Adaptive Optics for Extremely Large Telescopes

Stefan Hippler

1Max-Planck-Institut für Astronomie, Heidelberg, 69117, Germany, hippler@mpia.de

Received (to be inserted by publisher); Revised (to be inserted by publisher); Accepted (to be inserted by publisher);

Adaptive Optics has become a key technology for the largest ground-based telescopes currently under or close to begin of construction. Adaptive optics is an indispensable component and has basically only one task, that is to operate the telescope at its maximum angular resolution, without optical degradations resulting from atmospheric seeing. Based on three decades of experience using adaptive optics usually as an add-on component, all extremely large telescopes and their instrumentation are designed for diffraction limited observations from the very beginning. This review illuminates the various approaches of the Extremely Large Telescope, the Giant Magellan Telescope, and the Thirty-Meter Telescope, to fully integrate adaptive optics in their designs. The article concludes with a brief look into the requirements that high-contrast imaging poses on adaptive optics.

Keywords: Adaptive Optics, ELT, TMT, GMT, High-Contrast Imaging, Review

1. Introduction
Over the past 30 years, ground-based astronomical observations have drawn level with their space-based counterparts. Thanks to adaptive optics (AO), the seeing limit caused by optical turbulence of the Earth atmosphere is decreasingly a real limitation for existing large optical telescopes. For the three extremely large telescopes currently under construction or about to begin construction, adaptive optics is an integral part of telescope design, allowing to achieve the highest angular resolution on sky: the telescope’s diffraction limit.

1.1. Basic principle
The technique behind AO was first formulated by American astronomer Horace W. Babcock (1953) and can be summarized as cancelling optical aberrations caused by the atmosphere in real-time. Babcock’s proposal to compensate astronomical seeing was to measure wavefront distortions (using a rotating knife-edge) and feedback that information to a wavefront correction element (Eidophor mirror). In modern applications a fast real-time controller (RTC) sits in between a wavefront sensor (WFS) and a wavefront corrector (e.g. a deformable mirror (DM)) such that these three elements build a closed-loop system, i.e. controlling wavefronts before they reach the telescope instrument (e.g. the scientific camera). However, it took until the early 1970s before Babcock’s idea could be tested experimentally [Hardy et al. 1977].

1.2. Early years of AO in astronomy using single natural and laser guide stars
The usage of AO in routine astronomical observations on telescopes of the 3–4 m class can be dated back to the end of the 1980s when the instrument Come-On [Rousset et al. 1990] delivered diffraction limited images in the near-infrared spectral range on a 1.5 m telescope. Upgrades from Come-On to Come-On-Plus [Gendron et al. 1991] and eventually to ADONIS [Beuzit et al. 1994] allowed diffraction limited imaging on a 3–4 m class telescope in the 1–5 µm spectral range.
Around 10 years later, at the end of the 1990s, the first AO system on a 8–10 m class telescope – the Keck II telescope – began operation (Wizinowich et al., 2000).

First laser guide star (LGS) assisted AO systems, which were installed during the 1990s on smaller telescopes can be seen in retrospect as prototypes, even though few scientific results have been published (Davies et al., 1999; Hackenberg et al., 2000). Laser guide stars boost the operational readiness of AO-assisted observations of faint objects. An overview and historical review of sodium laser guide stars can be found in d’Orgeville & Fetzer (2016). Laser guide star systems using other wavelengths than the sodium one at 589 nm, are usually called Rayleigh laser guide star systems, and for example the first Rayleigh system was built and used by the US military in the early 1980s (Fugate et al., 1991).

On 8 m class telescopes, sufficiently bright LGS AO systems can increase the low sky coverage obtained with natural guide star (NGS) AO systems from a few percent up to about 80%, depending on the criterium for sky coverage. The most simple criterium for the sky coverage of an AO system is that the AO improves the natural seeing. This gives the highest sky coverage values. A much more stringent criterium is that the AO shall deliver fully diffraction limited point spread functions with long exposure Strehl numbers >80% at the observing wavelength. NGS AO sky coverage with sufficiently bright guide stars depends on the isoplanatic angle, while LGS AO sky coverage depends on focal and tilt anisoplanatism (van Dam et al., 2006). These limitations are due to atmospheric anisoplanatism that can be partially eliminated with the usage of multiple guide stars, either natural, artificial or a combination of both.

1.3. Wide-field and extreme AO

A first attempt with multiple natural guide stars took place on the 8 m VLT on Paranal observatory in Chile in 2007. Implemented in an AO type named multi-conjugate AO (MCAO) was the MCAO demonstrator instrument MAD (Marchetti et al., 2008). Results with this instrument, cf. Campbell et al. (2010); Meyer et al. (2011), showed that reconstructing and correcting wavefronts over large field of views using multiple deformable mirrors and wavefront sensors matched the predictions. Compared to – nowadays sometimes called classical AO – single conjugate AO (SCAO) systems with a typical non-homogeneous corrected field of view of a few ten arcsec, MAD delivered a 2 arcmin wide homogeneously corrected field of view.

About 4 years later in 2011, the Gemini MCAO system GeMS, the first multiple laser and natural guide star AO system saw first light on Cerro Pachón in Chile (Rigaut et al., 2014; Neichel et al., 2014). It is currently the only operational facility instrument of its kind. GeMS has an estimated sky coverage of almost 100% in the galactic plane, >35% at medium galactic latitudes, and ~20% at the galactic poles (Marin et al., 2017), limited mainly by the required 3 natural guide stars for measuring tip and tilt aberrations over the 85” x 85” corrected field of view.

Another prediction of MCAO in combination with a tomographic wavefront reconstruction over the entire observing volume in the atmosphere (Ragazzoni, 1999; Ragazzoni et al., 2000) was the sky coverage boost to almost 100% of the sky for an up to 100 m sized future optical telescope (Gilmozzi et al., 1998) with natural guide stars only. Nevertheless, for the currently planned MCAO systems on the 39 m ELT and the 30 m TMT (sect. 2), both natural and laser guide stars are foreseen. The expected/required sky coverage for the TMT MCAO instrument is above 70% for median seeing conditions and close to 100% under 25% best seeing conditions (Wang et al., 2012). In terms of image quality, under nominal conditions, MCAO systems deliver lower Strehl ratios compared to SCAO systems.

Another type of wide field (≥ 2’ x 2’ up to 10-20’ x 10-20’) AO system, which delivers a corrected image image quality between seeing limited performance and MCAO performance, are so called ground-layer adaptive optics (GLAO) systems or “seeing improvers”. Proposed by François Rigaut in 2002 (Rigaut, 2002), GLAO only corrects the optical turbulence located within the first 100 m above the telescope pupil. The performance depends on the amount of optical turbulence within the ground layer compared to the total atmospheric optical turbulence. Using multiple natural guide stars, first results obtained with a GLAO system on 8 m class telescopes were achieved in 2007 (Marchetti et al., 2007). Using a 5 Rayleigh laser guide stars GLAO system on the 6.5 m MMT telescope in Arizona (Hart et al., 2010), the uncorrected seeing at 2.2µm of 0.61” was improved to 0.22”, about a factor of 3. Results (see fig. 1) obtained with a 3 Rayleigh laser guide stars GLAO system on the 8.4 m LBT telescope in Arizona (Orban de Xivry et al.,...
Fig. 1. Exemplary ground layer adaptive optics performance at the large binocular telescope (LBT) with Rayleigh laser guide stars. (Left) LBT LUCI+ARGOS observation of the elliptical galaxy Maffei1 in J, H and K\textsuperscript{s} broad band for a total of 7.5 minutes exposure time. The field of view (FoV) spans 4' x 4' and shows a uniform resolution all over. In green is highlighted the field-of-view available to pick a natural guide star (NGS) for tip-tilt and truth sensing. (Right) Point-spread function full width at half maximum (FWHM) as a function of radius from the center of the FoV, where was also natural guide star for tip-tilt sensing. The constant distribution shows that there is no apparent sign of anisoplanatism and that the GLAO correction is very uniform. Figures and slightly modified caption taken from Orban de Xivry et al. (2016).

show that a seeing improvement by a factor of 2 can be achieved under good conditions, down to 0.2" at 1.6µm over a 4 arcmin wide field of view.

GLAO systems using multiple sodium laser guide stars are currently installed and commissioned on Paranal (Paulique et al. 2016; La Penna et al. 2016). First results obtained with the adaptive optics facility (AOF) and the instrument MUSE – good to recognize in (fig. 2) – show the potential of this technique in particular for wide-field GLAO spectroscopic observations. During the MUSE science verification in 2017, observations under one arcsecond seeing conditions were improved with GLAO down to ~0.6. arcsec across the full 1 arcmin field of view (Leibundgut et al. 2017).

The planning and development of second generation AO systems for 8–10m class telescopes, often in the context of exoplanet characterization in combination with high-contrast imaging (Milli et al. 2016), started at the beginning of the 21st century (Gratton et al. 2004; Fusco et al. 2005; Beuzit et al. 2006; Fusco et al. 2006; Feldt et al. 2007; Esposito et al. 2006; Macintosh et al. 2006a; Graham et al. 2007; Martinache & Guyon 2009; Guyon et al. 2010). First science results with instruments based on these extreme AO (XAO) systems were achieved around 10 years later (Esposito et al. 2010; 2013; Macintosh et al. 2015; Vigan et al. 2016; Maire et al. 2016; Currie et al. 2017). Typically, AO systems tagged “extreme” sample wavefronts at kilohertz frame rates, and correct wavefronts with a high number of actuators (for example: 672 actuators in the LBT first light AO system (Esposito et al. 2006) or 4096 actuators available in the Gemini planet imager AO system (Macintosh et al. 2006a)).

The last flavor of AO type to mention before looking at the AO related hardware designs for the upcoming extremely large telescopes, is the multi-object adaptive optics (MOAO) system. The goal of MOAO is to compensate atmospheric turbulence over a wide field of view up to 5–10 arcmin, using individual deformable mirrors for each object to be observed. Using a small number of either natural or laser guide stars, similar to MCAO, the wavefront is reconstructed using tomographic methods (Ragazzoni et al. 1999; Vidal et al. 2010). Each deformable mirror is optimally shaped to correct the turbulence in its viewing direction, like a multi-SCAO system operated in open-loop. MOAO demonstrator systems used in the laboratory (Laag et al. 2008; Ammons et al. 2008) and on sky (Gendron et al. 2011; Lardière et al. 2014), have shown that MOAO performs close to conventional SCAO systems.
Fig. 2. Exemplary ground layer adaptive optics performance at the very large telescope (VLT) with sodium laser guide stars. VLT MUSE+AOF view of the planetary nebula NGC 6563 without GLAO correction (left) and with GLAO correction using 4 sodium laser guide stars (right). The field of view is 1.01 x 1.03 arcmin. Both images are color composites observed in the optical with various band filters ranging from 500nm to 879nm. (ESO 2017).

The first MOAO system installed on an 8m class telescope was the RAVEN (Andersen et al., 2012; Lardière et al., 2014; Davidge et al., 2015; Ono et al., 2016; Lamb et al., 2017) demonstrator, which was in operation at the Subaru telescope between 2014 and 2015. Developed as a pathfinder for the 30m TMT, results obtained with this instrument are encouraging, with better performance than GLAO (Fig. 3) but not reaching SCAO performance. RAVEN can use either three natural guide stars or a combination of one sodium laser guide star and two natural guide stars. Two deformable mirrors with 145 actuators each, allow AO corrections on two science fields with a maximum separation of about 3.5 arcmin.

Conceptual drawings of the various AO concepts, i.e. SCAO, GLAO, MCAO, LTAO, and MOAO, including drawings of conventional wavefront sensors and photos of deformable mirrors, can be found in the review article of Davies & Kasper (2012).

It goes without saying that the current, often already the 2nd generation of AO systems on 8–10m class telescopes has generated a wealth of experience. These experiences and lessons learned (see for example Lloyd-Hart et al. (2003); Wizinowich (2012); Fusco et al. (2014); Lozi et al. (2017)) are of course incorporated into the design and simulations of the AO facilities to be built. Since it would go beyond the scope of this review, here are just two current examples.

