Features of adaptive phase correction of optical wave distortion under conditions of intensity fluctuations

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Abstract. For the first time the reason of loss of efficiency of adaptive phase correction at propagation of optical waves in turbulent atmosphere under conditions of strong intensity fluctuations is experimentally explained. According to the data of experiments performed both on horizontal and vertical atmospheric routes, it was found that when the radius of coherence in the optical wave becomes less than the first Fresnel zone, intensity fluctuations begin to affect the data of phase measurements. This results in the fact that the main meter of the adaptive optics (AO) system - Hartmann's sensor - in the presence of deep amplitude modulation no longer provides the correctness of phase distribution measurements. Based on the study of the behavior of the modal components of the phase fluctuations reconstructed from the measurement data at different operating modes, it was found that, first of all, the lower modes of phase fluctuations decomposition - tilts, defocusing and astigmatism - are distorted and, as the analysis of these modes shows, they differ greatly from the classical modes corresponding to the mode of weak fluctuations.

1. Introduction
When analyzing the efficiency of phase correction systems, it is usually assumed that there are no intensity fluctuations. It is interesting to consider another limiting case - the case of strong intensity fluctuations, assuming that the adaptive system has an unlimited spatial and temporal resolution with respect to the correction of phase distortions.

It is known that the phase distortions acquired during the passage through the optically heterogeneous medium are transformed into the modulation of spatial intensity distribution as the wave propagates further. At sufficiently deep modulation points with zero intensity may appear. If we describe any optical wave in terms of complex amplitude \( U \), such points are formed at the intersection (or touch) of lines, where its real and imaginary parts are equal to zero. If \( \text{Re}U \) and \( \text{Im}U \) change the sign from positive to negative when passing through these lines, such intersection points are the dislocation points of the wave front. From the point of view of adaptive phase correction, it is important that the continuity of the two-dimensional phase distribution is disturbed when dislocations appear [1, 2]. When such gaps appear, the error of the wave front approximation by the adaptive mirror will increase significantly. Application of special correctors in general case will not give effect.
also, as at correction of turbulent distortions of dislocation arise in randomly located points of an aperture. Algorithms for drawing the reference wave aberration map, which are used today in most wavefront sensors, give a continuous function of transverse coordinates at the output. In fact, they filter the vortex part of the measurement vector.

2. Numerical experiments
Let us consider the results of [2-7] numerical experiments showing the influence of intensity fluctuations and dislocations on the correction of turbulent distortions. Two aspects are of practical and scientific interest. The first is how much the loss of amplitude information affects the efficiency of phase correction. The second is how much the loss of information contained in the vortex part of phase measurements reduces the efficiency of adaptation.

Numerical experiments were carried out for two correction schemes. The first is the distortion compensation scheme. The second one - adaptation scheme is the PC scheme. For each of the two schemes, two variants of the phase measurement algorithm were considered. In the first case, the ideal adaptive system instantly and accurately reproduces the phase of the reference wave on the entire plane of the cross-section, including special points of the wavefront (dislocation). In the second variant, only the component corresponding to the potential part of the vector field of local slopes of the wave front is corrected. Further on, we will call such correction a correction of the "potential" (or "eddeless") phase. Thus, in fact, we have implemented four schemes of numerical experiment:

1) an ideal compensation system,
2) a system of compensation only for the "potential" part of aberrations,
3) the ideal PC system,
4) the system of PC of the "potential" part of aberrations.

You can enter four numerical parameters of the task, which are the following values: trace length $L$, aperture diameter of the system $D$, wavelength $\lambda$, turbulence intensity $Cn2$. In accordance with the similarity theory, the problem of plane wave propagation in the turbulent atmosphere is characterized only by two scales: the coherence radius $r_0$ can be chosen as a transverse scale, and the length of diffraction at the coherence radius $L_t = kr_0*2$ can be chosen as a longitudinal scale. Then the problem will be characterized by the normalized length of the $L/L_t$ trace and the normalized aperture diameter $D/r_0$. The scintillation index of the plane wave $\beta_o*2$ for the power spectrum of turbulence is unambiguously related to the ratio $L/L_t$: $\beta_o*2 = 2.9(L/L_t)*5/6$. It can be used as a parameter instead of the $L/L_t$ ratio.

