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PROBLEMS OF ADAPTIVE OPTICS USED IN THE ATMOSPHERE

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Abstract:The atmospheric scintillation ,atmospheric dispersion and anisoplanatism set a limit to the application of adaptive optical technique in atmosphere . In this paper ,this limit is summarized ,and the methods to reduce these effects are introduced.

I. Introduction

Since the presentation of the original concept by Babcock [1] in 1953 on adaptive optics technique there have been 40 years of developments to date. Developments were especially rapid in the recent decade because of the spread of high-tech. In September 1985, successful short wavelength long-distance, real-time compensation experiments were carried out on the island of Maui, Hawaii. In March 1989, a southern European observatory obtained star images with the closest diffraction limit of resolving power, with a large-aperture telescope, in recorded history. These two milestones of progress marked that adaptive optics has left the laboratory for the practical stage. However, a similar unquestionable fact is the very noncooperative atmosphere. It is quite difficult to realize long-distance and higher-performance compensation (such as more than 90% of anomalies) is to be achieved in laser engineering with high illumination on the target. Even without discussing what problems exist technically, this is not easy to realize all aperture phase coherence at short wavelengths. This paper will discuss the effect on adaptive optics from three aspects: atmospheric scintillation (fluctuation of oscillation amplitude), atmospheric chromatic dispersion, and anisoplanatism, in order to be advantageous to the applications and developments in adaptive optics.

II. Strehl Ratio

Many concepts can be used to indicate the capability of adaptive optics to compensate for phase anomalies. The widely applied is the Strehl ratio (SR). It is defined as the ratio of peak intensities between the peak value intensity of a light beam and the peak value intensity of the light beam when propagating in free space, after being compensated. Beginning with optical transfer, the author and his colleagues derive the Strehl ratio [4] for a rotating symmetric system under the conditions of intensive eddy currents:

$$\begin{aligned} \mathrm{SR} = {} & \frac{16}{\pi}\exp\left[-0.294\,N^{-0.866}\left(\frac{D}{r_0}\right)^{5/3}\right]\left[2+1.83\left(\frac{kr_0^2}{L}\right)^{1/3}\right]^{-1/4} \\ & \cdot\int_0^1 \mathrm{d}x\,x\left[\cos^{-1}x - x(1-x^2)^{1/2}\right]\left[1+B_l(Dx)\right]^{1/4} \end{aligned} \tag{1}$$

In the equation, N is the number of subapertures (or the impetus elements) adopted by the system; D is the aperture of the optical system; R_0 is the coherent length of the atmosphere; $k(=2\Pi/\lambda)$ is the number of waves; L is the propagation distance; and B1(Dx) is the intensity correlated function. At the right-hand side of the equation, in the index term, is the mean-square value of the residue phase error after compensating for phase anomaly in a relatively ideal adaptive optical system. In the second bracketed portion is the contribution due to fluctuations of the vibration amplitude. The final integration term is contributed by the fluctuation correlation of the vibration amplitude.

In Fig. 1, the effect of the Strehl ratio on the number of subapertures and the coherence length, is cited as an example of $\lambda=1\mu$, L=10km,D=0.5m. From the figure we know that the shorter the coherence length (that is, the more intensive the eddy current in the atmosphere), the smaller is the number of subapertures, and the smaller is the Strehl ratio. Eq. (1) is supported experimentally. Reference [1] reports the experimental results on the optical path at the 340m level. The researchers used a system of 21 units to obtain SR=0.64 when r_0=5cm. Calculated from Eq. (1), the theoretical value is 0.65. The experimental results and the theoretical results agree closely.

For astronomical applications, the most recent conclusion is that when SR=0.5, the star image close to the diffraction limit [6] can also be obtained. If this is used as a criterion, then the system of N=69 can also satisfactorily operate when $r_0 \geqslant 4$cm.

