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Algorithm of restoration for short exposure of the ERS image spatially-non invariant to atmospheric distortions

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Abstract. Negative influence of the atmospheric turbulence on the ERS systems is noted. Hardware and software technologies for partial correction of atmospheric influence are reviewed. New algorithm for recovering of an image not distorted by atmosphere, which has a diffraction-limited resolution of the ERS telescope in its broad field of view is proposed and substantiated.

Key words: turbulent atmosphere, problems of vision and isoplanacity, spatial filtration, image restoration.

Introduction

Optical images of objects observed through the turbulent atmosphere, are distorted both by the imaging process and the process of their registration. This distortion in the image formation process is caused by spatiotemporal fluctuations of the refractive index of the turbulent atmosphere, and the distortion in the registration process is due to the quantum character of the interaction of light with the photosensitive layer of the photographic material and nonlinearity of the process of photoexposure. To correct these distortions several image filtering algorithms have been developed [1]. These algorithms are based on the assumption of linearity and spatial invariance of the imaging systems. However, if the non-linearity of the registration process in some cases may be disregarded and consider the imaging system as linear, the spatial invariance (isoplanaticy) of the systems that form images through the turbulent atmosphere, is limited [2]. This restriction is significant in filtering of instant (short exposure) images of the extensive tracts of the Earth's surface and those images cannot be handled by the known spatial filtering algorithms [1].

This paper proposes a new statistical processing and recovery algorithm for the short-exposure remote sensing images, spatially noninvariant to the atmospheric distortions.

Effect of the turbulent atmosphere on the remote sensing systems

The presence of turbulent atmosphere between the surveyed region of the Earth surface and the earth remote sensing spacecraft significantly limits the information capabilities of the earth remote sensing systems [3]. Two problems arise: the problem of "vision" through the turbulent atmosphere and the problem of "isoplanaticy" of the surveyed region. The core of those issues is that the "vision" imposes restrictions on the minimum size of the detail resolvable by the atmosphere-remote sensing telescope system on the sensed region of the Earth's surface, and the problem of "isoplanaticy" limits the maximum size of the sensed region of the Earth's surface which is spatially invariant to atmospheric distortions, i.e. this problem limits the field of view of the atmosphere-remote sensing telescope system.

These issues substantially depend on the conditions of observation and, in particular, from the conditions of the remote sensing images registration.

If the registration (exposure) time t_E exceeds the interval of temporal correlation of the atmospheric fluctuations t_A (so-called time of "frozen" atmospheric turbulence), the registration time is considered long-exposure, and if the registration t_E is less than t_A, then it is considered a short-exposure registration. These two extremes significantly differ in nature of atmospheric distortion. If the long exposure picture, averaged over atmospheric distortions during the time $t_E>t_A$ has a lower resolution than instant short-exposure image register during the time $t_E<t_A$, it is spatially invariant to atmospheric distortions in the whole field of view of the atmosphere-remote sensing telescope system, unlike the short-exposure image, consisting in this field of a series of instant regions of isoplanaticy spatially invariant to atmospheric distortions.

In accordance with this, at the early stages of development of ERS technologies, the pursuit of a wider field of view stimulated the application of long-exposure ERS imaging both on Russian ERS SC: "Resurs-DK1" [4] and "Resurs-P", and the American ERS SC: "QuickBird", "WorldView" and "GeEye" [6].

The technology of time delay and integration, used in surveying, leads to registration of a long-exposure ERS image, averaged by the atmospheric distortions.

This image is characterized by a medium (long-exposure) optical transfer function (OTF), defined [7] as

$$\langle t(\vec{f})\rangle_{\text{l-e}}=\langle t(\vec{f})\rangle = t_0(\vec{f})\exp\left\{-3{,}44\left[\bar{\lambda}F\vec{f}/r_0\left(\bar{\lambda},\mathrm{H}\right)\right]^{5/3}\right\} \quad (1)$$

With the development of ERS equipment, new technologies emerge that allow identifying and correcting the atmospheric distortions. Those technologies can be conventionally categorized into two classes: hardware and algorithmic technologies. Let us review them.

