THE FUTURE OF FILLED APERTURE TELESCOPES: IS A 100m FEASIBLE?

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Abstract

We explore the scientific case and the conceptual feasibility of giant filled aperture telescopes, in the light of science goals needing an order of magnitude increase in aperture size, and investigate the requirements (and challenges) these imply for possible technical options in the case of a 100m telescope. The 100-m f/6.4 telescope optical concept is of a four mirror design with segmented, spherical primary and secondary mirrors, and 8-m class aspheric tertiary and quaternary mirrors, providing a 3 arc minutes field of view. Building on the experience of the VLT and other large telescope projects, we investigate mirror fabrication issues, a possible mechanical solution, the requirements for the absolutely essential adaptive optics system and for the instrumentation package, and the implications for budget and schedule.

1. Introduction

Astronomical discoveries are usually made in one of two ways: as a result of a carefully planned program for which tools and instruments may be devised and built, or as a result of the capabilities afforded by some new instrument possibly built with a different aim in mind. A case in point would be the HST, which was built mainly to determine once and for all the value of some critical cosmological constants (H_0 and q_0), which it is doing, but which also owes many of its most exciting discoveries to its unprecedented high spatial resolution. The next generation of (exceedingly large) ground based telescopes, we believe, will provide both capabilities.

A very convincing case for the need of at least 50m diameter to carry out a very demanding scientific project (spectroscopy of all galaxies in the HDF field) has been made in a previous SPIE conference by M. Mountain[1]. Much along the same lines, but also keeping in mind the potentiality for new discoveries afforded by a "large" quasi-diffraction limited imaging capability, we study here a concept for a 100m telescope (which we have christened OWL for its keen night vision and for OverWhelmingly Large). This concept includes full adaptive optics correction, a field of view of 3 arc minutes, and working in the optical and near infrared domains. The need for full adaptive optics correction is self-evident as it is the only way to avoid source confusion while at the same time reducing the background contribution (with the diffraction limit at 1.4 mas in V, and a pixel scale of < 1 mas, the sky background in an OWL deep image is actually lower than in a typical image taken with current non-AO instruments at a 4m class telescope). Without full correction, i.e. not reaching the diffraction limit, it would not make sense to consider a telescope of this diameter (unless it was only for spectroscopy). One consequence of the adaptive optics use is of course that spectrographs can be extremely compact (e.g. a 10^6 resolution spectrograph would have the same beam size as a VLT instrument). Since the AO corrected field will probably be smaller than the actual

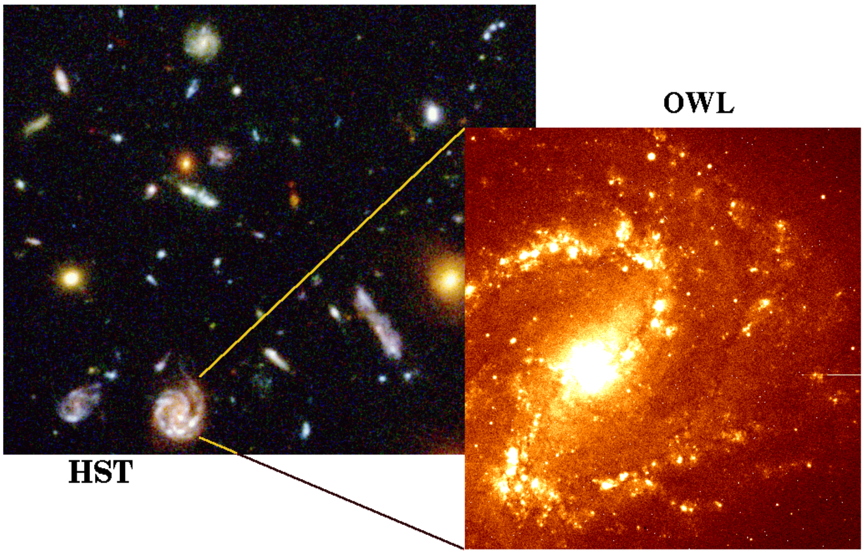


Figure 1 OWL's eye on Hubble Deep Field

field of view (but see §4 for a more optimistic view on this), the remaining focal plane could be paved with parallel instruments, either lower resolution imagers, or 3D spectrographs or a suite of tilted Fabry-Perot imagers[2]: the latter, in particular, could offer a relatively low-cost way to get simultaneous data cubes over most of the telescope field, with 40 wavelength bins and a maximum spectral resolution of ~750.

