Towards an Adaptive Secondary for the VLT?

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Putting an Adaptive Secondary on one of the VLT Unit Telescope would offer a significant boost in the observing efficiency of the Telescope and would also constitute an important step on the roadmap towards the future ESO Extremely Large Telescope. First evaluation is that such a system, when coupled to instruments with adequate performance and equipped with proper wavefront sensors could provide either diffraction-limited performance in a small field or "enhanced seeing" images over a large field. It should be able to improve on any capability of the present M2 unit, except chopping for which one would get a smaller stroke than today. The technology is mature and a comprehensive feasibility design study will start soon, hopefully to be followed by a full design in the frame of the OPTICON FP6 program. In parallel, we will carefully evaluate in liaison with Paranal Observatory and the Instrumentation Division the cost to benefit ratio of such a system coupled to an optimized set of instruments. These will be the basis for a mid-2005 decision on whether to proceed.

Pioneering work in the development of Large Deformable Mirrors (also called Adaptive Secondaries) has been steadily pursued by the Osservatorio Astronomico di Arcetri (INAF-OAA) with DIAPM-Milano for more than 10 years. The basic concept is to correct wavefront aberrations at the Telescope final focus by the elastic deformation of a large mirror, made from a thin glass shell, through an array of voice-coil driven position actuators. Two Italian industrial partners have been associated with this development since its start, namely Microgate and ADS (see http://www.ads-int.com/MMTadopt.htm). The design and manufacturing of the thin mirror shells (Martin et al. 2000), another difficult accomplishment, has been done at the University of Arizona's Center for Astronomical Adaptive Optics (CAAO).

The first telescope using this technology is the Cassegrain 6.5m diameter MMT at Mt Hopkins AZ. The MMT Adaptive Secondary is made of a 2mm thick, 640 mm diameter zerodur plate. It "hovers" some 30 µm away from a thick reference plate and is deformed by 336 voice-coil actuators pushing on magnets glued on its back surface (Fig. 1). First light on the sky was obtained in November 2002 (Fig. 2). First science results with this system can be seen at http://mmtao.as.arizona.edu/~lclose/talks/ins/ESO_MMTAO_3.

Although this constitutes a crucial mile-

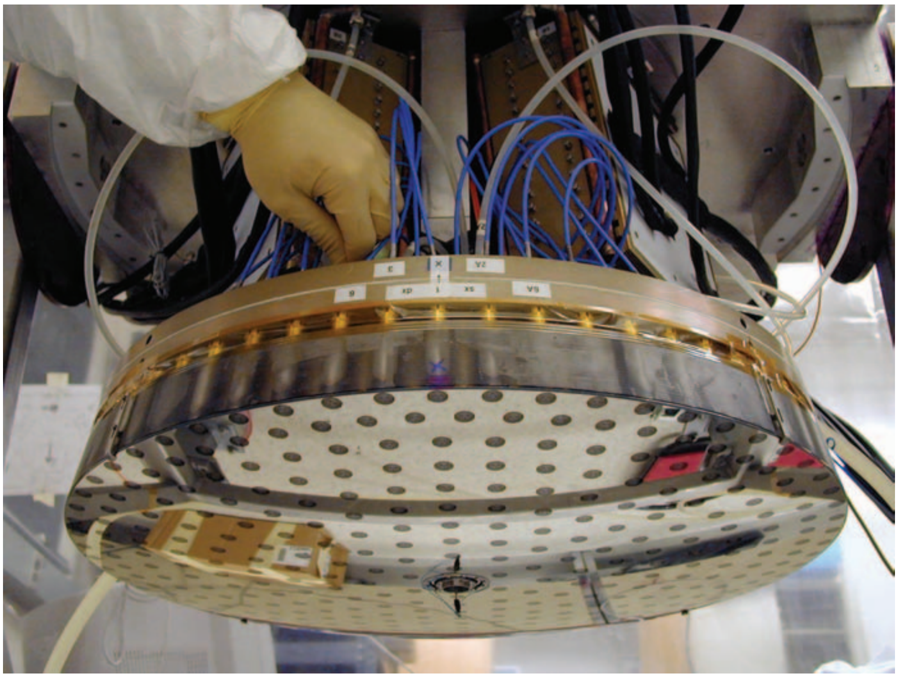


Figure 1: The MMT adaptive secondary. The black dots correspond to magnets glued on the back surface of the mirror. Photo Credit: Laird Close, CAAO, Steward Observatory.

