Print ISSN: 0976-2876 Online ISSN: 2250-0138

Available online at: http://www.ijsr.in

INDIAN JOURNAL OF SCIENTIFIC RESEARCH

DOI:10.32606/IJSR.V14.I1.00013

Received: 26-04-2023 Accepted: 25-07-2023 Publication: 31-08-2023

Indian J.Sci.Res. 14 (1): 77-84, 2023 Review Article

ENHANCING THE GROUND-BASED TELESCOPE PERFORMANCE UTILIZING THE CONCEPT OF ADAPTIVE OPTICS AND ITS IMPLICATIONS IN THE ONGOING THIRTY METER TELESCOPE PROJECT

KSHITIJ SRIVASTAVA[a] **AND ANCHAL SRIVASTAVA**[b1]

[ab]Department of Physics, University of Lucknow, Lucknow, U.P., India

ABSTRACT

Whenever an optical wavefront passes through the turbulent or turbid media it gets distorted as a result of which no faithful information is obtained. The passage of light from an astrophysical object through atmospheric turbulence leads to degradation in the image quality and causes significant blurring. Adaptive optics is a technique that deals with correcting the aberrated wavefront and reconstructing the original wavefront. It employs the use of a wavefront corrector to compensate for the optical aberrations, in a closed loop with the wavefront sensor which quantifies and measures the shape of the wavefront and passes the information or signal to the deformable mirror to change its shape according to the imperfections in the wavefront. Laser guide stars are used as a probe to sample the atmospheric turbulence and increase the sky coverage appreciably. One prominent application of adaptive optics is within the realm of ground-based astronomy. Due to its low cost, longer lifetime, flexibility, and ease of repair, it is considered an alternative to space-based telescopes.

KEYWORDS: Adaptive Optics, Ground-Based Telescope, Thirty-Meter Telescope, Laser Guide Star

The atmosphere of the Earth acts as a blurring window between the observer on the Earth and the rest of the universe. Earth's atmosphere nurtures life on Earth, gives protection against harmful radiation, and maintains habitable pressure and temperature. But the turbulence of the Earth's atmosphere, which is caused by the mixing of air of different temperatures, appears as a culprit for an astronomer because it distorts the light coming from an astronomical object. This turbulence causes the stars to twinkle which puts hindrance in observing the minute details due to the blurring of an astronomical image (Travouillon *et al.*, 2021). Turbulence also spreads out the light from the object and makes it appear as a fuzzy blob rather than a point. Therefore, the perfect plane wave coming from the star at infinity becomes aberrated. To cope with such aberrations the technique known as "adaptive optics" is utilized to correct random optical wavefront distortions in real time.

The concept of adaptive optics was proposed by Horace Babcock in the seminal paper "The Possibility of Compensating Astronomical Seeing" in 1953. In 1957 V.P. Linnik independently proposed the idea of using a segmented mirror and an artificial guide star. The concepts proposed previously were shaped into reality when DARPA (Defense Advanced Research Projects Agency) utilized them for satellite imaging and the first successful demonstration of the technique was made in a laboratory with Real-Time Atmospheric Compensator (RTAC) in 1973 (Hardy J.W., 1998). Enthralled by the success of the DARPA's adaptive optics program astronomers started applying the technique in the field of astronomy. In the subsequent years with the development of new wavefront sensors, laser guide systems, and related concepts, adaptive optics became the prominent technique for astronomical imaging and is now deployed in various observatories around the globe.

CONCEPT OF ADAPTIVE OPTICS

Adaptive optics is a technology that compensates the distortions or aberrations in the incoming wavefront and hence enhances the performance of an optical system. Pertaining to ground-based astronomy, adaptive optics is used to correct for rapidly changing image distortions owing to the turbulence in the Earth's atmosphere (Max C.E., 2012). Stated differently, adaptive optics deals with the manipulation of an imperfect wavefront to restore its original form as it was before encountering any sort of disturbance.