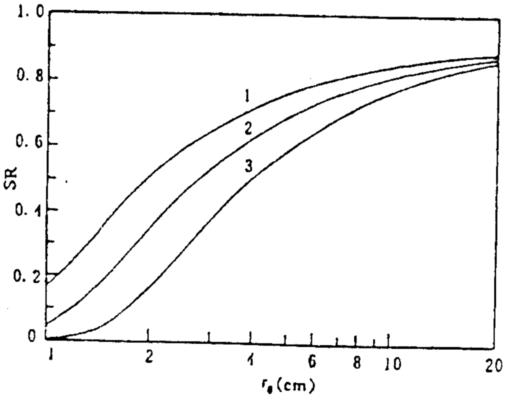

Fig. 1 Subaperture number as a function of Strehl ratio

$1-N=261$ $-N=133$ $3-N=69$

Consideration is given to the fact that the infrared wave region can be used in the astronomical applications. The corresponding length of atmospheric coherence will be increased by several times (near-infrared) to scores of times ($\lambda \geqslant 10\mu m$). Therefore, prospects are bright for adaptive optics in astronomy. In the United States alone, up to October 1992, there have been 13 sets [7] of adaptive optical systems in operation and in planning. However, for the laser compensation system aimed at improving light beam quality, the Strehl ratio is required to be higher than 0.9. This is quite difficult. Especially for large-aperture systems, if whole aperture phase coherence is to be required, the dimensions of the subaperture should correspond to small-scale eddy currents. For the latter, the scale is approximately between 1 and 10mm. Even if calculated for 10mm, 120,000 subaperture elements are required for a 4-m telescope. However, it is difficult to reach 0.9 for the Strehl ratio in the intermediate intensity of the eddy current. If the laser power is sufficiently high, or energy is sufficiently high, thermal blooming exists. However, with interaction between thermal blooming and eddy currents, instability of phase compensation will appear. These problems will be further studied theoretically and experimentally.

III. Effect of Atmospheric Chromatic Dispersion

When adaptive optics is applied to revise the eddy current effect in the atmosphere, the guide star is required. However, the wavelength of the guide star is often inconsistent with the wavelength of the target light that is to be corrected. At this point, correction will be incomplete because of the atmospheric effect of chromatic dispersion. As indicated in theoretical research, if selection is improperly done, very high residual phase error will result. Beginning from the Zernike polynomial, the author and his colleagues considered the diffraction effect and derived the correlation function of the development coefficient of the dual-frequency phase. Furthermore, the corresponding equation of solving for the variance of the residual phase is to be derived [8]:

$$\sigma^2_{\Delta\varphi}=\left[\frac{D}{r_0(\lambda_1)}\right]^{5/3}\sum_i\Big[P_i(\lambda_1,\lambda_2)+\left(\frac{\lambda_1}{\lambda_2}\right)^2P_i(\lambda_1,\lambda_2)-2\left(\frac{\lambda_1}{\lambda_2}\right)P_i(\lambda_1,\lambda_2)\Big] \quad (2)$$

$$P_i(\lambda_1,\lambda_2)=1.95(n+1)\int_0^\infty dKK^{\;14/3}J^2_{n+1}K\left[\frac{\sin(AK^2)}{A}+\frac{\sin(BK^2)}{B}\right] \quad (3)$$

$$A=\frac{2L(k_1+k_2)}{k_1k_2D^2},B=\frac{2L(k_1-k_2)}{k_1k_2D^2}$$

In the equations, $k_i = 2\pi/\lambda_i\,(i = 1, 2)$, J_n (x) is the n-th order Bessel function.

