COMPUTATIONAL PROBLEMS OF ELECTRICAL ENGINEERING

Vol. 5, No. 1, 2015

FACTORS AFFECTING THE QUALITY OF FORMATION AND RESOLUTION OF IMAGES IN REMOTE SENSING SYSTEMS

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Abstract: The article deals with the factors affecting the quality of formation and resolution of an image in a high-resolution scanner (HRS). It is shown that the stabilization parameters of a spacecraft (SC), on which a HRS with a charge-coupled device operating in time delay integration mode (TDI-CCD) is installed, significantly affect an image distortion, namely its blurring, and this blurring increases when the number of integration lines goes up in the TDI sensor. The analysis and modelling of the maximum permissible number of integration stages in CCD8091 TDI-sensor employed in a HRS are conducted. We analyse the effect of a deviation in the nominal (planned) flight altitude of a SC above the Earth's surface on limiting the highest possible number of integration stages. The results obtained make it possible to assess the impacts on the image quality and resolution, and choose a compromise variant for the best results.

Key words: image processing, spatial resolution, TDI sensor, high-resolution scanner.

1. Introduction

High quality imaging is an important task of Earth remote sensing systems. The quality of a digital image is characterized primarily by its resolution, which is in turn determined by the number of pixels the image is composed of; however, not always the high resolution of the digital image generated testifies its high quality. This is due to the fact that the resolution of a digital image is the number of dots (pixels) per unit area, and this quantity does not carry information on the quality of the object image transmission by the optical system of a forming apparatus. Therefore, the quality of the generated digital image should be considered and evaluated as the resolution of an optical system in combination with an image sensor (light sensor), in this case, a matrix [1].

The image quality is currently evaluated using two criteria: the limit of resolution – i.e. the Rayleigh criterion and the optical transfer function – i.e. the Foucault criterion.

The limit of resolution is a minimum distance between two points at which their image can be distinguished from the image of one point.

The Rayleigh criterion states that if the intensity of the image of two close points between the points dips not less than 20%, then the points are observed as separate (are resolved) as shown in Fig. 1. For this, it is necessary that the maximum of one point image coincides with the first minimum of the other [2].

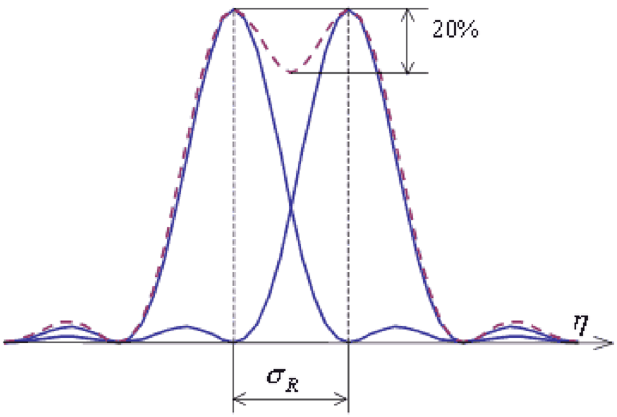

Fig. 1. Resolution by the Rayleigh criterion.

The Foucault criterion [2] is used to measure the image quality in optical systems, which transmit images of objects with complex structures. The resolution s_R is defined as a maximum spatial frequency of a grating consisting of black and white bars of equal width (Foucault pattern) in the image of which the bars are resolved. The resolution is usually determined for the patterns with unit (absolute) contrast according to the diagram of contrast-frequency characteristics (CFC) of an optical system (Fig. 2). The resolution s_R is determined by w_{gr} for a given contrast (usually for contrast $k = 0,2$).

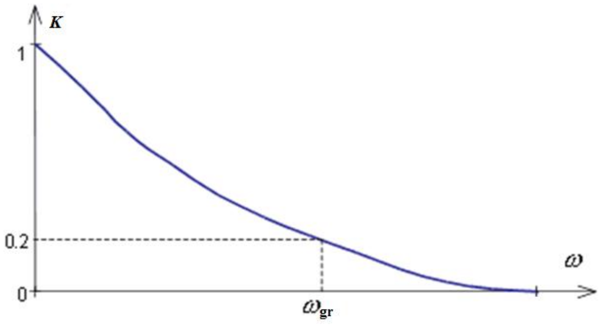

Fig. 2. Resolution by the Foucault criterion.

