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COMPARISON BETWEEN SINGLE-APERTURE AND MULTI-APERTURE APPROACHES TO COMPUTER CORRECTION OF IMAGES

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ABSTRACT

The effectiveness of the reconstruction of images formed by single- and multi-aperture systems and distorted by an atmospheric turbulence is analyzed in this work. Based on numerical simulation, we show that the use of multi-aperture observation systems for the computer correction of atmospheric distortions under anisoplanar conditions can significantly reduce the exposure time. Main distortions are well corrected during image synthesis for a short exposure time, which corresponds to a "frozen" turbulence. The time required for the correction of residual small-scale distortions is an order of magnitude shorter than in the case of synthesis of long-exposure images with the use of traditional single-aperture observation systems.

1. INTRODUCTION

Methods for post-detection (computer) correction of images are often used in observations of distant objects through the atmosphere. One of the most effective approaches to computer correction is based on the solution of the inverse problem of retrieval of the structure of an object from its blurred image [1, 2]. For the correct solution of the inverse problem (deconvolution) under conditions of strong turbulence, the accumulation of images is commonly used [2–5]. A disadvantage of this approach to the formation of isoplanar distorted images is impossibility of analyzing dynamically changing scenes of observation.

An alternative to the long-exposure method for the formation of isoplanar distorted images is an approach based on the division of the receiving aperture [1, 7–8]. This approach can be implemented in multi-aperture systems when several identical subimages are simultaneously recorded: the number of subimages is determined by the number of receiving subapertures. To solve the inverse problem in this case, an image is synthesized as the sum (superposition) of simultaneously recorded subimages. In addition to averaging the inhomogeneity of short-exposure distortions, which is required for correct solution of the inverse problem, this approach allows compensation of local (within each subaperture) tilts of the wavefront arrived from an object and distorted by turbulent air inhomogeneities.

In this work, we compare the effectiveness of the reconstruction of turbulence-distorted images when using single-aperture and multi-aperture observation systems.

2. LONG-EXPOSURE IMAGING BASED ON SINGLE-APERTURE APPROACH

If an object is observed through the atmosphere along horizontal paths, short-exposure images formed during a time substantially shorter than the time of correlation of turbulent air inhomogeneities are characterized by strongly anisoplanar distortions, which is a significant obstacle in computer reconstruction of images using deconvolution algorithms. In the case of long exposure, anisoplanar distortions are averaged for a time much longer than the time of correlation of turbulent air inhomogeneities, which results in uniform blurring of the entire image. Although the width of the long-exposure point spread function (PSF) in this case is larger than the effective width of the short-exposure PSF, the isoplanatism of a long-exposure image allows the deconvolution to be performed the most accurately.

Figure 1 shows how the quality of an image synthesized by a single-aperture system depends on the exposure time, which was determined in our numerical experiment by the number of realizations of turbulent air inhomogeneities over which short-exposure images were averaged. It is seen that the anisoplanar distortions are averaged as the number of pseudo-random realizations of a "frozen" turbulent medium increases. The sum of five non-correlated short-exposure images already allows much better identification of an object than any short-exposure realization. An increase in the number of realizations of turbulence to 100 during long-exposure imaging allows us to speak about almost isoplanar distortions even under sufficiently strong turbulence along an observation path. It should be noted that an increase in the receiving aperture increases the rate of averaging of anisoplanar distortions.

