Optical design and adaptive optics properties of the OWL 100-m telescope

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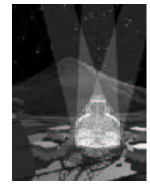
Beyond Conventional Adaptive Optics



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ABSTRACT

The baseline optical design for the OWL 100-m telescope relies on a 6-mirror solution, with spherical primary and flat secondary mirrors, providing a 10 arc minutes well-corrected field of view. We briefly review the design, its nominal properties and limitations. We also outline the main results of a detailed sensitivity analysis and derive potential implications for active optics. In view of the possible use of Laser Guide Stars (LGS) as references for adaptive optics, we apply simple geometrical optics to make a detailed assessment of the telescope properties with respect to imaging of such references. We conclude that Rayleigh guide stars would not provide suitable references, and demonstrate that Sodium LGS altitude variations exclude proper control not only of focus but also of third order aberrations.

1. INTRODUCTION

Several concepts of Extremely Large Telescopes are being explored worldwide (Andersen *et al.*, 2000; Dierickx & Gilmozzi, 2000; Nelson, 2000), with diameters in the range 30 to 100-m. The science cases for such telescopes is under consolidation, and there is already a general consensus that adaptive optics capability is crucial at the lower end of the diameter range, and mandatory at the upper one. Optical properties and interfaces with adaptive optics must therefore be explored.

It is tempting to assume that adaptive optics would provide a global and definite solution to wavefront control in an optical telescope. In practice, and although the progress of technology may in the far future lead to merging active and adaptive optics into a broad and integrated solution to wavefront control, we consider it unreasonable to require that the adaptive elements be able to cover error amplitudes, spatial and temporal frequencies for which they are intrinsically not optimized. Therefore, we require the opto-mechanical design of OWL to provide a well-corrected field of view prior to adaptive optics correction, and to incorporate active optics, including active alignment and field stabilization.

Various concepts of adaptive compensation of atmospheric turbulence, allowing wide-field correction (up to several arc minutes), have been proposed and are still under elaboration. A common feature of these concepts is that they require re-imaging of atmospheric turbulent layers onto adaptively controlled mirrors, hence the need to characterize any design in terms of re-imaging of such layers. A second crucial feature is the use of either natural or artificial references for sensing the phase perturbation associated with atmospheric turbulence. In this respect the current situation is less clear. There are indications that with the upper range of telescope diameter (ESO's OWL 100-m concept), natural guide stars may allow acceptable sky coverage (Ragazzoni, Farinato & Marchetti, 2000; Ragazzoni, 2000). On the other hand Laser Guide Stars should provide a convenient solution to sky coverage, but their re-imaging becomes evidently more complex with increasing telescope diameter. We must, therefore, also assess the properties of the telescope optical solution with respect to re-imaging of Laser Guide Stars (LGS).

In this article we will rely on simple geometrical optics to review the Owl telescope properties prior to adaptive correction. We will derive some of the characteristics adaptive modules would have to comply with. We will calculate a possible distribution of LGS and demonstrate that natural references are required not only for sensing wavefront tilt, but also focus and third order aberrations.

The discussion does not take into account possible anisoplanatic effects, which may eventually imply a number of LGS far exceeding that established in this article.

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2. OPTICAL DESIGN AND PROPERTIES

The Owl optical solution is similar to that of the Hobby-Eberly telescope, with 100-m spherical, segmented primary mirror and a 4-elements corrector. Dimensions set aside, the essential difference is the presence of a large (∼34-m) flat, segmented secondary mirror which folds the beams back into the corrector located mid-way between the primary and secondary mirrors (Fig.1). The flat secondary mirror relaxes constraints on the primary mirror focal ratio (f/1.42), reduces structure height (M1-M2 separation 95-m), and allows for lose centering tolerances where they are most difficult to meet.

