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Computer correction of an image distorted by turbulent atmosphere

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Abstract. **The method for computer correction of images distorted by turbulent atmosphere is realised by means of the simplest optical system comprising a telescope and digital TV-camera. Real-time images with the diffraction resolution are obtained at ground paths of length up to 1800 m.**

Keywords: *correction of image distortion, turbulence, adaptive optics, digital processing, Fried parameter.*

1. Introduction

Presently, in addition to classical methods of adaptive optics, which employ the correction of the wave front (adaptive mirrors) [1], the methods for computer recovery of images distorted by a turbulent atmosphere are widely used. In particular, it was shown [2] that the diffraction-limited image of an object observed through a turbulent atmosphere can be obtained with relatively inexpensive aberration optical systems without using adaptive units. In this paper we use the distribution of the radiation intensity in an additional plane in order to recover the instrumental function of the 'atmospheren + telescope' system [the optical transfer function (OTF)], by virtue of which the recovered image of the object tested is obtained.

As early as the era of traditional photography the method was suggested for recovering images distorted by a turbulent atmosphere, which was based on the statistical treatment of sequential frames [3]. In this method the object was successively shot with the exposure not longer than the 'frozen time' of atmosphere. Each frame corresponded to a particular spatial distribution of the atmosphere density. Based on the fact that the changes in the wave-front inclination angle at the collective aperture cause shifts of the image centre it is possible to sum the images with their preliminary alignment. Finally we obtain the image of a higher quality.

It is obvious that recovering the high-quality image in this way in traditional photography is a rather complicated task because of the laborious treatment process and cumbersome obtaining the corrected image. In this work we solve the problem by means of a digital TV-camera combined with a long-focus objective used for shooting.

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2. Algorithm for information processing and image correction

The algorithm for data processing is based on the model of forming an object image that makes allowance for the passage of the light flux through a turbulent atmosphere [4]. It comprises three factors responsible for image distortion. These are the image jitter due to random variations in the wave-front tilt angle within the aperture limits, blurring of image details due to averaged small-scale fluctuations, and, finally, diffraction blurring due to the limited collective aperture.

Also we used the expression for the averaged OTF $H(\Omega)$ calculated for the case of short-duration exposures with the shifts excluded by image alignment [3, 5]:

$$H(\Omega) = \exp\left\{-3.44\left(\frac{\lambda\Omega}{r_0}\right)^{5/3}\left[1-\alpha\left(\frac{\Omega}{\Omega_0}\right)^{1/3}\right]\right\}. \qquad (1)$$

Here, Ω is the angular spatial frequency; λ is the wavelength; $\Omega_0 = D/\lambda$ is the optical system cut frequency of the spatial spectrum; D is the aperture diameter; r_0 is the Fried parameter. The parameter $\alpha = 1$ for the 'near-field' case (where only phase effects are substantial) and it is 0.5 for the 'far-field' case (it is appropriate when the amplitude and phase distortions are equally substantial); $\alpha = 0$ corresponds to the case of a long-duration exposure.

If this OTF is used as the inverse filter after performing the alignment then the residual small-scale blurring of the image will be corrected.

Thus, if the successive object images distorted by the turbulent atmosphere are available then one should consecutively perform the following procedures in order to recover the image: measure the random shifts, exclude them from the images (alignment), average the aligned images, estimate the Fried parameter, calculate the inverse OTF $H^{-1}(\Omega)$, filter the averaged image. The resulting stabilised image should be of the diffraction quality if the collective aperture is not too large as compared to the Fried parameter [$D \leqslant (5-7)r_0$].

