IMAGE PROCESSING

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Computer correction of turbulent distortions of image of extended objects on near-Earth paths

A.P. Averin, Yu.B. Morozov, V.S. Pryanichnikov, V.V. Tyapin

***Abstract*. An algorithm of computer-based correction of images of extended objects distorted by turbulent atmosphere is developed. The method of computer correction is used to correct a distorted image of an extended object on a horizontal 2300-m-long observation path. The angular size of the corrected-image region was 15′.**

Keywords: *correction, turbulent distortions of images, adaptive optics, digital image processing.*

1. Introduction

Adaptive astronomical systems, which are aimed at compensating for the effect of atmospheric turbulence, correct star images in only a small part of the field of view: the isoplanatism zone [1]. However, even in this small angular field, there is an inhomogeneity in determining the distortions of light wavefront in the presence of only one reference point: laser star or conventional bright star in the field of view. To obtain uniform correction, one needs several reference points to determine phase distortions with a higher accuracy. Currently, the problem of expansion of the corrected field of view beyond one isoplanatism zone for large and very large modern astronomical telescopes is rather urgent [2].

For visual observation instruments that are used in horizontal near-Earth paths, the development of methods aimed at compensating for the atmosphere turbulence has some peculiarities, which impede direct application of the adaptive methods used in astronomy. These peculiarities are as follows:

(i) a weak-contrast (because of the haze) object image, which fills most of the field of view;

(ii) the absence or impossibility of forming reference points;

(iii) the application of observation instruments mainly in the daytime;

(iv) a much wider field of view.

A.P. Averin, Yu.B. Morozov, V.S. Pryanichnikov, V.V. Tyapin Federal State Unitary Enterprise 'Kos'minov State Scientific-Research Test Laser Centre (Polygon) Raduga of the Russian Federation', PO Box 771, 600910 Raduzhnyi, Vladimir region, Russia;
e-mail: anaaverin@yandex.ru, morozov@trassa.org, vitya-pr@yandex.ru, vvtyapin@yandex.ru

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In addition, turbulence is maximal near the Earth's surface, and it distorts an image over the entire observation path (in contrast to vertical or oblique astronomical paths [3]).

Under these conditions the instrumental implementation of an adaptive system with application of classical methods for compensating distortions using flexible mirrors meets serious difficulties; hence, it is important to develop alternative ways for suppressing turbulent distortions of images.

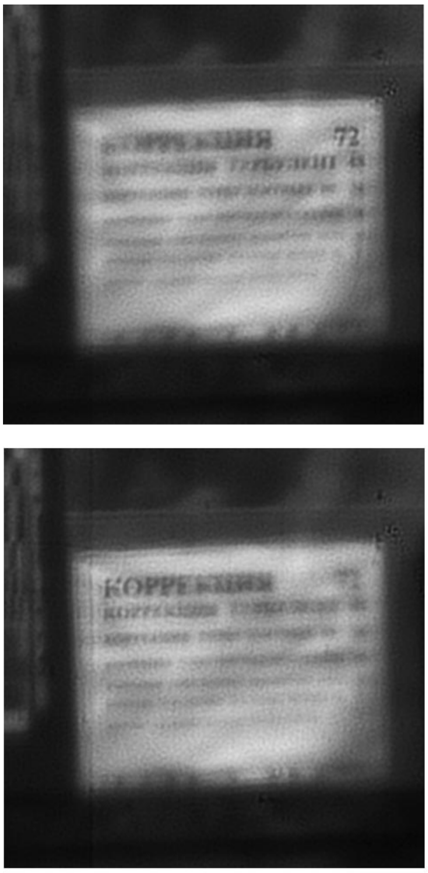
It was experimentally shown in [4] that computer correction of turbulent distortions (without applying adaptive mirrors) can significantly improve the image quality on near-Earth paths. The method used is based on the accumulation of shifted short-exposure images (shift-and-add procedure), which was proposed for the first time in [5]. A generalisation of this approach in the case of anisoplanatic distortions was presented in [6], where a sequence of frames from a digital video camera (matched with a small telescope) was recorded. The processing program was based on the model of atmospheric distortions proposed in [7], and consisted in centring frames of a vibrating image; their time averaging; and subsequent filtering, in which the calculated optical transfer function of atmosphere was used. In fact the resulting image was equivalent to an image with a long exposure time and free of atmospheric distortions. This corrected image was formed in a small fragment of the object image, whose contrast part was analysed by the program.