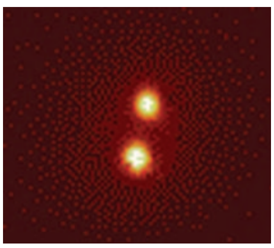


Figure 2: Twenty-three seconds integration time *H*-band image on the ARIES camera of the 0.24 arc-second separation binary star ADS8939. This image was obtained at the MMT during its November 2002 1st observing run with the Adaptive Secondary. 52 modes were corrected with an update frequency of 550 Hz, using an $m_V \sim 9$ reference star. The two stellar images have diffraction limited cores and a ~ 10% Strehl ratio. Photo Credit: Laird Close, CAAO, Steward Observatory.

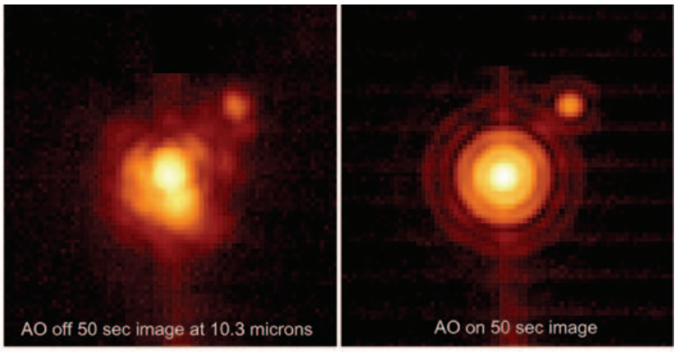


Figure 3: First mid-IR image made with the MMT Adaptive Secondary in November 2002. With AO on, the Strehl ratio is 96%, whereas with it off it is only 58%. Photo Credit: Phil Hinz (Steward Observatory).

stone, the MMT adaptive secondary was considered on the technical side as a working prototype and major re-engineering activities have been initiated by the same Consortium for the production of two Adaptive Secondary Units for the Large Binocular Telescope or LBT (D. Gallieni et al. 2002). Construction of the first 911 mm diameter LBT Adaptive Secondary, with 672 voice-coil actuators, is well advanced with final integration expected in 2004. Note that the LBT is of the Gregorian type. This makes deriving the command matrix for the adaptive mirror particularly easy by inserting a point-like calibration source at the location of the telescope prime focus.

On ESO's side, a first meeting with Microgate/ADS was held in mid-2003 to investigate the feasibility of an eventual adaptive secondary for the VLT and define the content of a conceptual design study for such a facility. The top level specifications are discussed below. From the first evaluations, it appears that such an adaptive secondary system could potentially replace the chopping unit + beryllium mirror of the VLT, therefore keeping the present general structure of the VLT M_2 unit within the available space and weight.

The motivations to implement an Adaptive secondary for the VLT can be summarized as follows:

– An adaptive secondary equipped UT would constitute a general AO facility that could feed all available foci (Nasmyth 1 & 2, Cassegrain, coudé VLTI and even a coudé instrument if there is one) of this particular UT.

–An adaptive secondary would give directly either a NACO-like diffraction-limited correction in a small field or "improved seeing" correction in a large field by acting on the ground layer turbulence only; these improvements are obtained without the light loss and increased thermal emission coming from the extra-optical components in classical AO systems.