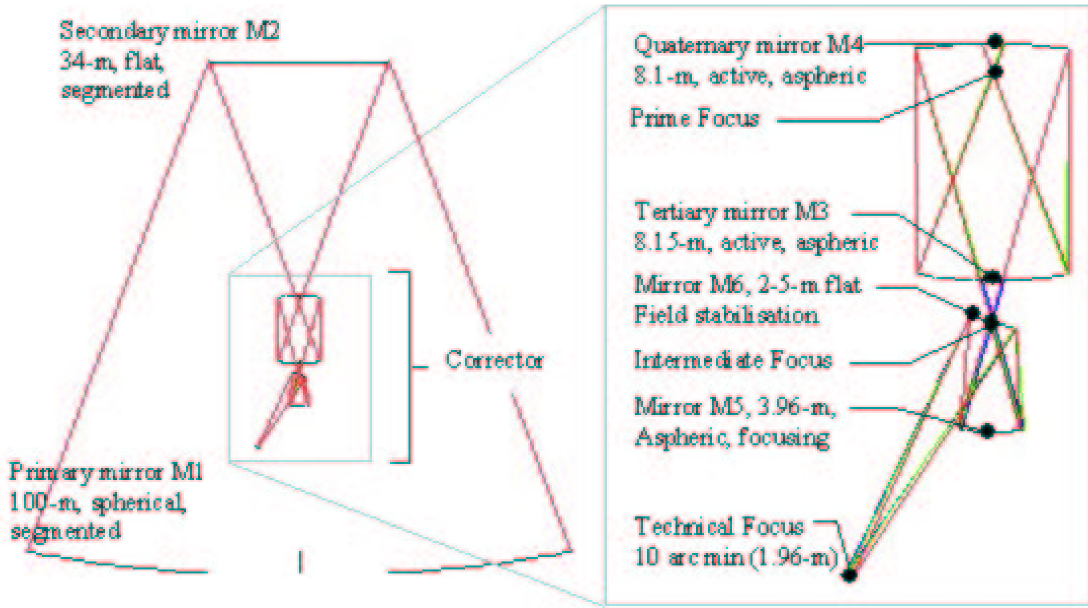

Figure 1. Owl optical design layout.

First order properties are given in table 1. The design incorporates suitably located surfaces for active optics, including two active, 8-m class thin menisci (M3 and M4, M4 being located in an intermediate pupil), a focusing mirror (M5, 4-m class) and a tip-tilt mirror in the exit pupil (M6, 2.5-m class) for field stabilization. The design provides evident advantages in terms of baffling, although particular precautions must be taken in view of the very large spherical aberration at prime focus.

Parameter		Value	
Entrance pupil	Diameter	100000	mm
	Position	M1	
Exit pupil	Diameter	2261.3	mm
	Position	31.3	mm behind M6
Focal ratio		5.980	-
Fiel of view	Total	10.0	arc min
	Unvignetted	6.14	arc min

Table 1. First order properties.

The total field of view is 10-arc minutes diameter ("*technical field*") and constrained by the allowable central obscuration (35% linear) and the diameter of the hole of M3. The required science field of view is 2 arc minutes (goal 3 arc minutes) in the infrared, down to 30 arc seconds (goal 60) in the visible. The field area outside the science field is mainly used for auto-guiding, field stabilization, active optics and possibly phasing or calibration of the segmented mirrors. In this article we concentrate on the telescope properties in the technical field. It is assumed that adaptive compensation of the effect of atmospheric turbulence will be made in dedicated modules placed after the technical field. Therefore, characteristics relevant to adaptive optics such as images of atmospheric layers or LGS should be not be understood as “final” but as the input adaptive modules shall cope with.

Fig. 2 shows the optical quality (Strehl Ratio) over the science field. The diffraction-limited field of view is 3 arc minutes in the visible and 5 arc minutes in the near infrared i.e. about 4 times larger than that of an equivalent 100-m Ritchey-Chrétien solution. The wavefront RMS slope increases as the cube of the field but remains less than 0.07 arc seconds over 10 arc minutes, hence the technical field is fully seeing-limited. There is, therefore, no need for an additional field corrector.