The key components of an adaptive optics system include a wavefront corrector, a wavefront sensor, a control system, and a guide star (natural or artificial). The distortions in the wave front are first compensated with the help of a Deformable Mirror (DM). The light is then partially directed towards the wave-front sensor which measures in real time the remaining optical aberrations that need to be corrected. A servo system continuously modifies the DM shape in an effort to achieve zero aberration. All these components work in a

---

[1]**Corresponding author**

closed loop. The light from a guide star is used as a probe to measure the aberrations and blurring caused by the local atmosphere. The general adaptive optics system is illustrated in Figure 1.

(www.ctio.noirlab.edu/~atokovin/tutorial/intro.html)

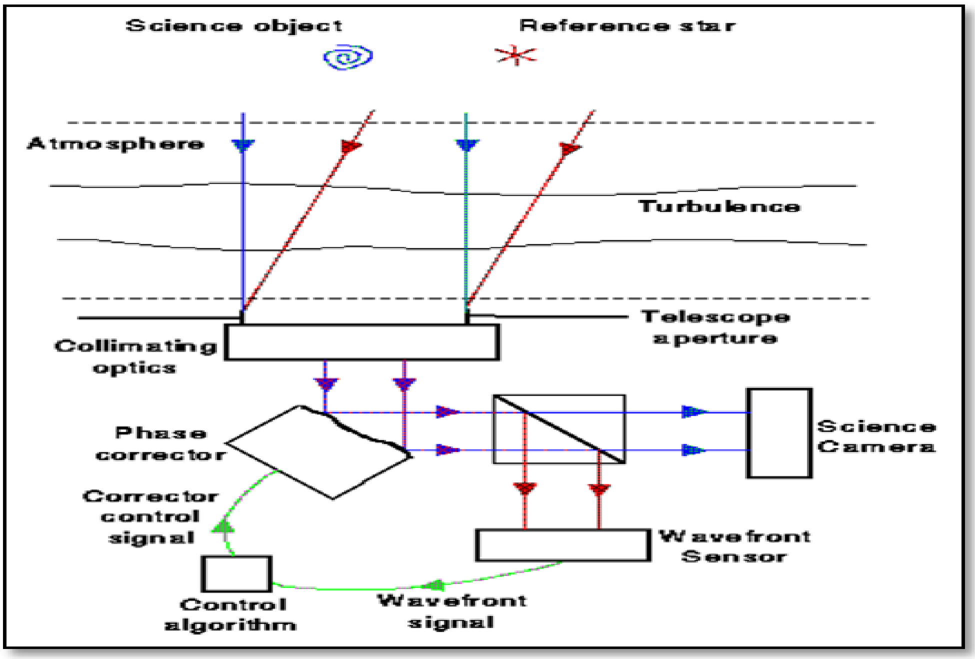

Figure1: The general Adaptive optics (AO) system

REFINING OPTICAL DISTURBANCES: HARNESSING DEFORMABLE MIRRORS FOR TURBULENCE CORRECTION

Deformable mirrors (DM) are the mirrors whose surface can be deformed and by utilizing this feature of the DM the wavefront can be controlled and optical aberrations can be corrected. In adaptive optics, deformable mirrors are used in combination with wavefront sensors and real-time control systems. The number of actuators affects how many degrees of freedom (wavefront inflections) the mirror can correct.

Each part of the beam needs to be corrected in real time if the distortion in the wavefront is high, which is a result of heterogeneous light propagation media like atmospheric turbulence, intricate optical systems, and biological cells. Multichannel correctors are devices that function in this way, such as segmented mirrors or continuous faceplate DMs.

A BRIEF OVERVIEW OF THE DIFFERENT TYPES OF DEFORMABLE MIRROR

Segmented Deformable Mirrors

Segmented deformable mirrors are made up of an array of compactly spaced mirror segments. They have individual flat segments that can move in tip-tilt and piston motion with three actuators or more driving each segment, or just in an up-down piston mode (Tyson R.K., 2000). These segment mirrors can be designed in a square, hexagonal, or circular shape. The main benefit of segmented mirrors is that they make use of a collection of elementary mirrors that are all identical and easily repairable. Compared to maintaining a continuous-surface mirror, replacing a single segment is much less expensive and less challenging. The creation of segmented mirrors with more than 10,000 segments is now possible with modern technology (Tyson R.K., 2011).