–Instruments which could potentially benefit from such a system are: MUSE, either with a ground-layer correction (wide field mode) or by a reconfiguration of the laser guide stars allowing diffraction limited resolution in the visible over a small field of view. This configuration could still use a single deformable mirror (the adaptive secondary); a large (2′ diameter) FOV MCAO diffraction limited IR imager, ultimately replacing NACO; the Planet Finder is an attractive potential candidate with its exacting goal of observing faint companions near a very bright star. The suitability of this approach remains to be confirmed however, since calibration of the large adaptive mirror command matrix to the level required by the PF looks challenging; Hawk-I (or KMOS) for improved seeing over at least 5–6′ FOV; VISIR, as the adaptive secondary would introduce no extra instrumental background in the MIR and would provide very high Strehl ratio images (see Fig. 3), crucial for the detection of extremely low-mass companions or zodiacal disks from their thermal emission; the FALCON approach of positioning both adaptive optics and science "buttons" in a ~ 25 arc min patrol field could also benefit from an adaptive secondary which would be used as a first correction stage; this would reduce the actuator number and stroke requirements on the small AO buttons.

– Large deformable mirror technology is now reasonably matured and well-engineered solutions can be reached for the VLT.

– Large deformable mirror is a crucial technology that ESO needs to have experience with, in view of a future ELT development. Implementing this technology on the VLT will give us the necessary hands-on knowledge to develop such optimized systems, including the calibration and operational aspects.

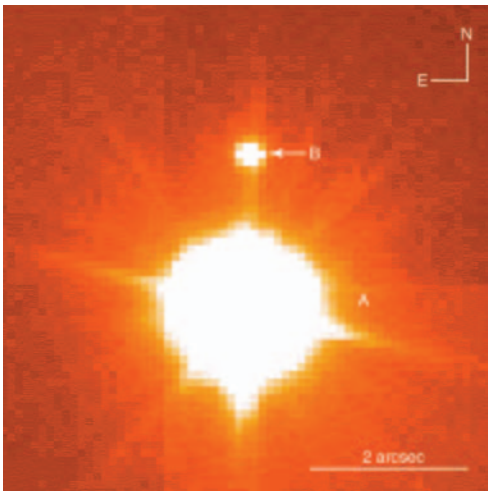


Figure 4: I-band, 1 second exposure, image of the TWA-5 double brown dwarfs system made with the FORS2 instrument on UT2 (Kueyen).
The point spread function full width at half maximum of this seeing-limited image (with fast tip/tilt correction from the secondary mirror) is a record low 0.18 arc sec.

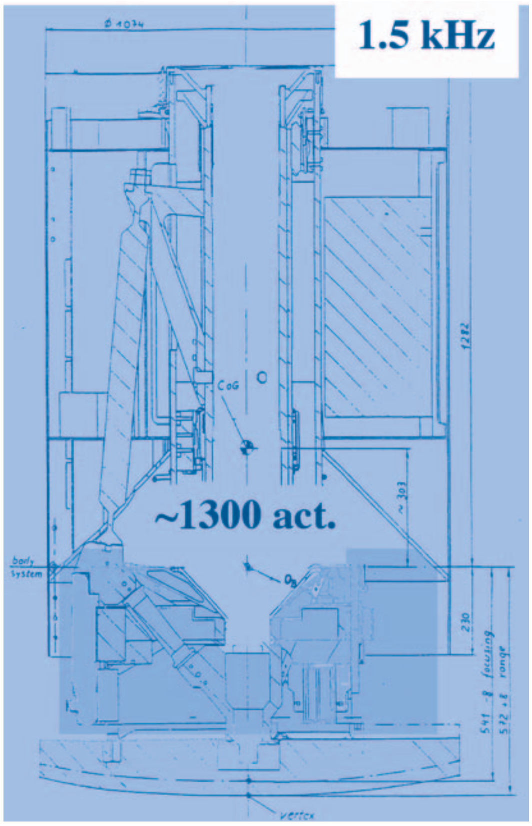
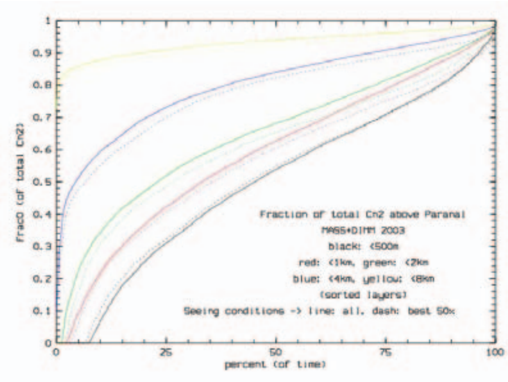


Figure 5: Schematic drawing of the M2 unit. The new adaptive secondary system would be put in lieu of the present chopping system (red) and mirror (green). The current focusing (1 d.o.f.) and centering (2 d.o.f.) systems would be kept.