2. Image resolution factors

Improving of image resolution requires using of sensors with small pixels. Decrease in pixel size leads to sensor sensitivity degradation and distortion of the obtained image by noise. To rise SC scanner sensitivity, and reduce weight and dimension characteristics of the optical system, it is desirable to utilize time delay integration sensors (TDI) [8, 9]. Nevertheless, these sensors can only be used after evaluation of permissible number of integration stages, otherwise the image is blurred, and this, in turn, reduces the system resolution.

The quality of the image obtained from the scanner, is normally evaluated by using the modulation transfer function (MTF) [2, 5], i.e. the dependence of sinusoidal pattern image contrast on a spatial frequency.

Let us consider the main factors affecting the image quality. Suppose that the pattern consisting of light and dark stripes of the width δ is used as a test object on the Earth. The quality of the test object's image is influenced by the following factors:

1) Contrast of the test object on the Earth, which depends on the albedo (reflection coefficient) of the object under observation and the reflection coefficient of uniform background of the Earth's surface;

2) MTF of the atmosphere – $M_{atm}(v_x,v_y)$, where v_x,v_y are the spatial frequencies of the optical signal in the directions x and y, respectively. The atmosphere changes the parameters of the object radiation due to absorption and scattering of light and atmospheric turbulence. When sensing through the atmosphere layer, the image of the object becomes blurred in the turbulent layers. The amount of the blur is determined by the MTF of the atmosphere;

3) MTF of the scanner lens – $M_{os}(v_x,v_y)$, which depends on such lens parameters as diffraction and aberration;

4) MTF of the CCD line – $M_{CCD}\ (v_x,v_y)$. Since the CCD photodetector is a spatial system, the system transmits an image with the help of a limited number of discrete points, while the maximum spatial frequency v_H, which can be uniquely converted and transferred by the CCD line, is the Nyquist frequency at which each pixel of the CCD line corresponds to a maximum or minimum of the image. The Nyquist frequency is related to the pixel size with the aspect ratio v_N = 1/2b [3], where b is the pixel size in the direction of the line length;

5) MTF of the phase position of test object stripe – $M_{Ob}(v_x, \Delta x, v_y, \Delta y)$. The position of the stripe object can be arbitrary with respect to the centre of the pixel and fall not onto one, but two neighbouring pixels which leads to a drop in the image contrast;

6) The function of the MTF decrease in the direction of SC flight due to the image "shifting" – $M_{shift}(v_x, \Delta x')$. Since the SC moves around the Earth, the scanner constructs, line by line, the image of the Earth's surface. The movement during the signal exposure causes the blurring of an image, and consequently causes a reduction of the image contrast and scanner resolution along the flight direction;

7) The function of the MTF decrease due to the SC axis position instability during the exposure − $M_{\omega}(v_x,v_y)$. Because of this instability over the exposure time t_E, the image in the focal plane of the scanner lens is shifted by the following value:

$$\Delta X(w_X) = f_0' \cdot tg(w_X \cdot t_E), \quad \Delta Y(w_Y) = f_0' \cdot tg(w_Y \cdot t_E) \tag{1}$$

where w_X and w_Y (°/s) represent the angular velocities of the SC axis shifting in the direction of flight and in the direction that is perpendicular to the flight direction, respectively; f_0' stands for the focal length of the lens. The values of angular velocities w_X and w_Y of the SC axis shift are typically within 0,001...0.005 °/s, thus using standard CCD lines in the scanner (without a time delay integration) results in a slight shift of the image in the focal plane during the exposure, and, consequently, in a slight decrease of the MTF. However, when using a scanner with a TDI sensor, the signals from neighbouring pixels of different sensor lines sum up. Therefore, the average shift of the image in the focal plane due to integration of signals from n lines becomes n times greater resulting in significant blurring of object images and superposition of the images of adjacent surface parts.