Continuous Faceplate Mirror

A continuous faceplate mirror consists of a single mirror section and a number of actuators. Continuous faceplate mirrors can have force or displacement actuators behind the faceplate, which push and pull on the surface to deform it (Tyson R.K., 2000). Displacement actuators include piezoelectric or magnetostrictive actuator and electromechanical or hydraulic actuators are the examples of force type actuator.

The majority of popular actuators for deforming optics use the piezoelectric effect, which is essentially the generation of a strain-inducing stress under an applied electric field. One such substance, Lead Zirconate Titanate (also known as PZT) exhibits strong piezoelectric effect. Due to the negligible edge diffraction, continuous DMs have the benefit of producing extremely crisp images.

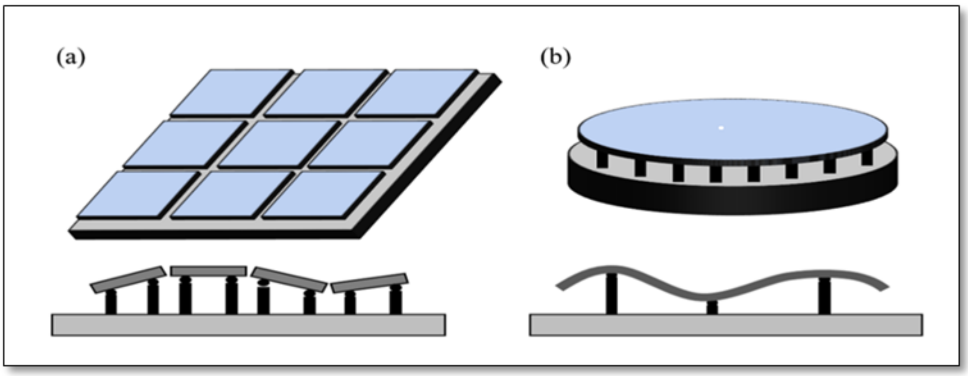

Figure 2: (a) Segmented and (b) continuous faceplate Deformable Mirrors

Bimorph Mirror

Bimorph mirror is formed by joining two piezoelectric ceramic wafers which are oppositely polarized parallel to their axes. Between the two wafers, an array of electrodes is deposited. Surfaces on the bottom and front are grounded. The front surface serves as a mirror. A wafer contracts locally and laterally as the other wafer expands in response to a voltage applied to an electrode, causing a bending. The bimorph mirror's local radius of curvature varies proportionally to the applied voltage. These DMs are also called curvature mirrors. (www.ctio.noirlab.edu/~atokovin/tutorial/part2/dm.html)

REQUIREMENTS OF A DEFORMABLE MIRROR

1. **Dynamic Range:** The typical astronomical ‘stroke’ varies with telescope diameter. For a 10- m telescope, stroke is of the order of few microns likewise for a 30 m telescope, it is of the order of 10-15 microns.
2. **Temporal frequency response**: Deformable Mirror is required to respond more quickly than a fraction of the coherence time.
3. **Influence function**: They can be used to determine the actuator signal pattern necessary to produce a certain desired mirror shape.
4. **Hysteresis of actuators:** When the same voltage is applied in reverse, it is expected that the actuators should return to their original position.
5. **Power dissipation:** Heat is unfavourable (poor for ‘seeing’, distorts mirrors), therefore too much resistive loss in actuators is undesirable. Therefore, a lower voltage is preferable since the power dissipation is less in this case.
6. **Deformable Mirror size:** It is not too crucial for small diameter telescopes but for big telescopes such as TMT (Thirty Meter Telescope), the big deformable mirrors are needed (at least 30 cm). (https://www.ucolick.org/~max/289/Lectures%202016/Lecture%208%20Deformable%20Mirrors/Lecture8_2016.v1.pdf).