We have constructed an imaging simulator for OWL and used it to determine the expected performance under various conditions. The ingredients are the input PSF, the optics characteristics of both OWL and a focal enlarger camera, the properties of the detector (assuming multiple readouts to avoid CR contamination and reduce the effects of saturation from bright stars -- bright meaning here brighter than V=26: this will have implications on the choice of 'deep' fields to be observed as one should avoid areas with too many such stars; on the other side, the field of view will be some tens of arc seconds and areas of such size without stars that bright are easily found). Figure 2 shows the result of one simulation in the case of a V=35 point source and an integration time of 1 hour in the case of full adaptive optics correction.

Using the simulator we have determined that for a theoretically achievable Strehl ratio of 0.5 at optical wavelengths, the limiting magnitude for point sources would be V=38 in 10h. This would allow, among other things, the study of Cepheids out to a distance modulus >43 (i.e. to $z \approx 0.8$ thus affording the measurement of H -- *not* Ho -- unencumbered by *local* effects; note that confusion will start affecting the results about there as we are about 100 times further than Virgo with a resolution about 100 times better than HST), the study of *any* supernova at redshifts <10 (!), to image 1 $M_{\odot}$ stars in Virgo, WDs in M31, brown dwarfs in the LMC etc. A great contribution to the 'known' problems would be, we believe, in the area of the star formation history of the Universe, now based on comparisons between models and integrated properties of galaxies, but which would become a matter of *counting* (and of course studying, see fig 1) the number of HII regions and/or O stars in galaxies at high redshift imaged in the near IR at resolutions of 2-3 mas (an *individual* O5 star would be detectable in 10h at $z \geq 2$). At even higher redshifts, the star formation history would be deduced by the statistics of Type II SNe, since OWL would be able to see the redshifted blue or ultraviolet light (where they are brightest) from all of them below $z = 10$.

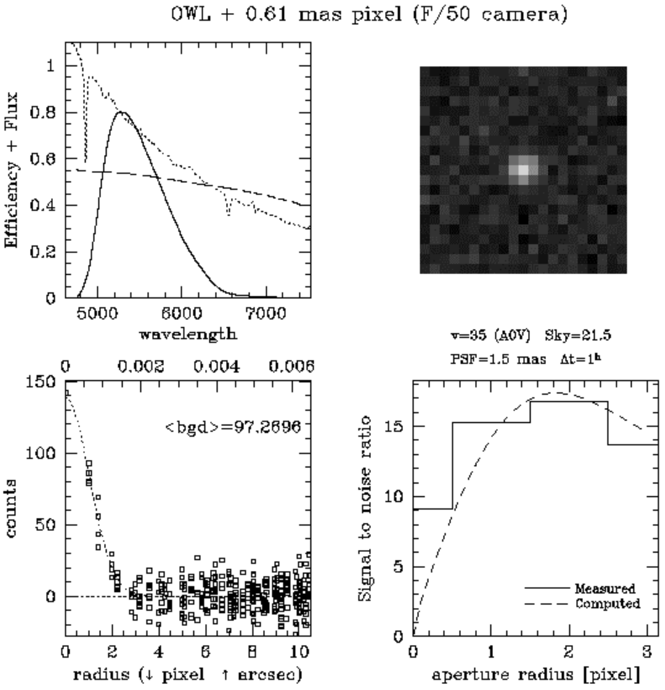


Figure 2. 60 minutes exposure on a V=35 point source

In the nearer Universe, OWL would permit the imaging of the surface of stars, "promoting" them from points to objects, determine the luminosity function of brown dwarfs in the Galaxy and the LMC, shed light on the baryon contribution to the missing mass, image extrasolar planetary systems while also affording the spectroscopic search for biospheres, analyze rapid variability phenomena (here the gain on current telescopes is enormous as the power spectrum $P \propto flux^2 \propto D^4$), etc. It is not the scope of this paper to explore in detail what OWL would be able to do. However, many of the scientific results hinted at here can only be achieved with a filled aperture telescope of at least 100m diameter (in particular the "detailed" cosmology and the study of SNe at redshift < 10).

