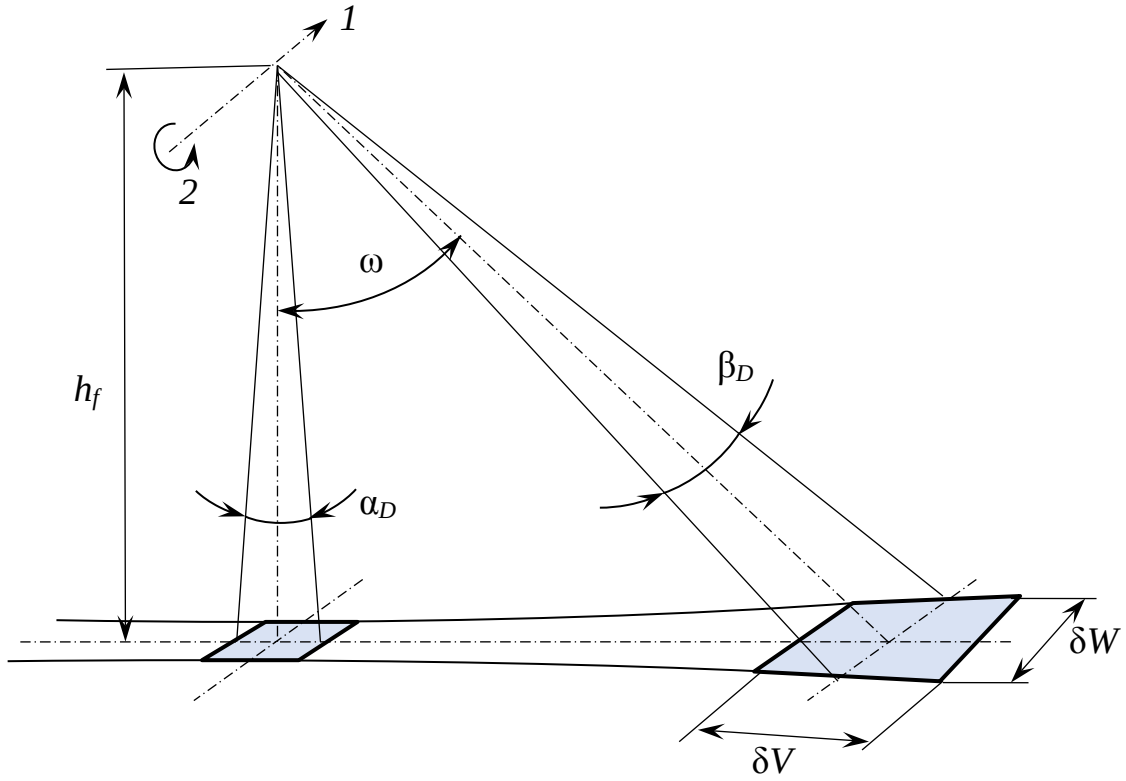


Fig. 3. Geometric resolution when the sighting axis is inclined: 1 is the direction of flight of the satellite, 2 is the direction of scanning with a flat mirror and $\alpha_D \times \beta_D$ is angular resolution of the television camera

The field of view of the lens is determined by maximum size of the MDR's matrix

$$l_D = \sqrt{(V_D N X_D)^2 + (W_D N Y_D)^2}.$$

Obviously,

$$2\omega_o = 2\omega_{ox} = 2 \arctg \frac{l_D}{2f'_o}.$$

Similarly, one can determine the linear field of view of the OEES on the Earth's surface

$$V = \frac{lX_D}{f'_o} h_f; \quad W = \frac{lY_D}{f'_o} h_f. \quad (28)$$

Diameter D_p of the lens's entrance pupil, the relative aperture D_p / f'_o or the effective aperture value $k_{eff} = f'_o / D_p$ determine energetic resolution of the television camera. Threshold contrast of the reflection coefficient and the threshold illumination of the MDR are input values for calculation D_p

$$E_n = \frac{H_n}{t_i}, \quad (29)$$

where t_i is the time of charges integration (accumulation) of MDR.

