INDIAN JOURNAL OF PHYSICS, 80

Laser guide artificial star for high resolution imaging

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Abstract

A large telescope encodes the information about the source, but unable to get the diffraction-limited informations. Due to the inhomogeneity of the propagating medium that carries the light to the Earth's surface, the image of a point source (unresolved stars) cannot be smaller than a limit at the focal plane of the telescope. In order to estimate the point spread function of both the atmosphere and the telescope, observation of a bright unresolved star is needed. Astronomers do face difficulties in locating such an object within isoplanatic patch. Over the years, several observatories have developed the laser guide artificial star in order to palliate the limitations of low sky coverage (the probability of finding a suitable reference star within isoplanatic patch). This article discusses the utility of such an instrument.

Key words: adaptive optics, laser guide stars, atmospheric optics.

PACS Nos. 95.75, 42.68

1 Introduction

The understanding of the effect of atmospheric turbulence on the structure of stellar images and of ways to overcome this degradation has prompted Labeyrie [1] to introduce stellar speckle interferometry. Such a technique deciphers diffraction-limited information of a stellar object and has made impacts in several important fields in astrophysics [2-4]. Further benefits have been witnessed when the degraded images of stellar objects are applied to post-detection image restoration techniques. Over the last few decades, owing to the significant improvements in hardware technologies, it became feasible to compensate in real time the wavefront distortion. This method, known as adaptive optics (AO) system, recovers near diffraction-limited images and improves the point source sensitivity [5-7].

One of the major problems in applying adaptive optics to astronomical observations is to locate a bright reference object within isoplanatic patch, which is required to measure the wave-front errors. The sources are in most of the cases are too faint, hence their light is not sufficient for the correction. An alternative source is found in the form of introducing the laser guide star source [8] as a reference to measure such errors by means of a wave-front sensor, as well as to map the phase on the entrance pupil. In what follows, we discuss the principle of laser scattering in the atmosphere and pros and cons of laser guide star.

2 Effect of Atmospheric Turbulence

When an idealized astrophysical source of monochromatic radiation passes through atmosphere, it suffers a phase fluctuations and reaches the entrance pupil of the telescope with patches of random excursions in phase [9]. Due to the motion and temperature fluctuations in the air above the telescope aperture, inhomogeneities in the refractive index develop. These inhomogeneities have the effect of breaking the aperture into cells with different values of refractive index which are moved by the wind across the telescope aperture. Kolmogorov law [10] represents the distribution of turbule sizes, from millimeters to meters, with lifetimes varying from milliseconds to seconds. Changes in the refractive index in different portions of the aperture result to the phase changes in the value of the aperture function. The time evolution of the aperture function implies that the point spread function (PSF) is time dependent. The image of an astronomical object recorded at the focal point of the telescope is convolved with the combined PSF of the atmosphere and the telescope. Such an image taken with exposure time shorter than the evolution time is called short-exposure image, which corresponds to fixed (frozen) atmospheric aberrations. The atmospheric time constant, τ_0, is a function of the atmospheric coherence length, widely known as, Fried parameter, r_0 and the transverse component of the wind velocity, v, and is given by,

$$\tau_0 = 0.31\frac{r_0}{v}, \tag{1}$$

and the Fried's parameter, r_0, is represented by,

$$r_0 = \left(\frac{6.88}{a}\right)^{3/5}, \tag{2}$$

in which

$$a = 2.91\kappa^2 \int_{-\infty}^{\infty} \mathcal{C}_n^2(h)dh, \tag{3}$$

with $\kappa = 2\pi/\lambda$ is the wave number, λ the wavelength of the light, h the height of the turbulence layer, and $\mathcal{C}_n$ the refractive index structure constant.