COMMONLY USED WAVE-FRONT SENSORS IN ADAPTIVE OPTICS

The aberrations of an optical wavefront are measured using a Wavefront Sensor (WFS). In other words, wavefront sensor is an instrument which is used for measuring the shape of a wavefront.

Shack-Hartman Wave-Front Sensors

A lenslet array is used to split an incoming beam into an array of smaller beams in a Shack-Hartmann wavefront sensor, which is intended to measure wavefront deviation from a reference wavefront. The Shack-Hartman Wavefront Sensor (WFS) functions based on the principle of the interaction between radiation and a photodetector subsequent to its traversal through a grid of microlenses known as the lens raster. This lens raster consists of a collection of identical lenses, termed subapertures, whose function is to partition the incoming wavefront into smaller segments, focusing them onto a receiver typically represented by a CCD (Charge-Coupled Device) array. In the scenario where the incident wavefront is flat, the focused images align precisely within the predetermined grid due to the systematic arrangement of the lenses. Conversely, distortions present in the incoming wavefront lead to the displacement of these focused images from their expected values. The term "Hartmanogram" is used to describe the image of these focal spots (Matital *et al.*, 2018). The local slope or tilt of the wavefront at the site of lenslet is proportional to the amount of shift in the centroid of each spot. It is possible to reconstruct the wavefront phase using the collected spot displacement data.

Lateral Shearing Interferometer

In adaptive optics (AO) the beam must be self-referenced because there isn't a plane wave reference beam available. In a shearing interferometer, the beam is split into two beams by amplitude division, which are then superimposed and mutually displaced to create an interference pattern. To create interferences, the Lateral Shearing Interferometer combines the wavefront with a shifted version of itself (Roddier F., 1999). The incoming wavefront is divided into two parts, and one of them is shifted by a shearing device. The shear refers to the distance through which the two wavefronts are displaced. The phase difference over the shear distance in the shear direction is measured by the interference fringes' position.

Curvature Sensor

Roddier in 1988 devised and created the curvature sensor (CS) to conduct Wavefront curvature measurements rather than Wavefront slope measurements. The source is captured in the focal plane of the telescope with focal length ‘f’. Two ‘out of focus’ detector arrays make up the CS (refer Figure 3). At a distance ‘l’ before the focal plane, the first detector array captures the irradiance distribution in plane P1. In the second, at the same distance ‘l’ behind the focus, the irradiance distribution in plane P2 is captured. A local WF curvature in the pupil causes an excess of light in one plane and a deficiency in the other. To reimage the pupil, symmetry is achieved by using a field lens. The planes P1 and P2 can alternatively be thought of as the two defocused pupil planes (Roddier F., 1999). A local wave-front curvature causes one image to be brighter and the other to be darker in the geometrical optics approximation, the normalised intensity difference is expressed as

$$\frac{I_1(\mathbf{r}) - I_2(-\mathbf{r})}{I_1(\mathbf{r}) + I_2(-\mathbf{r})} = \frac{\lambda f(f-l)}{2\pi l}\left[\frac{\partial\varphi}{\partial n}\left(\frac{f\mathbf{r}}{l}\right)\delta_{\mathrm{c}} - \nabla^2\varphi\left(\frac{f\mathbf{r}}{l}\right)\right],$$

In the above equation, first term represents the phase gradient at the edge of the aperture. δ_c is the ‘edge function’.