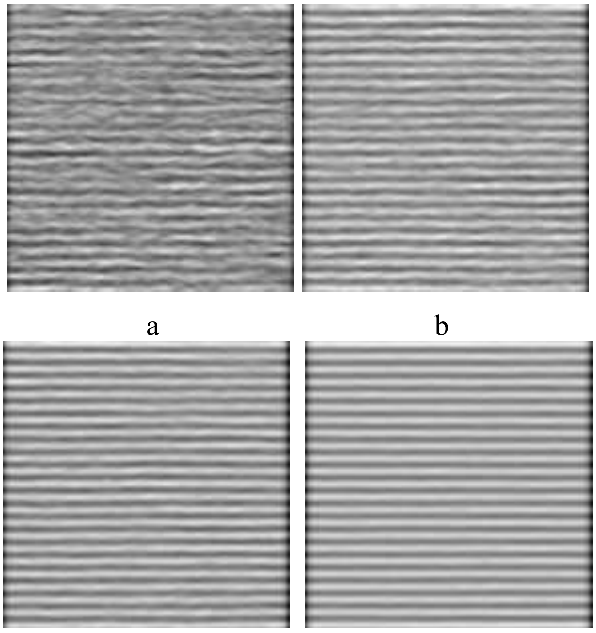

Figure 1. Effect of the exposure time on image parameters in anisoplanar turbulence. The observation range $z = 0.05ka_t^2$; $D/r_0 = 9.6$, where $D = 2a_t$. $N_{pix} = 512$; averaging over (a) 1, (b) 5, (c) 20, and (d) 100 realizations of short-exposure images.

The operation of reconstruction of the object structure from its image based on fast Fourier transform *FT*, used in the numerical simulation, is written as

$$I_{obj}^{rec}(\mathbf{r}) = FT^{-1}\left[\frac{FT\left[I_{im}(\mathbf{r})\right]}{FT\left[PSF(\mathbf{r})\right]}\right], \quad (1)$$

where $I_{im}(\mathbf{r})$ is the distorted image and *PSF* is a selected point spread function.

Figure 2 shows that the reconstruction of a short-exposure image by means of deconvolution increases the image contrast, but almost does not improve the object identification. As the exposure time increases (the number of pseudo-random short-exposure images), the inhomogeneity of distortions decreases. In addition to the object contrast, a possibility of object identification (resolution) significantly enhances.

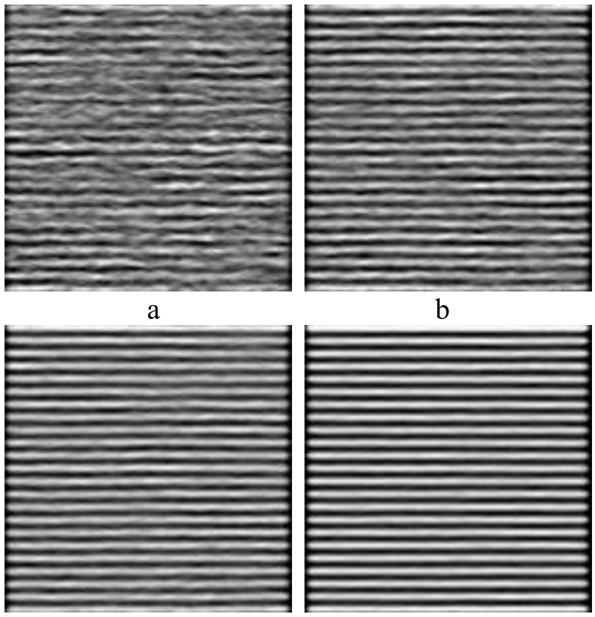

Figure 2. Effect of the exposure time on the efficiency of reconstruction of the object structure in anisoplanar turbulence. The conditions are similar to those in Fig. 1.

3. LONG-EXPOSURE IMAGING BASED ON MULTI-APERTURE APPROACH

Traditional systems with a single focusing lens (system of lenses along the optical axis) form a single image of an object observed on a CCD array. A multi-aperture system, considered in this work, forms a number of images, where their number is determined by the number of receiving subapertures. By analogy with corrected long-exposure images, an image synthesized by this system is understood as a sum (superposition) of the subimages with corrected random turbulent shifts.

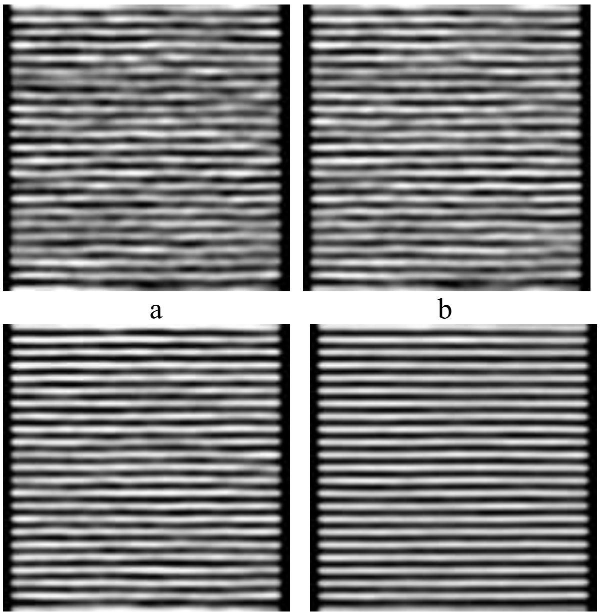

Figure 3. Reconstructed image of a periodic harmonic object in the case of an array of 64 subapertures for the number of short-exposure realizations N_{SE} = 1 (a), 2 (b), 5 (c), and 20 (d) used for the image synthesis.

