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Method for obtaining diffraction-limited incoherent images of objects observed through a turbulent atmosphere

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Abstract. **A new approach is developed for obtaining diffraction-quality incoherent images of objects observed through a distorting optical medium. In particular, a method is proposed for achieving the diffraction limit for resolving power, including the case of objects observed through a turbulent atmosphere, using comparatively cheap aberrational optical systems (including systems with composite apertures) without using any auxiliary adaptive devices. It is shown that the instrumental function of the atmosphere + telescope system can be reconstructed with the help of the radiation intensity distribution in an auxiliary plane, and then used for obtaining a diffraction-limited image of the observed remote object. Numerical simulation demonstrates the application of this method for identifying various objects by observing them through a turbulent atmosphere.**

Keywords: *diffraction-limited image, turbulent atmosphere, instrumental function, phase recovery.*

1. Introduction

At present, detection and identification of artificial extraterrestrial objects located at a distance of 300 – 40000 km from the Earth's surface is one of the topical problems. The problem of obtaining detailed information about natural space objects like planets in the solar system, stars, remote galaxies also remains quite important. Investigations of these problems require telescopes working in the optical wavelength range with the angular resolution better than 0.02″ [1]. With such instruments, objects of size smaller than 10 cm could be discerned in detail at a distance of 1000 km. Note that such a high angular resolution can be achieved by using the receiving aperture exceeding 10 m. The development of telescopes with such a large aperture involves considerable difficulties. One of these is the problem of manufacturing large-size optical elements with a high optical quality. Apart from the high cost of fabrication (proportional to the cube of the aperture diameter), such elements will possess weight characteristics leading to uncontrollable deformations and to inadmissibly high loads on the rotary support. Various approaches proposed by researchers to overcome these difficulties by going over to composite apertures of various types are encountered with problems of the adjustment and phasing of these apertures for obtaining a single high-quality optical surface.

At the same time, ground-based telescopes operate in the terrestrial layer of turbulent atmosphere. As a result, the real angular resolution does not exceed 0.5″ – 1.0″. The use of adaptive optics [2] for overcoming this difficulty leads to a considerable increase in the cost of the system as a whole, and also does not provide any indication about the effective operation of the adaptive system for obtaining images of objects with a complex configuration.

The experience of foreign scientists who created in recent years telescopes with composite apertures ~ 10 m and adaptive systems (KeckI and KeckII, SUBARU, HET, GEMINI, etc.) shows that apart from being quite costly ($\sim 100 - 200$ million US dollars), these devices are quite complex and unreliable, and do not possess the predicted values of the observational parameters. The projects (SALT, ELT, OWL) for developing telescopes with apertures exceeding 10 m being discussed abroad have an estimated cost of up to 1 billion US dollars, and hence the realisation of such projects requires wide international cooperation [3].

Thus, considerable progress in developing observational instruments with the required angular resolution in the presence of a terrestrial atmospheric layer can be made only by using a basically new approach for obtaining a diffraction-quality image through the turbulent atmosphere with the help of relatively inexpensive aberrational optical systems (including systems with composite apertures) without resorting to any auxiliary adaptive devices.

We show in this paper that such an approach can be used for obtaining an incoherent image with the help of a reconstructed instrumental function of the atmosphere + telescope system. By incoherent image we mean the image of real incoherent sources or image of real sources illuminated by quasi-monochromatic (including laser) radiation with a small coherence length (much smaller than the size of the object being exposed). A common feature in these situations is that radiation propagating in free space does not form interference patterns that could be detected by instruments.

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Significantly, the instrumental function is reconstructed only for radiation intensity distributions that exist or can be recorded at the instant of observation of the object of interest.

The idea behind the method is based on the fact that the intensity distribution of the incoherent image observed in the receiving plane is a convolution of the intensity of the real image with the instrumental function of the atmosphere + telescope system. The latter is just the distribution in this plane of the intensity of a plane wave passing through the atmosphere + telescope system. Obviously, if we know this distribution, the desired image of the object can be obtained by applying double Fourier transform to the initial convolution and dividing it by the result of Fourier transform of the instrumental function after the first transformation (see, for example, the Labeyrie method [4]).

