Adaptive optics widens its view

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A multi-conjugate adaptive optics demonstrator has delivered astronomical images of remarkable sharpness covering a very large field of view.

Astronomical images obtained with ground-based telescopes are severely affected by atmospheric turbulence, which degrades the resolution capability by 10 to 50 times with respect to the theoretical limit. The light wavefront incoming from a distant object and crossing the Earth’s atmosphere is progressively distorted by tiny differences in the refractive index of the air due to temperature fluctuations. When reaching the telescope, the wavefront is corrugated and produces a blurred image of the observed object at the focal plane. The loss of the finest details in astronomical images prevents astronomers from accessing crucial information about the intrinsic nature of the physical processes involving all classes of objects, from planets to the most distant galaxies. This problem doesn’t affect space-based telescopes, but they are limited in size and much more expensive than those located on the ground.

To overcome this problem, a technique called adaptive optics (AO) has been developed for astronomical instrumentation. AO corrects atmospheric turbulence in real time by using a mirror that deforms its surface and flattens the distorted incoming wavefront. The amount of deformation is determined by a wavefront sensor, which looks at a star near the observed object. The correction quality depends on the turbulence conditions (seeing) during observations and works better at longer wavelengths (near infrared) where the atmosphere looks calmer. The main limitation of AO is that the correction is optimal only in the direction of the sensed star, and nearby objects are corrected only partially, since their wavefronts cross a different volume of atmosphere. Multi-conjugate adaptive optics (MCAO) has been proposed for extending the correction to larger fields.

MCAO senses and corrects for the entire atmospheric volume probed by the observed field of view (FoV). First, several sensors observe a few stars. The tridimensional structure of the turbulence is then reconstructed (tomography), and the correction is applied using deformable mirrors that are optically conjugated at different altitudes in the atmosphere. The solution to the tomographic reconstruction was first proposed theoretically and then statically demonstrated on sky. Two main factors limit the correction capability of MCAO: the small number of corrected conjugation altitudes, which prevents full compensation for a continuous vertical turbulence structure, and the limited number of sensed stars, whose light doesn’t completely probe the atmospheric volume of interest. To prove the capabilities of MCAO and understand its limitations, our team at the European Southern Observatory (ESO) developed the MCAO demonstrator (MAD), a prototype instrument devoted to on-sky observations.

Built to undergo two different phases of laboratory and on-sky testing, MAD is supposed to correct a FoV up to 2 arcminute in diameter by acting on two deformable mirrors conjugated at 0 and 8.5km in the atmosphere. It is equipped with three Shack-Hartmann-type wavefront sensors for sensing three stars located in the FoV, and they can move freely in order to acquire the most suitable stars useful for MCAO correction. MAD is dimensioned to provide the best correction in the K band (2.2µm), and it feeds

Figure 1. The MCAO demonstrator installed at the Nasmyth focus of the Melipal telescope of European Southern Observatory's Cerro Paranal observatory.
Figure 2. 20×20 arcsecond region near the center of the globular cluster Omega Centauri. The image on the left was obtained in the K-band by a seeing-limited instrument and has an average full width at half maximum (FWHM) of 0.6 arcseconds. We obtained the right-hand image at the same wavelength by MAD with MCAO correction. In the latter case, the FWHM is often below 0.1 arcsecond, a remarkable value considering that the closest guide star is ∼1 arcminute away. The angular resolution improvement is dramatic and allows very close and faint stars to be distinguished.

an infrared imaging camera that acquires the MCAO-corrected images. In the laboratory, we coupled MAD with a device reproducing time-evolving tridimensional atmospheric turbulence injected into the system for performance characterization. Then we installed it in early 2007 at the Nasmyth focus of Melipal telescope at the ESO’s Cerro Paranal observatory (see Figure 1).

The on-sky testing included three runs over a period of about six months. Our test object was the globular star cluster Omega Centauri, a fairly crowded object very suitable for providing bright stars both for sensing and mapping the performance in the FoV. We observed this target under different seeing conditions, and correlated the performance to the seeing. The demonstrator successfully achieved MCAO correction under good and median seeing conditions with a Strehl ratio in the K band up to 25–30% in a 2 arcminute FoV and with extremely uniform results (10% peak-to-valley, PTV). We obtained star images with an average full width at half maximum (FWHM) of 80 milliarcseconds in the full FoV with a variation of 20% PTV and less than 10% in ellipticity. MCAO proved to be robust in correcting for the upper atmosphere even when turbulence was significantly concentrated there. Even in bad seeing conditions, we could achieve good correction by selecting closer stars for sensing.

After the test phase, we proposed MAD for scientific demonstration and offered it to the astronomical community, which observed several targets. One of the most noticeable scientific results involves Omega Centauri itself, for which MAD achieved the deepest-ever imaging in the K band with a limiting magnitude of 20.5 (3σ) and 90% completeness compared to Hubble Space Telescope visible imaging of the same target (see Figure 2). For the first time, ∼10 white dwarves have been observed in the K band in a globular cluster, and exhibit an infrared excess that could provide new insights into the details of their evolution. Another remarkable result has been the sharpest-ever imaging of Jupiter from the ground at infrared wavelengths (see Figure 3). In this case, we used two of Jupiter’s satellites, Io and Europa, as sensing stars, and implemented differential tracking to compensate for proper motion. The result is a resolution of ∼90 milliarcseconds on the full disk.

In on-sky demonstrations, the MCAO technique has proven capable of delivering sharp and uniform images on a FoV ∼10 times larger than the one provided by normal AO systems. The preliminary scientific results have revealed the potential of MCAO for astronomical fields ranging from planetary science to extragalactic observations, including studies of star-forming regions and globular clusters. An MCAO facility under construction at the Gemini 8m-class telescope will be equipped with

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laser-based sensing stars to increase the sky coverage. MCAO-based instruments have been recognized as key systems for future extremely large telescopes, such as the Thirty Meter Telescope and the European Extremely Large Telescope.

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Enrico Marchetti is an astronomer whose specialty is high-resolution instrumentation. He led the MAD project and is now actively collaborating in the definition and design of the AO integrated system for the European Extremely Large Telescope.

References