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Improving the throughput of telescope by adaptive optics methods

[1]V. Chinnappan, [1]A.K. Saxena and [2]A. Sreenivasan

[1]*Indian Institute of Astrophysics, Bangalore 560034, India*

[2]*B.M.S. College of Engg., Bangalore 560019, India*

1. Introduction

Optical and Infrared (IR) telescopes are precision devices which collect the radiation from the faint stellar objects and put in as sharp an image as possible. As the source is normally faint and the photons received from these distant objects are feeble, more collecting area is often required and the time of observation is increased. If the telescope is to make sharper and smaller size image of point sources, then the accuracy of the mirror surface should be very high and the surface errors should be a very low fraction of the observing wavelength. This surface accuracy has to be maintained during operation of the telescope. Self weight of the mirror, gravitational effects on the mirror and the supporting structure tend to distort the mirror surface accuracy. As the present day mirror designs have large diameter to thickness ratio to save weight of the telescope, surface accuracy cannot be maintained without on line measurements and correction as done in active control of the mirror. Controlling large optics is not an easy task in the fabrication shop and even less easy on mountain site under observing condition. The mechanical structure which holds the mirror should be rigid, have natural frequency as high as possible and the mass moment and thermal inertia as low as possible. For IR observations, the thermal radiation from the structures in the light path should be minimal. The motors controlling the telescope should have enough torque ratings and control system should have high bandwidth. External disturbance like wind gusts should not shake the telescope. The telescope enclosure is to be designed carefully such that there is no appreciable temperature difference between the outside of the enclosure and inside. It is indeed a difficult task to get sharper and small size image from the telescope.

2. The resolution of the telescope

Diffraction limits the resolving power of a good telescope. The minimum angle of resolution provided by the telescope of aperture size D at wavelength λ is $1.22\lambda/D$. But it was found that this limit was never reached in practice. Newton recognized that his observations were often limited by the fact that "the air through which we look is in perpetual tremor" and he speculated on the best kinds of sites for obervatories: "The only remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest mountains above the grosser Clouds".

(Coulman 1985). Although telescope obervatories are sited at high altitudes, variation in refractive index in the atmosphere above them can lead to severe distortion of the wavefronts coming from the stars. The resultant images are shifted and broadened to sizes many times larger than the diffraction limit as shown above. This broadening process is referred as the atmospheric seeing. The traditional way to characterize image degradation is to measure the full width at half-maximum (FWHM) intensity of a star at the focus of the telescope. The image degradation produced by atmospheric turbulence is characterized by Fried's parameter r_0. (Fried 1966) and the image size is given by ~ λ/r_0.

3. The atmospheric turbulence and seeing effects

Atmospheric turbulence has long been recognized as one of the most significant factors limiting the performance of the optical system. These optical systems include imaging system like telescopes, laser beam projection system and optical communication system. When the ground objects were photographed from high altitudes, soon it was realized that there was a limiting resolution dictated by the atmosphere. Even though the imaging optics was good enough, the film or detector resolution fine enough and the platform stable enough, this limit can be approached but cannot be exceeded. In a similar manner, it was found that a well collimated beam of thin ray from sources like laser had spread into a small circle when it had passed through the atmosphere. Turbulence with its associated random refractive index inhomogeneities in the atmosphere distort the characteristics of light travelling through the atmosphere and limit the resolution with which an object can be viewed through the atmosphere. The limitation is due to warping of isophase surface and intensity variation across the wavefront which prevent all portions of the lens from "working to-gether" (Fried 1966). The disturbance takes the form of distortion of the shape of the wavefront and variations of the intensity across the wavefront. The quality of astronomical image is generally dependent on the phase fluctuations introduced by the atmosphere and the amplitude fluctuations across the wavefront are usually weak. Structure functions of the refractive index and phase fluctuations are the main characteristics of the light propagation through the turbulent atmosphere. Currently the Kolmogorov-Obukhov model of turbulence (described by a power-law spectrum for the so-called inertial intervals of wave numbers) is accepted as the most reasonable one for astronomical purposes.(Tatarskii 1993).

Although the large aperture telescopes are efficient light collectors, they are not able to resolve objects any better than a small size telescope of aperture size r_0. The best sites in the world have seeing in the order of 0.5 arcsec and the r_0 value of about 20 cm; therefore the best telescope in the world resolve no better than a good amateur astronomer's 8-inch telescope in the visual band (Gavel 1994). However, under favourable circumstances, it can be diffraction limited in the infrared. (Roddier 1981).

Seeing is the total effect of distortion in the path from the source like star and until it reaches the detector in the telescope. Distortion from the atmosphere comes from different layers. The three main contributing layers are: the free atmosphere above 1km, the boundary layer which includes the first kilometer and the surface layer which is a few meters above the ground. The other two contributing elements are the dome seeing and the mirror seeing.

Degradation of the seeing takes place predominantly in the upper atmosphere (between 1 to 10 km), in the dome boundary layer and inside the telescope enclosure. The effects of boundary layer turbulence have received attention to identify the best location on the site, the optimum height of telescope above ground, and the best shape of the telescope enclosure. Mirror seeing is an important source of image spread and amounts to 0.5 arcsec for 1 deg C difference. It is found that if the primary mirror is kept 1 deg below the ambient it suppresses the mirror seeing. (Iye 1992). The dome seeing is marginally significant, four to five deg C difference in temperature between outside and inside the dome degrades the seeing by 0.5 arcsec. (Racine 1991). When the wind speed is high, it deteriorates the seeing. The surface layer contribution can be a significant factor and it has to be measured. There may be substantial benefits in placing the telescope on raised platforms. (Marks 1996).