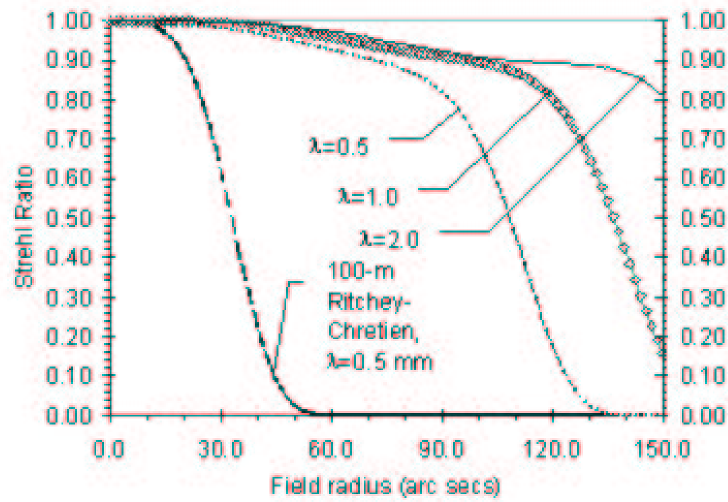

Figure 2. Strehl ratio.

A detailed sensitivity analysis has been performed. As expected, the aberrations introduced by tilt and lateral decenters are essentially third and fifth order coma and remain constant over the field of view. This is illustrated in figure 3, which gives the effect of unit lateral decenters, tilt and piston of each surface M1 to M6 and of the entire corrector, considered as rigid body. The left graphs show the global effect, the right ones the maxima of the field-dependent terms over the science field of 3 arc minutes.

There are several options for removing field-constant terms without introducing depointing: rotations of M3, M4 or M5 about their center of curvature, or of groups of surfaces (entire corrector, groups M3-M4 or M5-M6) about suitable nodes. Detailed analysis shows that residual field-dependent terms are completely negligible. As a consequence, tolerances for individual decenters can be relaxed to some extent. A detailed assessment is still to be made, but the figures above show that it should be possible to close the on-sky active alignment loop once surfaces are positioned within ∼1 mm and 2-3 arc seconds from their nominal position. In practice, piston and rotation of the corrector about M2 vertex fully compensate the effects of M1 and M2 decenters, and the tolerances mentioned above would apply only to the corrector itself, considered as rigid body, and to the surfaces within the corrector.

We envision setting the telescope in two steps. The first would basically consist in pre-setting of the corrector location and of the active mirrors surfaces, on the basis of internal metrology and look-up tables. This step would not be repeated until the telescope is re-pointed towards a new target. The second would be the closing of the active optics loop, including active alignment, focusing, and field stabilization. A minimum of three guide stars at technical focus would be required to establish the required correction. Taking into account the field size (10 arc minutes), the wavefront sensors sub-aperture size (2 to 5-m), and the integration time (∼10-30 seconds) there is no issue of sky coverage. This second step is evidently iterative.

The overhead implied by this scheme is expected to be of the order of 2-3 minutes per science target.

Once the active optics loop is closed, we expect the telescope to deliver low spatial frequency errors with ∼0.05-0.10 arc seconds RMS wavefront slope. This figure is derived from VLT experience and does not take into account the improvement in accuracy which would result from using several guide stars and from the better spatial sampling allowed by the size of the aperture. With the VLT, sampling is 20x20; with OWL this figure could easily be increased to 50x50,