In the case of incoherent radiation, the intensity distributions at the input and output of the spatially homogeneous optical system are connected by the relation

$$I_{\rm im}(\boldsymbol{y}) = \int_{-\infty}^{\infty} \left|h(\boldsymbol{y}-\boldsymbol{x})^2\right| I_{\rm ob}(\boldsymbol{x})\mathrm{d}\boldsymbol{x}, \quad (1)$$

where $I_{\rm ob}(\boldsymbol{x})$ and $I_{\rm im}(\boldsymbol{y})$ are the intensity distributions in the object and image planes, respectively; $h(\boldsymbol{x})$ is the field (response) of a point source in the output plane of the optical path, which is called the coherent instrumental function in optics; $|h(\boldsymbol{x})|^2$ is the scattering function of the point, also called the incoherent instrumental function of the optical path; and $\boldsymbol{x}$ and $\boldsymbol{y}$ are two-dimensional vectors. In actual practice, the instrumental function varies with time, as a rule, and hence the concept of 'freezing time' of the optical path (for example, of the turbulent atmosphere) is introduced. Therefore, a distinction is made between short and long exposures, i.e., short and long 'freezing times' respectively, upon obtaining images of objects. The images with short and long exposures, obtained with the help of quite large apertures, may differ considerably as regards the information contained in them about the object being observed.

If the exposure time does not exceed the 'freezing time' of the instrumental function, the application of Fourier transform F to expression (1) leads to the relation

$$I_{\rm im}(\boldsymbol{\theta}) = H(\boldsymbol{\theta}) I_{\rm ob}(\boldsymbol{\theta}), \quad (2)$$

where $I_{\rm ob}(\boldsymbol{\theta})$ and $I_{\rm im}(\boldsymbol{\theta})$ are the spatial spectra of the object and the image, respectively; $H(\boldsymbol{\theta})$ is the transfer function of the optical system; and $\boldsymbol{\theta}$ is a two-dimensional vector. The function $H(\boldsymbol{\theta})$ contains all the frequencies that can pass through the optical system, up to the frequency determined by the diffraction limit. Therefore, having determined $I_{\rm ob}(\boldsymbol{\theta})$ from (2) and applying the inverse Fourier transform to it, we obtain

$$I_{\rm ob}(\boldsymbol{x}) = \mathrm{F}^{-1}\left[\frac{I_{\rm im}(\boldsymbol{\theta})}{H(\boldsymbol{\theta})}\right], \quad (3)$$

i.e., the diffraction-limited image of the object.

The fundamental problem underlying this method is the derivation of $h(\boldsymbol{x})$ from the information about radiation intensity distributions that are available at the instant of observation of the object. In fact, this is a problem of obtaining the field distribution for a point source by observing an arbitrary object.

It will be shown below that when remote objects of an arbitrary shape are observed through an optically inhomogeneous medium using quite monochromatic radiation (of spectral width $0.1-100$ cm^{-1}), the transverse distribution of the radiation intensity at certain distances behind the receiving lens is independent of the structure of the object and is essentially determined only by the phase inhomogeneities of the medium. Significantly, this distribution virtually coincides with the distribution obtained from the field of a point source passing through these inhomogeneities. This circumstance leads to the assumption that by recording the intensity distribution in a plane where the structure of the object being observed is not yet manifested (this distribution virtually coincides with the radiation intensity distribution for a point source), we can calculate the image of this source in the focal plane of the lens, i.e., reconstruct the instrumental function for the atmosphere + telescope system.

In the Gerchberg–Saxton method [5], which is analogous to this procedure (reconstruction of the desired phase for calculating the field in the required plane), the experimental intensity distributions recorded in the image plane of the object and in the plane of its Fourier transform are used for reconstructing the field phase information.

To separate the information about the instrumental function for the atmosphere + telescope system from the information about the object, it seems more reasonable to reconstruct the phase information by using not the Fourier transform, but the Fresnel transform which is more general for optical systems. This provides the necessary freedom in the choice of planes in which the intensity distribution can be used for reconstructing the instrumental function. The only constraint imposed on these planes is that the structure of the object being observed should not be manifested yet in the intensity distribution in these planes.

Note that such a freedom of choice in Fresnel transform (which is essentially its own convolution) is due to the fact that all the operations are carried out in the conventional coordinate space (unlike, say, in Fourier transform which connects the image with its spatial spectrum, thus fixing rigidly the planes in the optical system in which the intensity distribution must be recorded).

