Isoplanatic requirements for adaptive-optics systems

Lidia Bolbasova and Vladimir P. Lukin

The optimal angular separation of laser-guide stars depends critically on the order of the wavefront’s phase aberrations, the outer scale of turbulence, and the telescope’s aperture.

Atmospheric turbulence imposes serious limitations on astronomical observations. Fortunately, adaptive-optics (AO) systems can significantly improve image quality. Information about the distribution of turbulent inhomogeneities in the atmosphere is obtained from laser-guide-star (LGS) measurements. Application of multiple LGSs as reference sources offers the highest efficiency, but questions remain regarding the optimal guide-star separation on the sky. This relates directly to the isoplanatic angle or isoplanatic area (see Figure 1), the projected area where the wavefronts from the object of interest and the wavefront-reference source are similarly affected by turbulent cells. Obviously, AO system performance depends strongly on the quality of the information used. Therefore, LGSs must be generated within the isoplanatic angle, and angular anisoplanatism imposes serious restrictions on AO-system operation.

The concept of the isoplanatic angle was introduced in the early 1980s. It determines, for instance, the extreme angular separation between one’s object of interest and a reference source. However, this simple concept does not take into account the fact that we nearly always deal with partial or modal-phase adaptive wavefront correction. In addition, this definition ignores both the telescope’s aperture size and the influence of the outer scale of turbulence. The latter causes residual distortions in AO systems.

If we define isoplanatism as the degree of uniformity of aberrations of an optical system across its field of view, we must describe it mathematically as an aberration function in terms of ray coordinates. In geometric optics, it is either a wave aberration or eikonal (light-travel-time related). In atmospheric AO systems, this role is played by turbulence-induced wave aberrations. The size of the isoplanatic area in such a system is therefore determined by the existence of correlations between wavefront phase distortions in the turbulent atmosphere.

We calculated the angular correlation of the modal components of the phase fluctuations and considered their practical application to AO. We represented the wave-aberration function as a series expansion of Zernike polynomials, which contain information about the spatial properties of the phase fluctuations. Figure 2 shows the normalized correlation functions for the first three aberrations for the infinite outer scale of turbulence, i.e., two tilt positions, defocusing, and coma. These aberrations provide the main contributions to image deformation by the turbulent atmosphere. The behavior of the correlation strictly depends on the order of the aberrations and decreases with increasing order. The angle within which the tilts remain correlated is greater for these than for higher-order aberrations. In general, the size of the isoplanatic area is equivalent to the order of the AO-corrected aberration.

Continued on next page
Figure 2. Angular correlation for different modal components of phase fluctuations: two positions of wavefront tilts, Y (1) and X (2), defocusing (3), and coma (4). D: Aperture diameter. $h_{\xi}$: Defines the action of atmospheric turbulence.

Figure 3. Angular correlation coefficient for two positions of wavefront tilts and for different values of the effective outer scale of turbulence: Y (1), X (2), $\chi=0$; Y (3), $\chi=0.1$; X (4), $\chi=0.3$; X (5), $\chi=0.1$; and X (6), $\chi=0.3$, where $\chi$ is inversely proportional to the effective outer scale of turbulence.

Finally, we considered how the angular correlation changes with aperture size. The ratio of the angular separation between the optical beams, $\theta$, to the traditional isoplanatic angle, $\theta_0$, becomes the dominant parameter (see Figure 4). The aperture size obviously determines the size of the area over which phase fluctuations are correlated: with increasing aperture size, the angular correlation increases. The correlation is much higher for the tilt, and as the angle between the beams increases, it decreases more slowly than for higher-order aberrations.

Our results indicate that the optimal angular separation of LGSs and consequently the size of the isoplanatic area depend directly on the order of the wavefront’s phase aberrations as well as on the outer turbulence scale and the aperture of the telescope. It must therefore be taken into account for modal correction of atmospheric distortions. In conclusion, this approach allows us to both estimate the allowed angular separation in realistic observational scenarios and determine the requirements for AO bandwidth. We are currently planning atmospheric experiments to measure the angular correlation functions of the modal-phase distribution of wavefront fluctuations.

This work was performed within the framework of integration project 80 of the Siberian branch of the Russian Academy of Sciences (RAS), ‘Development methods of precision astroclimatic observations for ensuring adaptive optical systems operation’ and program 16 of the RAS Presidium, part 3, ‘Development of adaptive systems and atmospheric turbulence test setups for improving solar astronomical observations.’
Author Information

Lidia Bolbasova and Vladimir P. Lukin
Institute of Atmospheric Optics
Siberian Branch of the Russian Academy of Sciences
Tomsk, Russia

Lidia Bolbasova received her MS in 2005, followed by a PhD in AO in October 2009, both from Tomsk State University (Russia).

Vladimir Lukin is a professor and a fellow of both SPIE and the Optical Society of America, and also received a Galileo Galilei award. He is head of the Adaptive Optics Laboratory and author or co-author of over 555 scientific papers and 11 monographs in the field of atmospheric AO.

References