![Figure 1. Dependence of the ratio SR on the scintillation index for each of the correction schemes.](image)

The results of our numerical experiments [5-7] are shown in Fig. 1. This figure shows the dependence of the ratio SR on the flicker index for each of the correction schemes. The normalized aperture diameter was $D/r_0 = 10, 20, 30$. Therefore, each scheme corresponds to a family of three curves. For an ideal compensation scheme, the SR ratio practically does not depend on either the normalized aperture diameter or the trace length. The difference between the SR value and the
The efficiency of correction in the scheme of ideal phase conjugation (Fig.2) is not indifferent to the value of intensity fluctuations. However, the dependence is not as strong as one might expect. At $\beta_0^*2 = 3$ the SR parameter decreases to 0.8 and is practically independent of the aperture diameter.

3. The American experiment

There are limited experimental data with which to compare the results of the numerical analysis. Thus, one experiment was carried out at the Lincoln Laboratory in the United States on a 5.5 km long path [8]. The adaptive system included a Hartmann sensor and a deformable mirror. The phase coupling algorithm for the focused beam was used (Fig.3). The wavelength of the reference and corrected beams was 633 and 514 nm, respectively.

![Figure 3. Experimentally obtained dependence of SR on the variance of amplitude fluctuations of a spherical wave and that calculated in the Rytov approximation $\sigma^2 R$.](image)
The vertical axis shows the values of the Strehl parameter for the system. The horizontal axis shows the dispersion of fluctuations in the logarithmic amplitude for the spherical wave. It should be noted that the dispersion of intensity fluctuations is 4 times larger $\sigma^{*2}R$ and the scales of horizontal axes in Figures 1 and 2 practically coincide.

4. Conclusions

Based on the above [1-7], the following conclusions can be drawn:

1. The proposed numerical model of AO system, including the "filtering" algorithm of wave front reconstruction, allows adequately modeling and quantifying the effectiveness of the existing adaptive system under conditions of strong intensity fluctuations.

2. At correction of turbulent distortions efficiency of phase correction decreases approximately twice at increase of the normalized dispersion of fluctuation of intensity (shimmering index) $\beta^{*2} = 0.2$ from zero to one. In this range of values 0.2 correction efficiency practically does not depend on the ratio between aperture diameter and coherence radius. At further increase of intensity fluctuations the dependence of correction efficiency on aperture diameter begins to appear. The increase $\beta^{*2}$ of 0.2 to 3 leads to a drop in the correction efficiency by an order of magnitude or more, and the SR parameter tends to the value obtained in the system without correction.

3. Since the level of $\beta^{*2} = 3$ approximately corresponds to the boundary of applicability of the method of smooth perturbations method (SPM), it can be assumed that the applicability of SPM is also associated with the occurrence of dislocations. Note that at the dislocation points, the intensity is equal to zero and the logarithm of the amplitude turns to infinity, while perturbation method is actually a perturbation method for the logarithm of the field.

4. The decrease in the efficiency of the adaptive correction of the "eddeless" phase with the growth of intensity fluctuations is approximately the same in both the phase compensation scheme and the phase conjugation scheme. The differences between the plane wave and beam are also insignificant, which follows from the comparison with the Lincoln Laboratory experiment.

It is interesting to note [7] that even at large amplitude fluctuations, the use of adaptive phase correction still provides a certain and quite significant benefit compared to the case without correction. The value of the SR parameter is compared here. Table 1 shows the ratio of the corrected SRc parameter to the uncorrected SRu parameter value for the scheme of compensation of the "eddeless" phase at the variance of $\beta^{*2} = 3$.

| $D/r_0$ | $SR_u$ | $SR_c$ | $SR_c/SR_u$ |
|---------|---------|---------|-------------|
| 10      | 0.0324  | 0.129   | 3.98        |
| 20      | 0.0106  | 0.038   | 3.58        |
| 30      | 0.0051  | 0.025   | 4.90        |

Table 1 shows that for all values of $D/r_0$, the corrected value of the Strehl parameter is approximately four times greater than the unadjusted value.

