About restoration of the scanning images received onboard a Sich-1M space vehicle by inverse filtering method

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Abstract – The spatial distortions are inherent to images of MSU-E scanner that installed onboard Sich-1M space vehicle. They are conditioned by errors of navigation angles keeping and by impossibility of precise synchronization of CCD photodetectors array reading frequency with speed of a space vehicle orbital movement. A result of such distortions is the reduction of received image quality.
The purpose of this research is the development of the algorithmic approach to restoration of the scanning images. The general model of scanning image is offered. This model permits to consider both spatially-independent and spatially-dependent distortions that originated during spaceflight.
The correction of spatially-independent distortions, such as motion blur, accomplished by method of an inverse filtration. The algorithmic procedure of estimation of an image optical transfer function cross-section with using current scene digital snapshot is designed. Also construction procedure of the inverse operator for image restoration is designed.
The examples of experimental researches on digital restoration of scanning images distortions that induced by satellite motion are described.

Keywords: Electro-Optic Scanner, Distortions, Space Images Restoration, Optical Transfer Function, Inverse Filtering.

1. INTRODUCTION

Among electro-optical scanners, which are installed onboard majority of modern space vehicles of remote sensing most widespread are the systems, that transform the radiation of Earth surface to electrical signals by CCD photodetectors arrays placed perpendicularly to flight direction. In such scanners the photodetectors array provides registration of single row of terrain image, and the assembling of sequential row's signals when space vehicle moves above the Earth surface, aggregates the two-dimensional image. The prevalence of scanners based on CCD photodetectors arrays is explained by simplicity of their construction and potential possibilities of high-quality videosignal obtaining.

Such factors, as a finite exposure time of CCD photodetectors and possible declines of a scanner main optical axis from nadir when space vehicle moves make negative influence to scanned image quality [1]. An exposition of CCD photodetectors when space vehicle moves along straight-line causes image blur, and declines of a scanner main optical axis from nadir result to perspective distortions.

The high resolution multizonal electro-optical scanners MSU-E type that installed onboard Sich-1M space vehicle belong to considered kind of scanners. The scanning of terrain in this system generates 200 lines per second (exposure time near 5 ms), that provides high signal/noise ratio, but results to some motion blur of the image. In flight the MSU-E scanner optical axis can oblique in a plane perpendicular to space vehicle orbit plane to obtain a wide field of view. If the such decline takes place, it results to perspective distortions, in particular, to variations of image scale.

The objective of this study is the research of the restoration possibility of scanner images formed onboard Sich-1M space vehicle with allowance for originated distortions removing.

2. MAIN BODY

The scheme of image creation by scanner based on CCD photodetectors array is shown in a fig. 1. Here denoted: H is the height of space vehicle flight, f is the focal length of the scanner optics, α is the angle of declination of scanner main optical axis from a nadir, β is the scanner's angular field of view.

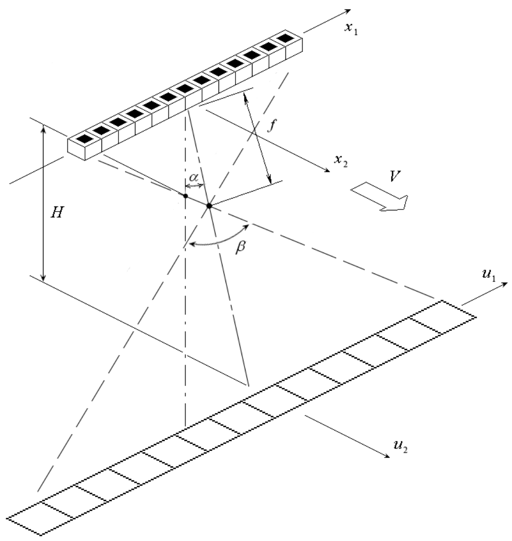

Figure 1. Scanned image creation geometry

It is known in a photogrammetry [2], in this case relation between coordinates express by formula:

$$x_1 = g(u_1) = f \cdot \frac{H \sin\alpha - u_1 \cos\alpha}{H \cos\alpha + u_1 \sin\alpha} \quad . \qquad (1)$$

The formula (1) shows, that the image distortions in various points are unequal, i. e. spatially-dependent. At the same time it is known [1], that the image distortions caused by space vehicle rectilinear movement are spatially-independent, and may be described by convolution integral

$$E(x_1, x_2) = \iint_{-\infty}^{\infty} w_1(x_1 - u_1) \cdot w_2(x_2 - u_2) \cdot E_0(u_1, u_2) \cdot du_1 \cdot du_2 \quad , \qquad (2)$$

where $E_0(u_1, u_2)$ is the source distribution of the Earth surface radiance intensity, $E(x_1, x_2)$ is the distribution of intensity registered by scanner, $w(x_1–u_1, x_2–u_2)$ is the point-spread function (PSF) in image.