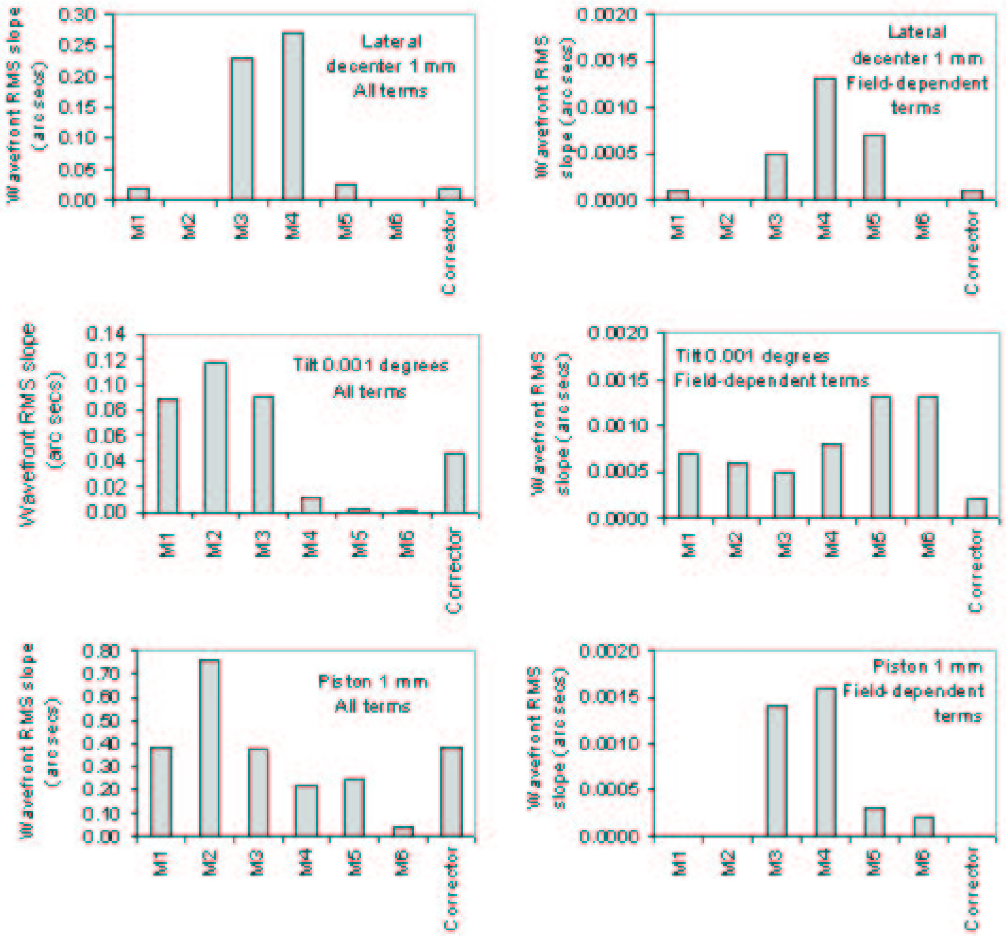

Figure 3. Sensitivity to decenters.

still with a gain in limiting magnitude of ∼3.5. Nevertheless, we must assume that feedback from the adaptive sensors will be required to complete the active correction.

3. IMAGING OF ATMOSPHERIC LAYERS

In the following atmospheric layers are conveniently considered as objects located at altitudes of up to 20 km above ground, and radiating towards the telescope within a solid angle whose numerical aperture is equal to the science field. The pupil of this imaging system now coincides with the science field itself and is therefore at infinite distance. We examine the properties of the images of such layers, as seen through the telescope and before adaptive correction. These properties should therefore be understood as object properties for the adaptive modules.

The axial distance from technical focus to the paraxial image of a specified layer is given by

$$a = \frac{f^2 \cos z}{h_{a0} - kf \cos z}, \tag{1}$$

where h_{a0} is the altitude above ground of the specified layer, f the telescope focal length, k≈44 the pupil compression factor i.e. the ratio of the entrance pupil diameter divided by the exit pupil diameter, and z the zenithal distance. A negative value of a corresponds to "before-focus" and a positive one to "after-focus" positions, respectively. The singularity $h_{a0} = kf \cos z$ occurs at $z \approx 55^o$ with h_{a0}=15 km ($z \approx 41^o$ with h_{a0}=20 km) and corresponds to the layer "crossing" the object focus at a distance of ∼26.5-km (and its image changing from real to virtual). The minimum distance from technical focus is ∼13.5-m (image of the ground layer).