The degradation of the astronomical images is called seeing; it varies from place to place and time to time. Seeing disk is defined as the full width half maximum (FWHM) of a Gaussian function fitted to a histogram of image in arcsec. The seeing fluctuates on all time scales down to minutes and seconds. The quality of seeing is characterized by,

$$\theta_s = 0.976\frac{\lambda}{r_0}, \tag{4}$$

in which θ_s is the seeing disk that determines the image quality.

The instantaneous atmospheric phase aberrations depends on the isoplanatic angle, θ_0, that is defined to be the cone within which the beam does not posses different phase variance due to turbulence and is expressed as,

$$\theta_0 = 0.43\frac{r_0}{L}, \tag{5}$$

where L is the mean effective height of the turbulence.

This parameter, θ_0, limits the distance between guide star and the scientific objects. It turns out that for most objects there is no suitable (bright and close-by) guide star, hence artificial laser guide stars are required.

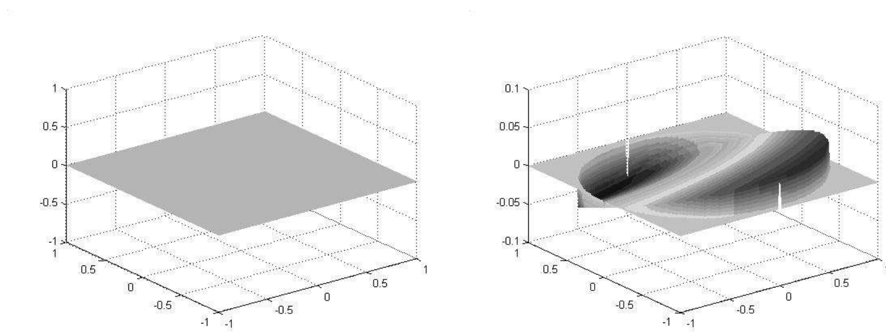

Figure 1: (a) The left side defines a plane wavefront and (b) the right side is a wavefront tilt generated at the laboratory (Courtesy: V. Chinnappan). 3-D picture is generated by using Matlab.

Due to refractive transmission of the beam by eddies of sizes larger than the beam diameter, the wavefront tilt takes place. The first order tilt aberration is expressed as,

$$\langle \sigma_j^2 \rangle = 1.83\mathcal{C}_n^2 \lambda^{-1/6} L^{17/6}. \tag{6}$$

Figure (1a) depicts the plane wavefront that is generated at the laboratory with a laser source offering zero volt to the tip-tilt mirror, while Figure (1b) depicts the wavefront tilt measured with the same source after applying one volt to the said mirror [11]. These images are grabbed by a CMOS imager based Shack-Hartman (SH) wavefront sensor. These plane and tilted wavefronts resemble to the wavefronts arriving to a detector from a distant star before and after passing through the turbulence of the atmosphere respectively. The laboratory experiment shows only tilt as a major error, while in the case of atmosphere, the wavefront will have tilt superimposed with complicated contours. Nevertheless, a conjugate wavefront can be created by employing the AO systems which can improve the throughput of a large telescope.

3 Adaptive optics

The adaptive optics systems (AO) remove the turbulence induced wavefront distortions by introducing controllable counter wavefront distortion which both spatially and temporally follows that of the atmosphere. The purpose of this system is to (i) sense the wavefront perturbations, and (ii) compensate for them in real time [12-13].

As the wind moves the eddies past the telescope aperture, the tilt of the intercepted wavefront changes. Therefore, the wind velocity also dictates the speed of measurement and correction. In order to take a corrective measure, Greenwood [14] derives the mean square residual wavefront error as a function of servo-loop bandwidth for a first order controller,

$$\sigma_{cl}^2 = \left(\frac{f_G}{f_{3db}}\right)^{5/3} rad^2, \tag{7}$$

where f_{3db} is the closed loop bandwidth of the wavefront compensator and $f_G = 0.426v/r_0$ the Greenwood frequency, in which v is the wind velocity in the turbulent layer of air.