Accepting that space vehicle moves rectilinearly along u_2 axis with constant velocity V, and the exposure time is t, it is possible to show, that

$$w_2(x_2–u_2) = \begin{cases} \frac{1}{V} \text{ if } 0 \le x_2 - u_2 \le V \cdot t, \\ 0 \text{ else.} \end{cases} \quad (3)$$

Usually consider that the functions $E_0(u_1, u_2)$ and $E(x_1, x_2)$ can be represented correspondingly as $E_0(u_1, u_2) = E_{01}(u_1)\cdot E_{02}(u_2)$ and $E(x_1, x_2) = E_1(x_1)\cdot E_2(x_2)$. Assumpting this lets apply Fourier transform to both parts of a convolution integral (2), then we have:

$$\mathscr{E}_1(\nu_1)\cdot\mathscr{E}_2(\nu_2) = \mathscr{E}_{01}(\nu_1)\cdot\mathscr{E}_{02}(\nu_2)\cdot\mathscr{W}_1(\nu_1)\cdot\mathscr{W}_2(\nu_2) \quad , \quad (4)$$

where, for example,

$$\mathscr{W}_2(\nu_2) = \int_{-\infty}^{\infty} w_2(x_2)\cdot\exp(-i2\pi\nu_2 x_2)\cdot dx_2 \quad . \quad (5)$$

The value $\mathscr{W}_2(\nu_2)$ is named as optical transfer function (OTF) along x_2 direction.

Thus, the problem of MSU-E image restoration can be solved in two stages. At the first stage the transformation

$$u_1 = g^{-1}(x_1) \quad , \quad (6)$$

that provides correction of geometrical distortions caused by photodetectors array angular declination is executed.

At the second stage the problem of image blur removing is solved. To do this in case of straight-line flight along u_2 direction it is enough to analyze a convolution integral

$$E_2(x_2) = \iint_{-\infty}^{\infty} w_2(x_2 - u_2)\cdot E_{02}(u_2)\cdot du_2 \quad . \quad (7)$$

Applying Fourier transform to the left and right parts of (7) expression, the convolution will be transformed to ordinal multiplying:

$$\mathscr{E}_2(\nu_2) = \mathscr{E}_{02}(\nu_2)\cdot\mathscr{W}_2(\nu_2) \, , \quad (8)$$

where $\mathscr{E}_{02}(\nu_2)$, $\mathscr{E}_2(\nu_2)$ is the Fourier spectrums in frequency domain of input and output signals correspondingly. The very important advantage of (8) notion is that space vehicle movement along u_2 direction, acts simply as one multiplicand. This circumstance allow to use an inverse filtering method for image blur removing [3].

The essence of a method is multiplying of input image frequency domain spectrum $\mathscr{E}_2(\nu_2)$ to some restoring frequency domain operator $\mathscr{R}_2(\nu_2)$, that is inverse for OTF, which describes distortions [4]:

$$F_2(x_2) = \int_{-\infty}^{\infty} \mathscr{R}_2(\nu_2)\cdot\mathscr{E}_2(\nu_2)\cdot\exp(i2\pi\nu x)\cdot dx_2 \quad , \quad (8)$$

where $F_2(x_2)$ is the restored image.

The digital processing methods give especially significant possibilities when restore images. The continuous Fourier transform (5) is substituted to discrete one (DFT) to restore digital images:

$$\mathscr{W}_2(\nu_{2k}) = \sum_{j=0}^{n_2-1} w_{2j}\cdot\exp\left(-\frac{i2\pi}{n_2}\nu_{2k}\cdot j\right) \quad , \quad (9)$$

where ν_{2k} is the k-sample of a Fourier spectrum; $k = 0, .. , n_2–1$; n_2 is the total number of both image and frequency domain spectrum discrete samples.

The image restoration for blur removing performs by inverse Fourier transform, which is written as

$$F_{2j} = \frac{1}{n_2}\cdot\sum_{k=0}^{n_2-1} \mathscr{F}_2(\nu_{2k})\cdot\exp\left(\frac{i2\pi}{n_2}\nu_{2k}\cdot j\right) \quad , \quad (10)$$

where F_{2j} is the j-sample of restored image.

The majority of existing imagers has a spatial isotropy, i. e. their PSFs are symmetric and can be completely described by itself arbitrary one-dimensional cross-section. This important feature gives possibility of experimental OTF determination immediately from the output images by PSF analysis along any direction [5].

However not all components of system's resultant OTF may be considered as isotropic. Such case inherent to scanner image creation when move along u_2 direction, as it is shown in a fig. 1. Whereas the space vehicle movement vector is directed along only one axis, the OFT that describes image distortion (blur) out of space vehicle movement may be restored by image analysis along two separate directions that form linear base. It is worth to select longitudinal and transversal axes as such directions, because the image shift acts along one axis only.