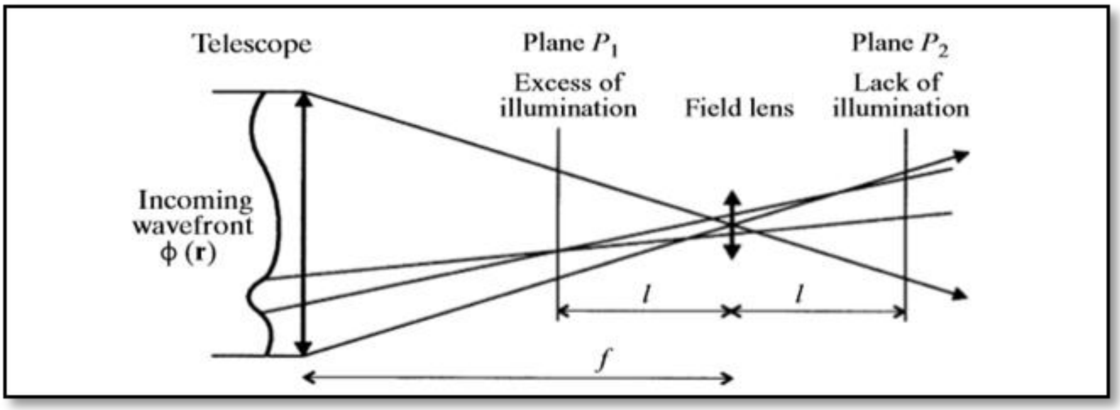

Figure 3: Principle of the Curvature Sensor

WAVE-FRONT RECONSTRUCTION

A reconstruction of the wavefront from the data is necessary for the three wavefront sensors shown in the preceding section. Determining the phase of a wavefront from a map of its gradient or Laplacian is the general issue. Consider a vector ‘**S’** whose length is twice the number of sub-apertures ‘N’ for a given Shack-Hartman wavefront sensor and equal to ‘N’ for a curvature sensor. This vector **S** can be used to represent the measurements i.e. the data obtained from the wavefront sensor. The unknowns i.e. the wavefront, are described as phase values on a grid by the vectorΦ. It is assumed that, at least to a first approximation, the relationship between the measurements and unknowns is linear. By multiplying matrices, a linear relation may be expressed in its most generic form.

$$\mathbf{S} = \mathbf{A}\boldsymbol{\Phi}$$

Where, **A** is a matrix called as ‘interaction matrix’. In actual AO systems, the interaction matrix is determined empirically by applying all conceivable signals to a DM and observing how the WFS respond. The inverse procedure viz. obtaining the wave-front vector from the data is carried out using a reconstructor matrix (Roddier F., 1999) or a command matrix denoted by **B**:

$$\boldsymbol{\Phi} = \mathbf{B}\mathbf{S}$$

LASER GUIDE STAR

For the real-time analysis of the wavefront, adaptive optics systems require a bright guide star within the isoplanatic field. If the target has a bright, point-like centre structure, such as an active galactic nucleus or a young star object, it may be feasible to utilise the target itself to sense the wavefront. Unfortunately, a lot of astronomical objects are either extended, dim, or both. One way to overcome this issue is to observe a bright star nearby the target, but this natural guide star needs to be within the target's isoplanatic angle (http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/telescopes/phy217_tel_adaptive.html), or else the target and guide stars would be sampling different atmospheric turbulence. The isoplanatic angle is extremely small (only few arcseconds) in the optical region of the spectrum, and it barely increases to a few tens of arcseconds in the infrared. Therefore, only a very small portion of the sky (on the scale of 1–10%) can realistically be corrected using adaptive optics with natural guide stars. The only way to significantly increase the sky coverage is to create a ‘laser guide star’, an artificial guide star that is produced close to the target using a laser.

The atmosphere deflects a laser beam twice, once in its upward journey and once in its downward journey, whereas a star beam is only deflected once. This indicates that the LGS is unable to detect tip and tilt. The upward and downward tilts totally compensate if LGS is projected from the main telescope, and the LGS image is steady in the telescope focal plane.

Types of Laser Guide Star

Rayleigh scattering of light by air molecules at moderate altitudes (up to 20 km) and resonance scattering from sodium atoms at an altitude of roughly 90 km are the two methods that have been tested for the creation of laser guide stars. Resonance scattering happens when an incident laser is tuned to a particular atomic transition.