It should be noted that in view of the very small numerical aperture of the conjugation, sensitivity to defocus is low i.e. field depth is large, and increases with the altitude of the layer to be re-imaged. The equivalent focal ratio *R* can be derived from the ratio of the distance to technical focus divided by the science field diameter (the science field playing the role of pupil for imaging of atmospheric layer):

$$R = \frac{f\cos z}{2\theta_0(h_{a0} - kf\cos z)}, \quad (2)$$

where θ_0 is the science field radius, in radians. The focal ratio R is minimal at zenith and with the ground layer. With a total science field of 3 arc minutes, R_{min}=26, and the adaptive mirror conjugated to the ground layer needs to be located within a few mm of its theoretical position. This tolerance becomes a few cm for a layer 15 km away of the telescope.

The apparent angle *u* under which the image of a layer is seen from technical focus is, in absolute terms:

$$u = \frac{1}{f/D} + 2\theta_0\frac{h_{a0}}{f\cos z}, \quad (3)$$

where *f/D* is the telescope focal ratio at technical focus. With a science field $2\theta_0$ of 3 arc minutes and f/D=6, images of atmospheric layers are seen under a fairly constant apparent diameter, in the range 9.5-13.0^o.

Images of atmospheric layers are understandably of rather poor quality in absolute terms. It should, however, be borne in mind that the system is only required to deliver a resolution smaller than the atmospheric coherence length.

To evaluate image quality, we propagate beams emanating from atmospheric layers through the telescope, the science field of view determining the pupil and numerical aperture of this particular imaging configuration, and determine the geometrical spot RMS radius, projected onto the object layer. We find out that the projected RMS spot radius is largest with the ground layer. With the required visible and infrared fields of view (0.5 and 2.0 arc minutes), we find RMS spot radii of $\sim$15 and $\sim$65 mm, respectively. These figures represent acceptably small fractions ($\sim$10%) of typical atmospheric coherence lengths r_0 in the visible and infrared. With the target science fields of 1.0 and 3.0 arc minutes in the visible and infrared, respectively, the projected RMS spot radii become $\sim$33 and 98 mm ($\sim$20% of r_0) in the worst case figure (ground layer). Distortion is of the order of $\sim$1.2%.

4. LASER GUIDE STARS

In the following we characterize the properties of the telescope optical design with respect to imaging of Sodium Laser Guide Stars. Such objects are known to be extended and have variable luminance along the axis of the laser beam. In this article, we only seek to derive approximate properties and will therefore neglect axial elongation i.e. we will assume LGS to be point sources.

Fig.4 illustrates the geometry, in the object space, of the science and Laser Guide Star (LGS) imaging, respectively. For the moment we assume that all LGS are at the same distance from the entrance pupil, a condition that would normally be fulfilled only at zenith.

Let P1 and P2 be two opposite, extreme field positions of the science (adaptively corrected) field, and $2\theta_0$ be the corresponding angular field. Let h be the distance to the LGS and θ the angle between marginal ray L originating from the LGS and the telescope axis. For a turbulent layer at distance h_a to be properly illuminated, the condition $\theta \geq \theta_w$ must be fulfilled, which implies that the field angle η for the LGS must fulfill the condition

$$\eta \geq \frac{D}{2h} + \theta_0 \quad (4)$$

With a total science field of 3 arc minutes we find that the LGS must be positioned at least 3.41 arc minutes off-axis at zenith. As marginal ray L should not be vignetted to ensure proper sampling of the lowest altitude layers, θ should also be smaller than the unvignetted field of view θ_u, which leads to

$$\eta \leq \frac{D}{2h} + \theta_u \quad (5)$$

Taking into account θ_w=1.5 arc min (maximum science field), θ_u=3.07 arc min, h $\approx$ h_0 / cos z where z is the zenithal distance and h_0 $\approx$90 km, in the worst-case figure (z=60^o), η_{max}=4.0 arc minutes. η_{max} is calculated to prevent vignetting of marginal ray L, but not L', and should therefore not be confused with the unvignetted field for the LGS, which is 2$\times$3.49 arc minutes at zenith and 2$\times$3.89 arc minutes at z=60^o. In case of aberrated beams, particular care must be taken