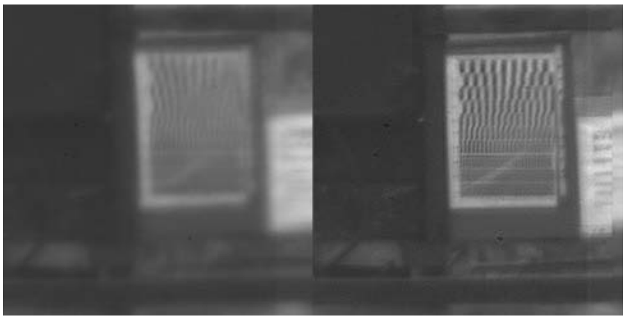
At the beginning a small area is chosen on the image (the shift analysis square) with the element of sufficiently contrast along both the coordinates. The dimension of the square (from 16 to 32 pixels) is determined by the zone of isoplanatism in atmosphere and by resolution of the optical system. In the process of correction, a current frame is compared to the reference one. Initially, the reference frame is the first one, then it is the recursively averaged aligned frame. For determining the shift of the analysing square in the current frame, the correlation between the reference and current frames is calculated in the analysing interval (approximately from -15 to $+15$ pixels along each coordinate). Then the current frame with the centre in the analysing square is aligned (for this purpose the measured shift with the opposite sign is used) and recursively averaged with the reference frame. The recursion factor can be changed in order to trace slow variations of the image. For stationary objects it is $0.01-0.04$. After correction and averaging the image is filtered with the mentioned OTF as the inverse filter [4]. The corrected image is the inverse Fourier transformation of the ratio of the average image Fourier transform to OTF. The Fried parameter included into the OTF expression is determined by iterations issuing from the best quality of the corrected image observed visually. The quality criterion is the contrast of the corrected image. The Fried parameter can also be estimated from the dispersion of frame displacements. The corrected image obtained in this way is displayed as the current frame for visual estimation and comparison. The duration of frame processing on a dual-core processor with the clock frequency of 2.3 GHz only slightly affects the frame frequency and image correction can be visually observed in real time. At faster processing it is possible to correct the image in all frame areas and then join them. In this way not only the zone of isoplanatism is corrected but the whole frame as well.

3. Experimental results

A telescope with ocular magnification was used in the experiments. Its entrance aperture was 100 mm (the MTO-1000 objective) and the focal length of the system was 9.3 m. The image was detected by the RT-1000DC programmable digital camera with the performance of 25 (or 50) frames per second and the frame of 1024×1024 (or 1024×512) pixels. The object used for determining the system resolution was the black-and-white test chart placed on a building roof at a distance of 780 m. The observing path was from 15 to 5 m above the underlying terrain. The width of vertical strips on the test chart reduces downright from 10 to 1 mm. The angular resolution of the optical system by Relay was $0.7''$, which corresponds to 2.3 pixels on matrix and 2.7 mm on the test chart. The amplitude of image fluctuations was $1-5$ pixels and at strong turbulence it was $10-15$ pixels.

In Fig. 1, the frames are shown of the film recorded in summer under fair weather. Left image is the domain measuring 512×512 pixels of a frame from the initial file (all the frames from the film are approximately of similar quality). Right image is the result of correcting this domain over 500 frames. The analysing square is at the centre of the frame. Visually the image considerably improves after several dozens of frames ($2-3$ s) since the start of the image correction program. After $100-150$ frames the image quality reaches the maximum and then does not change. No fluctuations of the recovered image are observed over the whole film.

Quality of the stabilised corrected image surpasses that of any initial frame. Resolution of the corrected image is approximately twice higher. The central part of the corrected image (in the analysing square domain) has actually the diffraction resolution. The strips 3 mm in width in the third raw from bottom are distinguished. Far from the frame centre the clearness is worse because image distortions are different in different parts of the frame. A dimension of the isoplanatism zone at such a distance can be estimated as $5-10''$, the Fried parameter is $10-20$ mm (about 1/6 of the aperture diameter).



a b

Figure 1. Image of the test chart before the computer correction (a) and after the correction (b). The correction area is 512×512 pixels.

An example of the image correction program operation is shown in Fig. 2. The registration number of a car on asphalt sun-heated road is recognised at a distance of about 1800 m in a strong air upstream. The linear resolution of the optical system at such distance was approximately 7 mm, the thickness of car registration number digits was 10 mm.

a b

Figure 2. Car registration number before correction (a) and after it (b). The correction area is 256×256 pixels.

4. Conclusions

In this work, real-time computer correction of the image distorted by a turbulent atmosphere is realised with a simplest optical scheme. The correction is performed on the basis of the statistical treatment of successive frames that are taken by the TV-camera along surface atmosphere paths of length of up to 1800 m.

It has been experimentally shown that the optical system resolution in the isoplanatism zone increases up to the diffraction limit. It has been established that this limit is reached after first $100-150$ frames have been processed.

Note that the employment of a faster camera may shorten the process duration to fractions of a second and thereby expand the correction zone to the entire field of view. This, in turn, will help the computer recovering of the image distorted by a turbulent atmosphere for not only static objects, but moving objects as well including varied illumination of the object.

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