As seeing plays a crucial role in telescope throughput, care should be taken in selecting the best site possible. It is well known that for many purposes the power of a telescope is proportional to the primary collecting area divided by the solid angle formed by the image, thus a 2.5-m telescope with 0.5 arcsec image is equivalent in performance to a 5-m telescope with 1 arcsec image (Woolf 1982).

4. Overcoming the limitation of the atmosphere and seeing

Adaptive optics (AO) removes the wavefront distortions introduced by the earth's atmosphere by means of an optical component which is introduced in the light path and which can introduce controllable counter wavefront distortion which both spatially and temporally follows that of the atmosphere. Although this technique was first proposed by Babcock, it could not be implemented until recently because of the technological and cost limitations. The main components of AO system are wave front sensing, wavefront phase error computation and control of a flexible mirror whose surface can be electronically controlled in real time such that a conjugate surface is created such that the distortion created by the atmosphere is compensated. To achieve this, a reference source is needed to measure the wavefront errors by means of a wavefront sensor. Even if the compensation for atmospheric distortion is partial, improvement in the image quality can be achieved. These are the low order AO systems in which fast tip-tilt correctors or image stabilization devices able to correct atmospherically induced image motion. Low order systems are limited to two Zernike modes (x and y tilt). To remove high frequency errors, higher order system compensating many Zernike mode is required.

5. Wavefront sensing

There are three types of wavefront sensors; the Shack-Hartman sensor, curvature sensor and the shearing interferometer sensor. In the Shack-Hartmann sensor, an array of small lenslets form an array of images whose positions are measured to give the full vectorial wavefront tilt in the areas of the pupil covered by each lenslet. The dimension of the lenslets is often taken to correspond approximately to r_0. As the r_0 value keeps varying (seeing varies over the duration of observations) a minimal number of lenslet array for a given aperture size is required. The test consists of recording the ray impacts in a plane slightly before the focal plane. If optics were perfect, the recorded spots would be exactly distributed as the position of lenslets but on a smaller scale. Due to aberrations, light rays are deviated from their ideal direction, producing spot displacements. The amount of displacement is a measure of the deviation of the ray, which is also the deviation of the local wavefront slope since rays are normal to the wavefront. The curvature sensing is a variation of a Hartmann theme (Roddier 1990). This is a differential Hartman technique in which the spot displacement can be inverted. It is easy to see that if the ray impacts are recorded on the other side of the focal plane, the displacement occurs in the opposite direction. Hence, by comparing spot displacement on each side of the focal plane one can double the test sensitivity. The difference between the two spot displacement is a measure of wavefront slope independent of the mask irregularities. Both the local wavefront slope and local wavefront curvature can be mapped with the same optical setup, doubling the number of reconstructed points on the wavefront.

By laterally shifting (or shearing) the wavefront and mixing it with itself interference patterns are obtained which correspond to the wavefront tilt in the shear direction. But it is necessary to make two orthogonal measurements to assess the full wavefront tilt.

An implementation of lateral shearing interferometer using Babinet compensator (BC) is developed and used by Saxena (Saxena 1981,82). The necessary optical setup used is similar to that of a single beam lateral shearing polarizing interferometer. In such an arrangement, cone of light passing through the BC will produce fringe pattern due to the different phase change introduced between the extra-ordinary and the ordinary vibrations at different points during the oblique passage of the ray. This sensor is very compact and rugged to use and it is planned to use this as the sensor for our AO program.

6. Wavefront error computation and correction of wavefront distortion

Basically, phase reconstruction methods can be categorized as being either zonal or modal, depending on whether the estimate is phase value in a local zone or a coefficient of an aperture function. Whether the estimation is modal or zonal, its objective is to find the relationship between measured values and the unknown wavefront. For example, in curvature sensing, the two out of focus images taken are subtracted and the sensor signal is computed. Then the Poisson equation is solved numerically and the first estimate of the aberrations by least squares fitting Zernike polynomials to the reconstructed wavefront is obtained. There can be variations to the above methods but the basic principle is same for other sensors also.

Once the wavefront distortion is known, then a conjugate shape can be created using this data by controlling a deformable mirror. It is typically composed of many actuators in a square of hexagonal array. Deformable mirrors employ piezoelectric, electrostrictive or magnetostrictive devices. The primary parameters of deformable mirror based AO system are the number of actuators, the control bandwidth and the maximum actuator stroke. The mirrors can be segmented mirror or continuous faceplate mirrors. Actuators are normally push-pull type. For curvature sensing, bending moment type actuators are used. These mirrors are difficult to fabricate and cost also is high. The number of actuators are normally more than fifty hence there is a need for controlling all the actuators nearly simultaneously. The frequency of control of the surface of the mirror is about 1 khz. The high cost of the system and the complexity prevents the common use of AO system.

Presently, flexible mirrors micromachined in silicon is being manufactured for use in AO system. An integrated electrostatically controlled adaptive mirror should combine the advantages of a micromachined device, such as low cost, integrated circuit compatibility with high optical quality. Unlike the piezoelectric actuators, these micromirrors exhibit no hysteresis, making them easier to control. They operate at low voltages and consume very little power. Even though not many mirrors of this type is widely available, research in this area will yield results soon (Krishnamoorthy 1997).

7. Conclusion

If the cost of the AO system is not high, then even existing telescopes can be fitted with AO system to give corrected images. The advantage of improving the image size and resolution using AO technique will make the medium size telescope more productive and the big size telescopes diffraction limited capability. This will reduce the observing time, improve the throughput of high resolution spectrographs and it will enable new exciting programs like finding planetary system around stars and high resolution imaging.

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