The required components for implementing an AO system are: (i) wavefront sensor, (ii) wavefront phase error computation and (iii) a flexible mirror whose surface is electronically controlled in real time to create a conjugate surface enabling to compensate the wavefront distortion [12]. In order to remove the low frequency tilt error, generally the incoming collimated beam is reflected by a tip-tilt mirror. After traveling further, it reflects off of a deformable mirror (DM) that eliminates high frequency wavefront errors (see Figure 2). A beam-splitter divides the beam into two parts: one is directed to the wavefront sensor to measure the residual error in the wavefront and to provide information to the actuator control computer to compute the DM actuator voltages and the other is focused to form an image. The control system acts as feedback loop; the next cycle corrects the small errors of the last cycle. This process should be at speeds commensurate with the rate of change of the corrugated wave-front phase errors.

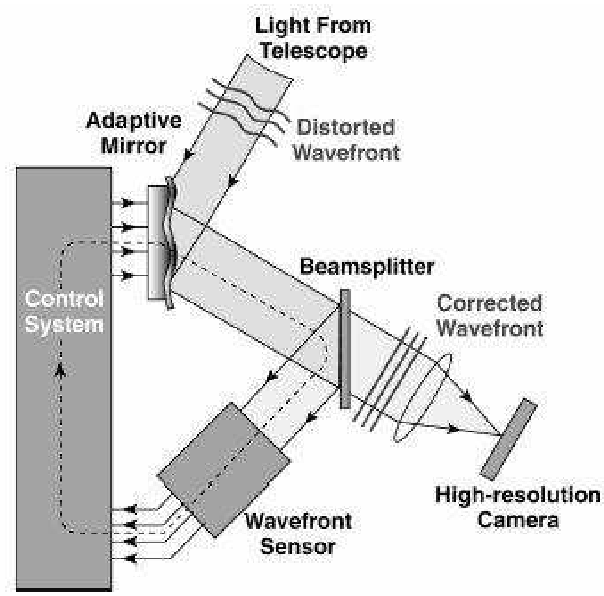

Figure 2: Schematic diagram of the adaptive optics system.

The shape of the image compensation devices is controlled such that perturbed incident wavefront phase-shifts are canceled as the optical field bounces from their surfaces. It is easier to achieve diffraction-limited information using AO systems at longer wavelengths since $r_0 \propto \lambda^{6/5}$, which implies that the width of seeing limited images,

$$\frac{1.22\lambda}{r_0} \propto \lambda^{-1/5}, \tag{8}$$

varies with λ.

The number of degrees of freedom, i.e., the number of actuators on the DM and the number of sub-aperture in the wavefront sensor, in an AO system is determined by,

$$(D/r_0)^2 \propto \lambda^{-12/5}. \tag{9}$$

3.1 Seeing optimization

The shape of an optical wavefront is represented by a set of orthogonal whole-aperture modal functions. One possible approach is to apply Zernike polynomials as spatially dependent functions $f_n(\mathbf{r})$, which corresponds to systematic optical aberrations such as defocus, astigmatism etc. The real-time computation of the wave-front error, as well as correction of wave-front distortion involves digital manipulation of wave-front sensor data in the wave-front sensor processor, the re-constructor and the low-pass filter, and converting to analog drive signals for the deformable-mirror actuators. The functions are to (i) compute sub-aperture gradients, (ii) compute phases at the corners of each sub-aperture, (iii) compute low-pass filter phases, and (iv) provide actuator offsets to compensate the fixed optical system errors and real-time actuator commands for wave-front corrections.

The main sources for errors in an AO systems are wavefront fitting errors, σ_F, which depends on how closely the wavefront corrector matches the detection error, σ_D, and the prediction error, σ_P. The detection error is the reciprocal to the S/N ratio of the wavefront sensor output, and the prediction error is due to the time delay between the measurement of the wavefront disturbances and their correction. The overall residual error, σ_R, is given by,

$$\sigma_R^2 = \sigma_F^2 + \sigma_D^2 + \sigma_P^2. \tag{10}$$

The wavefront fitting error is described by,

$$\sigma_F^2 = \alpha \left(\frac{d}{r_0}\right)^{3/5} \lambda^2, \tag{11}$$

where the spatial error is a function of the coherence length r_0, the size of the inter-actuator center-to-center spacing d of the deformable mirror, and the shape of the wavefront deformation produced by correcting elements described the parameter α.