8) The function of the MTF decrease due to the Earth's rotation during the exposure – $M_{Erot}(v_y,\alpha)$. Since the plane of the SC circular solar orbit approaches very closely the Earth's poles, there occurs, during the exposure, the displacement of a sub-satellite point along the row of the CCD line due to the Earth's rotation around its axis. The rate of the sub-satellite point displacement depends on the latitude α of the portion

where a picture is taken, and is defined by the expression given below:

$$V_{Erot} = \frac{2p\, R_E \cdot \cos a}{24 \cdot 3600} \text{ (km/s)}, \qquad (2)$$

where R_E denotes the Earth radius.

According to the value of the sub-satellite point displacement, the image in the focal plane of the lens is also shifted, and when a TDI sensor is used in the scanner, this shift becomes n times greater, where n is the number of rows of the TDI sensor, involved in the integration of signal. This also leads to the image blurring;

9) The function of the MTF decrease due to the SC orbit altitude instability during the exposure – $M_{\Delta H}(n_x)$. The orbit of the SC is not precisely circular with its every point located at the altitude H above the Earth, but can be rather represented by a movement "along a potholed road". Depending on the orbit point above the Earth's area the SC flies over, the orbit altitude can vary in the range of H±20 km. For the altitude H, the scanner is assigned a certain frequency of rows' reading, which corresponds to the time of sub-satellite point's passing some distance A (m) on the Earth's surface. But as the SC altitude varies, so does the value of pixel projection on the Earth and the passed distance on the Earth's surface, as well as the speed of a sub-satellite point. At a fixed value of the exposure time for the altitude H (and the frequency of rows' reading, respectively), this leads to a "creeping" of the images of two neighbouring rows on each other and to decrease in the MTF. This is especially noticeable when the number n of TDI sensor lines involved in the signal integration increases.

10) The function of the MTF decrease due to the influence of the aperture of an image sensor pixel. If we consider a typical image sensor, it contains pixels that are commonly square. The shape of a sensor pixel effects the impulse response of an imaging system which is called the point spread function $h(\xi, \eta, x, y)$ [4] and describes the dependence of image luminosity on the coordinates (ξ, η) of the image plane points for a point source with the coordinates (x, y). In an ideal diffraction-free optical system, a point source is imaged as a dot, but in a real optical system it appears as a spread spot (for the systems with a round aperture as Airy disc) [5,6]. A linear filter model of the imaging process, which is based on the consideration, in the spectral band, of Fredholm equation of the first kind with the core of convolution type, looks like application of a low-frequency spatial filter, followed by the spatial sampling of the initial image [7]:

$$I(k,l) = S \cdot D\{I(x,y) \oplus h(x,h,x,y) + N(x,y)\}, \quad (3)$$

where S is the sensitivity function; $N(x,y)$ represents the noise; $D\{-\}$ denotes the discretization operator; $I(x,y)$ stands for the initial image; $h(x,h,x,y)$ is the function of pixel aperture, x,h,x,y are the linear coordinates, k,l denote the discrete coordinates, $\oplus$ is the convolution operator.

The resulting value of the modulation transfer function is defined as the product of the above-mentioned effects.

3. Simulation of SC stabilization parameters influence on the permissible number of integration stages

Impact of the Earth's rotation and change in the SC orbit altitude on the quality of the image obtained from a TDI scanner was investigated in some sources [8, 9]. However, those sources did not analyse the effect of SC stabilization parameters on the permissible number of integration stages in TDI sensors while taking image of a specific area of the Earth's surface. Hence, we shall perform such an analysis and calculate the permissible number of integration stages in the CCD8091 TDI sensor, which would provide 1.9 m pixel's projection on the Earth for 490 km altitude of the SC orbit (or 2.6 m for 668 km altitude, respectively) for the parameters of SC stabilization reached with modern domestic satellites.

Let a spacecraft with a high-resolution scanner installed in it rotate around the Earth on a circular orbit at altitude H above the Earth's surface. Then the linear orbital speed of the SC, according to [3] is $V_{SA} = \sqrt{\frac{m_0}{R_E + H}}$, and the linear speed of a sub-satellite point movement along on the Earth's surface equals:

$$V_{SP} = \frac{R_E \cdot \sqrt{m_0}}{(R_E + H)^{3/2}}, \qquad (4)$$

where R_E=6371 km is the radius of the Earth; H denotes the SC orbit altitude with respect to the Earth's surface; $m_0 = 3{,}98602 \cdot 10^5$ km^3/s^2 represents the Earth gravitational constant.

