The rolling surface of the Sun is periodically affected by dramatic explosive events releasing enormous amounts of energy in space, which when directed earthward can disrupt satellite operations, as well as terrestrial telecommunications and power grids. Prof Phil Goode, long time, and now former Director of Big Bear Solar Observatory, New Jersey Institute of Technology and Dr Dirk Schmidt at the US National Solar Observatory are working on the development of a new generation of adaptive optics for solar observations, which will help to provide a deeper understanding of the dynamics of the solar atmosphere and of the origin of solar storms in what is broadly called “space weather”.

Next generation adaptive optics for solar observation: a new view of the Sun

All observations of stars, planets and the Sun using ground-based telescopes suffer from the distorting effects of the Earth’s atmosphere, which dramatically affects the level of resolution achievable in remote object imaging and limits the amount of information obtainable using standard optical techniques. Air turbulence, especially close to the ground, causes stars to twinkle at night and planet and Sun images to blur when observed at high magnification through a telescope. One of the most important advances in ground astronomy, which came near the end of the last century, has been the development of methods to correct for the presence of the atmosphere – adaptive optics (AO) – used in the effort to push the image resolution toward its theoretical limit.

ASTROPHYSICS WITH ADAPTIVE OPTICS
In standard optical telescopes, the light from distant objects travelling through space and the Earth’s atmosphere is typically collected and focused by a large mirror, and a magnified image is then created for observation and recording in optically downstream focal plane instrumentation. The resolution of the image is determined by the quality and size of the primary mirror, and there is a fundamental maximum of resolution achievable with a given telescope, called the diffraction limit, which is proportional to the wavelength of the light collected and inversely proportional to the diameter of the mirror. In actual observations, however, atmospheric turbulence, created for instance by temperature gradients, can distort and jitter images, reducing their quality well below the diffraction limit. The standard adaptive optics (AO) system tries to correct these distortions by rapidly changing the shape of a single small (hand-sized) mirror surface to counteract the blurring effects of the atmosphere. All major solar observatories in the world are equipped with a single, deformable mirror (DM) AO system. Lying just before the focal plane instrumentation, adaptive optics uses a wavefront sensor to characterise the optical aberrations caused by the atmosphere, and a computer calculates the optimal deformation that should be applied to the mirror to cancel the wavefront error. The whole process happens very quickly, with the image correction applied on the order of a 1,000 times per second. The use of single DM adaptive optics restores image details approaching the diffraction limit, but only in a narrow angular regime (~10") or about 7000 km on the surface of the Sun near the centre of field of view.

The correcting of wavefront distortion allows scientists to build and exploit larger and larger telescopes to observe ever finer details of remote objects. This technology has been steadily improving over the last twenty years, and, today, adaptive optics is considered an indispensable tool in astronomical observations with large telescopes.

SPACE WEATHER
The main limitation of existing adaptive optics systems is in the use of a single deformable mirror, which is unable to restore fine image details over a wide field of view. This is caused by the fact that turbulence affects light in different ways depending on the distance from the ground while its path through the atmosphere expands through the troposphere.
Adaptive optics is used to remove atmospheric distortions in astronomical images, to exploit the resolution capabilities of large telescopes.

Astronomy

Below: Schematic of Shack-Hartmann Adaptive Optics.

When using a single mirror, all solar telescopes with AO have very good image correction in a small field of view. In Big Bear, users of single DM AO have two choices—the standard very good image over a small field or a medium-quality correction over a wider field (more like 20000 km on the solar surface). This issue is especially problematic in the case of solar observations, particularly in the study of the powerful explosive events, like flaring and coronal mass ejections caused by the Sun’s magnetic field dynamics, which appear to start over wide regions of the solar atmosphere all at once, which is the attraction of the medium quality, wider field single DM AO. These phenomena are important drivers of what is broadly called “space weather”, i.e., the variable conditions on the Sun and in the Solar System, including the solar wind, that can influence the performance of technology on Earth and in its vicinity, potentially causing damage to critical infrastructures, like power grids and satellite communication. In this case, being able to work at the diffraction limit and to detect fine details over wide areas of the Sun’s surface, to understand the cause and evolution of these solar events, is a crucial and long sought-after goal.