The SPHERE XAO system installed at the Paranal observatory discovered a so named low wind effect Milli et al. (2018) (sometimes also named island effect), which basically distorts the wavefronts in the pupil of large telescopes obstructed by spiders. The effect occurs mainly when wind speeds above the telescope are close to zero. The SPHERE XAO system cannot measure these piston aberrations, thus they propagate uncorrected to the science channel and degrade the image quality. The solutions proposed and tested will influence the design of possible upgrades to the SPHERE XAO system as well as future AO systems.

The second example concerns a general problem of most AO systems: telescope vibrations and their impact on AO performance. Experiences with the SCExAO system at the Subaru telescope Lozi et al. (2016) show weaknesses of the control system in handling vibrations, which may be mitigated by the use of predictive-control Males & Guyon (2018).
2. ELT, GMT, and TMT AO systems

2.1. AO architecture and types for first light instrumentation

All extremely large telescopes currently under design and construction have adaptive optics kind of built-in. This means that either all components of the AO are part of the telescope or that the AO pieces are split among telescope and instruments.

The 39m European Southern Observatory’s (ESO) Extremely Large Telescope (ELT, previously E-ELT) on Cerro Armazones in Chile has a five-mirror optical design. Its large adaptive quaternary mirror (fig. 4) has about 5000 actuators.

The Gregorian-type 25.4m Giant Magellan Telescope (GMT) at Las Campanas observatory in Chile, developed by a United-States led consortium, will have a large segmented adaptive secondary mirror (fig. 5) with roughly the same number of actuators as the ELT.

The Thirty Meter Telescope (TMT), which will be located either on Mauna Kea, Hawaii or Canary Islands, Spain, is developed by a consortium of universities, foundations, and national observatories in the United States, Canada, China, India, and Japan. It has a Ritchey-Chrétien optical design and no adaptive mirror built-in. The TMT will probably start operation with a conventional 3m class "active" secondary mirror and a facility AO device including deformable mirrors and wavefront sensors. This AO facility, called NFIRAOS (see sect. 2.2), includes deformable mirrors with about 8000 actuators in total, and will feed three instruments.

TMT first-generation instruments
First-generation instruments of the TMT using adaptive optics are IRIS (Larkin et al. 2016) and IRMS (Mobasher et al. 2010).

IRIS (infrared imager and spectrograph) is a first-generation near-infrared (0.84–2.4 μm) instrument being designed to sample the diffraction limit of the TMT. IRIS will include an integral field spectrograph (R=4000–10000) and imaging camera (34"x34"). Both the spectrograph and imager will take advantage of the high spatial scales (0.004", 0.009", 0.025", 0.05") of the TMT. The features of the design will enable a vast range of science goals covering numerous astrophysical domains including: solar system science, extrasolar planet...
studies, star formation processes, the physics super-massive black-holes and the composition and formation of galaxies, from our local neighborhood to high-redshift galaxies. Description for IRIS taken from \cite{TMT-UCR}.

The IRMS (infrared multi-slit spectrograph) is a near diffraction-limited multi-slit near-infrared spectrometer and imager. It will be fed by NFIRAOS. IRMS will provide near-infrared imaging and multi-object spectroscopy in the spectral range 0.97–2.45 μm. The science case for IRMS includes planetary astronomy (exoplanets), stellar astronomy (massive stars, young star clusters), active galactic nuclei (co-evolution of black holes and galaxies), inter-galactic medium (interaction with galaxies at high-z), and the high-redshift universe (population III stars, cosmic re-ionization, nature of the high-z galaxies). Description for IRMS taken from \cite{TMT-UCR}.

---

Fig. 4. Single-conjugate adaptive optics scheme for the ELT METIS instrument. Atmospheric turbulence distorts the observed starlight collected by the ELT's segmented primary mirror M1. Reflected up to mirror M2 and down to mirror M3, passing through a hole in the deformable mirror M4, the last reflection on the tip-tilt mirror M5 forwards the light into the METIS cryostat on the right, outside of the telescope. The METIS internal wavefront sensor measures the atmospheric distortions. A real-time computer estimates the actual wavefront and delivers the corresponding information to properly shape the deformable mirror M4 as well as to properly steer the tip-tilt mirror M5 with the M4/M5 control unit. Eventually, an exoplanet like 51 Eri b can be detected at 2 different wavelengths (see blue-colored inset on the right).

---

**ELT first-generation instruments**

First-generation instruments of the ELT are HARMONI (\cite{Thatte2016}), MAORY (\cite{Diolaiti2016}), METIS (\cite{Brandl2016}), and MICADO (\cite{Davies2016}). The short descriptions of these instruments, enclosed in quotation marks below, are taken from \cite{ESO2018}.
Adaptive optics for extremely large telescopes

6.2 Overview

6.2.1 Optical Design

The GMT primary mirror sets the collecting area of the telescope and defines the telescope subapertures. The size and shape of the mirror segments drives the phasing strategy. The largest practical size for monolithic mirrors is around 8 meters. Current generation 6.5-8 m optical telescopes use a single monolithic mirror (Magellan, MMT, VLT, Subaru). The 10 m telescopes (e.g., Keck, GTC) employ a mosaic of small (~1.5 m) segments. The LBT with two 8.4 m mirrors is the only existing telescope combining multiple large-segments in a common mount. The next generation of extremely large telescopes will all have segmented primary mirrors.

The GMT project considered omitting the central segment in the interest of cost reduction and operational simplicity. However, the center segment was retained because the six-mirror configuration falls short of providing the desired collecting area and has two other significant drawbacks relative to seven segments:

- The image point spread function is significantly broadened with just the outer six segments.
- Phasing the primary mirror segments would be much more difficult without the center segment to anchor the array.

The seven segments share a common parent optical surface to provide 25 m diffraction limited imaging with adaptive optics and a wide field of view for natural seeing applications. The segments provide large subapertures of well-corrected wavefront so that phasing is not required for natural seeing operation or GLAO. The large gaps between segments add to the difficulty of

![Figure 6-2. GMT Optical layout](image)

Table 1. Type of adaptive optics planned for first light instrumentation. List of used abbreviations:

| Telescope and instrument | Extremely Large Telescope (ELT), 39.3 m | Giant Magellan Telescope (GMT), 24.5 m | Thirty Meter Telescope (TMT), 30 m |
|--------------------------|---------------------------------------|---------------------------------------|---------------------------------|
| SCAO\(^a\)               | METIS, HARMONI, MICADO                 | GMTNIRS                               | NFIRAOS+IRIS                    |
| MCAO\(^a,b\)             | MICADO-MAORY                           | —                                     | NFIRAOS+IRIS, NFIRAOS+IRMS      |
| LTAO\(^b\)               | HARMONI                                | GMTIFS, GMTNIRS                       | —                               |
| GLAO\(^a\)               | —                                     | G-CLEF, GMACS                         | TFOS                            |
| MOAO                     | MOSAIC\(^a,b\) (phase A study [Morris et al. 2016]) | —                                     | TMT-AGE (feasibility study [Akiyama et al. 2014]) |

\(^a\) Using natural guide stars. \(^b\) Using sodium laser guide stars.

HARMONI, the high angular resolution monolithic optical and near-infrared integral field spectrograph, "will be used to explore galaxies in the early Universe, study the constituents of the local Universe and and characterise exoplanets in great detail."

METIS, the mid-infrared imager and spectrograph, will "focus on five scientific goals: exoplanets, protoplanetary disks, Solar System bodies, active galactic nuclei, and high-redshift infrared galaxies."
MICADO, the multi-adaptive optics imaging camera for deep observations, “is the first dedicated imaging camera for the ELT. MICADO’s sensitivity “will be comparable to the James Webb Space Telescope, but with six times the spatial resolution.”

MAORY, the multi-conjugate adaptive optics relay for the ELT, “is designed to work with the imaging camera MICADO and with a second future instrument ... MAORY will use at least two deformable mirrors, including the deformable mirror of the telescope. It measures the light from a configuration of six sodium laser guide stars, arranged in a circle on the sky, to obtain a kind of three-dimensional mapping of the turbulence. The laser guide stars are projected from around the circumference of the telescope’s primary mirror.”

Table 2. Planned laser guide star facilities on ELT, GMT, and TMT

| Telescope | Laser system                | Power per laser [Watt] | Comments                                      |
|-----------|-----------------------------|------------------------|-----------------------------------------------|
| ELT       | sodium laser CW             | ≈ 22                   | At least 4 lasers based on the VLT four laser guide star facility [Bonaccini et al. (2014)] |
| GMT       | sodium laser                | ≈ 20                   | 6 lasers for LTAO observations, [D’Orgeville et al. (2013); Bouchez et al (2014)] |
| TMT       | sodium laser CW or pulsed   | 20–25                  | Up to 9 lasers, [Li et al (2016)]             |

Fig. 6. The GMT LTAO, SCAO design. Light reflected from the telescope’s 3rd mirror (M3), before entering the science instrument, passes through the wavefront sensing area of the telescope. Figure taken from [Bouchez et al. (2014)].
GMT first-generation instruments

For the GMT, the suite of first-light instruments \cite{Jacob2016} using AO consists of a fiber-fed, cross-dispersed echelle spectrograph able to deliver precision radial velocities to detect low-mass exoplanets around solar-type stars, hence the name of the instrument GMT-consortium large earth finder G-CLEF \cite{Szent2016}. Both, the wide-field optical multi-object spectrograph GMACS \cite{DePoy2012} and G-CLEF will benefit from the GMT’s ground-layer AO observing mode \cite{Bouch2014, vanD2014}. The near-infrared integral field spectrograph and imager GMTIFS \cite{Shar2016} and the near-infrared high-resolution spectrograph GMTNIRS \cite{Jaff2016, Jacob2016} will use the GMT’s laser tomography AO system \cite{Bouch2014, vanD2016}.

An overview of all three telescopes, their adaptive optics type, and their planned first suite of instrumentation is given in table 1.

2.2. Wavefront sensing set-up

2.2.1. Natural and artificial laser guide stars

Wavefront sensors analyze light passing through the Earth’s atmosphere. The ideal light source for wavefront sensing, called natural guide star, is a stellar point like object, as close as possible to the scientific target, and sufficiently bright to minimize measurement errors. Artificial light sources created high above the telescope – for example in the \( \sim 100 \text{km} \) high sodium layer of the mesosphere –, called laser guide stars, can be positioned as close as required to the scientific target. Their brightness depends on the used technology. Laser guide stars enormously increase the usability of AO systems. Laser guide stars as well as the technique of laser tomography AO are mentioned in this article but going into details is beyond the scope of this review. For an overview, table 2 summarizes for each telescope the plans for installing laser guide star facilities.

2.2.2. Wavefront sensing architecture

The GMT SCAO and LTAO architecture (fig. 6) is designed to use reflected light from a tilted instrument entrance window for wavefront sensing, using either light from natural or laser guide stars. The reconstructed wavefront is used to shape the adaptive secondary mirror of the GMT, such delivering corrected wavefronts to the instrument. In the case of laser guide star wavefront sensing additional on-instrument wavefront sensors are required to sense low-order atmospheric aberrations. For GLAO operations, the GMT has an integrated acquisition, guiding, and wavefront sensing system (AGWS) analyzing the light in an annular field of view outside the science instruments field of view. This "technical" field of view with an inner diameter of about 6 arcmin and an outer diameter of about 10 arcmin, is large enough to find suitable natural guide stars for GLAO operations.

In contrast to the GMT, the ELT does all AO related wavefront sensing inside the instruments. An exception from this ELT AO design is MAORY, which is designed to support two instruments. Wavefront compensation is performed using the ELT’s internal adaptive mirrors M4 and M5 as shown in fig. 4. Active optics and possible GLAO support is done in a similar way as for the GMT, i.e. using a "technical" field of view.