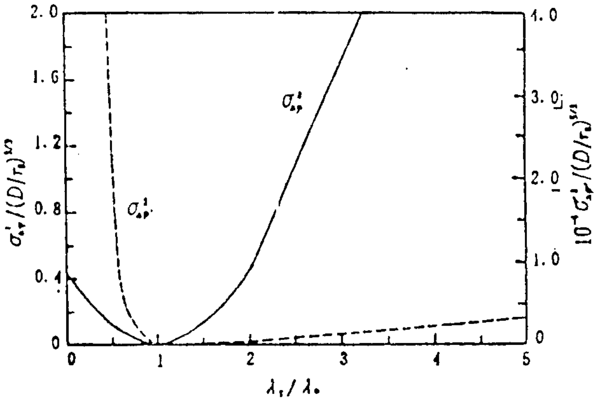

Fig. 2 Normalized residual phase variance vis λ_T/λ_B

In Fig. 2, the calculation results are given under the conditions of L $= 10\text{km}, D = 4\text{m}, \lambda_1 = 1\mu\text{m}$ (the calculation results are shown with the solid line). It is apparent that only when the guide star wavelength λ_B is consistent with the transmitted wavelength λ_T, is the residue phase error zero. When $\lambda_T/\lambda_B < 1$, that is, the information of the long wavelengths is to be used to correct the phase anomaly in the short wavelengths; the result is insufficient compensation. With reduction of the ratio, finally it will tend to have a value without compensation. However, in the opposite situation $(\lambda_T/\lambda_B > 1), \sigma_{\Delta}^2$ will increase quickly. The result is to have the compensation worse than the case without compensation. The basic cause for this situation is that the shorter the wavelength, the greater is the phase error. To overcome this effect, we can let $\varphi_B\lambda_B/\lambda_T$ be the correction quality ϕ_T of the light phase of the phase target. At this stage, Eq. (2) becomes

$$\sigma^2_{\Delta_\phi}=(\frac{D}{r_{01}})^2\sum_i[P_i(\lambda_1,\lambda_1)+P_i(\lambda_2,\lambda_2)-2P_i(\lambda_1,\lambda_2)] \quad (4)$$

The dashed lines in Fig. 2 stand for the calculated results of the solid lines. It is very apparent that the variance of the residue phase at this point is very smaller, generally smaller by three to five orders of magnitude. Then we can see that in order to overcome or reduce the effect of chromatic dispersion in the atmosphere, whatever the wavelength of the guide star and the target light, the multiplied product of phase error ϕ_B of the guide star by the ratio (λ_B/λ_T) is used as the correction quantity of the phase anomaly.

IV. Effect of Isoplanatism

If the guide star and the target are not at the same location, there is an extended angle between guide star and target with respect to the adaptive optical system. Since the properties of eddy currents in the atmosphere are correlated over a local region, the information in the guide star channel may possibly not indicate the properties of the target light path. Thus, the compensation will be incomplete. This situation is often called anisoplanatism. If it is correlated in the conical region, the correlation function is reduced in the region included by e^{-1}; this region is called the isoplanatic region; the extended angle is called the isoplanatic angle, marked as Θ_0. Obviously the value of Θ_0 is limited by the conditions of the eddy currents and can be calculated by using the following equations, theoretically [9]:

$$\theta_0 = \{2.91k^2(\sec\psi)\int_{h_0}^{\infty} C_n^2(h)h^{5/3}\mathrm{d}h\}^{-3/5} \tag{5}$$

In the equation, ϕ is the zenith angle; and h_0 is the height of the observation point.

In a general situation, $\theta_0 = 10\mu\mathrm{rad}$; when the eddy currents are relatively intensive, Θ_0 may be small as 5µrad. With respect to astronomical observation, the guide star stars in the visible light wave segment can cover only 0.02% of the sky. Thus, it is very difficult to find the appropriate guide star. However, for a space object moving in low orbit, the round-trip transmission time of a light beam will move to over 20µrad. Both applications are very difficult to satisfy the isoplanatic conditions. Therefore we should find, or artificially form, an appropriate guide star source. At the same time, this is also an important approach in applying some measures to enlarge the isoplanatic region.