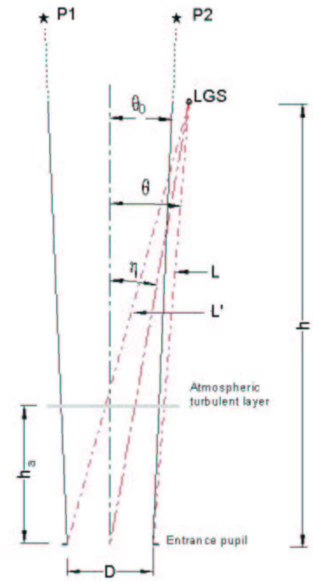

Figure 4. LGS imaging geometry.

of vignetting of intermediate rays (between chief and marginal ray at the LGS field position). With ηgn the range 3.5 to 4.0 arc minutes, conditions (Eq. 4) and (5) are simultaneously fulfilled between z=0^o and z=60^o i.e. the laser beams do not need to be relocated.

It can be shown that in the case of Owl, the pupil size and geometry allow that the envelope of the science beams footprints onto atmospheric layers be suitably illuminated by a 1-ring, axi-symmetrical distribution of LGS. In this context, *suitably* means that any location within the above-mentioned envelope is illuminated by at least two LGS. We find out that this condition is fulfilled with 7 LGS, 4 arc minutes off-axis, taking into account a total science field of 3 arc minutes, a zenithal distance range of 0-60^o, the highest layer being at an altitude of up to 18 km above the telescope –the figure increases to 8 LGS with a layer altitude of 20 km.

There are evident advantages to reduce the field angle of the LGS, but this comes at the cost of science field. In practice, we find that 7 LGS, 3.5-arc minutes off-axis, allow to properly cover a science field of 2 arc minutes.

We may now evaluate the properties of the images of LGS delivered by the telescope. Assuming an altitude of 90 km above ground, images of the Laser Guide Stars are located 2.4 to 5.8-m behind the technical focus with z=0 to 60^o. The axial distance *a* between the telescope focus and the paraxial image of a LGS is given by

$$a = \frac{f^2 \cos z}{h_0 - kf \cos z}, \tag{6}$$

where a is the axial distance from technical focus to the paraxial image of the LGS, f is the telescope focal length, h_0 the altitude above ground of the LGS, and k is the pupil compression factor k=$D/D_x$where D and D_x are the diameters of the entrance and exit pupils, respectively. With the current OWL optical design, k=44.222. Optical trombones will be necessary to compensate for the axial displacement in the LGS as given by Eq.6, and their lateral displacement resulting from the change in lateral magnification *m* given by

$$m = \frac{f \cos z}{kf \cos z - h_0}. \tag{7}$$

The settings of this trombone could in principle be adjusted in closed-loop on the LGS focus term. Atmospheric focus set aside, the LGS focus variation depends only on zenithal distance and altitude above ground of the LGS:

$$C_4 = \frac{D^2 dh_0 \cos z}{16\ h_0^2}\ , \tag{8}$$

where C_4 is the Zernike focus coefficient, D the telescope diameter and dh_0 the altitude variation of the Sodium layer. With D=100-m, h_0=90 km and assuming a Zernike coefficient C_4 determined within an accuracy of 1 μm, we find that the altitude of the Sodium layer could be monitored within $\sim$13-m. Sensitivity is indeed so large that it may have to be reduced and that pre-setting would be required –a convenient way to do so being to clip the pupil image in the wavefront sensor, so as to reduce D.

