Co-Phasing Segmented Optics: From LBT to ELT?

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Abstract: Heading from the *Very Large* era of 8–10m class telescopes towards the *Extremely Large* era and beyond, with telescope diameters of 30m up to 100m, segmentation and modularisation get increasingly important in order to keep the systems mechanically and optically feasible, and to minimise the number of single-point-of-failure items. However, deploying segmented optics on large scale structures turns active and adaptive optics into mandatory systems to align multiple optical paths and correct residual wavefront errors in real time operation. Featuring the highest bandwidth of correction, adaptive optics (AO) stand last in line to remove remaining artifacts of previous, slower, active stages, and – last not least – correct the wavefront for atmospheric turbulence to approach the diffraction limit of the telescope.
Recognising the utter importance of reliable, low-downtime adaptive optics to ensure a scientifically efficient operation of the telescope, this article investigates the option of installing several identical AO loops operating in parallel on sub-apertures of the telescope, in contrast to a single all-embracing AO loop over the full aperture. Especially the advantages of a segmented M5 mirror for OWL are presented in contrast to a single 2.4m deformable device.

Keywords: co-phasing, segmented mirrors, deformable mirrors, adaptive optics, fringe tracking

1. AN UNPRECEDENTED LEVEL OF COMPLEXITY

Looking at the various design studies of Extremely Large Telescopes (ELTs), like the Thirty Meter Telescope (TMT; [13]), the California Extremely Large Telescope (CELT; [11]), the Euro50 [2], or the 100m Overwhelmingly Large Telescope (OWL; [6]), the most intriguing common (engineering) aspect is their – truly overwhelming – extremely high level of system complexity. Speaking of the biggest representative, the OWL telescope, the long list of technical parameters [6] comprises for example the following breathtaking numbers:

- A primary mirror of 100m diameter and more than 6000m^2 of collecting area which is shaped out of more than 3000 mirror segments. This aperture resembles about the size of a soccer field – and has to be kept in shape to a precision of $\lambda/10 \sim 20$nm for diffraction limited operation at visible wavelengths.
- The overall moving mass of the telescope amounts to ∼14.800 metric tons, equivalent to the weight of about 25 Airbus A380 airliner. This weight has to be moved in a dusty desert environment with great precision – a pointing accuracy of 1 arcsec equals ∼2.4mm on an azimuth track of 100m diameter.
- The secondary mirror of the telescope is located about 100m in front of the primary mirror, representing a large lever for changing wind load and direction of gravity. Although the chosen multi-mirror design allows for a flat secondary mirror, thus minimising the impact of lateral displacement of this component onto the optical axis of the telescope, the large mechanical structure is susceptible to vibration and flexure at all frequencies, intensities and directions.

Considering the values above in comparison to 8–10m class telescope designs, it gets obvious that ELTs and OWLs have little in common with today's observatories, but introduce a so far unimaginable level of complexity at the field of astronomical instrumentation. Nevertheless, the new systems shall achieve highest optical performance, i.e. get close to the diffraction limit at visible wavelengths, what requires a wavefront error of less than $\lambda/10$ over the full aperture.

However, extrapolating from gained experience at today's observatories, like ESO's Very Large Telescope [9][3], or the Keck telescopes [15], it doesn't seem unrealistic that this challenge can be met – relying on active position control of optical elements and adaptive optics to correct fast high-order aberrations. Especially the application of adaptive optics (i.e. wavefront sensors and wavefront correcting surfaces) near the end of the optical trail of the telescope greatly reduces the technical requirements on the telescope structure (concerning flexure and low frequency vibrations) and optical surface quality (e.g. positional and axial alignment of elements). On the other hand, while reducing the demand on telescope mechanics, one has to be well aware that an operative adaptive optics system now turns from an image improving add-on into a mandatory key component of such telescopes.

2. ADAPTIVE OPTICS AS ESSENTIAL INGREDIENTS

As detailed in the section above, the implementation of active and adaptive optics is essential at Extremely Large Telescopes, in order to relax the tolerances of the mechanical structure to a technically feasible level. Furthermore, the concentration of resources (financial as well as manpower) onto the effort of building a (single) 30–100m ELT is well justified only (i.e. scientifically rewarding), if the telescope is able to deliver diffraction limited images. Accordingly, all of the science drivers for ELTs (see [6]) and references therein) require a diffraction limited performance.

To get the image quality of a ground based telescope close to the diffraction limit of its aperture, the wavefront perturbation introduced by earth's atmosphere has to be sensed and corrected for each atmospheric turbulence cell individually. For the near infrared wavelength domain, such adaptive optics systems are in routine operation at several of today's observatories [9][15][10][5]. However, when heading for visible wavelengths, the characteristic diameter of atmospheric seeing cells decreases by about a factor of 10 to ∼10cm, what, in combination with the larger aperture diameter of an ELT, increases the number of turbulence cells to be corrected by several orders of magnitude, from ∼100 at current 8–10m class systems up to about 600.000 for the case of OWL. Envisioning loop frequencies of several 100Hz up to 1kHz, the high number of correction cells poses a challenge to all 3 processing steps of an adaptive optics system.