Hardware technologies of correction of the effect of the atmospheric turbulence in remote sensing systems

The first hardware technology of increasing of the spatial resolution of the ERS systems is based on a modification of the ERS telescope, namely, the replacement of the glass refractor telescope with a mirror reflector telescope and the increase of the diameter of the receiving aperture of the telescope D to $D>2r_0(H)$. This technology allows in the conditions of atmospheric vision and long exposure ERS image registration to reach limit resolution of 4.6 cm. The main problem of the practical implementation of this technology is the necessity of creation of the aperture synthesis multi-mirror telescope with a diameter of aperture D=7 m at H=350 km or D=10m at H=500 km, where H is the altitude of the ERS spacecraft. This ERS technology was considered in [8], which proposes an alternative possibility to reach the maximum ERS resolution for aviation altitudes H=10–20 km with a continuous aperture reflector telescope with a diameter of D = 20–4) cm, respectively.

Another hardware technology for increasing the spatial resolution of the remote sensing systems based on pre-sensor adaptive compensation of random wave tilt, caused by the influence of atmospheric turbulence. This technology proposed in [9] and explored in [10]. It makes it possible to receive an averaged short-exposure image characterized by medium short exposure optical transfer function, which is defined [7] as

$$\langle t(\vec{f})\rangle_{s\text{-}e}=t_0(\vec{f})\exp\left\{-3{,}44\left[\bar{\lambda}F\vec{f}/r_0\,(\bar{\lambda},H)\right]^{5/3}\cdot\left[1-\left(\bar{\lambda}F\vec{f}/D\right)^{1/3}\right]\right\} \quad (2)$$

In expressions (1) and (2) $\vec{f}=(\vec{\rho}_1-\vec{\rho}_2)/\bar{\lambda}F$ – spatial frequency vector in the aperture $\vec{\rho}$ of the ERS telescope, $\bar{\lambda}$ - is the average wavelength of solar illumination radiation ($\bar{\lambda}$= 0.5 μm), F - focal length of the ERS telescope, $\tau_0(\vec{f})$ - optical transfer function of the ERS telescope and $r_0(\bar{\lambda},H)$, - spatial correlation radius of atmospheric fluctuations of light at an altitude H of the ERS spacecraft, which is defined [8] as

$$r_0\,(\bar{\lambda},H) \approx \frac{H}{L}\; r_0\,(\bar{\lambda},L), \quad (3)$$

where $r_0(\bar{\lambda},L)$ = 0.1 m - is the magnitude of spatial radius of correlation of atmospheric fluctuations of light on the border of the turbulent layer L (L ≈ 10 km).

It is easy to see that at the altitude H = 350 km the value $r_0(\bar{\lambda}, H)$ is equal to 3.5 m, at H = 500 km $r_0(\bar{\lambda}, H)$ = 5 m and with H = 750 km $r_0(\bar{\lambda},H)$ is equal to 7.5 m. Thus, the value of $r_0(\bar{\lambda},H)$ is significantly larger of the diameter D = 1.1 m of the existing remote sensing telescopes [5], and atmospheric wave front distortion on the receiving aperture of the ERS telescope represent random tilts of the wavefront, compensated in the adaptive system. It is obvious that the resulting average short-exposure OPF (2) prevails over the medium and long exposure OPF (1) in the entire field of frequencies, providing a gain in resolution of the averaged short-exposure ERS image. Studies have shown that at the optimum aperture diameter D = 3.5r_0, a system with adaptive compensation of random wavefront tilts compared to a system without compensation provides a resolution gain of up to 4 times [10].

In General, hardware technology, providing theoretically good results in resolution, practically require a substantial upgrade of ERS equipment. Algorithmic technologies provide a simpler way to achieve the improvement of spatial resolution and increase the isoplanatic field of view of ERS systems.

Algorithmic correction technologies of the effect of the atmospheric turbulence in remote sensing systems

The first algorithmic technology proposed in [11] is based on receiving and processing of a series of N spectrally-filtered short exposure ERS images. Studies [12] have shown that as a result of detecting and recording a series of instant ERS images, affected by various atmospheric distortions, and their subsequent statistical processing, a secondary short exposure image is received, which has a resolution of the averaged short-exposure OTF (2) and an field of view isoplanaticy of the averaged long exposure OTF (1). In this manner the algorithmic technology helps to improve the spatial resolution while increasing the spatially invariant field of view of the ERS systems. The complexity of the practical implementation of this technology results from the need to change the process of ERS image detection and the transition from the traditional detection of medium and long exposure TDI images to the selective detection of instantaneous short exposure ERS images, independent from each other for atmospheric distortions.