The pixel projection size P on the Earth can be calculated by the formula given below:

$$P = \frac{b \cdot H}{F}, \qquad (5)$$

where b represents the sensor pixel size, F stands for the focal length of the optical system.

Determine the data integration time on one row of CCD8091:

$$t_н = \frac{P}{V_\Sigma}, \qquad (6)$$

where V_Σ denotes the resulting linear speed of the image of an underlying Earth's surface point in the lens' field of vision.

The maximum number of integration stages is calculated by the following formula:

$$n \le \frac{a}{b} \cdot \frac{k \cdot r}{g_{\Sigma} + \frac{H}{V_{\Sigma}} \cdot \dot{\gamma}_{x0}}, \qquad (7)$$

where $a = b = 8.75$ μm is the pixel size of CCD8091; k is the permissible value of blurring expressed in fractions of pixel's projection; $r = 3438$ ′/rad stands for the number of minutes in one radian; $\dot{\gamma}_{x0}$ is the angular velocity of spacecraft oscillations around the x-axis coinciding with its momentary direction of movement; g_{Σ} represents the angular deviation of the longitudinal axis of a TDI sensor row with respect to the perpendicular to the direction of the underlying Earth's surface point movement in the lens' field of view.

While analysing the calculation results presented in Table 1, let us draw attention to the row 4 which shows the maximum permissible number of information integration stages when CCD8091 works in TDI mode, particularly during remote sensing of Earth's areas located near the Equator.

For these areas, the number of rows that can be used for information integration at the selected value $k = 0.5$ cannot be more than six.

The simulation results are given in Table 1.

Table 1

Simulation results

№	Parameter name		The numerical value of parameter at orbit altitude *H*	
			490 km	668 km
1	Orbital speed of the spacecraft (m/s)		7077.766	6811
2	The size of the pixel projection on the surface of the Earth, (m)		1.897124	2.586283
3	Time of information integration on one line of TDI sensor, (s)	at the Equator	$2.65 \cdot 10^{-4}$	$3.75 \cdot 10^{-4}$
		in the polar zone	$2.66 \cdot 10^{-4}$	$3.76 \cdot 10^{-4}$
4	The permissible number of lines used for information integration when working in TDI mode, (n)	at the Equator	6.25	5.99
		in the polar zone	31.12	29.31

4. Modelling of the effect of the spacecraft orbit altitude change on the optimal value of exposure time and frequency of rows' scanning of CCD8091 sensor

A particularly significant impact on the integration time value has a deviation of the real orbit altitude of the spacecraft from the nominal (planned) one, caused both by the instability of gravitational potential of the Earth and by the elliptic form of SC orbit. Thus, for example, for the "EgyptSat-1" SC at the nominal altitude of 668 km, the perigee of its orbit is equal to 666 km, and the apogee is equal to 683.6 km. Therefore, to assess the impact of the orbit altitude change on the exposure time, we tentatively assume that in the process of SC operation, the orbit altitude H can deviate by $\Delta H = \pm 20$ km. As the orbit altitude deviates, so concurrently the speed V_{Σ} of the sub-satellite point and the size P of the pixel projection on the Earth's surface change, that is why in accordance with these changes, it is imperative to change the duration of exposure time t_H on one row of CCD8091 TDI sensor, and, accordingly, the frequency f of rows' reading.

The permissible number n_1 of information integration stages, when changing the altitude, is calculated as follows:

$$n_1 \le \frac{k_1}{1 - \frac{H}{H + \Delta H} \cdot \left(\frac{R_E + H}{R_E + H + \Delta H} \right)^{3/2}}, \qquad (8)$$

where k_1 stands for the permissible value of blurring the image of an area of the underlying Earth's surface in the direction of SC flight expressed in fractions of pixel's projection. The simulations have been conducted for two values $k_1 = 0.5$ and $k_1 = 1$. Fig. 3 shows dependences of the permissible number of integration stages on the SC orbit altitude at the middle latitudes of the Earth's surface.