For a practical realisation of this method, it may be sufficient to introduce just one additional recording plane at a distance from the receiving lens equal to about one-tenth of its focal length. The input aperture with a uniform intensity distribution from a remote object for incoherent radiation will serve as the second plane in this case. Figure 1 shows the possible scheme for observing objects using this method.

2. Substantiation of the method

Let us substantiate in greater details the statements forming the basis of the above method by considering the example of an object in the form of two incoherent point sources and a phase screen serving as the distorting medium.

For the field of an object consisting of two incoherent point sources in the plane X, the following expression is valid for the mutual coherence function [6]:

$$\Gamma(\boldsymbol{x}', \boldsymbol{x}) = [I_1\delta(\boldsymbol{x}-\boldsymbol{x}_1) + I_2\delta(\boldsymbol{x}-\boldsymbol{x}_2)]\delta(\boldsymbol{x}'-\boldsymbol{x})], \quad (4)$$

where $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ are two-dimensional radius vectors of point sources in this plane, and I_1 and I_2 are their

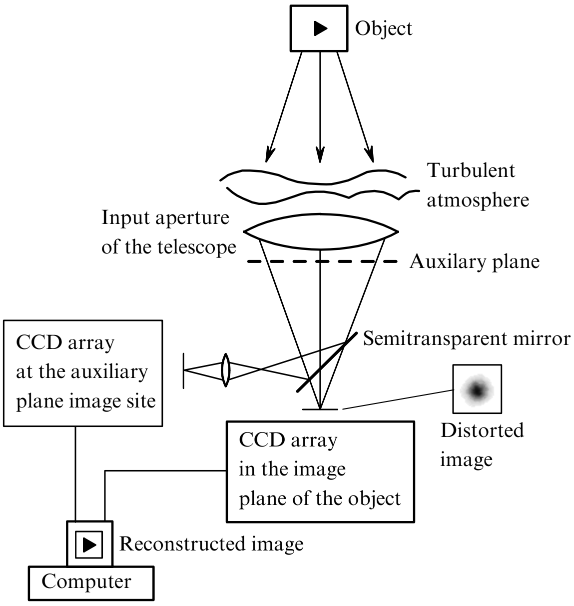

Figure 1. Scheme of the system for observing objects with the instrumental function reconstruction from the intensity distribution in an auxiliary plane.

intensities. In the plane Y parallel to the plane X and separated from it by a distance z, the mutual coherence function will have the following form (in order to simplify the expressions, we put $I_1 = I_2 = I_0$):

$$\Gamma(\boldsymbol{y}', \boldsymbol{y}'') = \frac{2I_0}{(4\pi)^2} \times \left[\frac{1}{|\boldsymbol{r}_1 - \boldsymbol{x}_1||\boldsymbol{r}_2 - \boldsymbol{x}_1|} + \frac{1}{|\boldsymbol{r}_1 - \boldsymbol{x}_2||\boldsymbol{r}_2 - \boldsymbol{x}_2|} \right], \tag{5}$$

where $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are three-dimensional radius vectors of the observation points $\boldsymbol{y}'$ and $\boldsymbol{y}''$.

The average field intensity $I(\boldsymbol{y})$ is connected with the mutual coherence function $\Gamma(\boldsymbol{y}', \boldsymbol{y})$ through the expression

$$I(\boldsymbol{y}) = \Gamma(\boldsymbol{y}, \boldsymbol{y}), \tag{6}$$

and hence the dependence of the average intensity on transverse coordinates is determined by a factor of the type $1/r_i^2$, where $r_i^2 = (\boldsymbol{y} - \boldsymbol{x}_i)^2 + z^2$. Note that $|\boldsymbol{y} - \boldsymbol{x}_i|/z$ are the angles at which the two point objects are seen, and $\max(y/z)$ is the angle at which the receiving aperture is seen. In the cases of interest (observation of remote objects), both these quantities are much smaller than unity and hence the distribution of the average intensity in front of the phase screen in the receiving lens aperture is almost independent of the transverse coordinates ($r_i^2 = z^2\{1 + [(\boldsymbol{y} - \boldsymbol{x}_i)z^{-1}]^2\} \approx z^2$) and will be the same as from the point source, i.e., uniform.