Another algorithmic technology of increasing the spatial resolution of the ERS systems proposed in [13] requires no changes to the methods of detection of TDI and is based on the post-detection adaptive filtering of the registered long exposure ERS image spatially invariant to the atmospheric distortions. Studies [14] of this algorithmic technology confirmed the effectiveness of the algorithm of adaptive filtering of a long exposure image to improve its spatial resolution. The gain in resolution does not exceed 2 times, but may be sufficient to improve the spatial resolution of Russian remote sensing data (1 m) to match the level of foreign ERS systems (0.5 m).

The algorithmic technology considered above is less efficient than the new ERS algorithmic technology based on statistical processing of subimages and fragments of one short-exposure ERS image not spatially invariant to atmospheric distortions, a posteriori determining of the instant OTF of the atmosphere-telescope system for each area of isoplanaticy of the source image, their use for further spatial filtering of the relevant subimages and merging the results of filtering to restore the undistorted atmosphere time limited images of the surveyed region of the terrain. Let us review this technology

Statistical processing of subimages and their fragments of a short-exposure non-isoplanatic ERS image

When surveying areas of the Earth's surface illuminated by the sun, the distribution of intensity of spectrally filtered in the $\Delta\lambda < \Delta\lambda_A$ band short-exposure $t_E < t_A$, image of the object (an area of the Earth's surface) $I_i(\vec{l})$ if the additive noise is negligible, is determined by the following superposition integral:

$$I_i(\vec{l})=\int I_O(\vec{r})I_A(\vec{r},\vec{l})d\vec{r}, \tag{4}$$

where $I_C(\vec{r})$ is the true intensity distribution of the object, $I_A(\vec{r},\vec{l})$ is the instant impulse response of the atmosphere-telescope system (point blurring function), $\Delta\lambda_A=\lambda/\sigma_Q$, and σ_Q, is the root mean square deviation of atmospheric fluctuations of the phase Q_A of light radiation.

Due to the spatial noninvariance of the registered image, the function $I_A(\vec{r},\vec{l})$ is different for different points of the $\vec{r}$ object $_O(\vec{r})$, which does not allow applying the convolution theorem of the theory of Fourier Transforms to expression (4) and get its corresponding description in the spatial-frequency domain.

For the spatial filtering of the received nonisoplanatic images, they are broken down into N subimages, commensurate with the size of the isoplanaticy area of the atmosphere-telescope system, i.e. for N independent areas, within each of which the spatial system invariant. Then, for each j-th subimage, expression (4) can be written as convolution integral

$$I_i^j(\vec{l})=\int I_O^j(\vec{l})I_A^j(\vec{l}-\vec{r})d\vec{r}, \tag{5}$$

where j = 1, 2, ... N is the index indicating the number of a subimage and the atmospheric realization, which took part in the formation of the subimage.

Now that each subimage is spatially invariant, by converting both parts of the equation (5) by Fourier, its description in the spatial frequency domain is given by:

$$|\tilde{I}_i^j|\exp(i\tilde{\Theta}_{Im}^j)=|\tilde{I}_0^j|\exp(i\tilde{\Theta}_0^j)|\tilde{I}_A^j|\exp(i\tilde{\Theta}_A^j) \tag{6}$$

Here $|\tilde{I}_{im}^j|$ - is the spatial frequency spectrum modulus of the distorted j-th subimage, $|\tilde{I}_O^j|$ and $|\tilde{I}_A^j|$ is the modulus of the spatial spectrum of the true j-th subimage of the object and the OTF modulus of the atmosphere-telescope system of the j-th area of isoplanaticy, $\tilde{\Theta}_{Im}^j,\tilde{\Theta}_O^j,\tilde{\Theta}_A^j$ are the phases of the relevant spectra and OTF of the atmosphere-telescope system.