How does the TMT compare with the GMT or ELT AO architecture? The TMT has a facility MCAO/SCAO system called NFIRAOS \cite{Herriot2014, Herriot2017}, which can feed three instruments: an infrared imaging spectrograph IRIS, an infrared multi-slit spectrometer IRMS, and a third future instrument. From this perspective, NFIRAOS is similar to the ELT’s MAORY "relay" system, which feeds MICADO and a second future instrument. In its current design, the TMT itself has no adaptive deformable mirror built-in, instead, the wavefront correction devices are located inside NFIRAOS. A laser guide star facility (LGSF) will provide at least six sodium laser guide stars \cite{Li2016} feeding NFIRAOS, thus enabling LGS MCAO observations \cite{Boyer2016}. In September 2017, a design study for an adaptive secondary mirror was launched \cite{TMT2017}. In particular, the wide-field optical spectrometer (WFOS) would benefit from such an integrated wavefront correction unit, as it is not connected to the NFIRAOS unit, and the LGSF is designed to provide various asterisms, including a GLAO asterism \cite{TMT2018}.
Table 3 summarizes the main characteristics of the wavefront sensors (WFS) used with the first light and first-generation respectively instrumentation.

| WFS → Instrument/ AO-module/ AO-mode ↓ AO type: | Type of WFS, high-order (HO) or low-order (LO) | Wavefront sensing spectral band [µm] | Wavefront linear spatial sampling [m] | Wavefront temporal sampling [Hz] | Wavefront sensor detector |
|-----------------------------------------------|-----------------------------------------------|--------------------------------------|--------------------------------------|---------------------------------|--------------------------|
| ELT                                           |                                               |                                      |                                      |                                 |                          |
| HARMONIa                                       | S 1 x Pyramid, HO                             | 0.5 – 1.0                            | 0.5                                  | 1000                            | CCD220g                  |
| HARMONIb                                       | G, L 6 x SHS, HO                              | 0.589                                | 0.5                                  | 500 – 1000                      | LVSMh                    |
| HARMONIc                                       | L 1 x SHS, LO                                | 1.4 – 1.8                            | 19.5                                 | 1000                            | Saphirai                  |
| METISa                                         | S 1 x Pyramid                                | 1.4 – 2.4                            | 0.5                                  | 1000 – 2000                     | Saphirai                  |
| MICADOa                                        | S 1 x Pyramid                                | 0.45 – 0.9                           | ≲ 0.5                                | 1000                            | CCD220g                  |
| MAORYa                                         | M 3 x SHS, HO                                | 0.6 – 0.8                            | ≲ 0.5                                | 500                             | CCD220g                  |
| MAORYb                                         | M 6 x SHS, HO                                | 0.589                                | ≲ 0.5                                | 500                             | LVSMh                    |
| MAORYc                                         | M 3 x SHS, LO                                | 1.5 – 1.8                            | 19.5                                 | 500                             | Saphira i                 |
| GMT                                           |                                               |                                      |                                      |                                 |                          |
| SCAOa,d                                        | S 1 x Pyramid, HO                             | 0.6 – 0.9                            | 0.28                                 | 1000                            | CCD220h                  |
| GLAOa,d                                        | G 4 x SHS, HO                                 | 0.5 – 1.0                            | 0.53 – 1.06                         | 200                             | EMCCDm                    |
| LTAOa,d                                        | L 6 x SHS, HO                                 | 0.589                                | 0.42                                 | 500                             | NGSDh                    |
| OIWFSa,cd                                      | S, L 1 x QC, LO                              | 2.03 – 2.37                         | 25.4                                 | 1000                            | Saphira i                 |
| OIWFSa,cd                                      | S, L 1 x SHS, LO                             | 1.65 – 1.8                           | 5.08                                 | 10                              | Saphira i                 |
| OIWFSa,cd                                      | S, L 1 x SHS, LO                             | 1.17 – 1.33                         | 1.59                                 | 0.1                             | Saphira i                 |
| TMT                                           |                                               |                                      |                                      |                                 |                          |
| NFIRAOSa,ce                                    | S 1 x Pyramid, HO                             | 0.6 – 1.0                            | 0.31                                 | 800                             | MIT/LL CCDj               |
| NFIRAOSa,ce                                    | M 6 x SHS, HO                                 | 0.589                                | 0.5                                  | 800                             | PC-CCDk                   |
| OIWFSa,cd                                      | M 3 x SHS, LO                                 | 1.1 – 2.3                           | 15                                   | 800                             | Hawaii-1/2RG or Saphira i|
| ODGWa,ce                                       | M 4 windows, LO                               | 0.84 – 2.4                           | 30                                   | 800                             | IRIS detector             |

a Using natural guide stars, usually for SCAO modes or truth sensing for laser guide star observations.
b Using sodium laser guide stars, usually for LTAO or MCAO modes.
c Low-order natural guide star wavefront sensors for laser guide star observations.
d The GMT wavefront sensing architecture foresees integrated wavefront sensors (SCAO, GLAO, LTAO), and on-instrument wavefront sensors (OIWFS).
e The TMT wavefront sensing architecture foresees integrated wavefront sensors (NFIRAOS; narrow field infrared AO system), on-instrument wavefront sensors (OIWFS), and instrument internal on-detector guide windows (ODGW). OIWFS and ODGW numbers are for the TMT instrument IRIS (Andersen et al., 2017).
f ELT data taken from (Correia et al., 2016; Neichel et al., 2016; Hippler et al., 2018; Sereni, 2017; Clénet et al., 2016; Esposito et al., 2015). GMT numbers taken from Bouchez et al. (2014); Pinna et al. (2014); van Dam et al. (2014). TMT numbers taken from (Boyer & Ellerbroek, 2016; Boyer, 2017; Dunn et al., 2016; Kerley et al., 2016; Herriot et al., 2017).
g Downing et al. (2016).h Teledyne e2v large sensor visible module (LSVM) and other sensors for adaptive optics (Jorden et al., 2017). For the natural guide star detector (NGSD) device see also Reyes-Moreno et al. (2016).i Atkinson et al. (2016) an references therein.j GMT/ Lincoln labs. 256x256 CCD. k GMT/ Lincoln labs polar coordinate CCD (Adkins, 2012).l TMT intention for OIWFS/ ODGW (Boyer & Ellerbroek, 2016).m Andor or Raptor EMCCD (Bouchez, 2017).
2.3. Wavefront correction devices

This brings us to the topic of wavefront correction devices, their characteristics and location within each of the described telescopes and instruments respectively. As shown in fig. 4, the ELT comes with a deformable mirror M4 and a fast steering mirror M5. The 2.4 x 2.5 m sized elliptic mirror M4 is supported by 5316 contactless voice-coil actuators (Biasi et al., 2016). This mirror can be controlled at frequencies up to 1 kHz. Together with the fast and flat steering mirror M5, which compensates for rather large amplitude atmospheric tip-tilt aberrations (field stabilization), this combination in interplay with the wavefront sensing devices, allows GLAO, SCAO, and LTAO observations. The ELT’s multi-conjugate adaptive optics relay MAORY adds another two deformable mirrors for instruments attached to it. Each of them with 500–1000 actuators (actuator number and technology not yet decided).

The GMT has two exchangeable secondary mirrors, each 3.25 m in diameter, segmented and shaped similar to the primary mirror (fig. 5). The fully adaptive secondary mirror (ASM) is supported by 4704 contactless voice-coil actuators. An alternative fast steering secondary mirror (FSM) with 7 rigid circular segments (Lee et al., 2017) will be used during commissioning of the telescope and later on during ASM maintenance or repair.

Wavefront correction at the TMT takes place in its NFIRAOS facility (fig. 7) operated at a temperature of -30 degrees. A tip-tilt stage and two deformable mirrors with a total number of 7673 actuators (3125 actuators for the ground layer DM and 4548 actuators for the high-layer DM) support MCAO observations. As mentioned in section 2.2, TMT organization has launched a design study for an adaptive secondary mirror in September 2017.

Table 4 summarizes some basic parameters of the planned wavefront correction elements for all 3 telescopes. From today’s perspective, piezo actuator technology is still in use, voice-coil actuator technology has become a standard, and bimorph mirror technology has disappeared. Liquid crystal spatial light modulators do not play a role in the context of AO for the first light instrumentation of the 3 telescopes. The role of micro electro-mechanical systems (MEMS) based deformable mirrors is rather small, only the GMT considers a MEMS DM for some of their first light instrumentation (Copeland et al., 2016).

A further increase in actuator density, i.e. for future XAO systems, from 5–10 actuators/m² to 12.5–25 actuators/m² seems possible but has to be developed (Madec 2012, Riaud 2012, Kasper et al. 2013, Kopf et al. 2017). For high-contrast XAO systems, high-density deformable mirrors might be used to remove residual speckles seen in the science focal plane. In combination with the science focal plane detectors behind coronagraphs, a second stage AO system can be set-up in order to calibrate and remove residual speckles seen in the science images (Macintosh et al. 2006b, Thomas et al. 2015).

2.4. AO real-time control systems

The last major component of an AO system is the real-time control system (RTC), which receives wavefront measurements from the wavefront sensors, calculates wavefront estimates, and eventually sends control signals to the wavefront correction devices like deformable mirrors and tip-tilt mirrors. For the SCAO case, the largest size of an interaction matrix using numbers from tables 3 & 4 has about 5000 actuators and 10000 wavefront x-y gradients. The time available due to AO latency requirements, i.e. the time to

• receive pixel data from the wavefront sensors,
• pre-process the raw wavefront sensor data,
• calculate the wavefront slopes from calibrated pixel data,
• reconstruct the wavefront using for example a matrix-vector multiplication (MVM),
• calculate the new shapes and positions of the wavefront corrections devices including tasks like vibrations control, deformable mirror saturation management, etc.,
• send control commands to the wavefront correction devices,

is rather short and of the order of 0.2–2 milliseconds (Gratadour et al. 2016, Kerley et al. 2016, Bouchez et al. 2014). This "low latency" requirement defines the control bandwidth of the AO system as well as the stability and robustness of the closed-loop system. Looking at the matrix-vector multiplication, one of the
most time consuming operations in this list, year 2016 off-the-shelf hardware is compliant with the latency requirements. Exemplary performance tests using Intel’s Xeon Phi (Knights Landing, KNL) CPU with 68 cores already shows satisfactory results as shown in fig. 8.

A schematic and simplified view of the real-time control system of the ELT instrument METIS is shown in fig. 9. The core of METIS SCAO real-time control system (AO RTC) consists of a hard real-time controller (HRTC) and a soft real-time controller (SRTC). While the low-latency HRTC processes WFS data and generates control commands for the control systems of the correction devices, the soft real-time controller receives additional wavefront correction signals from the science focal planes (FPs) and their detector control systems (DCSs), respectively. Such additional wavefront corrections signals can for example compensate non-common path aberrations between the science and WFS light path, through adding slope offsets to the actual measured wavefront slopes. The generated correction commands can be either sent directly to the ELT’s M4 and M5 local control systems (LCS) or through the ELT central control system (CCS). Further optical components within the common-path of the METIS science and WFS channel are an optical de-rotator and the pupil stabilizer (pupil stabil.). Monitoring the pupil position can be performed on the SRTC and if necessary correction commands generated and sent to the pupil stabilization controller. The field selector inside the WFS channel is pre-set via the AO observation coordination system (OCS) and the pyramid wavefront sensor modulator has to be synchronized with the SCAO WFS detector control system. Wavefront control taking into account non-common path aberrations (NCPAs) is achieved through a communication channel between the science detectors and the SRTC. The AO function control system (FCS) completes the METIS SCAO control system.

To investigate real hardware options supporting all first-generation ELT instruments, the Green Flash project (Gratadour et al., 2016) aims in building a prototype/demonstrator designed to support all AO systems. After having investigated GPU clusters like the NVIDIA DGX-1 (Bernard et al., 2017), Intel Xeon...
Table 4. Adaptive, deformable mirrors planned

| Telescope location | # act. | # seg. | act. spacing | act. time | technology | Comments |
|--------------------|--------|--------|--------------|-----------|------------|----------|
| GMT-M2 (ASM)       | 4704   | 7      | 0.36         | 1         | V          | Based on the LBT adaptive secondary mirror, optically conjugated to 160 m above ground. |
| GMT OIWFS-DM       | ≥20x20 | ≤1.27  | 0.5–2        | M, P, V   |            | on-instrument deformable mirror for GMTIFS. Actuator technology not yet decided. |
| TMT-NFIRAOS-DM0    | 3125   | 1      | ≤0.5         | ≤1        | P          | Optically conjugated to the ground. |
| TMT-NFIRAOS-DM11   | 4548   | 1      | ≤0.5         | ≤1        | P          | Optically conjugated to 11.2 km height above telescope. |
| ELT-M4             | 5136–6 | 0.5    | 1            | V         |            | ELT-M4 plus two deformable mirrors optically conjugated to 4 km and 14–16 km in the atmosphere. Actuator technology not yet decided (Lombini et al., 2016; Pagès et al., 2016). |
| ELT-MAORY          | ≈500–1000 | 1.5–2.0 | V, P        |           |            | |

a Total number of actuators (act.) and segments (seg.)
b Actuator linear spacing over conjugated pupil [m].
c Actuator settling time.
d Biasi et al. (2010); Bouchez et al. (2014); Copeland et al. (2016); Caputa et al. (2014); Pagès et al. (2016); Sinquin et al. (2012).
e Lombini et al. (2016); Oberti et al. (2017).