The two types of laser guide stars are

1. **Rayleigh Beacon:** Rayleigh beacon creates an artificial star at an altitude of roughly 20 km by using the Rayleigh back-scattering of light from molecules in the lower atmosphere.
2. **Sodium Beacon:** The sodium beacon employs a laser tuned to the yellow sodium D lines at a wavelength of 589 nm. At a height of about 90 km, this excites sodium atoms (deposited by micrometeorites) in the mesosphere, which subsequently re-emits the light to create an artificial star.

The Formation of Artificial Guide Stars

The fundamental principle involved in the formation of an artificial guide star is as follows – “The laser which is located near the telescope transmits a beam into the atmosphere and points it very close to the object of interest. The column of specific diameter, length and altitude backscatters the light which is observed as an artificial star. (Ageorges *et al.*, 2000)” Figure 4 illustrates the laser guide star in action.

Figure 4: Left: Photograph of a laser beam emanating from the 8.2 m Very Large Telescope in Chile. Right: Photograph of the laser guide star produced by the ALFA adaptive optics system on the Calar Alto 3.5 m telescope in Spain. The sodium beacon is the point-like image at the centre; the plume to the right is the Rayleigh back-scattered light.

A GLIMPSE INTO OUR EYES OF THE SKY: THE THIRTY METER TELESCOPE (TMT)

The Thirty Meter Telescope, which will cost over $2.6 billion to build and involves cooperation from India, China, Japan, Canada, and the US, will be the largest telescope ever constructed by the world. With crucial support from Indian scientists, engineers, and industries, the world's largest "eye on the universe", an optical, infrared, 30-meter telescope (TMT), is quickly coming into being at its proposed location on Maunakea in the US state of Hawaii. (https://www.tribuneindia.com/news/science-technology/coming-up-in-hawaii-with-indian-help-worlds-largest-eye-on-the-universe-462218).

An Insight into the Thirty Meter Telescope and its Significance

The Thirty Meter Telescope is a member of a new class of extremely large telescopes that will enable us to see cosmic objects with unrivaled sensitivity, and see farther into space. The primary mirror will be made up of 492 hexagonal mirrors, supported by an additional 1,476 actuators, 2,772 high-precision edge sensors, and 10,332 smaller actuators (https://www.tribuneindia.com/news/science-technology/coming-up-in-hawaii-with-indian-help-worlds-largest-eye-on-the-universe-462218). These components will align all the mirrors, identify even the tiniest deviations, and correct them so that clear images can be obtained from far-off locations in the cosmos.

Observations from ultraviolet to mid-infrared wavelengths will be possible with up to 80 times the sensitivity of today's greatest telescopes because of its 30m diameter prime mirror. Modern adaptive optics systems will correct for Earth's atmosphere's blurring effects and produce images at infrared wavelengths that are four times clearer than JWST and more than 12 times sharper than those of the renowned Hubble Space Telescope.

Tremendous Potential of TMT in Discovering the Boundless Universe

One of the biggest ground-based observatories in the world, the Thirty Meter Telescope will open up new opportunities for observation in almost all areas of astronomy and astrophysics. Astronomers will work to increase our understanding in several important scientific fields, including:

1. Exploration of galaxies and large-scale structures in the early universe, including the time when the majority of stars and heavy elements were formed and the galaxies in our universe were first assembled
2. Spectroscopic examination of the “Dark Ages” when the initial sources of light and the first heavy elements in the cosmos were formed
3. Investigations of massive black holes across cosmic time
4. Exploration of planet-formation mechanisms and extrasolar planet characterization (https://www.tmt.org/page/science-themes)

Collaborating Academic Institutions and Observatories in the Development of TMT

The TMT International Observatory LLC (TIO) is responsible for creating and developing the Thirty Meter Telescope. TIO is an international non-profit collaboration between the California Institute of Technology, the University of California, the National Institutes of Natural Sciences of Japan, the National Astronomical Observatories of the Chinese Academy of Sciences, the Department of Science and Technology of India, and the National Research Council (Canada). The Gordon & Betty Moore Foundation has generously funded TMT, and the Association of Universities for Research in Astronomy (AURA) is a TIO Associate (https://www.tmt.org/page/partners).