2.1. Wavefront sensing

Independent of the employed sensing scheme, several pixel of an imaging detector are necessary to sense the wavefront perturbation of a single turbulence cell (e.g. 2×2 for pyramid based systems or 3×3 for Shack-Hartmann systems). Thinking of up to 600.000 correction cells over the full aperture, an applicable wavefront sensing system affords a megapixel camera with a frame rate of several 100Hz. While it is quite unlikely to be able to realise such a camera on the basis of a single detector array within the next decade, there are realistic proposals to split the image plane onto several smaller detector arrays (e.g. 'smart fast camera' [12]). Although such 'combined' camera systems would still be complex devices (e.g. using 256×256 pixel fast-readout detectors it would require ∼35 arrays in parallel readout configuration), they may be considered a technically feasible possibility for wavefront sensing at Extremely Large Telescopes.

2.2. Wavefront reconstruction

The numerical effort to calculate the corrective parameters of the sensed wavefront scales linear with the number of apertures. Therefore, starting from the VLT adaptive optics system NAOS (featuring 144 sub-apertures and a system design of the late 90s) and extrapolating to a 100m

ELT AO system of 600.000 sub-apertures planned to get operational in the late 2010s, an increase of computing power of a few thousand is required on a timescale of about 2 decades. Based on the empirically founded Moore's law of computing power, which predicts an increase of ∼1000 within 2 decades, and given the fact that several wavefront calculations can be parallelised, the question of wavefront reconstruction may be assumed solvable.

2.3. Wavefront correction

The key component of wavefront reconstruction (WFR) is the respective corrective optical element, i.e. a fast deformable mirror. Based on OWL's phase A design [6] and one actuator per turbulence cell, the DM for WFR demands a mirror of ∼2m diameter and an actuator spacing of ∼2mm to accommodate the necessary 600.000 actuators. Both numbers are daring on their own: a spacing of only 2mm is on the edge of technical feasibility, and the high total number is challenging for adjacent control electronics. Taken together, both facts suggest a final product which is fragile on small and large scales – on high numbers of individually failing actuators (e.g. broken mirror contacts) and on a low MTBF of the overall device. Given the strong dependence of an ELT on its operative adaptive optics system, one has to emphasise, that especially the latter case represents a single-point-of-failure which directly leads to technical downtime and a reduced scientific efficiency of the whole telescope.

A very promising approach to counteract this vicious dependence on a single hardware item is to use several smaller (hexagonally shaped) DMs and assembled them next to each other to act like a single unit. Even the operational loss of a whole sub-unit would then become a recoverable event. That such a distributed scheme of wavefront correction is not merely fiction but already under construction at another telescope – the LBT – is detailed in the next section of this article.

3. A SEGMENTED DM FOR OWL – FROM LBT TO ELT

The Large Binocular Telescope (LBT) on Mt.Graham, AZ (USA), is a large scale interferometer featuring two 8.4m primary mirrors mounted on a common central pier [8]. Both halves of the LBT are equipped with adaptive secondary mirrors for diffraction limited operation, and because of the common central mount, the length of the interferometric baseline between the two primary mirrors stays constant in time, while the telescope tracks a celestial target, therefore removing the need of optical delay lines for interferometric observations.

The interferometric NIR imaging camera LINC-NIRVANA [7] will provide two separate sets of AO sensors to operate both halves of the telescope at their individual diffraction limit, i.e. the diffraction limit of a 8.4m telescope. After this first step of AO correction, the only remaining aberration of a flat incoming 23m wavefront at the focal plane of the instrument is a pistonic 1^{st} order Zernike mode, i.e. a phase offset between the (already flat within themselves) wavefronts of the two halves of telescope. This phase offset varies in time and is sensed and corrected by a dedicated fringe tracking system [14], which analyses the intensity distribution of the interferometric fringe pattern [4] at the focal plane of the instrument, and which introduces a corrective differential path difference into the optical path of the instrument. The result of this 2^{nd} step of AO correction, a diffraction limited point-spread-function (PSF) of the axially symmetric aperture of the LBT (left sketch in Fig. 1) is shown as left picture in Fig. 2.