Fig. 8. Matrix-vector multiplication timing histogram using Intel’s 1.4 GHz Xeon Phi 7250 (KNL) and Intel’s Math Kernel Library (MKL). Matrix size: 5000 x 10000. Vector size 10000 with changing content. No. of samples: 3 million. Median execution time is ~651 microseconds with a standard deviation of ~3 microseconds.

Phi multi-core devices (Jenkins et al., 2018), and a FPGA microserver (Green Flash Project, 2018), making the choice of a single solution (if necessary) remains open.

For the TMT’s multi-conjugate AO system NFIRAOS, more real-time tasks, compared to the METIS SCAO RTC, are required to process the data acquired by up to six high-order wavefront sensors. The sequence of the high-order AO data flow starts with pixel processing and wavefront reconstruction (HOP) for each wavefront sensor. A wavefront corrector control server (WCC) combines all measurements including
low-order (LO) wavefront errors (full aperture natural guide star tip/tilt as well as laser guide star tip/tilt), and finally sends the correction signals to the high-order deformable mirrors DM0 and DM11 as well as to a tip-tilt stage (TTS), the laser guide star fast steering mirrors (FSM), and the telescope control system. The TMT RTC design allows to run the high-order pixel processing and wavefront reconstruction using a matrix-vector multiplication (MVM) almost in parallel. Estimated start and execution times for the various tasks are show in fig. 10.

The GMT’s wavefront control system (WFCS) runs as an integral part of the telescope control system (Bouchez et al. 2014). The most demanding real-time requirements are set by the LTAO mode with a latency ≤ 200 µs. The GMT’s baseline WFCS design foresees 9 commodity servers, one slope processor for each of the 6 laser tomography wavefront sensors, 1 node for communication with the adaptive secondary mirror, 1 node for communication with the on-instrument deformable mirror, and 1 master node for combining all reconstructed wavefronts.

Whether commercial off-the-shelf components and commodity servers can be used for the required high performance AO controllers is currently under investigation. Table 5 lists hardware components under consideration at the particular telescopes. The table brings into focus the high performance computing (HPC) power only, while other hardware components like low-latency, high bandwidth networks (e.g. 10-100 Gbit-Ethernet, Infiniband, Omni-Path), sufficiently fast input/output channels (e.g. Camera Link, GigE Vision, sFPDP, USB3), and high throughput data storage are considered uncritical as it can be categorized as standard hardware.

Table 5. Exemplary AO real-time controller HPC hardware planned or under study. Multiple devices are necessary.

| Telescope | ELT         | TMT         | GMT |
|-----------|-------------|-------------|-----|
| Hardware  |             |             |     |
| CPUs      | Intel Xeon Phi (KNL) | Intel E7-8870 V4 | yes |
| GPUs      | NVIDIA DGX-1 | no          | yes |
| FPGAs     | Arria 10    | no          | no  |
Adaptive optics for extremely large telescopes

15

bandwidth memory) which can be used either directly or as L3 cache. Each core can simultaneously execute up to four threads. Single threaded performance of the KNL Xeon Phi is expected to be lower than single core performance of a Xeon CPU, but for use within a HOP server, a single KNL chip should be able to replace four Xeon E7 CPUs due to the high memory bandwidth of the MCDRAM (greater than 400GB/s).

Figure 2 - Estimated Pipeline Stage Execution Times

The Knights Landing Xeon Phi can use sub-NUMA (non-uniform memory access) clustering to appear to the operating system as a four socket Xeon server. This configuration mode provides the lowest memory latency if the workload is highly NUMA optimized. The RTC software will be optimized for NUMA architectures. To make the HOP software less dependent upon hardware selection, time critical HOP server software will assume a four-way NUMA architecture.

The HOP server software will use configuration files to allow control of the number of threads and their assignment to physical cores.

The use of the Knights Landing Xeon Phi is expected to increase system latency since the control matrix must be fetched from the MCDRAM for each frame (it is much too large to fit in the on-core caches), but is expected to significantly reduce system cost, power consumption, and size.

Fig. 10. Estimated real-time pipeline stage execution times of the TMT NFIRAOS real-time controller. Server name (left) and task name with box indicating the execution time in milliseconds. See text for details. Figure taken from Smith et al. (2016).

2.5. AO performance: requirements and expectations

Usually the scientific program determines the necessary minimum requirements for the measuring instrument. As an example, for the ELT METIS instrument various dedicated AO related top-level requirements influence the AO design. These are among others requirements on Strehl and contrast, for example, METIS shall deliver a minimum Strehl ratio of 60\% (goal 80\%) in L-band (λ=3.7μm). For the contrast, METIS shall deliver a 5σ contrast in L-band of 3×10^{-5} (goal: 1×10^{-6}) at a distance to the central PSF of 5λ/D (goal: 2λ/D).

Detailed end-to-end simulations are in the design phase the only way to figure out whether the design meets the requirements. Table 6 lists requirements on the AO for the instruments described in table 1 and, where available, simulated performance numbers.

3. High-contrast imaging requirements on adaptive optics

High-contrast imaging astronomy aims at uncovering faint structures and substellar objects very close to bright stars (an overview on this topic gives for example Oppenheimer & Hinkley (2009)). Investigating distances close to the diffraction limit, i.e. ~10-1000 mas, requires sophisticated AO installations, like XAO systems, that are able to spatially separate the light from, for instance, a host star and an orbiting planet.
Table 6. AO requirements (R), goals (G), and preliminary performance results (P)

| Instrument/ AO-module/ AO-mode | AO type | AO type | Strehl ratio | NGS mag. | Corrected field of view | Contrast at distance to central PSF | Comments and references |
|--------------------------------|---------|---------|--------------|----------|------------------------|-------------------------------------|-------------------------|
|                                |         |         |              |          |                        |                                     |                         |
| ELT                            |         |         |              |          |                        |                                     |                         |
| HARMONI S                      | P: 78% | P: 78%  | R ≤ 13       | ≤ 6.5” x 9” | R (λ=2.2μm): 1.E-6 @ 0.2” | Neichel et al. (2016) |
| λ=2.2μm                       |         |         |              |          |                        |                                     |                         |
| HARMONI L                      | P: ~ 40 – 67% | H ≤ 20 | ≤ 6.5” x 9” |          |                        | Zenith angles: 0 – 60 degrees. |                         |
| λ=2.2μm                       |         |         |              |          |                        |                                     |                         |
| METIS S                        | P: ~ 73 – 98% | K ≤ 10.8 | on-axis^c |          | R (λ=3.7μm): 3.E-5 @ 0.1” | Seeing conditions: 0.43–1.04”, zenith distance 30 degrees. | Hippler et al. (2018), Bertram et al. (2018), Clenet et al. (2016), Vidal et al. (2017) |
| λ=3.7μm                       |         |         |              |          |                        |                                     |                         |
| MICADO S                       | R: 60%  | P: 80%  | V ≤ 12       | 50” x 50’ |                        | see Perrot et al. (2018)            |                         |
| λ=2.2μm                       |         |         |              |          |                        |                                     |                         |
| MAORY M                        | R: ≥ 30% | G: ≥ 50% | R: >50%      | ≤ 75” diameter | n/a                      | Diolaiti et al. (2017). Corrected field of view is the MICADO science field of view. |                         |
| λ=2.2μm                       |         |         | of the sky   |          |                        |                                     |                         |
| GMT                            |         |         |              |          |                        |                                     |                         |
| NG(S)AO S                      | P: 89.3% | R<8     | on-axis (NIRS) |          | R (λ=3.8μm): 1.E-5 @ 0.12” | Zenith distance: 15 degrees. | Bouchez et al. (2014); Pinna et al. (2014) |
| λ=2.18μm                      |         |         | 20.4” x 20.4” |          |                        |                                     |                         |
| ≤ 4.4” x 2.25”                |          |         |              |          |                        |                                     |                         |
| LTAO L                         | R: >30%  | P: 79%  | of the sky   |          | n/a                    | Zenith distance: 15 degrees. Sky coverage at the galactic pole. | Bouchez et al. (2014) |
| λ=1.65μm                      |         |         |              |          |                        |                                     |                         |
| TMT                            |         |         |              |          |                        |                                     |                         |
| NFIRAOS S                      | P: 80.1% | R<8     | on-axis      | n/a      |                        | Boyer (2017)                      |                         |
| λ=2.2μm                       |         |         |              |          |                        |                                     |                         |
| NFIRAOS M                      | P: 71–75% | R: >50% | on-axis (NIRS) |          | n/a                    | Sky coverage at the galactic pole. | Boyer & Ellerbroek (2016); Boyer (2017) |
| (λ=2.2μm)                     |         |         | 34” x 34” (IRIS) |          |                        |                                     |                         |
| NFIRAOS M                      | M       | M       | 2.1’ x 2.1’ (IRM) | n/a |                        | NFIRAOS wide field mode with modest AO correction | Simard et al. (2012) |

A good measure to characterize the quality of an AO system is to look at the long and short exposure Strehl ratios it delivers. Together with the residual image motion, also for long and short exposures, one can use these static and dynamic performance data to estimate the imaging quality and the raw contrast delivered to the science channel. Per definition, the Strehl ratio defines the ratio of the measured AO corrected peak intensity of the point spread function (PSF) to the intensity measured or estimated of a perfectly imaged point spread function. If the delivered long exposure Strehl ratio at a wavelength of 3.7 μm is 95%, there is a fraction of 5% of intensity or energy in the halo of the stellar PSF. As the structure and the dynamic behaviour of this un-controlled halo is unknown, it contributes strongly to the achievable contrast. This becomes clear if we look at the standard technique used in high-contrast imaging, where a

---

^a L=LTAO, M=MCAO, S=SCAO

^b Natural guide star spectral band and magnitude or fraction of the sky observable.

^c METIS requirements and estimates given for on-axis PSF. The METIS total corrected field of view is ∼ 12”x12” (Brandl et al., 2018).

^d GMTIFS field of view. The larger field of view of 20.4” x 20.4” is for the IFS imager (Sharp et al., 2016).
stellar reference PSF is subtracted from the actual recorded stellar PSF.

In combination with a coronagraph, contrast values of point sources below $10^{-4}$ at angular separations of $5 \lambda/D$ on a D=8 m telescope can be achieved. As shown in fig. [11] using the adaptive optics instrument NACO at the 8 m VLT with an annular groove phase mask (AGPM), different contrast values can be achieved depending on the applied data reduction algorithm. The pure adaptive optics intensity profile of a standard star, which shows structures around the 3rd bright Airy ring and at the edge of the AO control radius, can be reduced by a factor of approx. 20 at an angular separation of 0.5 arcsec ($5 \lambda/D$) with $\lambda=3.8 \mu$m. The subtraction of the stellar PSF using the angular differential imaging (ADI, Marois et al. (2006)) method together with a principal components analysis (PCA, Gomez Gonzalez et al. (2016)) results in higher contrast values towards smaller angular separations. The rather flat contrast values at angular separations beyond the AO control radius indicate the highest contrast achievable at the smallest angular separations for this observation set-up. As the green curve in fig. [11] shows, there are still about 2 orders of magnitude contrast improvements possible. For that reason it is important to understand in detail the contributions of the non-corrected aberrations to this regime.