If the threshold contrast of the reflection coefficient is equal to $\Delta\rho_n=\rho_t-\rho_b$, then, according to (4), with consideration of the contrast, the illumination threshold will be equal to

$$\Delta E' = \frac{1}{4} \left(\frac{D_p}{f'_o} \right)^2 \int_{\lambda_1}^{\lambda_2} \tau_A(\lambda) \tau_o(\lambda) E_{0\lambda}(\lambda) [\rho_t(\lambda) - \rho_b(\lambda)] d\lambda. \quad (30)$$

For the integral parameters, the last expression is simplified to a form

$$E_n = \frac{1}{4} \left(\frac{D_p}{f'_o} \right)^2 \tau_A \tau_o E_0 \Delta\rho_n. \quad (31)$$

Then, the diameter of the entrance pupil of the lens will be equal to

$$D_p = 2 f'_o \sqrt{\frac{E_n}{\tau_A \tau_o E_0 \Delta\rho_n}}. \quad (32)$$

The above presented expressions help you to make a reasonable choice of the main components of a television camera. Let's show this at an example.

5. Choosing a TV camera and lens

Based on the main purpose of the space OESS, namely, monitoring of agricultural land, the geometric spatial resolution at the Earth's surface of 20-30 meters has been previously selected. In this case, the linear field of view should be several tens of kilometers. The expected height of a circular orbit of the nanosatellite is 600 km. It is convenient to control the TV camera and output the signal through the USB port. Below, for example we will fulfil estimation for the digital camera Sumix SMX-15M5C by Aptina Imaging Corp. [19] (Fig. 4).



Fig. 4. Five-megapixel digital camera SMX-15M5C [19]

The camera contains 2592×1944 active pixels having dimensions of $2.2 \mu\text{m} \times 2.2 \mu\text{m}$ of each. According to (18), the MTF of the MDR is

$$M_D(v'_x) = \text{sinc}(V_D v'_x) = \text{sinc}(0.0022 v'_x).$$

Let us analyze the lens, which will potentially provide the resolution threshold of 25 m when the image contrast is reduced by half ($C_0 = 0.5$). The equation (25) gives a value of the spatial resolution limit of the "lens-MTF" system at the detector's plane

$$V_s = 1.49 V_D = 1.49 \cdot 2.2 = 3.278 \mu\text{m}.$$

Then the focal length of the lens will be

$$f'_o = h_f \frac{V_s}{\delta V} = 600 \cdot 10^6 \frac{3.278 \cdot 10^{-3}}{25 \cdot 10^3} = 78.67 \text{ mm}.$$

The linear field of view at the Earth's surface will be equal to

$$V = \frac{IX_D}{f'_o} h_f = \frac{2592 \cdot 2.2 \cdot 10^{-6}}{78.67 \cdot 10^{-3}} 600 \cdot 10^3 = 43490 \text{ m};$$

$$W = \frac{IY_D}{f'_o} h_f = \frac{1944 \cdot 2.2 \cdot 10^{-6}}{78.67 \cdot 10^{-3}} 600 \cdot 10^3 = 32620 \text{ m}.$$

With equation (32) one can determine the smallest diameter of the entrance pupil of the lens with integral transmission coefficient $\tau_o = 0.5$. It is known that the maximum illumination created by the Sun on the Earth's surface at normal fall is approximately $E_{0 \text{ max}} = 10^5$ lux. Albedo range for plant coverings is approximately 0.1-0.25. Thus, assuming radiometric resolution of 0.1% to be sufficient, the value $\Delta\rho_n \approx 0.001$ can be accepted. For threshold illumination of the MDR in 3 lux, we have

$$D_p = 2 \cdot 78.67 \cdot \sqrt{\frac{3}{0.5 \cdot 0.5 \cdot 10^5 \cdot 0.001}} = 52.5 \text{ mm}.$$

For example, among commercially available high-quality light-weight lenses, the Planar T* 1.4/85 developed by Zeiss corporation [20] (Fig. 5) corresponds to estimated parameters.



Fig. 5. Scheme and appearance of Planar T*1.4/85 lens produced by Zeiss corporation [20]

With a relatively compact design (88 mm in length, 78 mm in diameter), this lens has focal length of 85 mm. It provides the F-number equal to 1.4 and the maximum diameter of the entrance pupil equal to 60.7 mm.