Apparently, the field phase variations as a result of passage through the phase screen and the lens do not change the intensity distribution in the plane right behind the lens. Hence we go over to an analysis of the mutual coherence function in the last segment of the optical path, i.e., the segment of free diffraction from the plane of the receiving lens to the image plane.

The field transformation $u(\boldsymbol{y})$ by the phase screen is described by the product of the complex field amplitude and the function $\exp[\mathrm{i}S(\boldsymbol{y})]$, where $S(\boldsymbol{y})$ is a real random function since the screen modulates only the phase while the amplitude remains unchanged.

For statistically uniform phase fluctuations $S(\boldsymbol{y})$ with the zero mean value ($\langle S \rangle = 0$), dispersion σ_S^2 and normal probability distribution law, the following formula holds for the mean field behind the screen (for the incident field normalised to unity):

$$\langle u \rangle = \langle \exp(\mathrm{i}S) \rangle = \exp\left(-\frac{\sigma_S^2}{2}\right), \tag{7}$$

while the coherence function is defined as

$$\Gamma(\Delta\boldsymbol{y}) = \langle u(\boldsymbol{y}')u(\boldsymbol{y}'') \rangle = \langle \exp\{\mathrm{i}[S(\boldsymbol{y}') - S(\boldsymbol{y}'')]\} \rangle$$

$$= \exp\{-0.5\langle [S(\boldsymbol{y}') - S(\boldsymbol{y}'')]^2 \rangle\}, \tag{8}$$

where $\Delta\boldsymbol{y} = \boldsymbol{y}' - \boldsymbol{y}''$.

For $\langle S \rangle = 0$, however, the mean square phase difference is the structural phase function $D_S(\Delta\boldsymbol{y})$ connected with the correlation phase function $\psi_S(\Delta\boldsymbol{y})$ through the relation $D_S(\Delta\boldsymbol{y}) = 2[\psi_S(0) - \psi_S(\Delta\boldsymbol{y})]$. Hence we obtain the following expression for the coherence function

$$\Gamma(\Delta\boldsymbol{y}) = \exp[-D_S(\Delta\boldsymbol{y})] = \exp[\psi_S(\Delta\boldsymbol{y}) - \psi_S(0)]$$

$$= \exp\{\sigma_S^2[K_S(\Delta\boldsymbol{y}) - 1]\}, \tag{9}$$

where K_S is the field phase correlation function, while for the transverse field correlation function we obtain the relation

$$\psi_\perp(\Delta\boldsymbol{y}) = \exp\{\sigma_S^2[K_S(\Delta\boldsymbol{y}) - 1]\} - \exp\left(-\frac{\sigma_S^2}{2}\right). \tag{10}$$

From the point of view of image reconstruction analysis, the most interesting case is that of strong distortions, i.e., large phase dispersions ($\sigma_S^2 \gg 1$). In this case, the mean field $\exp(-\sigma_S^2/2)$ is negligibly small compared to unity, while the quantity $\exp\{\sigma_S^2[K_S(\Delta\boldsymbol{y}) - 1]\}$ differs significantly from zero only for small $\Delta\boldsymbol{y}$. In view of these statements, it can be shown [7] that the field correlation length $r_\perp$ is connected with the phase correlation length $r_S \approx |K_S''(0)|^{-1/2}$ through the relation

$$r_\perp \approx \frac{r_S}{\sigma_S} \quad (\sigma_S^2 \gg 1). \tag{11}$$

Thus, for $\sigma_S^2 \gg 1$, the field correlation length is σ_S times smaller than the phase correlation length r_S.

It can be assumed naturally that for field propagation behind the lens, intensity fluctuations connected with interference of the parts of the wave front of the field passing through different inhomogeneities in the phase screen must be observed.

The intensity fluctuations $\tilde{I}$ are described by their correlation function

$$\psi_I(\Delta\boldsymbol{y}, z) = \langle \tilde{I}(\boldsymbol{y}', z)\tilde{I}(\boldsymbol{y}'', z) \rangle = \langle I(\boldsymbol{y}', z)I(\boldsymbol{y}'', z) \rangle - \bar{I}^2 \tag{12}$$

($\bar{I}$ is the aperture-averaged intensity) and by the so-called scintillation index

$$\beta(z) = \frac{\langle I^2(z)\rangle - \bar{I}^2(z)}{\bar{I}^2} = \frac{\sigma_I^2}{\bar{I}^2} \quad (13)$$

characterising the relative intensity fluctuations.