LGS image quality is inevitably poor in view of the short object distance in comparison to the telescope focal length. Since this quality is related to LGS distance, it will vary with the telescope elevation and with altitude changes of the Sodium layer. Fig. 5 shows the wavefront RMS, after refocus, with LGS 3.5 and 4.0 arc minutes off-axis, as a function of LGS distance to the telescope. The wavefront excursion can be as high as $\sim$40 μm RMS, which implies that a compensation relay system specific to the LGS path is mandatory to remove the telescope field aberrations in the LGS images. Such "*LGS corrector*" would most likely be integrated into the trombones mentioned previously.

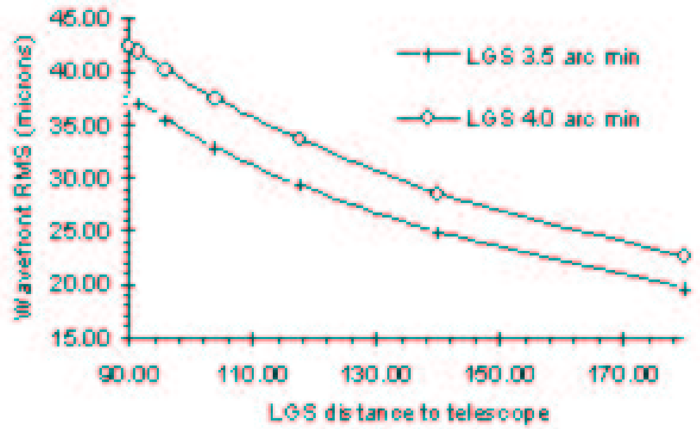

Figure 5. LGS image quality.

Unless the correction (as a function of zenithal distance and of altitude variations of the Sodium) can be calibrated accurately, atmospheric modes corresponding to the modes compensated by the LGS corrector could only be controlled with a Natural Guide Star. The calculation shows that the LGS corrector must compensate for the first 36 Zernike modes of the LGS imaging path. However, third order terms represent 99% of the error and the residuals beyond third order vary smoothly with the distance to the Laser Guide Star (Fig.6).

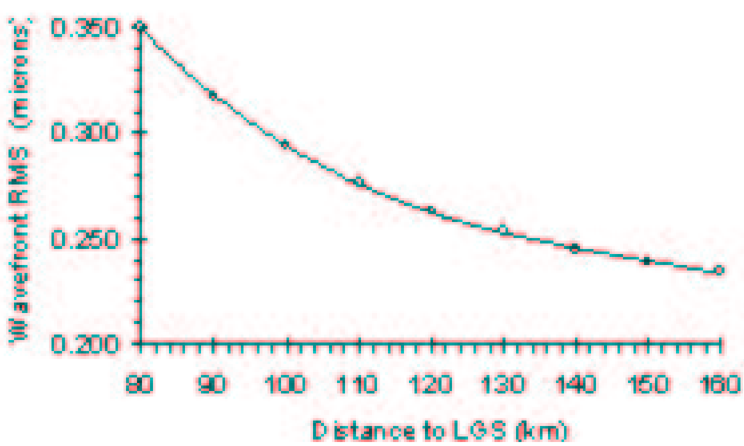

Figure 6. LGS wavefront residuals after 1st and 3rd ordeer corrections.

In order to assess whether accurate calibration is possible, we must evaluate the effect of errors in the input parameters: zenithal distance, field position of the Laser Guide Star, altitude variations of the Sodium layer. While the first two are evidently known with adequate accuracy, the third is not. If we assume that the altitude of the Sodium layer is known to ∼1-km accuracy, we find a calibration error in the 0.2-0.4 μm range. Once again, however, third order terms represent 99% of this error. Fig.7 shows that the wavefront RMS residuals beyond third order, for a +1 km variation of the altitude of the Sodium layer, is less than 3 nm.