6. Discussion of the estimated model

The proposed model and calculation technique are quite simplified. Therefore, they are intended to be used at preliminary design stages. They may be useful, for example, for small design companies that do not have dedicated research departments.

The model takes into account basic parameters of the lens and detector of radiation. However, for a more accurate prediction of the effectiveness of the OESS functioning, this model needs to be revised. In order to refine actual spatial resolution properties of the television camera under the conditions of space flight, it is necessary, in the future, to take into account the influence of the image smear caused by linear

and rotational satellite motions. The developed calculation model enables to advance in this by taking into account the corresponding modulation transfer functions. The model can also be refined in the direction of estimating the energetic resolution.

6. Conclusions

1. The mathematical model is developed for signal transformations occurring during remote observation from space with digital television cameras. The model is based on the theory of linear systems and describes the modulation of contrast in the main components. The model takes into account the main links of the information system "object/background – atmosphere – digital video camera". The calculation expressions based on this model enables to carry out the analysis of the lens and the matrix detector for a space-based television camera.

2. The method of matching the main parameters of the lens and the matrix detector is developed. The matching criterion is the equality of the modulation transfer functions of the lens and the matrix detector for the contrast value of 0.5.

3. The focal length and the entrance pupil diameter of the lens are established, which will potentially provide the spatial resolution on the Earth equal to 25 m with a radiometric resolution of 0.1% for an orbit 600 km high. The given set of tasks for space observation of agricultural land can be satisfied with the selected television camera Sumix SMX-15M5C produced by Aptina Imaging Corp. and with Zeiss Planar T*1.4/85 lens.

References

1. Nano/Microsatellite Market Forecast 2017 [Electronic resource]. SpaceWorks Enterprises, Inc. (SEI). – 2017. – Available at: http://spaceworksforecast.com/docs/SpaceWorks_Nano_Microsatellite_Market_Forecast_2017.pdf.
2. Hunyadi G., Ganley, J., Peffer, A., and Kumashiro, M. (2004). The University Nanosat Program: an adaptable, responsive and realistic capability demonstration vehicle," *Aerospace Conference Proceedings, IEEE Proceedings*, 5, pp. 2858; DOI: 10.1109/AERO.2004.1368091.
3. Small Spacecraft Technology Program (SSTP) – Projects 2014–2015 [Electronic resource]. National Aeronautics and Space Administration. Ames Research Center. 2014. Available at: <http://www.sumix.com/cameras/usb30-series.html>.
4. Zubko, V. P., Iskov, P. Y., Podoluk, I. Ya., Stefanydyn, Ya. I. (1998). Ohlyad stanu ta tendetsij rozvytku dystntsiynoho zonduvanya Zemli. *Kosmichna nauka i tehnologiya*. 4. 5/6. 67–87.
5. Tiagur, V. M., Lykholit M. I., Kolobrodov, V. G. (2006). Optychni systemy kosmichnyh bagatospektralnyh skaneriv. *Naukovi visti NTUU «KPI»*. 6. 125–132.
6. Kolobrodov, V. G., Lykholit, M. I., Marchenko, V. O., Mykytenko, V. I. Vybir optyko-elektronnoi systemy malorozmirnogo univesytetskogo suputnyka. *Visnyk ChDTU*. 2. 167–172.
7. National Land Imaging Requirements (NLIR) Pilot Project Summary Report – Summary of Moderate Resolution Imaging User Requirements [Electronic

resource]. USGS. 2017. Available at: <http://pubs.usgs.gov/of/2014/1107/pdJ7ofi2014-1107.pdf>.

8. CEOS EO Handbook. Catalogue of satellite instruments [Electronic resource]. CEOS. 2017. Available at: <http://database.eohandbook.com/database/instrumenttable.aspx>.

9. Morel, J., Todoroff, P., Bugue, A., Bury, A., Martine, J.-F., and Petit, M. (2014). Toward a satellite-based system of sugarcane yield estimation and forecasting in smallholder farming conditions: a case study on Reunion Island. *Remote Sensing*, 6, 6620–6635; doi:10.3390/rs6076620.