India's Integral Role in Advancing the TMT Project

Indian institutions that are the major collaborators of the TMT project include the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune; the Indian Institute of Astrophysics (IIA), Bengaluru; and the Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital (https://www.tribuneindia.com/news/science-technology/coming-up-in-hawaii-with-indian-help-worlds-largest-eye-on-the-universe-462218). Along with the IUCAA, IIA, and ARIES, over 50 Indian industries are also making contributions to the megaproject through various components and the direct or indirect participation of over 200 scientists, engineers, experts, technicians, and other professionals.

Adaptive Optics in TMT

IRIS (Infra-Red Imaging Spectrograph) and MODHIS (Multi-Objective Diffraction-limited High-Resolution Infrared Spectrograph), the first two TMT scientific instruments, will be able to see in the near-infrared (IR) with diffraction-limited wavefront quality and great sky coverage with the help of the first light Adaptive Optics (AO) architecture which has been designed. The TMT first light AO subsystems and their components are undergoing design, prototyping, and fabrication work in the US, Canada, and France. Observers will need to plan their observations in advance to utilize TMT, NFIRAOS (Narrow Field InfraRed Adaptive Optics System), and the science instruments to their full potential (https://www.tmt.org/page/instruments-adaptive-optics).

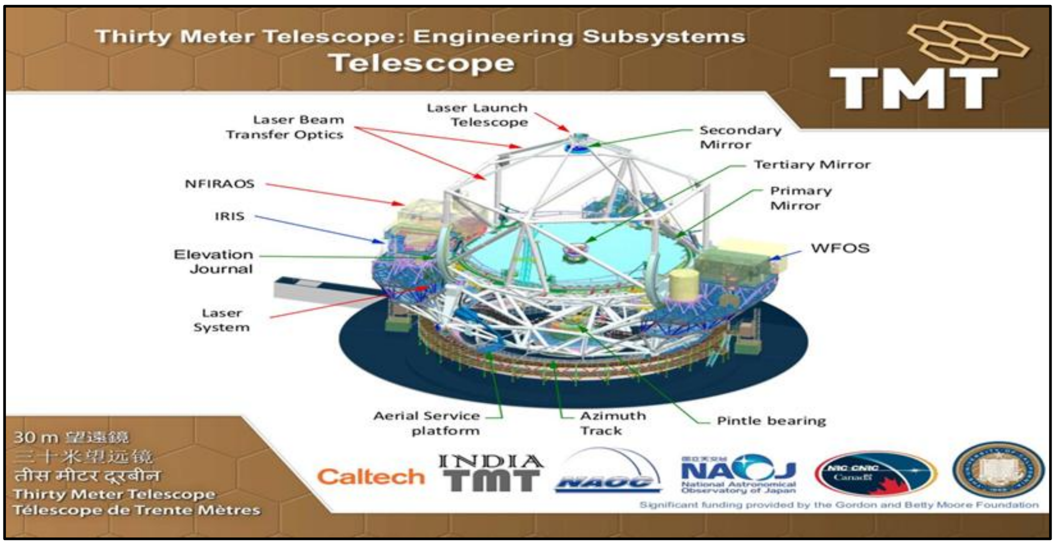

Figure 5: Thirty Meter Telescope

CONCLUSION

Adaptive optics (AO) is a technology that allows the manipulation of a wavefront in a controlled manner. It also encompasses the idea of restoration of the wavefront which becomes distorted while passing through the turbulent or dynamic media. The AO aims at mitigating the effects of a highly and rapidly variable atmosphere. Imaging through turbulence degrades the image quality and hence prevents astronomers from obtaining the minute details of the cosmos. AO has revolutionized the field of ground-based astronomy due to its fascinating results such as removing the blurring caused by the atmosphere, reducing significantly the optical aberrations, improving the angular resolution, allowing the world's largest telescopes to operate at their diffraction limit, etc.