Subsequently, each subimage is divided into M fragments corresponding to the number of elements of resolution of the atmosphere-telescope system within the isoplanaticy field.

By analogy with (5) and (6), an expression for the i-th fragment of the j-th subimage is given by

$$I_{Im}^{ij}=I_O^{ij}*I_A^j \tag{7}$$

and its spacial spectrum by

$$|\tilde{I}_{Im}^{ij}|\exp(i\tilde{\Theta}_{Im}^{ij})=|\tilde{I}_O^{ij}|\exp(i\tilde{\Theta}_O^{ij})|\tilde{I}_A^j|\exp(i\tilde{\Theta}_A^j) \tag{8}$$

Here i = l, 2,..., M is the number of fragments in an isoplanaticy area (subimage), $|\tilde{I}_{Im}^{ij}|$ and $\tilde{\Theta}_{Im}^{ij}$ respectively are the modulus and the phase of the spatial spectrum of the -th fragment of the registered image, $|\tilde{I}_0^{ij}|$ and $\tilde{\Theta}_0^{ij}$ are the modulus and phase of the spatial spectrum of the ij-th fragment of true distribution of the object's intensity, * denotes the convolution operation, similar to (5). Further the processing of the phase and amplitude information will be performed separately.

1. Recovery of moduli of instant OTF subimages

Square modulus of the spatial spectrum of each ij-th fragment of an image is defined as

$$|\tilde{I}_{Im}^{ij}|^2=|\tilde{I}_O^{ij}|^2|\tilde{I}_A^j|^2 \tag{9}$$

Were this value by index i, i.e. find the average square of the spatial spectrum module each piece within the j subizobrazhenija also.

$$\langle|\tilde{I}_{Im}^{ij}|^2\rangle_i = \frac{1}{M}\sum_{i=1}^{M}|\tilde{I}_{Im}^{ij}|^2 = \langle|\tilde{I}_O^{ij}|^2\rangle i|\tilde{I}_A^j|^2, \quad (10)$$

where $\langle.\rangle = \frac{1}{M}\sum_{i=1}^{M}|\tilde{I}_{Im}^{ij}|^2$ denotes an averaging operation.

Now we shall average (9) over the index j, i.e. average different fragments over all the N subimages

$$\langle|\tilde{I}_{Im}^{ij}|^2\rangle_j = \frac{1}{N}\sum_{j=1}^{N}|\tilde{I}_{Im}^{ij}|^2 = \frac{1}{N}\sum_{j=1}^{N}|\tilde{I}_O^{ij}|^2|\tilde{I}_A^j|^2 = \langle|\tilde{I}_O^{ij}|^2\rangle_j\langle|\tilde{I}_A^{ij}|^2\rangle_j \quad (11)$$

Function $\langle|\tilde{I}_A^j|^2\rangle_j$ represents the average square of the OTF modulus of the atmosphere-telescope system and is in general known for the given conditions of atmospheric vision [15]. Then, by inverse filtering [16] $\langle|\tilde{I}_{Im}^{ij}|^2\rangle_j$ of the definiendum (11), we have

$$\frac{\langle|\tilde{I}_{Im}^{ij}|^2\rangle_j}{\langle|\tilde{I}_A^{ij}|^2\rangle_j} = \langle|\tilde{I}_O^{ij}|^2\rangle_j \quad (12)$$

Since the vast majority of real long objects of ERS are statistically homogeneous [17] the following equality is true

$$\langle|\tilde{I}_O^{ij}|^2\rangle_j = \langle|\tilde{I}_O^{ij}|^2\rangle_i = \langle|\tilde{I}_O^{ij}|^2\rangle. \quad (13)$$

