RESTORATION OF THE EARTH'S SATELLITE IMAGES USING CARTOGRAPHIC INFORMATION

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An approach to deconvolution of images of the Earth's underlying surface observed under conditions of the distorting effect of the atmosphere is considered. A peculiarity of this approach is that in model of reconstruction we use the unknown point spread function to be estimated. Complementary information necessary for solving the problem is contained in the map of gradients and fragments of stochastic homogeneity of these video images.

Traditional methods for correction and restoration of aerospace images of the Earth's underlying surface are based on the use of the average statistical optical characteristics of the atmosphere and linear model of radiative transfer with the transfer operator which depends on the transmission coefficient.

However, the range of variation of the geometrical imaging parameters and optical situations in the atmosphere exist when the correction of images with satisfactory accuracy can be made only by using the information about the impulse response (the point spread function (PSF)) of an atmospheric optical channel. Necessary data can be obtained on the basis of model representation of the optical characteristics of the atmosphere considering meteorological situation in the region.

It should be noted that current optical weather may differ substantially in the moment of imaging from the statistically average weather. This results in lower accuracy of reconstruction of specific characteristics and distortion of the results of subsequent thematic processing.

In this connection, we consider two approaches to a solution of the problem of correction for atmospheric contribution without *a priori* knowledge of the transfer operator of the atmospheric channel, which is also reconstructed from the observed image. Necessary information is based on the approximate knowledge of a local relief of the examined region, namely, availability of cartographic data with indicated regions of stochastic homogeneity and boundaries between landscape formations.

This map may be synthesized from the topographic map of the region or from a "good" satellite image of this territory observed under favorable optical conditions with subsequent processing of the image by the segmentation algorithm. In other words, we assume that in the first approximation the examined territory includes quasihomogeneous landscape fragments (fields, forests, water surfaces, ploughed lands, and so on) and brightness gradients of heterogeneous landscape formations (water–coast, cleared strips–forest, and road–verge interfaces as well as fragments of shadowed–illuminated zones of mountain ridges, ravines, and so on).

Let us assume that the distorting effect of aerosol components of the atmosphere is fixed on the image of the Earth's underlying surface and we can represent it mathematically in the form of the convolution equation

$$g(x, y) = \iint\limits_R h(x - \xi, y - \eta)\, f(\xi, \eta)\, d\xi\, d\eta + n(x, y) , \tag{1}$$

where $g(x, y)$ is the radio-brightness function, that is, the image recorded with an electronic optical system; $\{x, y\} \subset R$; R is the domain of definition of the brightness function $g(x, y)$ (omitted from further considerations); $f(x, y)$ is the undistorted image of the surface at the scale of the image being observed; $h(x, y)$ is the point spread function spatially invariant and axisymmetric; $n(x, y)$ is the uncorrelated noise with zero mean and unknown variance (instrumental noise).

In standard formulation of problem (1), it is assumed that $h(x, y)$ is known and $f(x, y)$ is reconstructed (estimated) from the observed $g(x, y)$. As already mentioned, under real conditions of recording $g(x, y)$, optical–geometrical characteristics of the channel of image transfer are random and $h(x, y)$ is unknown.

In this situation, we first should reconstruct the point spread function (PSF) $h(x, y)$.

Let us consider the following structure model of the videodata[1] (under assumption of the Lambertian reflecting surface and the point light source)

$$f(x, y) = r(x, y)\, I \cos\theta(x, y) + r(x, y)\, D + H , \tag{2}$$

where $f(x, y)$ is the brightness of the image pixel with spatial coordinates (x, y); $r(x, y)$ is the coefficient of surface reflection (depending on wavelength λ omitted further for simplicity); I is the solar light flux; $\theta(x, y)$

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is the angle between the direction of solar ray incidence and the normal to the surface element at the point (x, y); D is the diffusely scattered light; H is the contribution of scattering by atmospheric haze. Let us write (2) in the following form:

$$f(x, y) = r(x, y)\, I_D + H, \qquad (3)$$

where $I_D = I\cos\theta(x, y) + D$ specifies the illumination of the analyzed and fixed fragments of the Earth's surface. During a short scan period of the satellite registration system (of about several fractions of a second), this parameter remains practically constant. An aerosol scattering layer smears the image of the surface and for model (1) we will have the image of the form

$$g(x, y) = \iint\limits_D h(x - \xi, y - \eta)\, r(\xi, \eta)\, I_D\, d\xi\, d\eta + $$
$$+ H + n(x, y).$$

Designating $r(x, y)I_D = f(x, y)$, we derive the equation for the observed surface image $f(x, y)$ with "frozen" illumination during imaging period, namely

$$g(x, y) = \iint\limits_D h(x - \xi, y - \eta)\, f(\xi, \eta)\, d\xi\, d\eta + $$
$$+ H + n(x, y)\ . \qquad (4)$$

Thus, the contribution of the atmospheric haze is additive.