10. Balan, M. (2008). GOLIAT Project Overview [Electronic resource]. *Proceedings of the Summer 2008 CubeSat Developers' Workshop*. 2008. Available at: <http://mstl.atl.calpoly.edu/~bklofas/Presentations/SummerWorkshop2008/Sun/1%20University%20of%20Bucharest.pdf>.

11. Barnhart, D., Vladimirova T., Baker A., Sweeting, M. (2009). A low-cost femtosatellite to enable distributed space missions. *Acta Astronautica*, 64, 11–12, 1123–1143.

12. Z. Xiong, Y. Zhang (2009). A generic method for RPC refinement using ground control information. *Photogrammetric Engineering and Remote Sensing*. 75, 9, 1083–1092.

13. Holst, G. C. (2008). Electro-optical imaging system performance. – JCD Publishing Company, 538 p.

14. Kolobrodov, V. G., Dobrovolska, C. V., Mykytenko, V. I., Tymchik, G. S., Tiagur V. M., Komada, P., Mussabekova, A., Targeusizova, A., Iskakova, A. (2017). Spaceborne linear array imager's spatial resolution for arbitrary viewing angles. *Proceedings of SPIE, 10445, Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments*. doi: 10.1117/12.2280909.

15. Kolobrodov, V. G. (1997). O prostranstvennom razreshenii kosmicheskikh IK-sistem dstantsionnogo zondirovaniya Zemli // *Kosmichna nauka i tehnologiya*. 3. 5/6. 55–87.

16. Rachim, E., Tahir, A. M., Herawan A. (2017). Preliminary of Optical Lens Design for Micro-Satellite. *IOP Conf. Series: Earth and Environmental Science*. 54, 012095; doi:10.1088/1755-315/54/1/012095.

17. Xing K., Cao S.-X., Yue, C.-Y., Zhou N., He H.-Y. (2017). Optimization Design Method of Optical Remote Sensor Based on Imaging Chain Simulation // *MATEC Web Conf. International Conference on Mechanical, Material and Aerospace Engineering*, 114, Article 04013; DOI <https://doi.org/10.1051/matecconf/201711404013>.

18. Sviridov, K. N. (2017). O predelnom instrumentalnom razreshenii kosmicheskogo apparata «Resurs-P». *Raketno-kosmicheskoe priborostroenie i informatsionnye sistemy*. 4, 2, 20–28.

19. Sumix Cameras. USB 3.0 Cameras [Electronic resource]. Sumix. 2017. Available at: <http://www.sumix.com/cameras/usb30-series.html>.

20. Zeiss Camera Lenses. Zeiss Planar T* 1,4/8 [Electronic resource]. Zeiss Group. 2017. Available at: <https://www.zeiss.com/camera-lenses/us/photography/products/classic-lenses/planar-1485.html#downloads>.

Kolobrodov Valentin

Doctor of Technical Sciences, Professor, Head of Department

Department of the optical and opto-electronic devices

National technical university of Ukraine «Igor Sikorsky Kyiv polytechnic institute»

Peremohy ave., 37, Kyiv, Ukraine, 03056

E-mail: thermo@ukr.net

Contact tel.: 067-936-42-33

Number ORCID: [http:// orcid.org/ 0000-0003-0941-0252](http://orcid.org/0000-0003-0941-0252)

Mykytenko Volodymyr

PhD, Senior Scientific Researcher, Associate Professor

Department of the optical and opto-electronic devices

National technical university of Ukraine «Igor Sikorsky Kyiv polytechnic institute»

Peremohy ave., 37, Kyiv, Ukraine, 03056

E-mail: v.mikitenko@nil-psf.kpi.ua

Contact tel.: 067-500-57-20

Number ORCID: 0000-0001-7213-9368

Sokurenko Vyacheslav

PhD, Associate Professor

Department of the optical and opto-electronic devices

National technical university of Ukraine «Igor Sikorsky Kyiv polytechnic institute»

Peremohy ave., 37, Kyiv, Ukraine, 03056

E-mail: sokurenko2@meta.ua

Contact tel.: 093-734-85-83

Number ORCID: [http:// orcid.org/0000-0001-5057-182X](http://orcid.org/0000-0001-5057-182X)