Figure 6 shows the result of the combined March-September 2003 Paranal seeing campaigns with MASS + DIMM in terms of the cumulative distribution of each atmospheric layer contribution to the total refractive index structure function parameter C_n^2 as measured with DIMM. The upper layers contributions were directly measured with MASS. The ground layer contribution was obtained by subtracting these values from the total observed C_n^2. Note that for 45% of the time, half of the seeing was located in the ground layer (i.e. at altitudes < 500 m). Very similar results were obtained during the two campaigns.



Top-level specifications

The present M_2 units are true technological marvels, providing five degrees of freedom (d.o.f.) adjustments, viz. centering, focusing and tip/tilt, with a high dynamics and very high accuracies. M_2 units offer in particular a fast (up to 5 Hz) chopping capability with a large ± 17″ on-sky throw. In addition, fast tip/tilt corrections at a minimum 10 Hz bandwidth are ensured for virtually the whole accessible sky; this capability plays a large role in the proven ability of the VLT to fully take advantage of even the best seeing at Paranal, as exemplified in Figure 4. We clearly need any new such device to provide or supersede all these capabilities, a non-trivial feat indeed!

With this in mind, provisional top-level specifications for a VLT Adaptive Secondary could be set as follows:

– 1.116 mm diameter convex hyperbolic mirror

– 1,200 to 1,500 actuators (25-30 mm actuator spacing at the level of M_2)

– 40-50 µm stroke able to provide AO correction, tip-tilt and (small stroke) chopping

– a response time goal of 0.5 ms

A provisional Interface with the present M_2 unit is shown in Figure 5. In that scheme, fast tip-tilt (2 d.o.f.) corrections would be provided by the adaptive mirror, with at least equal and actually even better performance. On the other hand, this technology simply cannot provide the present large M_2 chopping capability of ± 17″ on-sky. What would be offered instead is a fast but significantly smaller on-sky chopping of ~ ± 5″. One crucial feasibility point is whether this limitation would significantly harm the scientific capabilities of the instruments using this new unit and, in particular, **any** of the VLTI instruments since they should be able to use any of the 4 UT beams. A first analysis suggests that the potential impact of this limitation on the *a priori* most demanding mid-IR instruments VISIR & MIDI would be very minor, but this point clearly needs to be investigated further.

There does not seem to be any major technical showstopper in the design and eventual production of such a system. There will be interface problems of course, e.g. coming from the rather high heat dissipation inherent in that technology. In addition, one not yet fully resolved technical issue is the need to derive good command matrixes in the presence of turbulence, since the VLT convex secondary does not permit the use of the very simple LBT approach. We are currently exploring both open-loop and closed-loop (the MMT approach) techniques to achieve that goal, using a natural reference star.

A close look at the potential gains

We have estimated the potential gains in terms of improved image quality and energy concentration with such an adaptive mirror. This has been achieved through preliminary computations using the ESO Adaptive Optics Group “simulation farm”. One major uncertainty lies in the use of the present meager data on the stratification of turbulence with height over Paranal, which presently rests on only two 2-week long observing campaigns made with the MASS turbulence profiler (A. Tokovinin et al.) in March and September 2003.

We have mainly looked at the gains expected through the correction of the ground layer only. At the centre of a large field of view, 8′, the gain in “ensquared” energy (Fig. 7) is roughly a factor 2 compared to the purely seeing-limited case in all NIR wavelengths (*J, H* & *K*), with only a small degradation in the field, even at its corners (Fig. 8). For these simulations, we have chosen a relatively large 0″.9 seeing (at 0.5 µm) to realistically cover the case of ultra-deep exposures at the VLT covering tens of hours. This could be applied directly to in particular the HAWK-I NIR Imager. Note however that for all these simulations, we have only studied the limiting case where there is a bright enough reference object (a natural star or a laser guide star plus a natural one for tip/tilt correction) in the field.