An analysis of intensity fluctuations behind a random phase screen shows [7] that the peak of the scintillation index is observed at a distance

$$z_{\rm m} = \frac{kr_S^2}{\sigma_S} \quad (14)$$

from the screen, k being the wave number. The following simple geometrical interpretation can be offered to explain formula (14) as well as the very emergence of the peaks: intensity fluctuations are the strongest at places where the waves are focused behind the phase screen. Indeed, in the geometrical optics approximation, focusing occurs at a distance $z_{\rm m} \sim 1/v$ from the phase screen, where v is the curvature of the phase front. The order-of-magnitude estimate of v is $\sim k^{-1}\partial^2 S/\partial y^2$ and $\partial^2 S/\partial y^2 \sim \sigma_S/r_S^2$. Consequently, $z_{\rm m} \sim 1/v \sim kr_S^2/\sigma_S$, which coincides with formula (14). Obviously, the higher the phase dispersion, the closer the focusing zone to the screen. The consequences of the presence of a receiving (positive) lens of focal length F behind the phase screen are also obvious: the additional variation of the phase front curvature leads to a displacement of the focusing zone $z_{\rm m}$ in accordance with the formula

$$\frac{1}{z'_{\rm m}} = \frac{1}{z_{\rm m}} + \frac{1}{F} \quad (15)$$

from which it naturally follows that the maximum intensity fluctuations corresponding to the observed remote point source in the absence of turbulent distortions ($z_{\rm m} = \infty$) will be observed in the focal plane of the lens, i.e., in the image plane of this source. On the other hand, formula (15) shows that the presence of such distortions may displace the plane of maximum intensity fluctuations only towards the lens, while the very parameters of these fluctuations are determined by the characteristics of atmospheric distortions. This leads to the conclusion that if the difference $F - z'_{\rm m}$ is larger than the focal depth of the receiving lens (length of the focal waist), the instrumental function may be separated from the image of the object.

If we take into account the fact that the turbulent atmosphere is an extended randomly inhomogeneous medium rather than a phase screen, we will not obtain a uniform intensity distribution of the input radiation, including that for incoherent quasi-monochromatic light. However, even in this case the intensity distribution for a point source and for two incoherent point sources will also be close in some planes behind the receiving lens and in this case also we can use these distributions to reconstruct the instrumental function.

Moreover, for reconstruction of the instrumental function of the atmosphere + telescope system, it is sufficient to put the radiation intensity at the telescope inlet equal to a constant and consider only the fixing of the additional intensity distribution in just one auxiliary plane in this case also. This can be explained by the well-known fact that amplitude fluctuations, which are connected with the real extent of the atmosphere, have a much weaker effect on the interference pattern than the phase distortions [7].

3. Algorithm for reconstructing instrumental function and for image formation

The statements presented above were verified by computer simulation. The phase shifts corresponding to the fluctuations of the atmospheric refractive index or to the aberrations of the composite receiving aperture were taken into account by multiplying the field with a function of the type $\exp[iS(\boldsymbol{y})]$. The modulating phase function of the composite receiving aperture was defined in the form of a random shift and slope of the subapertures.

The algorithm used for realising the method proposed here can be divided into a number of stages. At the first stage, we calculated the intensity distribution $I_{\rm im}(\boldsymbol{x})$ for the incoherent image of the object being observed in the focal plane $z = F$ of the lens and the corresponding intensity distribution $I_0(\boldsymbol{x})$ in a certain auxiliary plane $z_0 = \mu F$ $(0 < \mu < 1)$. The incoherent radiation pattern was obtained by averaging the field intensity distributions derived from calculations of the diffraction from the observed object on which a random fine-mesh phase mask was applied. Averaging was carried out over an ensemble of phase masks having a volume of up to 1000 realisations. For an object in the form of two point sources, this procedure boils down to the assignment of a random phase to the field of one of the sources.