The starting *a priori* assumptions about the existence of the brightness gradient in the surface image fixed on the contour map of gradients allow us to refine[2] model (4)

$$f(x, y) = r(x, y)\ \mathrm{step}(w),$$

where $\mathrm{step}(t) = \begin{cases} 1, & t \geq 0, \\ 0, & t < 0 \end{cases}$ is the stepped brightness gradient (for simple presentation) along the Oz coordinate, perpendicular to Ow direction, and new local coordinates associated with the stepped brightness gradient, have the form:

$$\begin{pmatrix} z \\ w \end{pmatrix} = \begin{pmatrix} -\sin\varphi & \cos\varphi \\ \cos\varphi & \sin\varphi \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix},$$

φ is the angle of rotation of the new coordinate system zOw about the old one xOy, $r(x, y)$ is the surface image without the boundary of brightness gradient, if this boundary is removed in any way. In this case, Eq. (4) has the form:

$$g(x, y) = \iint r(x - \xi, y - \eta)\ \mathrm{step}(w - w')\times$$
$$\times\, h(\xi, \eta)\, d\xi d\eta + H + n(x, y), \qquad (5)$$

where $w = x\cos\varphi + y\sin\varphi$; H is the contribution from haze and aerosol scattering in the direction toward a recording device.

Upon differentiating Eq. (5) in the direction Ow considering that $r(x, y)$ is a slowly varying function in the vicinity of the stepped jump and $d\ \mathrm{step}(t)/(dt) = \delta t$ is the delta function, we obtain the partial derivative in the direction Ow of the form

$$\frac{\partial g(x, y)}{\partial(w)} \cong r(x, y) \int h(z, w)\, dz, \qquad (6)$$

where the integration is carried out in the direction of the Oz axis orthogonal to the Ow axis. The right side of Eq. (6) is nothing but the expression for a smeared "luminescent" line, weighted by a constant[3] $r(x, y)$; its effect can be eliminated by normalization of $h(w)$. Scanning the observed smoothed image of the smeared edge $\frac{\partial}{\partial t} \int\limits_{-\infty}^{t} \int\limits_{-\infty}^{\infty} h(z, w)\, dz\, dw$ over all boundaries on the fragments of quasihomogeneity $h(x, y)$ of the cartographic data, we reduce or remove the effects of $r(x, y)$ through subsequent averaging.

As a result, we obtain a set of different approximate projections for different angles φ of the coordinate Ow in Eq. (5). Taking advantage of the topographic method for spatial function reconstruction from a set of projections $h(w) = \int h(z, w)dz$ entering Eq. (6), we reconstruct the two-dimensional point spread function $h(x, y)$. When the form of the point spread function is rather simple, for example, when the function $h(x, y)$ is axisymmetric, a single projection is sufficient for reconstruction of the spatial point spread function.

After the reconstruction of $h(x, y)$, we proceed to the problem of deconvolution of $f(x, y)$ from Eq. (1). Let us take advantage of the approach based on the alignment of the energy spectra[4] (representing the Fourier transform of the correlation function). In this case, the image being restored is obtained as a linear estimate of the functional from the observed image having the structure analogous to (1), namely,

$$\hat{f}(x, y) = \iint l(x - \xi, y - \eta)\ g(\xi, \eta)\ d\xi\ d\eta\ , \qquad (7)$$

where $l(x, y)$ is the kernel of the reconstructing operator. In this case, it is assumed that the power spectrum of the estimate is equal to the power spectrum of the original surface image[4,5]

$$F_{\hat{f}}(u, v) = F_f(u, v), \qquad (8)$$

where $F_{\hat{f}}(,)$ and $F_f(,)$ are the Fourier transforms of the correlation functions of the estimate and image (power spectra), respectively, and (u, ν) is the plane of spatial frequencies.

Considering linearity of the reconstructing operator (7) and assumptions about the noise characteristics, the power spectrum of estimation $f(x, y)$ is equal to

$$F_{\hat{f}}(u, \nu) = |L(u, \nu)|^2 \, [\,|H(u, \nu)|^2 \, F_f(u, \nu) + + F_n(u, \nu)] \,, \tag{9}$$

where $H(u, \nu)$ and $L(u, \nu)$ are the spatial Fourier spectra of $h(x, y)$ and $l(x, y)$, respectively, and $F_n(u, \nu)$ is the noise power spectrum.