A detailed look at the PSF shows that there is essentially an improved seeing effect in the whole field, with no diffraction-limited central core and very little anisoplanetism. With such a large field, fair sky coverage could be achieved in the K band with natural guide stars only; for smaller wavelengths and especially in the Visible, multiple laser guide stars would nevertheless be needed.

For smaller field of views, ~ 1′, we enter into NAOS-like corrections with now much

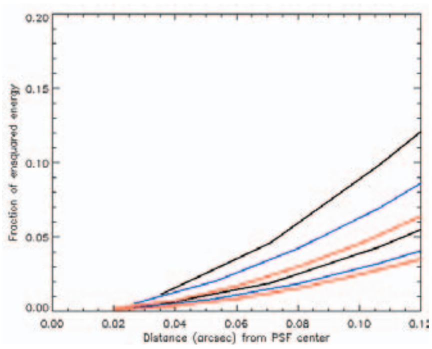


Figure 7: Fraction of “ensquared” energy at the field center with distance to the PSF center in arc sec. 3 bottom curves: without AO correction; 3 top curves: with AO correction. Black: *K*; Blue: *H*; Red: *J*. Note that typical pixel sizes on seeing-limited VLT instruments are in the 0″.12-0″.24 range corresponding to 0″.06-0″.12 on the horizontal axis of the figure.

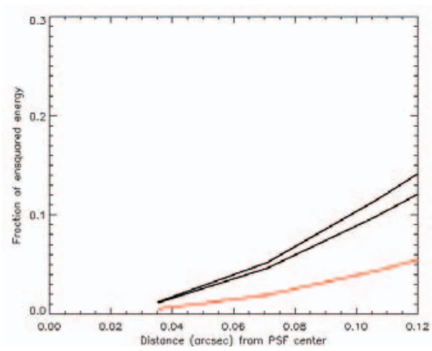


Figure 8: Fraction of “ensquared” energy in the K-band with distance to the PSF center in arc sec. Red: no AO correction; Black: AO corrected; top: in the center of the field; bottom: in the corners of the 8′×8′ field.