5. Experiments in the field of «strong fluctuations»

We have carried out experiments with mock-ups of AO systems [9-14] in recent years, both on extended vertical and horizontal atmospheric routes. Measurements made with the WFS on the long paths along the surface layer of the atmosphere showed that in addition to seasonal and daily variations, there is a rapid [13, 14] variability in the intensity of turbulence, which leads to variability of its integral value even on extended horizontal paths (Fig.4).

A sharp seasonal variation [9-12] in the level of integral turbulence (Fig.5) was detected on the inclined astronomical trails: for summer, the coherence radius is 4.6 cm on average, and for winter - 1.5 cm.
Figure 4. Temporary changes of the coherence radius, measured by a wavefront sensor on a horizontal optical path 2 km long.

Figure 5. Seasonal changes of the coherence radius (for a wavelength of 0.535 µm) measured by a wavefront sensor on an astronomical optical path near lake Baikal.

Comparison of the behavior of the measured modal components of phase distortions at weak and strong intensity fluctuations shows that the appearance of intensity fluctuations leads to a parasitic modulation of the lower modes spectra, which causes the loss of efficiency of phase correction. And it, first of all, affects the data of phase measurements made with the help of the classical sensor of a wavefront - Shack-Hartmann.

It is known that the Shack-Hartmann sensor determines phase fluctuations from the positions of the focal spot system's centers of gravity. Under conditions of weak intensity fluctuations these values are measured with high accuracy (pixel fraction). Deep amplitude modulation in the optical wave causes strong fluctuations in the illumination of individual spots, up to their complete freezing, which leads to a loss of signal informativeness (Fig.6). From the measurement point of view, this means that the actual amplitude fluctuations influence the measurement data of phase fluctuations.

For the further analysis of the situation the accuracy analysis of estimation of the position of the focal points of gravity in Hartmann's sensor with the use of various threshold values of illumination (Fig.7) up to the value of 1.5 times higher than their background value was made.

The next step in the development of the AR systems is to search for the possibilities of the AO system operation at "strong" amplitude manifestations. In our opinion, one of the methods of struggle [15] with the influence of flickers can be automatic rejection of individual subpertures in the sensor picture, which will not be used to restore the phase. In the process of calculating the phase fluctuations, only "good" subpertures will be used, where the illumination exceeds the threshold.

Fig.8 shows the sequence of frames in the realization of optical experiment, where the Shack-Hartmann sensor was used. The figure gives dependence of number of subpertures on which
illumination in a maximum appears below a threshold. Thus, it turns out that on some frames there is a "freeze" of illumination level almost to zero.

**Figure 6.** Characteristic appearance of the pattern of focal spots in the Hartmann sensor under different modes of weak (left) and strong (right) fluctuations.

**Figure 7.** Change of the maximum illumination values of the images formed by the wavefront sensor subapertures. \( E_{\text{max}} \) - the maximum illumination value of the image formed by the wavefront sensor subaperture, \( E_{\text{th}} \) - the threshold value of the maximum illumination of the image formed by the wavefront sensor subaperture, \( E_{\text{th}} = 1.5 E_0 \), where \( E_0 \) – maximum background illumination.

In addition to carrying out the culling of individual subapertures, it is also possible to use multistage phase correction with the use of non-phase sensors to measure the general inclination fluctuations and wave front defocusing to combat the influence of amplitude fluctuations.
Figure 8. $N_1$ - number of subapertures that form images with maximum illumination values below the threshold, $N_0$ - total number of fully illuminated wavefront sensor subapertures.

6. References

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