Analogous to the non-circular aperture of the LBT, its PSF exhibits two different angular resolutions in parallel and perpendicular to the interferometric baseline. However, while a single exposure might suffer from the lower resolution along one axis of the image, it takes only 3 exposures at different position angles of the interferometric baseline, to be able to numerically

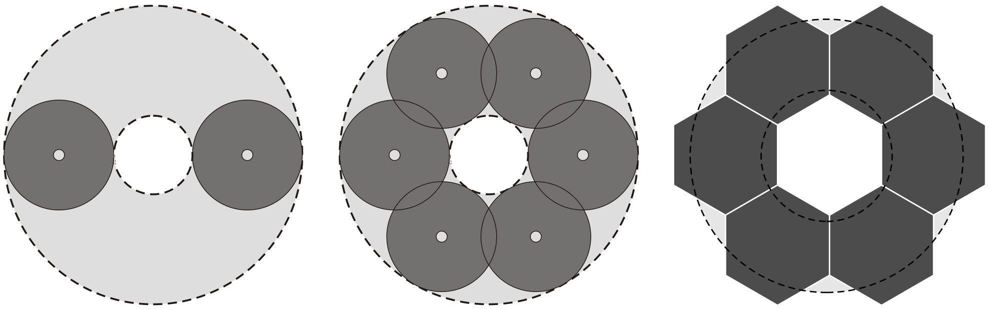

Figure 1. Sketch to illustrate the affinities of different aperture geometries at the LBT and the OWL telescope. The apertures are scaled to same size for better comparison, i.e. the longest baseline of the OWL (outer dashed circle in the right image) is of course more than 4 times larger than the respective measure of the LBT. *Left:* The pupil geometry of a single exposure of the LBT. The two primary mirrors are shown in dark grey colour. The dashed circles indicate the extent of the longest baseline and the diameter of the gap between the mirrors. *Middle:* The synthesized pupil geometry if 3 exposures of the LBT (taken at interferometric position angles of 0°, 60° & 120°) are numerically combined to a single image at post processing. *Right:* The pupil geometry of the OWL telescope when using a segmented M5 mirror. The extent of the primary mirror is shown in light grey, and the six proposed segments of the M5 are overlaid in dark grey. For the calculation of the PSF the intersection of both areas has been used.

combine them to a proper high resolution image [1]. The resulting synthesised PSF and aperture of such a combined image are shown in the middle columns of Figs. 2 & 1 respectively.

The right hand images in both figures show the case of OWL using a segmented M5 deformable mirror consisting of six hexagons, and especially when comparing the respective aperture shapes, the affinity of the threefold combined LBT case with a segmented OWL gets clearly visible. A possible fringe tracker for OWL could be based on a single low resolution pyramid wavefront sensor, since it has to deal with 6 sub-apertures only. Looking at the calculated PSFs, OWL is clearly superior – the fact that OWL needs only 1 exposure instead of 3 LBT shots not even taken into account. OWL's PSF gets quite close to an ideal Airy distribution, showing a deep 1^{st} minimum, little pronounced and discrete side maxima, and a good circular shape. It should be emphasized at this point, that the sixfold assembly of the M5 fits smoothly into the general structure of the telescope, which has been changed from a classical 4-strut "spider"-assembly towards a 6-armed structure, too. The unavoidable small gaps between the mirror segments can therefore be "hidden" under the mounting structure of OWL's secondary mirror, keeping the corresponding image degradation at a minimum level.

Figure 2. Calculated PSFs of the corresponding aperture geometries of Fig. 1. *Left to right:* A single exposure of the LBT; a numerically combined triple-exposure of the LBT; a single exposure of the OWL telescope using a segmented M5 mirror. The segmentation of OWL's primary mirror has been neglected for the calculation since its segmentation is more than a magnitude finer than the one of the M5 mirror.

Thus, while a segmented – i.e. modularised – M5 may be implemented in a way that it reduces the optical peak performance of the telescope system only marginally, it may increase the technical feasibility and operative stability of this 2.4m adaptive surface by a large factor. That a modularised system successfully eliminates the single-point-of-failure character of this critical device is illustrated in Fig. 3, which shows a series of simulated point-spread-functions based on an increasing number of 0, 1 & 2 disfunctional (i.e. broken, absent, or in off-position) mirror segments. Even in the bad case of 2 missing segments (i.e. 33%) the PSF still exhibits a pronounced core close to the diffraction limit, what – presuming proper data reduction (i.e. PSF subtraction) – still qualifies the images for further scientific analyses.

Figure 3. Calculated PSFs of the OWL telescope using a modularised M5 with an increasing number of absent segments. *Left to right:* All 6 segments in diffraction limited closed loop operation; 5 operative segments; 4 operative segments with the 2 absent ones located on opposite sides of the aperture.

4. CONCLUSION

Extremely Large Telescope projects like the OWL incorporate a breathtaking number of new components and subsystems, which – at least to a significant fraction – are technically very challenging and have never been used in routine operation at an astronomical telescope so far. Nevertheless, a low-downtime operation of most of these devices is mandatory for a scientifically rewarding and efficient operation of the whole observatory – a combination which may be considered daring for a >1000M€ project. This article concentrates on one of the possible single-point-of-failure items, the 2.4m diameter deformable M5 mirror, and presents a feasible alternative solution, a sixfold segmented adaptive mirror, which reduces the risk of total failure while keeping its maximum performance close to the ideal single mirror case.

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