As Mawet et al. (2012) point out, in particular low-order aberrations contribute to the contrast at angular separations between 1 and $4 \lambda/D$. One proposal to further improve the raw contrast behind an AO fed coronagraph is predictive control. Males & Guyon (2018) show that the raw contrast for bright stars can be increased by more than 3 orders of magnitude at an angular separation from the PSF center of $1 \lambda/D$, for $\lambda=800$ nm and D=25.4 m (GMT case). This corresponds to a raw contrast improvement of $\sim$50 at $\lambda=3.8 \mu$m.

![Fig. 11. VLT NACO coronagraphic observations of HD 123888 in L'-band ($\lambda=3.8 \mu$m). Normalised azimuthally averaged relative intensity profiles and contrast curve on a log-log scale. The plain red curve shows the intensity profile of a typical saturated NACO L’ PSF (similar brightness and exposure time). The blue dashed curve shows the AGPM intensity profile before PCA, demonstrating the instantaneous contrast gain provided by the coronagraph at all spatial frequencies within the adaptive optics control radius ($\sim$0.7 arcseconds). The green dash-dot curve presents the reduced PCA-ADI 5σ detectability limits (40 frames, 800 s, position angle difference $\approx 30^\circ$), taking both the coronagraph off-axis transmission and the PCA-ADI flux losses into account. Figures and caption taken from Mawet et al. (2013). See text for further explanations.](image-url)

Another way to further reduce low order aberrations is to increase the speed of the AO system in case there are enough photons available from the AO reference source. An exemplary case for the bright (K=4.5 mag) star 51 Eridani is shown in fig. [12] Increasing the AO loop frequency from 1 kHz to 2 kHz
improves the coronagraphic contrast by a factor $\approx 3$.

Guyon et al. (2012) have shown similar behaviour for a perfect AO system on a 30m class telescope, simulating wavefront sampling frequencies up to 100 kHz and limiting the closed-loop servo latency to 0.1 ms. As shown in fig. 13, raw H-band PSF contrasts at small separations between 10 to 20 mas of $\approx 1.e-5$ can be achieved.

This indicates that the stability of the AO controlled PSF is a critical factor for high-contrast imaging using coronagraphs and further post-processing techniques. This is long known but the impact on contrast is striking. In particular PSF subtraction in combination with ADI requires careful execution as it can subtract extended structures like circumstellar disks (Soummer et al., 2012). Measuring the reference PSF for post-processing PSF subtraction is a critical task in this context and requires that the AO performs as uniform as possible.

![Graph](image_url)

**Fig. 12.** ELT METIS 10 seconds simulated SCAO coronagraphic observations of the bright reference star 51 Eridani at $\lambda=3.8 \mu m$ (Absil & Carlomagno, 2018). This plot is to demonstrate that rather small changes of the long-exposure Strehl number from 0.978 at 1 kHz AO loop speed to 0.984 at 2 kHz AO loop speed results in a contrast enhancement of a factor $\sim 3$ at at separation of $5 \lambda/D$. For comparison, in fig. 11 this separation is at $\sim 0.5$ arcsec.

Table 7 provides an overview of the planned high-contrast instruments and the expected years of commissioning. Some of these instruments will also use the technology of high dispersion coronagraphy (HDC) not further explained here. A recent study on how exoplanets can be observed with HDC from the ground as well as with space telescopes can be found in Wang et al. (2017).

**Conclusions and outlook**

The technique of adaptive optics has matured over the past thirty years. Permanently installed on all future extremely large telescopes currently under design and construction, it will allow for diffraction-limited observations for wavelengths in the near-infrared regime and longer. Expanding the use of AO in the visible spectrum remains challenging – a niche observing mode for the very best nights as Close et al. (2017) suggest –, but we should keep our eyes on this.

All instruments under design for the ELT, GMT, and TMT can use AO, hence make use of the huge light collecting power and the maximum achievable angular resolution. Laser guide star facilities push the AO sky coverage to levels well above 50%.

Highly specialized instruments will further boost ground-based diffraction limited high-contrast imaging and characterization of exoplanets to unprecedented planet-star contrast ratios. The entire nearby Alpha
Centauri system, including the planet Proxima Centauri b (Kreidberg & Loeb 2016) orbiting in the habitable zone, has received strong attraction in the science community, accompanied by an intense public attention. The pure imagination to find nearby Earth-like planets in habitable zones has triggered ideas to fly there for further investigation (Popkin 2017).

Acknowledgments

I would like to thank my colleagues Markus Feldt, Dietrich Lemke, and Kalyan Radhakrishman for their advice and comments. Special thanks to the anonymous reviewer for his/her very valuable comments and suggestions to improve the quality of this review.

I thank the following organizations and journals for allowing me to reproduce the figures listed below.
in this publication. The international society for optics and photonics (SPIE) for figures 1, 6 & 9, the Monthly Notices of the Royal Astronomical Society for fig. 3, the European Southern Observatory (ESO) for figures 2 and the background of fig. 4, the Giant Magellan Telescope Organization (GMTO) for fig. 5, the Thirty Meter Telescope International Observatory (TIO) for fig. 7, and The Messenger for fig. 11.
Adaptive optics for extremely large telescopes

References

Absil, O. & Carlomagno, B. [2018] “METIS coronagraphic simulations, March 2, 2018,” personal communication.

Adkins, S. M. [2012] “Measured performance of the prototype polar coordinate CCD array,” Adaptive Optics Systems III, p. 84470R, doi:10.1117/12.926474.

Akiyama, M., Oya, S., Ono, Y. H., Takami, H., Ozaki, S., Hayano, Y., Ikeda, Y. [2014] “TMT-AGE: wide field of regard multi-object adaptive optics for TMT,” Adaptive Optics Systems IV, p. 914814, doi:10.1117/12.2056320.

Ammons, S. M., Johnson, L., Laag, E. A., Kupke, R. & Gavel, D. T. [2008] “Laboratory demonstrations of multi-object adaptive optics in the visible on a 10 meter telescope,” Adaptive Optics Systems, p. 70150C, doi:10.1117/12.790188.

Andersen, D., Dunn, J., Larkin, J., Wright, S., Eric, C., Atwood, J., Chapin, E., Hardy, T., Smith, R. & Trancho, G. [2017] “Acquisition and dithering with the tmt iris on-instrument wavefront sensor system,” AO4ELT5 Proceedings, doi:10.26698/AO4ELT5.0124, http://www.iac.es/congreso/AO4ELT5/media/proceedings/proceeding-124.pdf

Andersen, D. R., Jackson, K. J., Blain, C., Bradley, C., Correia, C., Ito, M., Lardière, O. & Vérán, J.-P. [2012] Publications of the Astronomical Society of the Pacific 124, 469, doi:10.1086/665924.

Atkinson, D. E., Hall, D. N. B., Baker, I. M., Goebel, S. B., Jacobson, S. M., Lockhart, C. & Warmbier, E. A. [2016] “Next-generation performance of SAPHIRA HgCdTe APDs,” High Energy, Optical, and Infrared Detectors for Astronomy VII, p. 96100, doi:10.1117/12.2234314.

Babcock, H. W. [1953] Publications of the Astronomical Society of the Pacific 65, 229, doi:10.1086/126606.

Bernstein, R. A. [2018] “An introduction to the gmt: Telescope & first generation instruments,” http://www.astro.iag.usp.br/~eaa2018/Talks/Brazil_01_GMToverview_v5.pdf.

Bonaccini Calia, D., Hackenberg, W., Holzlöhner, R., Lewis, S. & Pfrommer, T. [2014] Advanced Optical Technologies 3, 345, doi:10.1515/aot-2014-0025.

Bouchez, A. [2017] “Giant magellan telescope wavefront control development status,” http://www.iac.es/congreso/AO4ELT5/media/monday/ao4elt5_bouchez.pdf

Bouchez, A. H., Acton, D. S., Biasi, R., Conant, R., Espeland, B., Esposito, S., Filgueira, J., Gallieni, D., McLeod, B. A., Pinna, E., Santoro, F., Trancho, G. & van Dam, M. A. [2014] “The Giant Magellan Telescope adaptive optics program,” Adaptive Optics Systems IV, p. 91480W, doi:10.1117/12.2057613.

Boyer, C. [2017] “Adaptive optics program update at tmt,” AO4ELT5 Proceedings, doi:10.26698/AO4ELT5.0131, http://www.iac.es/congreso/AO4ELT5/media/proceedings/proceeding-131.pdf

Boyer, C. & Ellerbroek, B. [2016] “Adaptive optics program update at TMT,” Adaptive Optics Systems V, p. 990908,
Brandl, B. R., Agócs, T., Aitink-Kroes, G., Bertram, T., Bettonvil, F., van Boekel, R., Boulade, O., Feldt, M., Glasse, A., Glauser, A., Giudel, M., Hurtado, N., Jager, R., Kenworthy, M. A., Mach, M., Meinsner, J., Meyer, M., Pantin, E., Quanz, S., Schmid, H. M., Stuik, R., Veninga, A. & Waelkens, C. [2016] “Status of the mid-infrared E-ELT imager and spectrograph METIS,” Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 990820, doi:10.1117/12.2233974.

Brandl, B. R., Quanz, S., Snellen, I., van Dishoeck, E., Pontoppidan, K., Le Floch, E., Bettonvil, F., van Boekel, R., Glauser, A. & Hurtado, N. [2018] “The Mid-IR ELT Imager and Spectrograph (METIS) and its Science Goals in the Context of AKARI,” The Cosmic Wheel and the Legacy of the AKARI Archive: From Galaxies and Stars to Planets and Life, eds. Ootsubo, T., Yamamura, I., Murata, K. & Onaka, T., p. 41.

Campbell, M. A., Evans, C. J., Mackey, A. D., Gieles, M., Alves, J., Ascenso, J., Bastian, N. & Longmore, A. J. [2010] Monthly Notices of the Royal Astronomical Society 405, 421, doi:10.1111/j.1365-2966.2010.16447.x.

Caputa, K., Atwood, J., Herriot, G., Veran, J.-P., Spanò, P. & Zielinski, A. [2014] “The 384-channel prototype of DM Electronics for ELT AO systems,” Adaptive Optics Systems IV, p. 914844, doi:10.1117/12.2056580.

Clénet, Y., Buey, T., Rousset, G., Gendron, E., Espisito, S., Hubert, Z., Busoni, L., Cohen, M., Riccardi, A., Chapron, F., Bonaglia, M., Sevin, A., Baudoz, P., Feautrier, P., Zins, G., Gratadour, D., Vidal, F., Chemla, F., Ferreira, F., Doucet, N., Durand, S., Carlotti, A., Perrot, C., Schreiber, L., Lombini, M., Ciliegi, P., Diolaiti, E., Schubert, J. & Davies, R. [2016] “Joint MICADO-MAORY SCAO mode: specifications, prototyping, simulations and preliminary design,” Adaptive Optics Systems V, p. 99090A, doi:10.1117/12.2231192.

Close, L., Males, J., Guyon, O., Schatz, L. & Morzinski, K. [2017] “Current visible light ao systems and science with magao and a look to elts,” http://www.iac.es/congreso/AO4ELT5/media/monday/ao4elt5_close.pdf.

Copeland, M., Price, I., Rigaut, F., Bloxham, G., Boz, R., Bundy, D., Espeland, B. & Sharp, R. [2016] “GMTIFS: deformable mirror environmental testing for the on-instrument wavefront sensor,” Adaptive Optics Systems V, p. 990980, doi:10.1117/12.2231550.

Correia, C. M., Neichel, B., Conan, J.-M., Petit, C., Sauvage, J.-F., Fusco, T., Vernet, J. D. R. & Thatte, N. [2016] “Natural guide-star processing for wide-field laser-assisted AO systems,” Adaptive Optics Systems V, p. 99094H, doi:10.1117/12.2232918.

Currie, T., Guyon, O., Tamura, M., Kudo, T., Jovanovic, N., Lozi, J., Schliedermair, J. E., Brandt, T. D., Kuhn, J., Serabyn, E., Janson, M., Carson, J., Groff, T., Kasdin, N. J., McElwain, M. W., Singh, G., Uyama, T., Kuzuhara, M., Akiyama, E., Grady, C., Hayashi, S., Knapp, G., Kwon, J.-m., Oh, D., Wisniewski, J., Kitko, M. & Yang, Y. [2017] Astrophysical Journal Letters 836, L15, doi:10.3847/2041-8213/1/L15.