3.2 Reference source

Adaptive optics to astronomical observations requires a bright reference point source within isoplanatic patch in order to correct wavefront errors. The numbers of such bright stars are small and the photons available from the faint sources are not sufficient for the correction. The number of photons for a star of visual magnitude m striking the Earth's surface is

$$n_{ph} = 8 \times 10^{(3-0.4m)} \tau\eta \int q(\lambda) d\lambda \qquad cm^{-2}, \tag{12}$$

where τ is the integration time, in seconds, η the transmission coefficient of the system, $q(\lambda)$ the detector quantum efficiency, and the integral is over the detector bandwidth expressed in nanometers, and the number of stars brighter than

m is, $1.45e^{0.96m}\, stars\, rad^{-2}$. According to which there are $150,000\, stars\, rad^{-2}$ brighter than 12 (in visible wavelength) are available. Since the number of isoplanatic patches in the sky is about 10^9, these stars are insufficient to provide one in each isoplanatic patch.

A laser would produce light from three reflections [8] such as, (i) resonance scattering by sodium (Na) in the Earth's mesosphere at an altitude of 90 km to 105 km, (ii) Rayleigh scattering from air molecules (oxygen and nitrogen) between 10 and 20 km altitude, and (iii) Mie scattering from dust. The major advantages of a laser guide system are (i) it can be put anywhere and (ii) is bright enough to measure the wavefront errors. Among the notable disadvantages are (i) laser light is spread out by turbulence on the way up, (ii) finite spot size (0.5 - 2 arcseconds), (iii) increases measurement error of wavefront sensor, and (iv) difficult to develop such an artificial star with high power laser.

In order to produce backscatter light from Na atoms in the mesosphere, a laser is tuned to a specific atomic transition; the strongest laser beacon is from NaD_2 line at 589 nm. Higher altitude of sodium layer is closer to sampling the same atmospheric turbulence that a starlight from infinity comes through. Existence of layer in mesosphere containing alkali metals such as sodium (10^3 - 10^4 atoms cm^{-3}), potassium, calcium, permits one to use such a technique. In the case of the Rayleigh guide stars, light is scattered back to telescope from higher altitude turbulence. However, the lights from either of these guide stars returns to telescope are spherical wave, unlike the natural light where it is plane wave, hence some of the turbulence around the edges of the pupil is not sampled well.

Concerning the flux backscattered by a laser shot, Thompson and Gardner [15] stressed the importance of investigating two basic problems: (i) the angular anisoplanatic effects and (ii) the cone effect that arises due to the parallax between the remote astronomical source and artificial source. The problem due to anisoplanatism occurs if an adaptive optics system uses natural guide stars to estimate the wavefront errors. The guide stars should be selected within the isoplanatic patch, θ_0, of the target. The zenith-angle corrected θ_0 is given by,

$$\theta_0 = 0.314 \frac{r_0}{L \sec\gamma}, \tag{13}$$

The mean square error due to anisoplanicity, $\langle \sigma_{\theta_0}^2 \rangle$, is expressed as,

$$\langle \sigma_{\theta_0}^2 \rangle = 6.88 \left(\frac{\theta L \sec\gamma}{r_0} \right)^{5/3}. \tag{14}$$

The above equation (14) shows that the mean square anisoplanicity error, $\langle \sigma_{\theta_0}^2 \rangle$, and it can be recast as,

$$\langle \sigma_{\theta_0}^2 \rangle = \left(\frac{\theta}{\theta_0} \right)^{5/3}. \tag{15}$$