At the second stage, the instrumental function of the optical path was reconstructed by using an iterative algorithm whose cycle consisted of the following steps. In the first step of the cycle, an amplitude $[I_0(\boldsymbol{x})]^{1/2}$ was assigned to the field amplitude $u_0(\boldsymbol{x})$ in the auxiliary plane, while the phase was conjugated $[u_0(\boldsymbol{x}) \to u_0^*(\boldsymbol{x})]$ (the phase was equated to zero in the first iteration). In the second step, the Fresnel transform ${\rm Fr}[u_0^*(\boldsymbol{x}), z_0]$ corresponding to the distance from the receiving lens to the auxiliary plane z_0 was calculated. In the third step, the phase of the obtained field $u(\boldsymbol{x})$ was conjugated $[u(\boldsymbol{x}) \to u^*(\boldsymbol{x})]$, and the amplitude was put equal to a constant. In the fourth step, the Fresnel transform ${\rm Fr}[u_0^*(\boldsymbol{x}), z_0]$ corresponding to the distance z_0 was calculated and the amplitude of the obtained field was compared with the amplitude $[I_0(\boldsymbol{x})]^{1/2}$. For an unacceptable mismatching, the whole cycle was repeated from the beginning. After completion of the iterative process (attainment of the desired precision in matching between $|u_0(\boldsymbol{x})|$ and $[I_0(\boldsymbol{x})]^{1/2}$, the field $u_0(\boldsymbol{x})$ in the auxiliary plane was recalculated to the plane of the lens and then to the focal plane, where the instrumental function $h(\boldsymbol{x})$ was obtained.

At the third stage, formulas (2) and (3) were used to calculate the intensity distribution $I_{\rm ob}(\boldsymbol{x})$ of the object under observation.

4. Results of numerical simulation

Simulation was carried out for objects with an angular size comprising of 2 to 12.5 diffraction resolution limits of the lens. The phase distortions were chosen in such a way that the blurring of the object image was equal to 20–30 diffraction diameters. Numerical simulation was carried out on a Pentium-4 PC (2.4 GHz, 512 megabyte memory) for a computational mesh of size 1024×1024 using a software packet developed in the C-Builder medium. The number of iterations required was between 40 and 200 in a period of 1 – 5 min.

Figure 2 shows the superimposed intensity distributions for one and two stars at a distance from the objective equal to 0.005, 0.025 and 0.05 of the focal length F. One can see from these distributions that they almost coincide in the vicinity of the objective, and retain a closeness in their shape for a long time upon an increase in the distance from the objective. This means that the field pattern in these planes is determined almost entirely by phase inhomogeneities and not by the structure of the object.

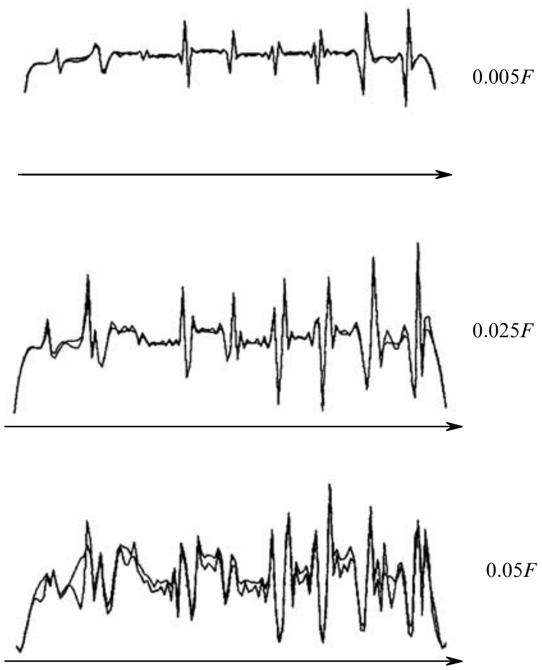

Figure 2. Radiation intensity distribution from one and two point sources (phase screen model) at various distances from the object.

The intensity distributions for one and two stars obtained by simulating the atmosphere by a spatially distributed medium with alternating layers of free space and phase screens are also found to be close in shape (Fig. 3).

Simulation of the image reconstruction was carried out for three stars and an extended T-shaped object.

Figure 4 shows the images of three stars in the focal plane of the receiving objective with and without turbulent distortions, as well as the image of a star for the same atmospheric pattern as the one obtained above by iteration. One can see that atmospheric turbulence does not allow a three point sources to be distinguished without image processing. However, a high-quality picture of the initial object was obtained after image processing using the technique described above (Fig. 4d).