David, T. J., Andersen, D. R., Lardière, O., Bradley, C., Blain, C., Oya, S., Akiyama, M. & Ono, Y. H. [2015] Astrophysical Journal 811, p. 133, doi:10.1088/0004-637X/811/2/133.

Davies, R. & Kasper, M. [2012] Annual Review of Astronomy and Astrophysics 50, 305, doi:10.1146/annurev-astro-081811-125447.

Davies, R., Schubert, J., Hartl, M., Alves, J., Clénet, Y., Lang-Bardel, F., Nicklas, H., Pott, J.-U., Ragazzoni, R., Tolstoy, E., Aigo, T., Anwand-Heerwart, H., Barboza, S., Baudouz, P., Bender, R., Bizenberger, P., Boccaletti, A., Boland, W., Bonifacio, P., Briel, F., Buey, T., Chapron, F., Cohen, M., Czoske, O., Dreizler, S., Fulono, R., Feautrier, P., Förster Schreiber, N., Gendron, E., Genzel, R., Glück, M., Gratadour, D., Greimel, R., Grupp, F., Häuser, M., Haug, M., Hennawi, J., Hess, H. J., Hörmann, V., Hofferbert, R., Hopp, U., Hubert, Z., Ives, D., Kausch, W., Kerber, F., Kravcar, H., Kuijken, K., Lang-Bardel, F., Leitzinger, M., Leschinski, K., Massari, D., Mei, S., Merlin, F., Mohr, L., Monna, A., Müller, F., Navarro, R., Plattner, M., Przybilla, N., Ramí, R., Ramsay, S., Ratzka, T., Rhode, P., Richter, J., Rix, H.-W., Rodeghiero, G., Rohloff, R.-R., Rouzet, G., Ruddenklaus, R., Schaffroeth, V., Schlichter, J., Sevin, A., Stuik, R., Sturm, E., Thomas, J., Tromp, N., Turatto, M., Verdoes-Kleijn, G., Vidal, F., Wagner, R., Wegner, M., Ziegler, B. & Zins, G. [2010] “MICADO: first light imager for the E-ELT,” Ground-based and Airborne Instrumentation for Astronomy V, p. 99081Z, doi:10.1117/12.2233047.

Davies, R. I., Hackenberg, W., Ott, T., Eckart, A., Rabien, S., Anders, S., Hippler, S., Kasper, M., Kalas, P., Quirrenbach, A. & Glindemann, A. [1999] Astronomy and Astrophysics Supplement 138, 345, doi:10.1051/1999278.

DePoy, D. L., Allen, R., Barkhouse, R., Boster, E., Carona, D., Harding, A., Hammond, R., Marshall, J. L., Orndorff, J., Papovich, C., Prochaska, K., Prochaska, T., Rheault, J. F., Snee, S., Shectman, S. & Villanueva, S. [2012] “GMACS: a wide field, multi-object, moderate-resolution, optical spectrograph for the Giant Magellan Telescope,” Ground-based and Airborne Instrumentation for Astronomy IV, p. 84461N, doi:10.1117/12.926186.

Dioiai, E., Ciliegi, P., Abicca, R., Agapito, G., Arcidiacono, C., Baruffolo, A., Bellazzini, M., Biliotti, V., Bonaglia, M., Bregoli, G., Brugio, R., Brissaud, R., Busoni, L., Carbonaro, L., Carlotti, A., Cascone, E., Correia, J.-J., Turatto, M., Verdoes-Kleijn, G., Vidal, F., Wagner, R., Wegner, M., Ziegler, B. & Zins, G. [2016] “MICADO: first light imager for the E-ELT,” Ground-based and Airborne Instrumentation for Astronomy V, p. 99081Z, doi:10.1117/12.2233047.
Cortecchia, F., Cosentino, G., De Caprio, V., de Pascale, M., De Rosa, A., Del Vecchio, C., Delboulbè, A., Di Rico, G., Esposito, S., Fantinel, D., Feautrier, P., Felini, C., Ferruzzi, D., Fini, L., Fiorentino, G., Foppiani, I., Ghigo, M., Giordano, C., Giro, E., Gluck, L., Hénault, F., Jocou, L., Kerber, F., La Penna, P., Lafrasse, S., Lauria, M., le Coarer, E., Le Louarn, M., Lombini, M., Magnard, Y., Maionano, E., Mannucci, F., Mapelli, M., Marchetti, E., Maurel, D., Michaud, L., Morgante, G., Moulin, T., Oberti, S., Pareschi, G., Patti, M., Puglisi, A., Rabou, P., Ragazzoni, R., Ramsay, S., Riccardi, A., Ricciardi, S., Riva, M., Rochat, S., Roussel, F., Roux, A., Salasnich, B., Saracco, P., Schreiber, L., Spavone, M., Stadler, E., Sztefek, M.-H., Ventura, N., Vérinaud, C., Xompero, M., Fontana, A. & Zerbi, F. M. [2016] “MAORY: adaptive optics module for the E-ELT,” *Adaptive Optics Systems V*, p. 99092D, doi:10.1117/12.2234585.

D’Orgeville, C., Bouchez, A., Conan, R., Espeland, B., Gardhouse, R., Hart, J., Price, I., Trancho, G. & Uhldorf, K. [2013] “GMT Laser Guide Star Facility,” *Proceedings of the Third AO4ELT Conference*, eds. Esposito, S. & Fini, L., p. 14, doi:10.12839/AO4ELT3.13119.

d’Orgeville, C. & Fetzer, G. J. [2016] “Four generations of sodium guide star lasers for adaptive optics in astronomy and space situational awareness,” *Adaptive Optics Systems V*, p. 99090R, doi:10.1117/12.2234298.

Downing, M., Casali, M., Finger, G., Lewis, S., Marchetti, E., Mehravan, L., Ramsay, S. & Reyes, J. [2016] “AO WFS detector developments at ESO to prepare for the E-ELT,” *Adaptive Optics Systems V*, p. 990914, doi:10.1117/12.2232504.

Dumas, C. [2018] “The thirty-meter-telescope project update, science in the 2020s,” [https://www.noao.edu/meetings/2020decadal/files/UpdateTMT-DUMAS-lowres.pdf](https://www.noao.edu/meetings/2020decadal/files/UpdateTMT-DUMAS-lowres.pdf).

Dunn, J., Andersen, D., Chapin, E., Reshetov, V., Wierzbicki, R., Herriot, G., Chalmer, D., Isbrucker, V., Larkin, J. E., Moore, A. M. & Suzuki, R. [2016] “The Infrared Imaging Spectrograph (IRIS) for TMT: multi-tiered wavefront measurements and novel mechanical design,” *Ground-based and Airborne Instrumentation for Astronomy VI*, p. 9908A9, doi:10.1117/12.2243030.

ESO [2017] “Cutting-edge adaptive optics facility sees first light,” [https://www.eso.org/public/news/eso1724/](https://www.eso.org/public/news/eso1724/).

ESO [2018] “The elt instruments,” [https://www.eso.org/public/teles-instr/elt/](https://www.eso.org/public/teles-instr/elt/).

Esposito, S., Agapito, G., Antichi, J., Bonanno, A., Carbonaro, L., Giordano, C. & Spano, P. [2015] *Memorie della Societa Astronomica Italiana* 86, 446.

Esposito, S., Mesa, D., Skemer, A., Arcidiacono, C., Claudì, R. U., Desidera, S., Gratton, R., Mannucci, F., Marzari, F., Masiadri, E., Close, L., Hinz, P., Kulesa, Ç., McCarthy, D., Males, J., Agapito, G., Argomedo, J., Boutsia, K., Bruglio, R., Brusa, G., Busoni, L., Cresci, G., Fini, L., Fontana, A., Guerra, J. C., Hill, J. M., Miller, D., Paris, D., Pinna, E., Puglisi, A., Quiros-Pacheco, F., Riccardi, A., Stefanini, P., Testa, V., Xompero, M. & Woodward, C. [2013] *Astronomy & Astrophysics* 549, A52, doi:10.1051/0004-6361/201219212.

Esposito, S., Riccardi, A., Fini, L., Puglisi, A. T., Pinna, E., Xompero, M., Bruglio, R., Quiros-Pacheco, F., Stefanini, P., Guerra, J. C., Busoni, L., Tozzi, A., Pieralli, F., Agapito, G., Brusa-Zappellini, G., Demers, R., Brynnel, J., Arcidiacono, C. & Salinari, P. [2010] “First light AO (FLAO) system for LBT: final integration, acceptance test in Europe, and preliminary on-sky commissioning results,” *Adaptive Optics Systems II*, p. 773609, doi:10.1117/12.858194.

Esposito, S., Tozzi, A., Puglisi, A., Pinna, E., Riccardi, A., Busoni, S., Busoni, L., Stefanini, P., Xompero, M., Zanotti, D. & Pieralli, F. [2006] “First light AO system for LBT: toward on-sky operation,” *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 62720A, doi:10.1117/12.673509.

Feldt, M., Gratton, R., Hippler, S., Schmid, H. M., Turatto, M., Waters, R. & Henning, T. [2007] “VI,” *The CHEOPS Project: Characterizing Exoplanets by Opto-infrared Polarimetry and Spectroscopy* (Springer-Verlag), p. 261, doi:10.1007/978-3-540-39756-4_69.

Fugate, R. Q., Wopat, L. M., Fried, D. L., Ameer, G. A., Browne, S. L., Roberts, P. H., Tyler, G. A., Boeke, B. R.,
Jaffe, D. T., Barnes, S., Brooks, C., Lee, H., Mace, G., Pak, S., Park, B.-G. & Park, C. [2016] “GMTNIRS: progress toward the Giant Magellan Telescope near-infrared spectrograph,” *Ground-based and Airborne Instrumentation for Astronomy VI*, p. 99081U, doi:10.1117/12.2232894.

Jenkins, D. R., Basden, A. & Myers, R. M. [2018] *Monthly Notices of the Royal Astronomical Society* **478**, 3149, doi:10.1093/mnras/sty1310.

Jorden, P., Bourke, D., Cassidy, R., Fryer, M., Jerram, P., Moore, S. & Pratlong, J. [2017] “Thirty Meter Telescope (TMT) Narrow Field Infrared Adaptive Optics System (NIRAO) real-time controller preliminary architecture,” *Software and Cyberinfrastructure for Astronomy IV*, p. 99134J, doi:10.1117/12.223709.

Kasper, M., Verinaud, C. & Mawet, D. [2013] “Roadmap for PCS, the Planetary Camera and Spectrograph for the E-ELT,” *Proceedings of the Third AO4ELT Conference*, eds. Esposito, S. & Fini, L., p. 8, doi:10.12839/AO4ELT3.12804.

Kenworthy, M. A., Absil, O., Agócs, T., Pantin, E., Quanz, S., Stuik, R., Snik, F. & Brandl, B. [2016] “High-contrast imaging with METIS,” *Ground-based and Airborne Instrumentation for Astronomy VI*, p. 9908A6, doi:10.1117/12.223655.

Kerley, D., Smith, M., Dunn, J., Herriot, G., Véran, J.-P., Boyer, C., Ellerbroek, B., Gilles, L. & Wang, L. [2016] “Thirty Meter Telescope (TMT) Narrow Field Infrared Adaptive Optics System (NIFRAOS) real-time controller preliminary architecture,” *Software and Cyberinfrastructure for Astronomy IV*, p. 99134J, doi:10.1117/12.223709.

Kopf, T., Dietzel, O., Dargatz, B., Kamm, A., Bach, M., Süssmuth, K., Richter, S., Broich, B., Damm, C., Eberhardt, R. & Reinlein, C. [2017] “Swap dm: preliminary design and schematics of a dm for extreme adaptive optics,” *AO4ELT5 Proceedings*, doi:10.26698/AO4ELT5.0009, http://www.iac.es/congreso/AO4ELT5/media/proceedings/proceeding-009.pdf

Kreidberg, L. & Loeb, A. [2016] *Astrophysical Journal Letters* **832**, L12, doi:10.3847/2041-8205/832/1/L12.