The laser beacon, Rayleigh beacon in particular, suffer from the cone effect since it samples a cone of the atmosphere instead of a full cylinder of atmosphere since it is at finite altitude, H, above the telescope, whereas the astronomical objects are at infinity. A turbulent layer at altitude, h, is sampled differently by the laser and starlight. Due to this cone effect, the stellar wavefront may have a residual error while compensating the laser beacon by the AO system, i.e.,

$$\langle \sigma_c^2 \rangle = \left(\frac{D}{d_0} \right)^{5/3}, \tag{16}$$

with D is the diameter of the telescope aperture, $d_0 \approx 2.91\theta_0 H$ the parameter characterizing the cone effect.

4 Summary

High resolution imaging by using both post-detection method and adaptive optics systems has been able to resolve diffraction-limited informations of stellar objects. A bright reference point source within isoplanatic patch is required to measure the wavefront errors, but the probability of finding a suitable reference stars, known as sky coverage, is low. Substantial improvement of sky coverage in an AO system has been witnessed after the implementation of the laser guide stars. Several observatories have employed such guide stars. Figure (3) depicts AO image of Θ1 Ori B taken with adaptive secondary mirror at the 6.5 meter Multi Mirror Telescope (MMT). Without AO, this object appears to be two stars, but with AO turned on it is revealed that the lower star is a close binary having separated by 0.1 arcseconds; the brighter one is a laser guide star, and the fainter one slightly to the right (see white arrow) is a very faint companion [16].

However, the sky coverage remains low at short wavelengths, because of tip/tilt problems. It is improbable to employ a laser guide star for the basic tip/tilt correction, since it moves around due to atmospheric refraction on the upward path of the laser beam. A different system must be developed to augment the AO system for tip/tilt, since it dominates the overall aberrations. The notable other drawbacks of using laser guide star are: (i) powerful laser beacons directed to the sky are dangerous for aircraft pilots and satellites, (ii) it increases light pollution at the observatory, and (iii) it cannot be useful for the spectroscopic sky conditions. The constrain due to the cone effect limits the performance of laser guide star based AO systems as well, making such a guide star inefficient at large telescope or at short wavelengths. The laser beacon from the resonance scattering from the mesospheric Na atom seemed to be more promising. Both pulsed and continuous wave (CW) laser are used to cause a bright compact glow in sodium laser guide star.

Acknowledgment: I express my gratitude to Dr. L. Close for providing the real

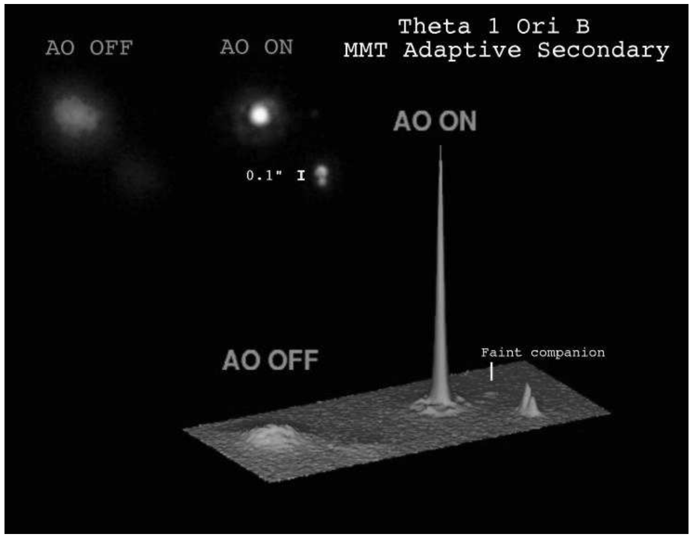

Figure 3: Adaptive optics image of Θ1 Ori B taken with adaptive secondary mirror at the 6.5 m MMT (Courtesy: L. Close).

time images of Θ Ori B.

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