It can be seen from Fig. 3 that the deconvolution method allows much better identification of an object even with the use of a short-exposure image synthesized in the multi-aperture system than in the case of a single-aperture system. When averaging the image synthesized over several short exposures, the quality of the image reconstructed noticeably improves. An increase in the number of short-exposure images synthesized in the multi-aperture system up to 10–20 can significantly improve the quality of correction.

4. RESULTS AND DISCUSSION

The quality of a reconstructed image of a single-aperture observation system synthesized of long-exposure images noticeably improves when the number of short exposures N_{SE} > 100. A significant decrease in the number of short-exposure images when using multi-aperture observation systems (see Fig. 3) can be explained by the fact that the strongest large-scale distortions can be corrected by superposition of subimages for each short exposure in this case. And accumulation of short exposures allows one to get rid of residual small-scale distortions.

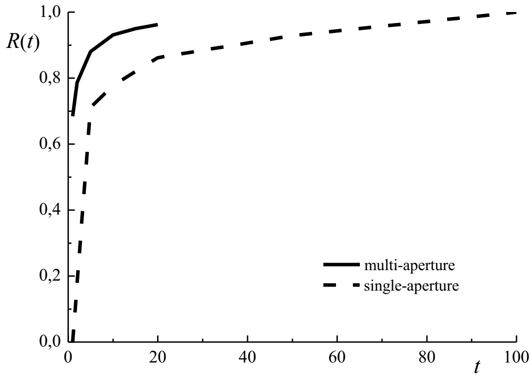

Figure 4. The coefficient of correlation between reconstructed and non-distorted images as a function of the number of short-exposure frames for multi- and single-aperture systems.

Thus, we can conclude that the use of multi-aperture observation systems for computer correction of atmospheric distortions in an anisoplanar turbulence can significantly reduce the exposure time (accumulation of short-exposure images) when synthesizing isoplanar distorted images. Main distortions are well corrected when synthesizing images for a short exposure time, which corresponds to a “frozen” turbulent medium. The time required for the correction of residual small-scale distortions is an order of magnitude shorter than in the case of synthesizing long-exposure images using a single-aperture observation system.

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REFERENCES

[1] Invanov, M. and McGaughey, D., “Image reconstruction by aperture diversity blind deconvolution,” Proc of the AMOS Technical Conference, E78 (2007).

[2] Huebner, C. S. and Greco, M., “Blind deconvolution algorithms for the restoration of atmospherically degraded imagery: a comparative analysis,” Proc. SPIE 7108, 71080M-1-12 (2008).

[3] Schulz, T., “Multiframe blind deconvolution of astronomical images,” J. Opt. Soc. Am. A 10(5), 1064–1073 (1993).

[4] Averin, A. P., Morozov, Yu. B., Pryanichnikov, V. S. and Tyapin, V. V., "Computer correction of turbulent distortions of image of extended objects on near-Earth paths," Quant. Electron. 41(5), 475–478 (2011).

[5] Zhu, X. and Milanfar, P., "Image reconstruction from videos distorted by atmospheric turbulence," Proc. SPIE 7543, 75430S-1-8 (2010).

[6] Hope, D. A., Jefferies, S. M., Hart, M. and Nagy, J. G., "High-resolution speckle imaging through strong atmospheric turbulence," Opt Express 24(11), 12116-12129 (2016).

[7] Dudorov, V. V. and Eremina, A. S., "Digital compensation of turbulent distortions of incoherent optical images using multiaperture systems," Opt. Atmos. Okeana 31 (02), 95–102 (2018) [in Russian].

[8] Dudorov, V. V. and Eremina, A. S., "Computer correction of turbulent distortions of incoherent optical images using multi-aperture systems," Proc. SPIE 10787, 107870E -1-9 (2018).