The purpose of this study was to significantly increase the corrected area, i.e., expand it to the entire area of video-recorded frame. Additional experimental results, obtained after improving the computer correction algorithm, are also presented.

2. Correction method

In visual observations, turbulent distortions are rapidly alternating changes in the shapes and profiles of extended objects in different parts of image. These distortions deteriorate the correction quality at the periphery of an area analysed, which is clearly demonstrated in Fig. 1. The object (A4 sheet of paper with text lines of different character size) was located at a distance of about 80 m and observed using a telescopic system with an aperture of 100 mm. The image detection (video recording) in the focal plane of the telescope was performed by an RT 1000DC video camera (Raster Technology) with a frame rate of 25 fps and exposure of 5 ms. After recording, the videos were processed according to the algorithm described in [4].

Figure 1a shows a small fragment of the image, which contains the number '72' and Fig. 1b contains a fragment with the letter 'K'. Then the entire image (with a transverse size of $\sim 1'$) was corrected. A comparison of the images shows that the correction quality drops with increasing distance from the fragment analysed. In other words, when correcting phase distortions in one image area, additional distortions are introduce into other areas.



a

b

Figure 1. Correction of turbulent image distortions for (a) the number '72' and (b) the letter 'K' in the upper line.

The natural development of this method of computer correction is the expansion of well-corrected area to the entire field of view. Generally, to this end, it is necessary to solve the hydrodynamic equation for the brightness flux in the image plane and find the field of displacement vectors of all points, as, for example, in [8, 9]. Here, this problem was solved by dividing the field of view into a large number of analysed fragments (100 – 500), whose random motion was recorded and centred independently. These fragments are squares with a side of 20 – 30 pixels, the centres of which are uniformly located in the image frame in the form of a rectangular net with a step of 10 – 30 pixels. As an example, Fig. 2 shows an area divided into six fragments. The squares bounded by dashed lines illustrate their random displacements in a current frame. The displacement is determined by calculating the correlation function of the brightness of all pixels of square in the reference (its essence will be clarified below) and current frames within some analysed area, the size of which is approximately equal to the square size, because the displacements that are really observed in

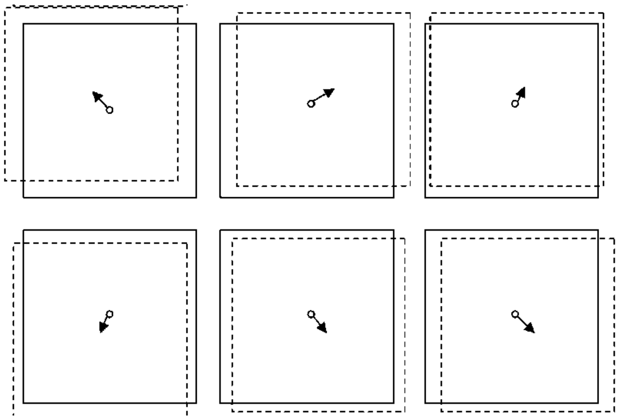


Figure 2. Image partition into analysed square fragments (bounded by solid lines). The squares bounded by dashed lines are their random displacements and the arrows are the measured displacement vectors of the central pixels of squares.

experiments do not exceed 10 – 15 pixels even in the case of strong turbulence. The position of the correlation function maximum in the analysed area for each square allows one to determine the displacement vectors of the reference points, i.e., the central pixels of squares (Fig. 2).

This procedure is followed by linear interpolation of the displacement vectors to all intermediate pixels, which are located between the reference points. As a result, a 'continuous' field of two-dimensional displacement vectors is obtained for each image point.

The next step is the inverse displacement or reduction of all image points in a current frame to the correct position, occupied by these points in the reference frame. Let the brightness distribution in the reference frame be described by the function $J_n(x,y)$. This function is formed and refined (after processing each current frame) as follows. Let us assume that $I_n(x,y)$ is the brightness distribution in the current nth frame and $rx_n(x,y)$ and $ry_n(x,y)$ are the components of the displacement vector at the point (x,y) of this frame. Then $I_n[x + rx_n(x,y), y + ry_n(x,y)]$ is the correct (unshifted) value of brightness at the point (x,y), and the brightness distribution in the reference frame is calculated via recursive averaging:

$$J_n(x,y) = (1-K)J_{n-1}(x,y) + KI_n[x + rx_n(x,y), y + ry_n(x,y)], \tag{1}$$

where $K = 0.01 - 0.05$ is the recursion coefficient. Now it is necessary to equalise all points with respect to the mean displacement. The recursive means of displacements are found:

$$\langle rx_n(x,y)\rangle = (1-K)\langle rx_{n-1}(x,y)\rangle + Krx_n(x,y), \tag{2}$$

$$\langle ry_n(x,y)\rangle = (1-K)\langle ry_{n-1}(x,y)\rangle + Kry_n(x,y), \tag{3}$$

and then the points in the reference frame are displaced by these means:

$$J_n(x,y) = J_n[x - \langle rx_n(x,y)\rangle, y - \langle ry_n(x,y)\rangle]. \tag{4}$$