LOOKING AT THE SUN: MULTI-CONJUGATE ADAPTIVE OPTICS

Prof Phil Goode and Dr Dirk Schmidt lead an international collaboration involving the Big Bear Solar Observatory (BBSO) of the New Jersey Institute of Technology, the US National Solar Observatory and the Kiepfer-Institut für Sonnenphysik (KIS) in Germany, devoted to developing and exploiting adaptive optics techniques specifically for solar observation. They have created an adaptive optics system, which is capable of providing very good image corrections over wide observation fields (~20,000 km). The technique they have created, generically referred to as multi-conjugate adaptive optics, exploits three deformable mirrors operating simultaneously with each correcting turbulence within different altitude layers of the atmosphere, utilising a single wavefront sensor to probe the optical aberrations over the targeted field of view and guide the deformable mirrors. Their system, called Clear (https://cuna.nso.edu/clear), has been installed and widely tested on the Goode Solar Telescope (GST) at BBSO, which, with a 1.6 m clear aperture, is currently the highest resolution solar telescope ever built and has been in regular operation for nine years. Extensive work carried out in 2016 and 2017 has shown that the Clear system provides imaging capabilities that are far superior to those of existing single-mirror adaptive optics setups for solar observation in a variety of the Sun’s and Earth’s atmospheric conditions. For instance, comparable image quality can be obtained using the Clear system for both active (sunspots) and quiet regions of the solar photosphere roughly trebling the corrected field over that from a single DM. The trebling is often the difference between fully resolving the whole, rather than part of large-scale solar phenomena. These observations represent the first-ever MCAO observations of the Sun showing such an apparent, wide-field elimination of the deleterious effects of atmospheric turbulence.

CHALLENGES AND OUTLOOK

The development of Clear paves the way for next generation studies of the dynamics and evolution of the solar storms so that one can address many basic questions that have so far eluded observational answers. Despite the impressive results obtained to date, however, multi-conjugate adaptive optics remains at an experimental stage, at least for the time being, owing to its complexity and hardware requirements. A number of issues need to be addressed before this technique reaches the levels of robustness and reliability required for routine observations. The needs for better characterisation and optimisation are needed to handle continuously developing images of the Sun’s surface for times longer than a few minutes, as most dynamic solar processes are characterised by longer lifetimes. The successes at Big Bear are built on earlier pioneering work at NSO and KIS. The successes at Big Bear will lead to a wider adoption of multi-conjugate adaptive optics in new telescopes, including the 4 m clear aperture Daniel K Inouye Solar Telescope (DKIST), currently under construction at Haleakala, Maui, Hawai’i, will bring this technique to maturity in the coming years, and potentially transform solar observations and, thus, our understanding of the powerful transient phenomena occurring on the surface of the Sun. The DKIST project director is Thomas Rimmele, who has been the key collaborator in all three generation of AO in Big Bear.

Despite the impressive successes of space-based telescopes, like the Hubble Space Telescope, ground-based observations continue to play a crucial role in observational astronomy. What are the advantages of ground-based astronomy compared to space telescopes?

The advantages of ground-based telescopes are as follows:

1) Resolution: Largest aperture telescopes are ground-based because mass and size are not such critical considerations.
2) Instrumentation: More complex and sophisticated instrumentation are ground-based because mass and size are not such critical considerations.
3) Repair: If something goes wrong with a ground-based telescope, engineers can tackle the problem(s) without a space suit.
4) Cost: Space missions are vastly costlier because the telescope has to be built with the realisation that post facto correction is extremely expensive (if it is even possible).

Then there is the cost of placing the telescope in orbit.

What are currently the most pressing questions in solar physics, and how will the development of larger telescopes, like DKIST, help to answer them?

We at the dawn of having the spatial and temporal resolution to be able to observe the Sun’s dynamics on their fundamental scales from the surface to corona. The GST can probe at the edge in the Sun’s surface and lower atmosphere, while DKIST will have more than twice the resolution of the GST and the DKIST will also reach out to the corona. Currently, we do not understand the fundamental origin of space weather. More broadly, the Sun has the largest scale magnetic field that we can resolve and understanding how it drives is a basic problem of wide interest.

What were the main technical challenges you encountered in realizing the development of multi-conjugate adaptive optics and the Clear system?

A solar MCAO system cannot be bought off the shelf, but it is a custom development that involves various state of the art technologies that are combined and need to work together flawlessly in a complex system. Challenges involve both fast digital imaging hardware and fast, parallel processing computers as well as the quality of the optical components, in particular of the DMs and wavefront sensors. Designed and built as an experimental pathfinder, Clear has allowed us to test and optimise critical parameters and algorithms over the years.

Is Clear restricted to the observation of the Sun, or can it be extended to study stars and other astronomical targets as well?

Clear is solely for the Sun. There are two MCAO systems in the world operating on telescopes. GeMS is in near IR on the 8m Gemini’s South nighttime telescope and Clear. Clear uses what is called a Shack-Hartmann WFS system, which is different than GeMS. Furthermore, GeMS uses laser and natural guide stars, while Clear uses features on the Sun’s surface as ‘guide stars’.

Clear has been the product of a successful and long-standing collaboration involving the US and Germany. What is the importance of this international aspect of the project, and how do you see the role of international collaborations develop in current and future observational astronomy?

As scientific technologies become more capable, they also become more complex and expensive (both hardware and implementation). It is most cost-effective and efficient to work in teams across institutions and national borders. This serves the interests of the taxpayers who ultimately support the scientific enterprise that underlies progress, like MCAO, and derive its economic and intellectual benefits.

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