Let the imaging system has isotropic OTF $\mathscr{W}_1(\nu_1) = \mathscr{W}_1(\nu_2)$. Image shift OTF $\mathscr{S}_2(\nu_2)$ in a longitudinal direction is convolved with it. Then joint longitudinal OTF $\mathscr{W}_2(\nu_2)$ will be

$$\mathscr{W}_2(\nu_2) = \mathscr{S}_2(\nu_2)\cdot\mathscr{W}_1(\nu_1) \quad , \quad (11)$$

and transversal OTF will leave as $\mathscr{W}_1(\nu_1)$. Determining experimentally both OTFs $\mathscr{W}_2(\nu_2)$ and $\mathscr{W}_1(\nu_1)$, it is possible immediately to find shift's OTF from (10) as

$$\mathscr{S}_2(\nu_2) = \frac{\mathscr{W}_2(\nu_2)}{\mathscr{W}_1(\nu_1)} \quad , \quad (12)$$

whence to determine a restoring operator as

$$\mathscr{R}_2(\nu_2) = \frac{\mathscr{W}_1(\nu_1)}{\mathscr{W}_2(\nu_2)} \quad , \quad (13)$$

and after substitution it in (8) to receive the restored image from it Fourier transformation, on this case the shift will be eliminated really.

The restored image generally is a complex value, as the one-dimensional correction can result in phase shifts of a Fourier-image. It is transformed to the real value by recalculation of DFT phase part to geometrical offset of pixels along a column. Thus, all information necessary for anisotropic distortions elimination is already contained in the digital space image itself as one-dimensional OTF determined separately along rows and columns, and the correcting operator is used only along columns of the digital image.

Usually OTF $\mathscr{H}_1(\nu_1)$ and $\mathscr{H}_2(\nu_2)$ of digital image are calculated as DFT from average discrete derivatives of boundary curves sets determined by analysis of rows and columns of the image [6]. In researches on digital processing and pattern recognition large attention is given to extraction of edges as determined discontinuities of intensity. The range of the known approaches includes different algorithms: from classical correlation methods of matching with template up to special methods of the semantic analysis and recognition of objects. The most popular are discrete finite difference approximating of various differential operators – Laplace, McLeod, Roberts, Sobel, Kirsch, Wallis with the threshold limitation at next step [7]. Main drawback of all methods developed on base of the above approximating is necessity to find the threshold heuristically or to adjust the threshold using template images. Besides the differential operators are unfairly sensitive to noise of the digital images.

In this study the statistical method of the threshold selection in the image is developed based on conjecture about good statistical separability of segments in the image, between which a boundary curve is created. The stochastic distribution of the boundary curve intensity is taken into account by the statistical description of optical signal differences of the given curve.

Each segment point of an analyzed digital image is transformed into probability of correct distinction of up and down races of an edge-spread function along a selected direction. Obviously, that the more probability, the better quality of the given edge-spread function realization, as this function according to its definition reflects ideal determined hop of a signal. Besides the probabilistic transformation in the implicit form takes into account influence of noise to a quality of digital image. And, at last, main advantage of the probabilistic transformation is the transparent physical sense of output data, that removes a problem of the threshold choice when selecting the significant differences: they are estimated using necessary level of reliability, as a rule, within the limits of 0,80 .. 0,95. Thus, there is no additional preprocessing of the digital image required and the probability of selection of the edge-spread function for each pixel is evaluated directly, that essentially increases quality of the analysis.

Fig. 2 shows application of inverse filtering for quality restoration of the digital space image. On the left input image of the satellite scanner MSU-E is shown, at centre – the same image with simulated blur, on the right – the same image restored by a method of inverse filtering.

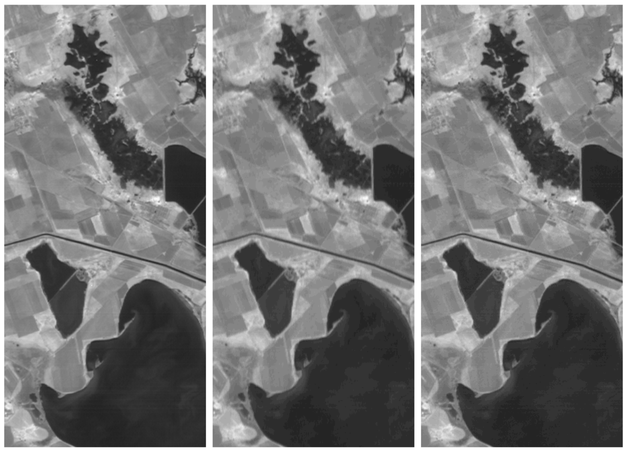

Figure 2. Inverse filtering of the digital space image

3. CONCLUSIONS

Thus, in the study the main types of geometrical distortions of electro-optical scanners with CCD arrays placed perpendicularly to flight direction are considered. The problem of the distortions restoration is formulated. Two-step improved procedure is offered that includes inverse coordinates transformation and inverse filtering. The improved procedure of OTF evaluation using digital image is proposed. The restoration operator is determined on base of the OTF. The outcomes of the image inverse filtering obtained by electro-optical scanner MSU-E mounted on Sich-1M space vehicle are presented.

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