The artificial guide star can be generated by backscattering of atmospheric molecules, or by resonant scattering of a laser by the Na ion layer in the high-altitude scattering layer (80 to 100km). Successful demonstrations were carried out for both methods. For example, Gardiner [10] et al. obtained images of laser echoes in an Na layer with a low noise CCD array with a 2.2-m telescope at the Mona Kaui Observatory. Their experimental data and theoretical analysis that modern laser technology can carry out adaptive corrections of ground-based astronomical telescopes. Because of a lower height (approximately 10km) of the artificial star that is formed, it is easier to carry out the technique of Rayleigh scattering. In addition, images much brighter than the Na layer guide star corresponding to the brightness of magnitude 1 stars can be obtained. However, the shortcoming is that the returning light rays of the guide star is not as parallel as light rays from heavenly bodies. Thus the focal plane is not a plane. This leads to lowered compensation efficiency.

To satisfy the conditions for isoplanatism, sometimes much more artificial guide stars may be required. If this arrangement can be carried out (in fact, an experimental plan in this aspect was executed), then it is possible to consider the wavefront anomaly as a function of distance, not to be studied as a whole integration that reached the telescope. Some scholars [11 to 13] proposed a concept of multiconjugate adaptive optics on this basis. In other words, the atmosphere is divided into M layers; each layer corresponds to a set of adaptive optical systems. In this way, the isoplanatic region can be significantly increased. In preliminary simulations, it is indicated that the dimensions of the isoplanatic region will be increased by $4M^2$. Although the optical system is increased by M-fold, yet the dimensions of the impetus unit can be increased with M, actually the number of elements of the adaptive reflective length is almost not related to M. Even if the conventional single system is applied, only can the conjugation of the mean eddy current layer enlarge the isoplanatic region. However, there are many difficulties in carrying out the multiconjugate adaptive technique because it requires a complete three-dimensional structure to determine the wavefront anomalies of the atmosphere.

Another method of expanding the isoplanatic region is the so-called "phase gradient method" [14]. The present wavefront inspection serves only to inspect the first-order information of the wavefront anomaly, and to neglect the higher-order information. If this higher-order information is adequately applied, this will certainly expand the isoplanatic region. This is the theoretical basis for the phase gradient method. On the basis of the expanded Wicken-Fenell principle, the author and his colleagues applied the Zernicke polynomial approach to the Gaussian light beam to prove that the relationship of the extended angle Θ between the Strehl ratio and the target guide star is:

$$SR = \left\{ \left[1 + 13.9 \left(\frac{\theta}{\theta_0} \right)^2 \left(\frac{Lr_0}{L,D} \right)^{1/3} \right] \cdot \left[1 + 41.8 \left(\frac{\theta}{\theta_0} \right)^2 \left(\frac{Lr_0}{L,D} \right)^{1/3} \right] \right\}^{1/2} \tag{6}$$

In the equation, the effect of atmospheric scintillations is neglected. By citing an example of horizontal light path in Fig. 3, the effect on the Strehl ratio due to anisoplanatism is given. It is apparent that the effect of Θ is quite large. As indicated in the calculations, with the same value of Θ/Θ_0,

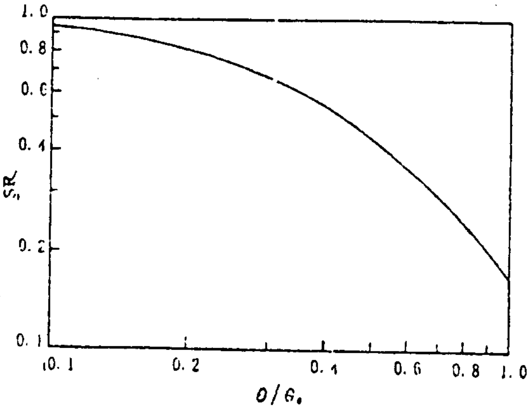

Fig. 3 Relationship between Strehl ratio and θ

whether the relative aperture (D/r_0) and the path is vertical or horizontal in the optical system have little effect on SR. This is mainly determined by the magnitude of the ratio Θ/Θ_0.