The adaptive optics compensates for the distortions in a wavefront by utilizing an optical element known as a 'Deformable Mirror' (DM). This optical element has the ability to change the shape of its reflective surface in response to the control signal applied. The shape of the DM required to correct the distortions in the incoming wavefront is decided by the information gathered by the wavefront sensor by measuring the aberrations of an optical wavefront. These components are made to work in a closed loop and hence measure the quality of the wavefront and rectify the aberrations in real-time. The sky coverage is significantly increased by the creation of artificial stars using the laser beacon, often called as 'Laser Guide Stars' (LGS). To sample the atmospheric turbulence laser guide stars are used as a probe.

Adaptive optics finds its important application in the field of astronomy and astrophysics. The imaging and spectroscopy of extended objects such as the sun, planets, stellar envelopes, star-forming regions, etc. require extensive use of AO technology. The merging of AO with extremely large telescopes will open up new horizons for the discovery and study of deep-space objects. It will allow the observations of astronomical objects which were considered faint to date. The AO will also be implemented in the Thirty Meter Telescope (TMT) which is currently under construction with crucial contributions from Indian scientists and engineers and also contributions from various global partners.

ACKNOWLEDGEMENT

The authors are grateful to Dr. Prasanna Deshmukh, Engineer-C, Indian Institute of Astrophysics (IIA), Bengaluru and Mr. Amritanshu Vajpayee, Member, Akash Ganga: Centre for Astronomy, Mumbai, for the insightful discussion.

REFERENCES

Ageorges N. and Dainty C., 2000. Laser Guide Star Adaptive Optics for Astronomy. Proceedings of the NATO Advanced Study Institute on Laser Guide Star Adaptive Optics for Astronomy Cargese, France. Springer Science+Business Media Dordrecht: 23-24.

Hardy J.W., 1998. Adaptive optics for astronomical telescopes. Oxford University Press, New York: 14-21.

http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/telescopes/phy217_tel_adaptive.html, accessed 12 January 2023

https://noirlab.edu/public/products/handouts/handout014/

https://www.ctio.noirlab.edu/~atokovin/tutorial/intro.html, accessed 23 December 2022 https://www.tmt.org/page/instruments-adaptive-optics, accessed 05 February 2023.

https://www.tmt.org/page/partners, accessed 05 February 2023

https://www.tmt.org/page/science-themes, accessed 05 February 2023

https://www.ucolick.org/~max/289/Lectures%202016/Lecture%208%20Deformable%20Mirrors/Lecture8_2016.v1.pdf, accessed 10 February 2023

Matital R., Gorelaya A.V., Kukaev A., Venediktov V. and Fedorov E.A., 2018. Review of holographic wavefront sensors. 535.

Max C.E., 2012. Adaptive Optics: An Introduction : 1

Park B., 2018. Development of a Low Voltage and Large Stroke MEMS-based Lorentz Force Continuous Deformable Polymer Mirror System. Ph.D. Thesis, The University of Manitoba, Winnipeg, MB : 24.

Roddier F., 1999. Adaptive optics in astronomy. Cambridge University Press, Cambridge: pp.95-108.

The Tribune, 2022. Coming up in Hawaii with Indian help, world's largest 'eye on the universe,https://www.tribuneindia.com/news/science-technology/coming-up-in-hawaii-with-indian-help-worlds-largest-eye-on-the-universe-462218, accessed 12 February 2023.

Travouillon T., d'Orgeville C. and Bennet F., 2021. Adaptive Optics Branches Out. Scientific American, https://www.scientificamerican.com/article/adaptive-optics-branches-out/

Tyson R.K., 2000. Introduction to adaptive optics. SPIE Press, Bellingham, Washington USA: 83-84.

Tyson R.K., 2011. Principles of Adaptive Optics (3rd ed.). CRC press: 181.