La Penna, P., Aller Carpentier, E., Argomedo, J., Arsenault, R., Conzelmann, R. D., Delabre, B., Donaldson, R., Gago, F., Gutierrez-Cheetam, P., Hubin, N., Joly, P., Kiekebusch, M., Kirchbauer, J. P., Klein, B., Kolb, J., Kuntschner, H., Le Louarn, M., Lizon, J.-L., Madec, P.-Y., Manescau, A., Mehrgan, L., Oberti, S., Quentin, J., Sedghi, B., Ströbele, S., Suárez Valles, M., Soenke, C., Tordo, S. & Vernet, J. [2016] “AOF: standalone test results of GALACSI,” *Adaptive Optics Systems V*, p. 99092Z, doi:10.1117/12.2232984.

Laug, E. A., Ammons, S. M., Gavel, D. T. & Kupke, R. [2008] *Journal of the Optical Society of America A* **25**, 2114, doi:10.1364/JOSAA.25.002114.

Lamb, M., Venn, K., Andersen, D., Oya, S., Shetrone, M., Fattahi, A., Howes, L., Asplund, M., Lardiöre, O., Akiyama, M., Ono, Y., Terada, H., Hayano, Y., Suzuki, G., Blain, C., Jackson, K., Correia, C., Youakim, K. & Bradley, C. [2017] *Monthly Notices of the Royal Astronomical Society* **465**, 3536, doi:10.1093/mnras/stw2865.

Lardiöre, O., Andersen, D., Blain, C., Bradley, C., Gamroth, D., Jackson, K., Lach, P., Nash, R., Venn, K., Vérán, J.-P., Correia, C., Oya, S., Hayano, Y., Terada, H., Ono, Y. & Akiyama, M. [2014] “Multi-object adaptive optics on-sky results with Raven,” *Adaptive Optics Systems IV*, p. 91481G, doi:10.1117/12.2055480.

Larkin, J. E., Moore, A. M., Wright, S. A., Wince, M., Beaulieu, J. E., Anderson, D., Chisholm, E. M., Dekany, R. G., Dunn, J. S., Ellerbroek, B. L., Hayano, Y., Phillips, A. C., Simard, L., Smith, R., Suzuki, R., Weber, R. W., Weiss, J. L. & Zhang, K. [2016] “High-contrast imaging with METIS,” *Ground-based and Airborne Instrumentation for Astronomy VI*, p. 99081W, doi:10.1117/12.2232212.

Lee, K.-D., Kim, Y.-S., Kim, H.-S., Lee, C.-H. & Lee, W. G. [2017] *Publications of the Astronomical Society of the Pacific* **129**, 095001, doi:10.1088/1538-3873/aa76bd.

Leibundgut, B., Bacon, R., Jaffé, Y. L., Johnston, E., Kuntschner, H., Selman, F., Valenti, E., Vernet, J. & Vogt, F. [2017] *The Messenger* **170**, 20.

Li, M., Wei, K., Tang, J., Jiang, C., Fan, M., Chen, F., Rui, D., Li, X., Boyer, C., Wang, L., Ellerbroek, B., Xian, H., Rao, C. & Zhang, Y. [2016] “The progress of TMT Laser Guide Star Facility,” *Adaptive Optics Systems V*, p. 99095Q, doi:10.1117/12.2231987.

Lloyd-Hart, M., Brusa, G., Wildi, F. P., Miller, D. L., Fisher, D. L. & Riccardi, A. [2003] “Lessons learned from the first adaptive secondary mirror,” *Astronomical Adaptive Optics Systems and Applications*, eds. Tyson, R. K.?
Lozi, J., Guyon, O., Jovanovic, N., Patrhak, P., Norris, B., Martinache, F., N'Diaye, M., Mazin, B. & Walter, A. [2017] “Sceaxa: lessons learned for a future tmt instrument,” *AO4ELT5 Proceedings*, doi:10.26698/AO4ELT5.0080, http://www.iac.es/congreso/AO4ELT5/media/proceedings/proceeding-080.pdf.

Lozi, J., Guyon, O., Jovanovic, N., Singh, G., Goebel, S., Norris, B. & Okita, H. [2016] “Characterizing and mitigating vibrations for SCExAO,” *Adaptive Optics Systems V*, p. 99090J, doi:10.1117/12.2233040.

Macintosh, B., Graham, J., Doyon, R., Gavel, D., Larkin, J., Oppenheimer, B., Saddlemeyer, L., Wallace, J. K., Bauman, B., Evans, J., Erikson, D., Morzinski, K., Phillion, D., Poyneer, L., Sivaramakrishnan, A., Soummer, R., Thibault, S. & Veran, J.-P. [2006a] “The Gemini Planet Imager,” *Journal of Astronomical Telescopes, Instruments, and Systems*, p. 9908AB, doi:10.1051/0004-6361/201526594.

Macintosh, B., Troy, M., Doyon, R., Baker, K., Bauman, B., Marois, C., Palmer, D., Phillion, D., Poyneer, L., Crossfield, I., Dumont, P., Levine, B. M., Shao, M., Serabyn, G., Shelton, C., Vasisht, G., Wallace, J. K., Lavigne, J.-F., Valee, P., Rowlands, N., Tam, K. & Hackett, D. [2006b] “Extreme adaptive optics for the Thirty Meter Telescope,” *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 62720N, doi:10.1117/12.672430.

Madec, P.-Y. [2012] “Overview of deformable mirror technologies for adaptive optics and astronomy,” *Adaptive Optics Systems III*, p. 844705, doi:10.1117/12.924892.

Maire, A.-L., Bonnefoy, M., Ginski, C., Vigan, A., Messina, S., Mesa, D., Galicher, R., Gratton, R., Desidera, S., Kopytova, T. G., Millward, M., Thalmann, C., Claudi, R. U., Ehrenreich, D., Zurlo, A., Chauvin, G., Antichi, J., Baruffolo, A., Bagnara, P., Amorim, M., Baruffolo, A., Bagnara, P., CAMCAO Consortium [2007] *The Messenger* 129, 8.

Marchetti, E., Brast, R., Delabre, B., Donaldson, R., Fedrigo, E., Frank, C., Hubin, N., Kolb, J., Lizon, J.-L., Marchesi, M., Oberti, S., Reiss, R., Santos, J., Soenke, C., Tordo, S., Baruffolo, A., Bagnara, P. & CAMCAO Consortium [2007] *The Messenger* 129, 8.

Marchetti, E., Brast, R., Delabre, B., Donaldson, R., Fedrigo, E., Frank, C., Hubin, N., Kolb, J., Lizon, J.-L., Marchesi, M., Oberti, S., Reiss, R., Soenke, C., Tordo, S., Baruffolo, A., Bagnara, P., Amorim, A. & Lima, J. [2008] “MAD on sky results in star oriented mode,” *Adaptive Optics Systems*, p. 70150F, doi:10.1117/12.787240.

Marin, E., Sivo, G., Garrel, V., Gigoux, P., Moreno, C., van Dam, M., Chinn, B., Hirst, P., Montes, V. & Rutten, R. [2017] “Tracking the sodium layer altitude with gems in the era of ngs2,” *AO4ELT5 Proceedings*, doi:10.26698/AO4ELT5.0090, http://www.iac.es/congreso/AO4ELT5/media/proceedings/proceeding-089.pdf
Adaptive optics for extremely large telescopes

Marois, C., Lafrenière, D., Doyon, R., Macintosh, B. & Nadeau, D. [2006] *Astrophysical Journal* **641**, 556, doi:10.1086/500401.

Martinache, F. & Guyon, O. [2009] “The Subaru Coronagraphic Extreme-AO Project,” *Techniques and Instrumentation for Detection of Exoplanets IV*, p. 744000, doi:10.1117/12.826365.

Mawet, D., Absil, O., Girard, J. H., Milli, J., O’Neal, J., Delacroix, C., Baudouz, P., Boccaletti, A., Bourget, P., Christiaens, V., Forsberg, P., Gonté, F., Habraken, S., Hanot, C., Karlsson, M., Kasper, M., Lagrange, A., Lizon, J., Muzic, K., Peña, E., Olivier, R., Slusarenko, N., Tacconi-Garman, L. E. & Surdej, J. [2013] *The Messenger* **152**, 8.

Mawet, D., Pueyo, L., Lawson, P., Mugnier, L., Traub, W., Boccaletti, A., Trauger, J. T., Gladysz, S., Serabyn, E., Milli, J., Belikov, R., Kasper, M., Baudouz, P., Macintosh, B., Marois, C., Oppenheimer, B., Barrett, H., Beuzit, J.-L., Devaney, N., Girard, J., Guyon, O., Krist, J., Mennesson, B., Mouillet, D., Murakami, N., Poyneer, L., Savransky, D., Vérinaud, C. & Wallace, J. K. [2012] “Review of small-angle coronagraphic techniques in the wake of ground-based second-generation adaptive optics systems,” *Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*, p. 844204, doi:10.1117/12.927245.

Meyer, E., Kürster, M., Arcidiacono, C., Ragazzoni, R. & Rix, H.-W. [2011] *Astronomy & Astrophysics* **532**, A16, doi:10.1051/0004-6361/201016053.

Milli, J., Kasper, M., Bourget, P., Pan metam, C., Mouillet, D., Sauvage, J.-F., Reyes, C., Fusco, T., Cantalloube, F., Tristram, K., Wahhaj, Z., Beuzit, J.-L., Girard, J., Mawet, D., Telle, A., Vigan, A. & Diaye, M. N. [2018] *ArXiv e-prints*.

Milli, J., Mawet, D., Mouillet, D., Kasper, M. & Girard, J. H. [2016] “Adaptive Optics in High-Contrast Imaging,” *Astronomy at High Angular Resolution*, eds. Boffin, H. M. J., Hussain, G., Berger, J.-P. & Schmidtobreck, L., p. 17, doi:10.1007/978-3-319-39739-9_2.

Mobasher, B., Crampton, D. & Simard, L. [2010] “An Infrared Multi-Object Spectrograph (IRMS) with adaptive optics for TMT: the science case,” *Ground-based and Airborne Instrumentation for Astronomy III*, p. 77355P, doi:10.1117/12.858061.

Morris, T., Basden, A., Buey, T., Chemla, F., Conan, J.-M., Fitzsimons, E., Fusco, T., Gendron, E., Hammer, F., Jagourel, P., Morel, C., Myers, R., Neichel, B., Petit, C., Rodrigues, M. & Rouset, G. [2016] “Adaptive optics for MOSAIC: design and performance of the wide(st)-field AO system for the E-ELT,” *Adaptive Optics Systems V*, p. 990911, doi:10.1117/12.2232411.

Neichel, B., Fusco, T., Sauvage, J.-F., Correia, C., Dohlen, K., El-Hadi, K., Blanco, L., Schwartz, N., Clarke, F., Thatte, N. A., Tezca, M., Pauifique, J., Vernet, J., Le Louarn, M., Hammersley, P., Gach, J.-L., Pascal, S., Vola, P., Petit, C., Conan, J.-M., Carlotti, A., Vérinaud, C., Schnetler, H., Bryson, T., Myers, R., Hugot, E., Gallie, A. M. & Henry, D. M. [2016] “The adaptive optics modes for HARMONI: from Classical to Laser Assisted Tomographic AO,” *Adaptive Optics Systems V*, p. 990909, doi:10.1117/12.2231681.

Oberti, S., Le Louarn, M., Diolaiti, E., Arcidiacono, C., Schreiber, L., Lombini, M. & Corteelia, F. [2017] “Maory design trade-off study: tomography dimensioning,” *AO4ELT5 Proceedings*, doi:10.26098/AO4ELT5.0162, [http://www.iac.es/congreso/AO4ELT5/media/proceedings/proceeding-162.pdf](http://www.iac.es/congreso/AO4ELT5/media/proceedings/proceeding-162.pdf).

OIR-Laboratory-UCSD [2017] “Iris, first light instrument for the thirty meter telescope (tmt),” [https://oirlab.ucsd.edu/IRIS.html](https://oirlab.ucsd.edu/IRIS.html).

Ono, Y. H., Correia, C. M., Lardiére, O., Andersen, D. R., Oya, S., Akiyama, M., Gamroth, D., Jackson, K., Martin, O. & Bradley, C. [2016] “On-sky MOAO performance evaluation of RAVEN,” *Adaptive Optics Systems V*, p. 990910, doi:10.1117/12.2232321.