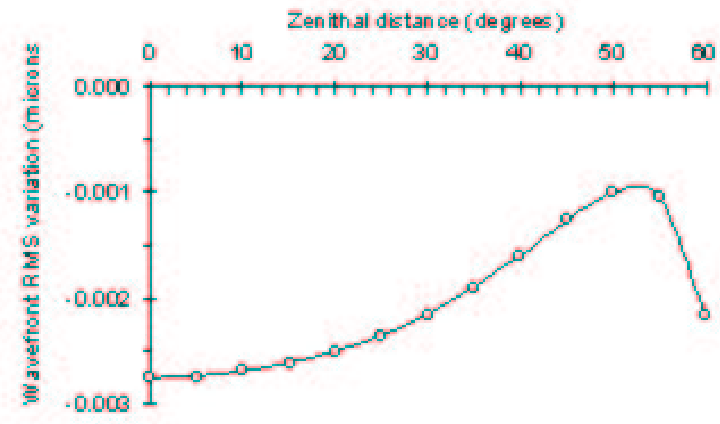

Figure 7. Residual calibration errors after removal of third order terms, for a +1-km variation of altitude of the sodium layer.

Calibration of modes beyond third order is therefore possible, while a Natural Guide Star would be required to control tilt, focus, astigmatism, coma and spherical aberration. Subpupils could evidently be rather large, typically ∼10-15-m, but the implied limitations in terms of sky coverage have not been assessed yet and may not be negligible.

This result also implies that the finite elongation of real LGS along their line of sight should not yield substantial noise in the sensing of modes beyond third order (contrarily to their elongation as projected on the sky).

It should be noted that the discussion above is over-simplified in terms of its implications onto the design of adaptive modules. The latter would normally require that the respective geometries of the conjugations science target – science field, atmospheric layers – adaptive mirrors, and LGS – wavefront sensors, be conserved, unless the adaptive correction is run in open loop. In other words, footprints of science beams and of LGS beams onto adaptive mirrors should be conjugated to equivalent footprints onto atmospheric layers. Trombones and/or LGS correctors located before the adaptive mirrors would have to comply with this condition. Whether this is possible without implying unreasonably complex re-imaging systems remains to be established.

The complexity of the system is basically driven by the ratio of the finite distance of the LGS to the telescope focal length and/or diameter. Such complexity becomes unbearable with Rayleigh Guide Stars, whose images after refocus would be ∼30 arc seconds RMS in size and located ∼56-m before the technical focus (at $z=0^o$).

5. CONCLUSIONS

Extremely Large Telescopes must rely on extensive wavefront control schemes in order to fulfill their scientific potential. Technological limitations, performance requirements and the need to compensate for atmospheric turbulence imply that such telescopes must integrate active and adaptive optics, on top of active control of segmented surfaces. We have shown that the design of the Owl telescope allows extensive active wavefront control, namely field stabilization, active focusing, centering, and active deformations of two monolithic, 8-m class mirrors which closely resemble the VLT primary mirrors. The corresponding degrees of freedom should allow delivering sufficiently low wavefront residuals on the part of the telescope and prior to adaptive correction, over a sufficiently large (several arc minutes) field of view.

In the context of multi-conjugate adaptive optics, a second aspect which must be carefully analyzed deals with the optical properties of the design with respect to re-imaging not only of the science target, but also of atmospheric layers and Laser Guide Stars - assuming that the latter may be required.

A telescope being designed to image objects that are at infinite distance, its properties in terms of imaging of atmospheric layers can hardly be optimal. However, since the science field sets the numerical aperture of this specific conjugation, the telescope aperture merely plays the role of field diaphragm and its size does not have a very strong influence on this conjugation's aberrations. This statement does not hold, however, for paraxial properties.

The situation is different with LGS, for which the entire telescope aperture remains the entrance pupil of the optical conjugation. In view of the enormous focal length, one can no longer assume that LGS images will have properties similar to those of natural star images. In a language familiar to adaptive optics scientists, one could say that the telescope has its own cone effect – which can be orders of magnitude larger than its atmospheric equivalent. In the case of Owl, this effect simply forbids the use of Rayleigh guide stars, and, with Sodium guide stars, implies that specific, active relay and correction optics be introduced in the LGS path. In addition, atmospheric first (tip-tilt, focus) and third (astigmatism, coma and spherical) order terms can no longer be controlled and require Natural Guide Stars.

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