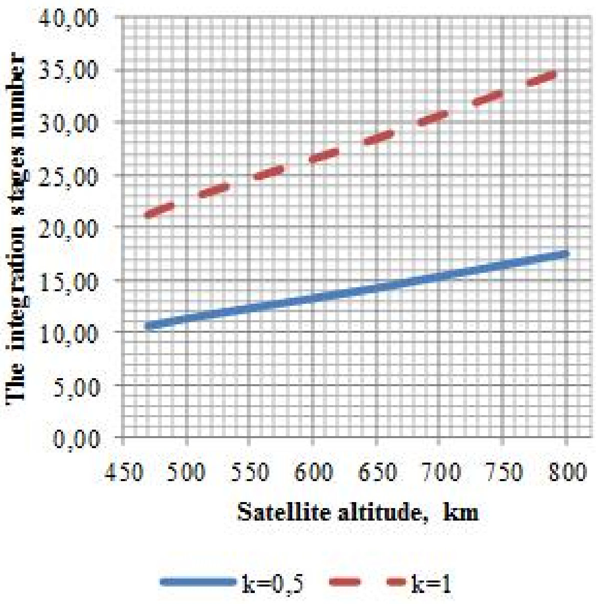

Fig. 3. Dependence of the permissible number of integration stages on the SC orbit altitude.

As a result of the simulation, we conclude that, if the orbit altitude suddenly changes and the basic parameters of a scanner, i.e. the information integration duration and the frequency of rows' reading keep the values calculated for the nominal altitude, then the scanner may malfunction. That failure is the effect of, firstly, a mismatch between the velocity of the image of underlying Earth's surface areas and the frequency of information reading, and, secondly, a mismatch between the integration duration and the frequency of information reading. In order to avoid such situations in the future, it is necessary, before each sensing, to arrange for determination and verification of orbital coordinates and location of a SC by installing on its board satellite navigation equipment that ensures the high-accuracy positioning of the SC. Having determined the orbit altitude, it is also necessary to reconfirm the value of the orbital inclination and calculate the current value of SC latitude.

Hence the Earth's surface sensing may be carried out only after completing the above-referred operations.

5. Conclusion

The article presents the simulation results of certain factors affecting the quality and resolution of systems for remote sensing of the Earth.

We have concluded that, when designing a HRS, it is necessary to find a compromise between the maximum permissible number of integration stages in the used CCD8091 TDI sensor, which is responsible for providing for a given for HRS signal-to-noise ratio, and the requirement for SC stabilization.

In order to prevent the "blurring" of an image, it is recommended, before each sensing, to determine the exact SC orbit altitude, specify the value of the SC orbit inclination, and determine the current value of the latitude the sensing is conducted at.

We have also concluded that the image formation process is affected by a pixel aperture, which works as a spatial filter of low frequency, and impairs the spatial resolution. An algorithm for eliminating the pixel aperture was proposed in our other publications [4, 7].

The results obtained can be applied to the development of newest high-resolution scanners.

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ФАКТОРИ ВПЛИВУ НА ЯКІСТЬ ТА РОЗДІЛЬНУ ЗДАТНІСТЬ ЗОБРАЖЕНЬ СИСТЕМ ДИСТАНЦІЙНОГО ЗОНДУВАННЯ

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В статті розглянуто фактори впливу на якість формування та роздільну здатність зображення у сканері високої роздільної здатності (СВРЗ). Показано, що параметри стабілізації космічного апарата (КА), на якому встановлено СВРЗ з фотоприймачем з часовим накопиченням заряду (ЧНЗ), суттєво впливають на розмивання зображення, і це розмивання збільшується при зростанні кількості рядків накопичення у ЧНЗ-фотоприймачі. Проведено аналіз та моделювання максимально-допустимого числа стадій накопичення у ЧНЗ-фотоприймачі типу CCD8091, застосованому у СВРЗ. Проаналізовано впливи відхилення номінальної (запланованої) висоти польоту КА над земною поверхнею на обмеження максимально-можливого числа стадій накопичення. Отримані результати дають можливість оцінити впливи на якість роздільну здатність зображення, та вибрати компромісний варіант для отримання найкращого результату.

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