After these operations the bendings of object profiles and lines are eliminated, and the image becomes almost immobile (at the aforementioned values of the recursion coefficient). Thus, the reference frame is formed from corrected frames; in fact, it is the corrected recursively averaged image.

At the next stage it is necessary to apply inverse filtration to eliminate the residual spread of the averaged image obtained, which is caused by the small-scale turbulence. For example, for one bright point this residual spread is a spot with a bell-shaped brightness distribution, the width of which depends on the turbulence intensity. The filtration consists in the transformation of this diffuse spot into a diffraction-limited Airy pattern. The image filtering and obtainment of the final result [i.e., distribution of undistorted-image brightness $J(x, y)$] are performed via a two-dimensional direct Fourier transform (operator F) of the correlated averaged image $J_n(x, y)$, multiplication of the spectrum obtained by the inverse optical transfer function $H^{-1}(x, y)$ (as in [4]), and inverse Fourier transform (operator F^{-1}):

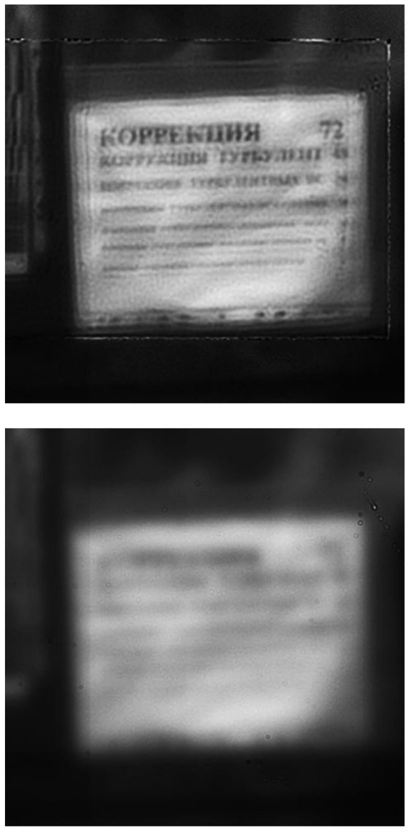
$$J(x, y) = F^{-1}[F(J_n(x, y))H^{-1}(x, y)]. \tag{5}$$

An application of this processing algorithm leads to gradual improvement of the final image $J(x, y)$ in the course of frame accumulation. On average, it is necessary to process no less than 100 successive frames.

3. Experimental results

An implementation of the above-described algorithm showed that it is quite effective and fit for work, but rather slow. The performance and operating speed of the computers used in processing are such that frames cannot be corrected on line over their entire area (1024×1024 pixels); therefore, only videos were processed. Figure 3a demonstrates the application of the algorithm to the same video as in Fig. 1. The correction area is divided into approximately 200 squares. In contrast to Fig. 1, the correction quality is the same throughout the entire area: all letters and number in the upper line can clearly be seen. To estimate the correction efficiency, Fig. 3b shows also an image that is equivalent to the image recorded with a long-term exposure and without a correction. It was obtained by simple averaging of frames with the same recursion coefficient (0.02) as upon correction. The object view will be approximately the same when observed by an eye, whose time constant is $\sim$ 40 ms. The limiting diffraction resolution of the telescope under these conditions is $\sim$ 3 mm on the object, which is approximately equal to the thickness of letters in the second line.

Figure 4 demonstrates the turbulent-image correction over the entire frame area and, therefore, in a large field of view, which is limited by the telescope resolution and the number of pixels in the video camera matrix. The resolution of the telescope used (about 1$''$) corresponds to one pixel in the image. For the given frame with a size of 800$\times$ 600 pixels the field of view is about 15$'$. The object is a metal tower 20 m high with an upper viewing platform 8 m wide; the tower is located at a distance of about 2300 m from the observation point. Figure 4a shows an image recorded with a short exposure (one frame from a video), which contains both random distortions of metalware profiles and general diffusion and fuzziness. These distortions change from frame to frame. The image in Fig. 4b is



a

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Figure 3. (a) Image correction over many fragments and (b) unprocessed averaged image.