Equating the right side of Eq. (9) to the right side of Eq. (8), we obtain the expression for the modulus of the spatial-frequency characteristic of the linear filter aligning the power spectra

$$|L(u, \nu)| = \{|H(u, \nu)|^2 + + [F_n(u, \nu)]/[F_f(u, \nu)]\}^{-1/2}. \tag{10}$$

It can be shown that characteristic (10) of this filter is equal to the geometric mean of the characteristics of the Wiener and inverse filters.

The spatial spectrum of the restored image, considering Eq. (10), is determined as follows:

$$\Phi_{\hat{f}}(u, \nu) = L(u, \nu) \, G(u, \nu) \,, \tag{11}$$

where $G(u, \nu)$ is the spatial Fourier spectrum of the observed image $g(x, y)$. Finally, taking the inverse Fourier transform of the spectrum $\Phi(,)$, we obtain the sought-after estimation $\hat{f}(x, y)$ of $f(x, y)$.

Now let us consider the second variant of reconstruction of $h(,)$.[4, 5] In contrast to the first variant using the smeared boundaries of brightness gradients, in this case the information is used about the correlation characteristics of the signal (image) and noise for quasistationary fragments of the observed image. To realize this method, we decompose the observed image of the fragment of quasistationarity of the distorting effect of the atmosphere and landscape on fragments; for each fragment we can write

$$g^i(x, y) = h(x, y) * f^{\,i}(x, y) + n^i(x, y) \,, \tag{12}$$

where the asterisk denotes the operation of convolution (1), $i = 1,..., N$, N is the number of fragments. The power spectrum of every fragment, in accordance with Eq. (9), has the form

$$F_g^i(u, \nu) = |H(u, \nu)|^2 \, F_f(u, \nu) + F_n(u, \nu), \quad i = 1, \ldots, N. \tag{13}$$

Now, we average the power spectra of various fragments of the image for the quasistationary fragment of the videodata. In this case, random deviations of the power spectra of fragments are smoothed and the average estimate has the form

$$\frac{1}{N} \sum_{i=1}^{N} F_g^i(u, \nu) = \frac{1}{N} \sum_{i=1}^{N} [\,|H(u, \nu)|^2 \, F_f^i(u, \nu) + +F_n^i(u, \nu)] = |H(u, \nu)|^2 \, \hat{F}_f(u, \nu) + \hat{F}_n(u, \nu), \tag{14}$$

where $\hat{F}_f(u, \nu)$ and $\hat{F}_n(u, \nu)$ are the estimates of the power spectra of signal and noise, respectively. The estimation of the modulus of the transfer function we obtain from Eq. (14):

$$|H(u, \nu)|^2 = = \left[\frac{1}{N} \sum_{i=1}^{N} F_g^i(u, \nu) - \hat{F}_n(u, \nu)\right] / [\hat{F}_f(u, \nu)] \,, \tag{15}$$

then reconstructing linear operator (10) has the form

$$|L(u, \nu)| = = \left\{\frac{1}{N} \sum_{i=1}^{N} F_g^i(u, \nu) / [\hat{F}_f(u, \nu)] - \frac{\hat{F}_n(u, \nu)}{\hat{F}_f(u, \nu)} + \frac{F_n(u, \nu)}{F_f(u, \nu)}\right\}^{-1/2}. \tag{16}$$

When $\hat{F}_n$ and $\hat{F}_f$ are close to true F_n and F_f ,

$$L(u, \nu) \cong \left\{\hat{F}_f(u, \nu) \Big/ \left[\frac{1}{N} \sum_{i=1}^{N} F_g^i(u, \nu)\right]\right\}^{1/2}. \tag{17}$$

To estimate the power spectra of the image and noise entering Eqs. (16) and (17), it is natural to use the videodata obtained for the period of preceding observations under "good" conditions of vision. The spectral representation of the reconstructing operator (7) so obtained is used in Eqs. (11) for the deconvolution of the image.

As a result, using *a priori* information about the landscape characteristics, tentatively called cartographic data, we can reconstruct, in principle, the transfer operator describing aerosol effects of the atmosphere and the surface image itself. For practical implementation of the above-indicated approach, one should classify the atmospheric situations and parameterize the point spread function which depends on these situations as well as to supplement the procedure of reconstruction of $h(,)$ and $f(x, y)$.

These problems will be considered in our future paper that will be published in the Journal *Atmospheric and Oceanic Optics* in 1997.

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