Oppenheimer, B. & Hinkley, S. [2009] *Annu. Rev. Astron. Astrophys.* **47**, 253, doi:10.1146/annurev-astro-082708-101717.

Orban de Xivry, G., Rahien, S., Busoni, L., Gaessler, W., Bonuglia, M., Borelli, J., Deyseurowth, M., Esposito, S., Gembperlein, H., Kulas, M., Lefebvre, M., Mazzoni, T., Peter, D., Puglisi, A., Raab, W., Rahmer, G., Sivitilli, A., Storm, J. & Ziegler, J. [2016] “First on-sky results with ARGOS at LBT,” *Adaptive Optics Systems V*, p. 990936, doi:10.1117/12.2240094.

Packham, C. [2017] “Michi: A thermal-ir instrument for the tmt,” [https://conference.ipac.caltech.edu/tmtsf2017/system/media_files/binaries/33/original/TMTSF2017-Packham.pdf](https://conference.ipac.caltech.edu/tmtsf2017/system/media_files/binaries/33/original/TMTSF2017-Packham.pdf).

Packham, C., Honda, M., Richter, M., Okamoto, Y. K., Kataza, H., Onaka, T., Fujiyoshi, T., Tokunaga, A., Chun,
M., Alonso-Herrero, A., Carr, J., Chiba, M., Enya, K., Fujiwara, H., Gandhi, P., Imanishi, M., Ichikawa, K., Ita, Y., Kawakatsu, N., Kotani, T., Levenson, N., Matsu, T., Matsuura, M., Minezaki, T., Najita, J., Nii, N., Ootsubo, T., Sakou, T., Takami, M., Telesco, C., Wright, C. M. & Yamashita, T. [2012] “Key science drivers for MICHI: a mid-IR instrument concept for the TMT,” *Ground-based and Airborne Instrumentation for Astronomy IV*, p. 84467G, doi:10.1117/12.224996.

Páges, H., Antonini, T., Aribi, T., Aubry, M., Bastard, A., Beaufort, E., Cousty, R., Dutey, G., Grézes-Besset, C., Grönenick, D., Krol, H., Marchet, N., Moreau, A., Morin, P., Palomo, R. & Sinquin, J.-C. [2016] “Developments of piezo deformable mirrors,” *Adaptive Optics Systems V*, p. 99097Z, doi:10.1117/12.2232971.

Paukne, J., Madec, P.-Y., Kolb, J., Kuntschner, H., Argomedo, J., Kiekebusch, M. J., Donaldson, R. H., Arsenault, R., Siebenmorgen, R., Soenke, C., Tordo, S., Conzelmann, R. D., Jost, A., Reyes-Moreno, J., Downing, M., Hibon, P., Valetzenuer, J. J. & Huguenauer, P. [2016] “GRAAL on the mountaintop,” *Adaptive Optics Systems V*, p. 99092H, doi:10.1117/12.2232826.

Perrot, C., Baudoz, P., Boccaletti, A., Rousset, G., Hubey, E., Clénet, Y., Durand, S. & Davies, R. [2018] *ArXiv e-prints*.

Pinna, E., Agapito, G., Quirós-Pacheco, F., Antichi, J., Carbonaro, L., Briguglio, M., Bonaglia, M., Riccardi, A., Puglisi, A., Biliotti, V., Arcidiacono, C., Xompero, M., Di Rico, G., Valentini, A., Bouchez, A., Santoro, F., Tranco, G. & Espósito, S. [2014] “Design and numerical simulations of the GMT Natural Guide star WFS,” *Adaptive Optics Systems IV*, p. 91482M, doi:10.1117/12.2057059.

Popkin, G. [2017] *Nature* **542**, 20.

Ragazzoni, R. [1999] *Astronomy and Astrophysics Supplement* **136**, 205, doi:10.1051/aas:1999207.

Ragazzoni, R., Marchetti, E. & Rigaut, F. [1999] *Astronomy & Astrophysics* **342**, L53.

Ragazzoni, R., Marchetti, E. & Valente, G. [2000] *Nature* **403**, 54, doi:10.1038/47425.

Reyes-Moreno, J., Downing, M. & Di Lieto, N. [2016] “ESO adaptive optics NGSD/LGSD detector and camera controller for the E-ELT,” *Adaptive Optics Systems V*, p. 990962, doi:10.1117/12.2232117.

Riaud, P. [2012] *Astronomy & Astrophysics* **545**, A25, doi:10.1051/0004-6361/201219707.

Rigaut, F. [2002] “Ground Conjugate Wide Field Adaptive Optics for the ELTs,” *European Southern Observatory Conference and Workshop Proceedings*, eds. Vernet, E., Ragazzoni, R., Esposito, S. & Hubin, N., p. 11.

Rigaut, F., Neichel, B., Bocca, M., d’Orgeville, C., Argomedo, J., Kiekebusch, M. J., Donaldson, R. H., Arsenault, R., Siebenmorgen, R., Soenke, C., Tordo, S., Conzelmann, R. D., Jost, A., Reyes-Moreno, J., Downing, M., Hibon, P., Valetzenuer, J. J. & Huguenauer, P. [2016] “GRAAL on the mountaintop,” *Adaptive Optics Systems V*, p. 99092H, doi:10.1117/12.2232826.

Rousset, G., Fontanella, J. C., Kern, P., Gigan, P. & Rigaut, F. [1990] *Astronomy & Astrophysics* **230**, L29.

Sereni, G. [2017] “Optical design of maory laser guide star objective,” PhD thesis, Università di Bologna, Italy.

Sharp, R., Bloxham, G., Boz, R., Bundy, D., Davies, J., Espeland, B., Fordham, B., Hart, J., Herrald, N., Nielsen, S., Sereni, G., Vaccarella, A., Vest, C., Young, P. & McGregor, P. [2016] “GMTIFS: The Giant Magellan Telescope Instrument Program,” *Optical Design of maory Laser Guide Star Objective,* PhD thesis, Università di Bologna, Italy.
Adaptive optics for extremely large telescopes

Instrumentation for Astronomy VI, p. 990822, doi:10.1117/12.2233506.

Thatte, N. A., Clarke, F., Bryson, I., Shetler, H., Tecza, M., Fusco, T., Bacon, R. M., Richard, J., Mediavilla, E., Neichel, B., Arribas, S., Garcia-Lorenzo, B., Evans, C. J., Remillieux, A., El Madi, K., Herreros, J. M., Melotte, D., O’Brien, K., Tosh, I. A., Vernet, J., Hammersley, P., Ives, D. J., Finger, G., Houghton, R., Rigopoulou, D., Lynn, J. D., Allen, J. R., Zieleniewski, S. D., Kendrew, S., Ferraro-Wood, V., Pécontal-Rousset, A., Kosmalski, J., Laurent, F., Loupias, M., Piqueras, L., Renault, E., Blaizot, J., Daguisé, E., Migniau, J.-E., Jarno, A., Born, A., Gallie, A. M., Montgomery, D. M., Henry, D., Schwartz, N., Taylor, W., Zins, G., Rodríguez-Ramos, L. F., Cagigas, M., Battaglia, G., Rebolo López, R., Hernández Suárez, E., Gigante-Ripoll, J. V., Piqueras López, J., Villa Martin, M., Correia, C., Pascal, S., Blanco, L., Voia, P., Epinat, B., Peroux, C., Vigan, A., Dohlen, K., Sauvage, J.-F., Lee, M., Carlotti, A., Verinaud, C., Morris, T., Myers, R., Reeves, A., Swinbank, M., Calcines, A., & Larrieu, M. [2016] “The E-ELT first light spectrograph HARMONI: capabilities and modes,” Ground-based and Airborne Instrumentation for Astronomy VI, p. 99081X, doi:10.1117/12.2230629.

Thomas, S. J., Belikov, R. & Bendek, E. [2015] “A method to directly image exoplanets in multi-star systems such as Alpha-Centauri,” Techniques and Instrumentation for Detection of Exoplanets VII, p. 96052G, doi:10.1117/12.2188637.

TMT [2017a] “call for tmt instrumentation white papers,” https://www.tmt.org/announcement/call-for-tmt-instrumentation-white-papers.

TMT [2017b] “Tmt first-light instrument enters final design phase,” https://www.tmt.org/news/tmt20171113.

TMT [2018a] “Tmt adaptive optics,” https://www.tmt.org/page/adaptive-optics.

TMT [2018b] “Tmt: Overview of instrument capabilities,” https://www.tmt.org/page/instrument-overview.

TMT-UCR [2014] “Irms, infrared multi-slit spectrograph for tmt,” http://faculty.ucr.edu/~mobasher/irms/3.

van Dam, M. A., Bouchez, A. H. & Conan, R. [2016] “Novel tip-tilt sensing strategies for the laser tomography adaptive optics system of the GMT,” Adaptive Optics Systems V, p. 990965, doi:10.1117/12.2231143.

van Dam, M. A., Bouchez, A. H. & McLeod, B. A. [2014] “Wide field adaptive optics correction for the GMT using natural guide stars,” Adaptive Optics Systems IV, p. 914813, doi:10.1117/12.2054154.

van Dam, M. A., Sasiela, R. J., Bouchez, A. H., Le Mignant, D., Campbell, R. D., Chin, J. C. Y., Hartman, S. K., Johansson, E. M., Lafon, R. E., Stomski, P. J., Jr., Summers, D. M. & Wizinowich, P. L. [2006] “Angular anisoplanatism in laser guide star adaptive optics,” Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, p. 627231, doi:10.1117/12.669737.

Vidal, F., Ferreira, F., Deo, V., Sevin, A., Gendron, E., Clénet, Y., Durand, S., Gratadour, D., Doucet, N., Rousset, G. & Davies, R. [2010] Journal of the Optical Society of America A 27, A253, doi:10.1364/JOSAA.27.00A253.

Vigan, A., Bonnefoy, M., Ginski, C., Beust, H., Galicher, R., Janson, M., Baudino, J.-L., Buenzli, E., Hagelberg, J., D’Orazi, V., Desidera, S., Maire, A.-L., Gratton, R., Sauvage, J.-F., Chauvin, G., Thalmann, C., Malo, L., Salter, G., Zurlo, A., Antichi, J., Baruffolo, A., Baudoz, P., Blanchard, P., Boccaletti, A., Beuzit, J.-L., Carle, M., Claudi, R., Costille, A., Delboulbé, A., Dohlen, K., Dominik, C., Feldt, M., Fusco, T., Gluck, L., Girard, J., Giro, E., Gry, C., Henning, T., Hubin, N., Huteg, E., Jaquet, M., Kasper, M., Lagrange, A.-M., Langlois, M., Le Mignant, D., Llored, M., Madec, F., Martinez, P., Mawet, D., Mesa, D., Milli, J., Mouillet, D., Moulin, T., Moutou, C., Origné, A., Pavlov, A., Perret, D., Petit, C., Pragt, J., Puget, P., Rabou, P., Rochat, S., Roelfsema, R., Salasnich, B., Schmid, H.-M., Sevin, A., Siebenmorgen, R., Smette, A., Staderl, E., Suarez, M., Turatto, M., Udry, S., Vakili, F., Wahhaj, Z., Weber, L. & Wildi, F. [2016] Astronomy & Astrophysics 587, A55, doi:10.1051/0004-6361/201526465.

Wang, J., Mawet, D., Ruane, G., Hu, R. & Benneke, B. [2017] The Astronomical Journal 153, 183, doi:10.3847/1538-3881/aa6474.

Wang, L., Andersen, D. & Ellerbroek, B. [2012] Applied Optics 51, 3692, doi:10.1364/AO.51.003692.

Wizinowich, P. [2012] “Progress in laser guide star adaptive optics and lessons learned,” Adaptive Optics Systems III, p. 84470D, doi:10.1117/12.925093.

Wizinowich, P., Acton, D. S., Shelton, C., Stomski, P., Gathright, J., Ho, K., Lupton, W., Tsubota, K., Lai, O., Max, C., Brase, J., An, J., Avicola, K., Olivier, S., Gavel, D., Macintosh, B., Ghez, A. & Larkin, J. [2000] Publications of the astronomical society of the pacific 112, 315, doi:10.1086/316543.