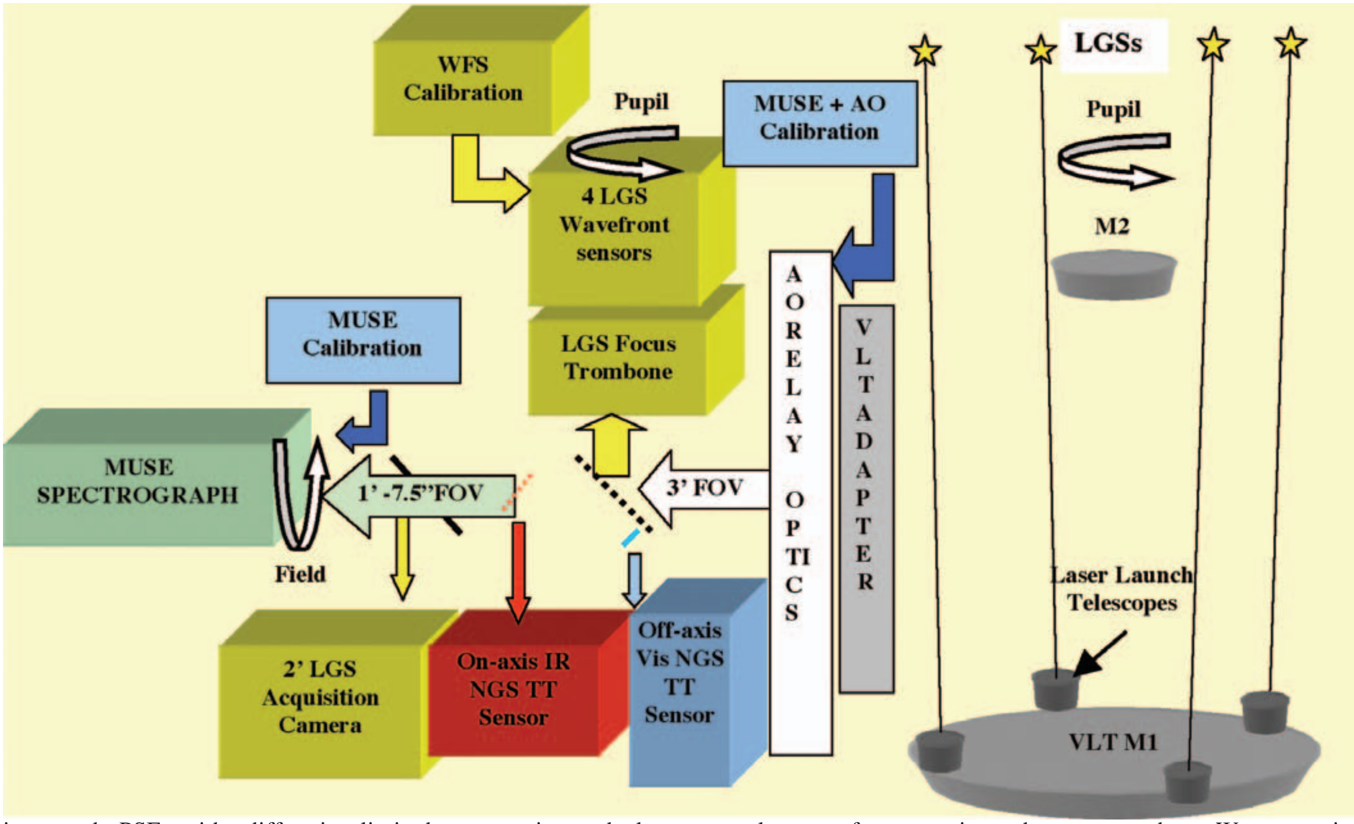


Figure 9: Conceptual design of the MUSE Ground Layer Adaptive Optics (GLAO) System. This illustrates the challenge to obtain significant Adaptive Optics corrections in the visible range. Getting a factor of 2 gain in energy concentration in the red in the 1' field of MUSE requires a high order (~ 1,200 actuators) deformable mirror, an adaptive secondary or a classical piezo-stack mirror located in a relay optical system, four ~ 12 W Na laser beams at optimum locations (60″ off-axis) and one natural guide (tip/tilt) star in a 3' field. Sky coverage would then be ~ 60% at the Galactic pole, a remarkably high value for any AO-corrected system and in particular one working in the visible range.

improved PSF with diffraction-limited cores, but also with large shape variations in the field. One also fully encounters the usual stringent sky coverage limitation which can be overcome only with a Laser Guide Star (and even multiple ones if observing in the visible range). Note that thanks to the large number of actuators on the adaptive secondary, diffraction limited imaging in the Visible (typically 20 mas FWHM at 750 nm) over a small field (~10″) seems feasible. This corresponds in particular to the MUSE narrow field mode.

And on the instrumental side as well

While an Adaptive Secondary mirror neatly suppresses the need for the bulky (and expensive) relay system, that is at the heart of any Adaptive Optics adapter (e.g. on NACO & SINFONI at the VLT), with at minimum 3 additional mirrors in the light path, it is still necessary to introduce equally expensive and always complex wavefront sensors in every instrument that must benefit from AO corrections.

Looking carefully at the cost to benefit ratio for in particular all relevant 2nd generation VLT instruments projects is thus necessary and being planned. As a first example, we are studying in close liaison with the MUSE Consortium a Ground Layer Adaptive Optics (GLAO) system coupled with the instrument and fed by the Adaptive Secondary (Fig. 9).

Conclusions

Equipping one VLT unit with an Adaptive Secondary is an exciting prospect that could in essence improve on the natural Paranal median seeing by a factor of ~ 1.4. There are however a few hurdles along the way and, in particular, the retrofitting of this technique to a working Telescope and the development of an optimized set of instruments, with adequate wavefront sensing. None of these is going to be easy, nor cheap. We are starting resolutely, but also cautiously, along this potential development, with the current feasibility study, hopefully followed by a full design study, gaining also technical know-how which is crucial on the long roadmap towards an ESO Extremely Large Telescope. Ultimately, the benefit to cost ratio of the global project will tip the scales on whether an Adaptive Secondary is implemented on the VLT or not.

References

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