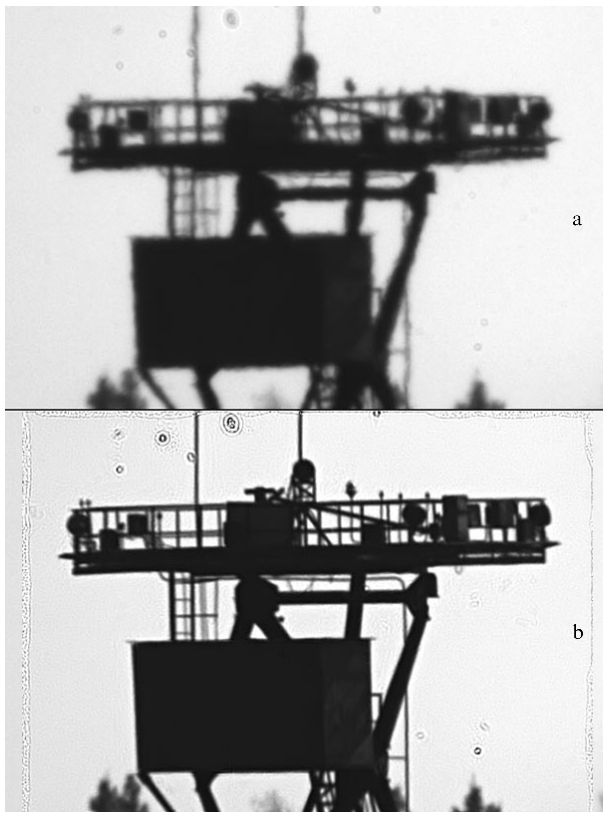
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Figure 4. Improvement of the image quality over the entire frame area in the case of multipoint correction.

the result of above-described multipoint correction after processing approximately 250 successive frames. A comparison of these images shows that in Fig. 4b the sharpness is much higher throughout the entire frame area, the image is immobile (when viewed in dynamics), and the object profiles and straight lines are not bent. Thus, the image quality is significantly improved. A further increase in the number of frames does not significantly improve the image. The large black dots against the sky background are specks of dust on the video camera matrix; the frame in Fig. 4b is the boundary of the correction area.

Note that this algorithm is efficient for only immobile objects, which is related to the operating speed of the video camera used. As was mentioned above, it is necessary to accumulate a fairly large number of frames (no less than 100) with different realisations of phase distortions in order to maximally improve the image. In principle, this can be done for $0.1-0.2$ s, because random realisations change for about 1 ms (atmosphere inertia). In this case, the images of objects moving in a frame with a small velocity can be corrected.

4. Conclusions

An algorithm of computer correction of turbulence-distorted images was developed, which made it possible to obtain images corrected over the entire frame area (for a field of view of about $15'$). This method improves the visibility of distant extended objects in atmosphere, eliminates to a great extent the turbulence effect, and increases the resolution of ground-based observation systems.

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References

1. Fried D.L. *J. Opt. Soc. Am.*, **72**, 52 (1982).
2. Tyler G.A. *J. Opt. Soc. Am.*, **1**, 409 (1994).
3. Orlov V.M., Samokhvalov I.V., Krekov G.M., et al. *Signaly i pomekhi v lazernoi lokatsii* (Signals and Interferences in Laser Location) (Moscow: Radio i svyaz', 1985).
4. Averin A.P., Pryanichnikov B.C., Tyapin V.V. *Kvantovaya Elektron.*, **40** (5), 418 (2010) [*Quantum Electron.*, **40** (5), 418 (2010)].
5. Bates R.H.T., Cady F.M. *Opt. Commun.*, **32**, 365 (1980).
6. Charnotskii M.I. *J. Opt. Soc. Am. A*, **10** (3), 492 (1993).
7. Kandidov V.P., Chesnokov C.C., Shlenov S.A. *Opt. Atmos. Okeana*, **11** (4), 401 (1998); **11** (5), 517 (1998).
8. Jahne B. *Digital Image Processing* (Berlin, New York: Springer Verlag, 2002; Moscow: Tekhnosfera, 2007).
9. Dudorov V.V., Kolosov V.V. *Opt. Atmos. Okeana*, **23** (5), 392 (2010).