If the wavefront and the gradient of the guide star beam are applied onto the phase pre-anomaly of the initial transmitted field, we can derive the Strehl ratio of the second-order derivatives:

$$SR' = \left\{\left[1+35.35\left(\frac{\theta}{\theta_0}\right)^4\left(\frac{Lr_0}{L,D}\right)^{7/3}\right]\left[1+176.8\left(\frac{\theta}{\theta_0}\right)^4\left(\frac{Lr_0}{L,D}\right)^{7/3}\right]\right\}^{-1/2} \quad (7)$$

When the guide star is at the margins of the isoplanatic angle, Eq. (6) becomes:

$$SR_0 = \left\{\left[1+13.9\left(\frac{Lr_0}{L,D}\right)^{1/3}\right]\left[1+41.8\left(\frac{Lr_0}{L,D}\right)^{1/3}\right]\right\}^{-1/2} \quad (8)$$

From Eqs. (7) and (8), we can obtain the number of times by

From Eqs. (7) and (8), we can obtain the number of times by which the isoplanatic angle was increased when SR'=SR:

$$A=\frac{\theta}{\theta_0}=\left\{\left[2.88\times10^{-4}+\left(\frac{Lr_0}{L_cD}\right)^{1/3}\left(0.093\left(\frac{Lr_0}{L_cD}\right)^{1/3}+8.91\times10^{-3}\right)\right]^{1/2}-0.017\right\}^{1/4}\left(\frac{L_cD}{Lr_0}\right)^{7/12} \tag{9}$$

In Fig. 4, the calculation results are shown in three situations. For horizontal distance, L_c=3.18L; for vertical paths, based on the eddy current distribution model in [15], it is calculated that L_c=4430m for weak turbulent flow. During more intensive turbulent flow, L_c=7100m. From Fig. 4, whether

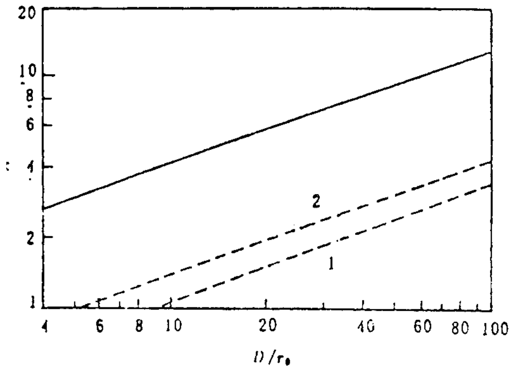

Fig. 4 Variation of amplication with D/r_0
—horizontal path ······vertical path
1—weak turbulence 2—stronger turnulence

horizontal path or vertical path, the phase gradient method can be used to effectively improve the isoplanatic conditions. The degree of improvement is related to the relative aperture. When

$D/r_0=40$, the improvement is a factor of 8.3 for the horizontal path. In the vertical path, the improvements are 2.2, and 2.8-fold, respectively.

Finally, it has to be pointed out that when the relative aperture is smaller, (D/r_0 <5 to 10), the improvement in the number of times is smaller than 1 for the vertical path. In other words, the phase gradient method shrinks the range of effective correction. This is so because the above-mentioned processing of the first-order terms of the phase gradient is revised. If higher-order information is to be used, this is beneficially to explain the isoplanatic region. The processing method for a high-order gradient is similar, and will be neglected here.

V. Conclusions

It has been 40 years in which there have been developments in adaptive optics. The achievements are quite satisfactory. For astronomical applications, it is sufficient in the current theoretical and technical levels. Some scientists propose to install adaptive distortion lens as the supplementary lens in an astronomical telescope. However, to enhance laser beam quality, there is still a long way to go to enhance laser beam quality. Several methods of improving the performance of adaptive optical systems were proposed; these include the field compensation technique to overcome atmospheric scintillation. The use of multiconjugate method and the phase gradient method of utilizing multiple guide stars in overcoming anisoplanatism still remains at the stage of proof. However, we can expect that the prospects for adaptive optics are quite bright in applying to various aspects and various atmospheric conditions with high performance.

The author Song Zhengfang was born in December 1935. As a researcher, he currently studies atmospheric optics, as well as the transmission of laser and infrared radiation. Figures in equations in Eqs. (6) through (9) are different from the original paper.

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