By substituting the value received given (12) and (13) $\langle|\tilde{I}_O^{ij}|^2\rangle$ in (10), after the inverse filtering, the square modulus of the instant OTF for the j-th region of isoplanaticy (of the j-th subimage)

$$\frac{\langle|\tilde{I}_{и}^{ij}|^2\rangle i}{\langle|\tilde{I}_0^{ij}|^2\rangle} = |\tilde{I}_A^j|^2 \quad (14)$$

and by taking the square root, the modulus of the instant OTF of the atmosphere-telescope for the j-th subimage is received

$$\sqrt{|\tilde{I}_A^j|^2} = |\tilde{I}_A^j|. \quad (15)$$

2. Recovery of moduli of instant OTF subimages

Simultaneously with the modulus of the instantaneous OTF it's phase should be recovered. It is easy to see from (8) that

$$\tilde{\Theta}_{Im}^{ij} = \tilde{\Theta}_O^{ij} + \tilde{\Theta}_A^j \quad (16)$$

To obtain the phase of the instantaneous OTF it is necessary to average the phases of the fragments belonging to one subimage, i.e. over i

$$\langle\tilde{\Theta}_{Im}^{ij}\rangle_i = \frac{1}{M}\cdot\sum_{i=1}^{M}\tilde{\Theta}_{И}^{ij} = \frac{1}{M}\sum_{i=1}^{M}\tilde{\Theta}_O^{ij} + \tilde{\Theta}_A^j = \langle\tilde{\Theta}_O^{ij}\rangle_i + \tilde{\Theta}_A^j \quad (17)$$

Further, in order to resolve the (17) the average phase of an object, we shall average (16) over j, i.e. sum the phases of the fragments belonging to different subimages

$$\langle\tilde{\Theta}_{Im}^{ij}\rangle_j = \frac{1}{N}\cdot\sum_{j=1}^{N}\tilde{\Theta}_{Im}^{ij} = \frac{1}{N}\sum_{j=1}^{N}\tilde{\Theta}_O^{ij} + \frac{1}{N}\sum_{j=1}^{N}\tilde{\Theta}_A^j. \quad (18)$$

Given that $\frac{1}{N}\cdot\sum_{j=1}^{N}\tilde{\Theta}_A^j = \langle\tilde{\Theta}_A^{ij}\rangle_j \equiv 0$[18], and subtracting (18) from (17) with regard for the statistical homogeneity of the object $\frac{1}{N}\cdot\sum_{j=1}^{N}\tilde{\Theta}_O^{ij} = \frac{1}{M}\sum_{i=1}^{M}\tilde{\Theta}_O^{ij}$,received is

$$\langle\tilde{\Theta}_O^{ij}\rangle_i + \tilde{\Theta}_A^j - \langle\tilde{\Theta}_0^{ij}\rangle_j = \tilde{\Theta}_A^j. \quad (19)$$

3. Filtering of subimages and recovery of an image of a region of the Earth's surface undistorted by the atmosphere

So we have recovered the modulus (15) and the phase (19) of the instantaneous OTF of the atmosphere-telescope system for the j-th subimage. Its instantaneous OTF is synthesized as

$$\tilde{I}_A^j = |\tilde{I}_A^j|\exp(i\tilde{\Theta}_A^j) \quad (20)$$

By inverse filtering the spatial spectrum of the j-th subimage (6), we obtain the diffraction-limited spatial range of the n-th filtered subimage of the object

$$\frac{\tilde{I}_{Im}^j}{\tilde{I}_A^j} = \tilde{I}_0^j = |\tilde{I}_0^j|\exp(i\tilde{\Theta}_0^j) \quad (21)$$

by reverse Fourier transforming it an undistorted by the atmosphere diffraction-limited subimage of the j-th isoplanatic area of the surveyed Earth's surface is restored

$$F^{-1}I0j=I0j \quad (22)$$

Performing a similar treatment for all N isoplanatic regions of the registered short-exposure image (4), we reconstruct the N subimages of the form (22), and by merging them, we reconstruct the diffraction-limited image of the probed non-isoplanatic object (of section of the earth's surface) I_0.

In conclusion, note that in the case when the original recorded image turns out to be substantially distorted by additive noise of background and registration, in place of inverse filtering, it is necessary to perform linear Wiener filtering in (12), (14) and (21) [19].

Thus, the proposed algorithm for processing of one short-exposure image spatially non-invariant to atmospheric distortions solves both the problem of "vision" and the problem of "isoplatality" caused by the presence of atmospheric turbulence. The algorithm can be effectively used to reconstruct undistorted images of extended areas of the Earth's surface when solving many ERS problems.

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