Analogous results were obtained for a T-shaped object (Fig. 5) using, among other things, a composite receiving optical system formed by nine subapertures (Figs 5, 6). The angular misalignment of the subapertures was equal to five diffraction angles, while the dephasing was found to exceed the radiation wavelength.

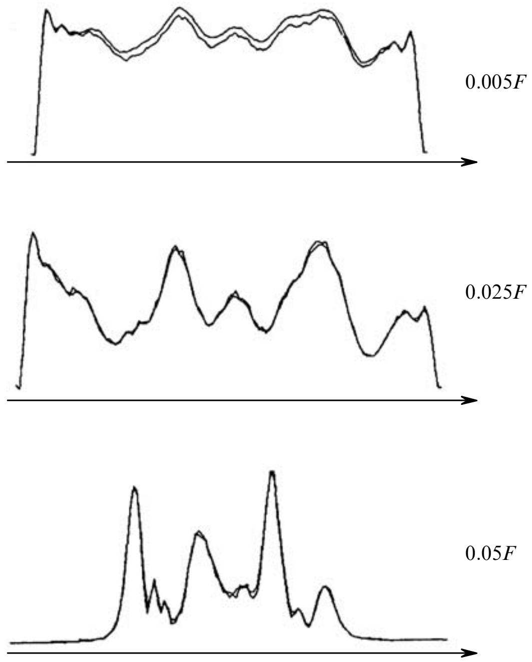

Figure 3. Radiation intensity distribution from one and two point sources (model of extended spatially distributed inhomogeneous medium) at various distances from the object.

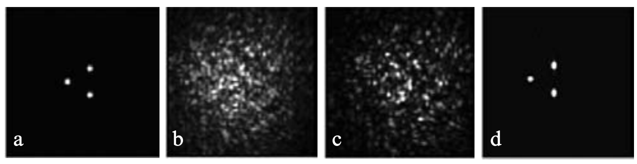

Figure 4. Image reconstruction for three stars: (a) initial object; (b) distorted image of the object; (c) image of a single star; and (d) reconstructed image of the object

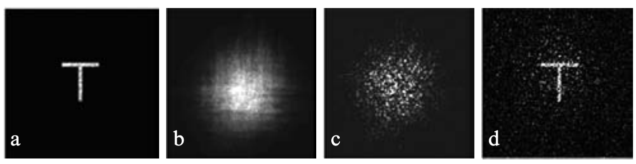

Figure 5. Reconstructed image of a T-shaped object observed using a composite aperture (misaligned subaperture matrix of size 3×3) through a turbulent atmosphere: (a) initial object; (b) distorted image of the object; (c) image of a single star; and (d) reconstructed image of the object.

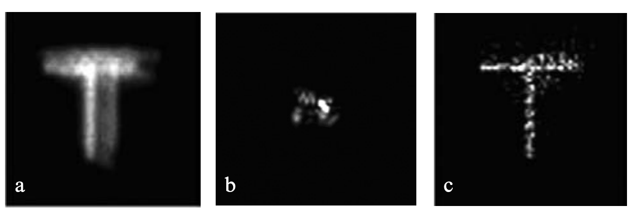

Figure 6. Reconstructed image of a T-shaped object observed using a composite aperture (misaligned subaperture matrix of size 3×3) in the absence of an atmosphere: (a) obtained image of the object; (b) image of a single star; and (c) the reconstructed image of the object.

Thus, the above analysis and the results of computer simulation show that for observations of remote incoherent luminous objects carried out in an appropriately chosen spectral range, the method proposed by us makes it possible to reconstruct the image function of the optical path without any additional reference source, and to obtain an image with an optical quality close to the diffraction limit. This means that the above approach can be used, on the one hand, for simulating the existing telescopes by introducing an additional system for registering radiation and, on the other hand, for casting a fresh glance at the problem of designing, functioning and exploitation of new telescopes with composite apertures having a total diameter of several tens of metres working in the terrestrial atmosphere without using any auxiliary adaptive systems and allowing an angular resolution of less than 0.01″. This is also true in the case of extraterrestrial telescopes for which the problems of simplification, cost-reduction and reliability enhancement of the instruments are even more acute than for terrestrial systems. Besides, owing to the use of relatively inexpensive aberrational optical instruments and the absence of adjustment and adaptation systems, the cost of such devices must be much lower than that of existing large-size telescopes as well as of those being designed at present [3].

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