One question that often arises when discussing large filled aperture telescopes is whether an interferometric array would achieve the same results. Granted that the resolution can be equaled by interferometry (or indeed surpassed for larger baselines), the sheer collecting power of a 100m telescope (with an area 10 times that of *every* optical telescope ever built put together) cannot be matched for a similar capital investment. Indeed, as pointed out e.g. by Mountain[1] or the NGST report[3], the efficiency of an interferometer is only a few percent compared to >50% for a filled aperture telescope, so reaching comparable magnitudes with interferometry would require collecting areas much bigger than OWL's. To this one should add that the field of view would be much smaller, and that the image quality (in the sense of 'shape' of the PSF which though with a narrow core is very complex, and extended, in interferometry) much worse.

From the above, it is our opinion that doubling the size of the next generation telescope, as done until now, even taking into account the advantages of the improved resolution afforded by adaptive optics (whereby $S/N \propto D^2$ in the background limit) does not appear to fit the requirements of the Astronomy of the 21st century. We have tried to analyze the possibility of having an order-of-magnitude improvement, in order to try and define the challenges that such a concept would likely entail, to test, in fact, whether we can achieve a design that is conceptually feasible. As a second but still critical requirement, we have set the goal of breaking the “cost law” ($\propto D^{2.6}$) which would otherwise make even a feasible concept into an impossibly expensive one.

We believe that we have succeeded, albeit in a preliminary form, to exclude obvious show-stoppers. We feel fairly confident that the optical design (see §2) provides the required scientific capabilities (relatively wide linear field of view with diffraction limited performance) and that the optics are feasible with the current technology (see §3) at a “reasonable” cost. The challenges still remaining are in the areas of adaptive optics (see §4) although the required improvements for a 100m telescope are not very different than those for telescopes ten times smaller, and in mechanics (see §5) where however our preliminary concepts offer some room for a cautious optimism (though a simple method to cool the gaps between the mirrors to improve the IR sensitivity has not been found yet). The estimated cost of the present concept is in the range of and quite likely less than $1,000 million.

2. Optical design

The optical design of the 100-m telescope is based on a 4-mirrors concept, with spherical primary and secondary mirrors[4] (figure 3; a VLT unit telescope in its enclosure is shown to approximate scale for reference). The asphericity of the tertiary and quaternary mirrors is moderate and very high, respectively. The telescope focal ratio is 6.36 and the unvignetted field of view 3 arc minutes in diameter. The tertiary and quaternary mirrors are constrained to having diameters of not more than 8.3-m so as to allow these mirrors to be monolithic, glass-ceramics. This constraint has major implications on the available field of view, asphericity of the quaternary mirror, vignetting and straylight. It should be noted that the field offset of the light beams on the tertiary mirror, together with the effect of the spherical aberration at intermediate focus, make it virtually impossible for the tertiary mirror to be segmented.

A most critical parameter is the focal ratio of the primary mirror. Being spherical, the mirror introduces an enormous spherical aberration, whose correction becomes quickly problematic. With the proposed design (f/1.575 primary mirror), the asphericity of the 5.7-m quaternary mirror is in the range of 5 mm, a very serious challenge in terms of manufacturing and testing. With a f/1.3 design, the asphericity would go up to 10.7 mm, a value deemed incompatible with fabrication constraints. Furthermore, the spherical aberration of the intermediate image requires the quaternary mirror to have a center hole of sufficient dimensions. At the same time, the size of this center hole should be kept within acceptable limits to avoid sky straylight to hit the detector -not only direct beams but also light which could reach the image field without the appropriate sequence of reflection (e.g. light reflected by M1 and M2 only).

The diameter of the center hole of the tertiary mirror must be dimensioned in a way that each point of the focal plane sees through this center hole the central obstruction of M2 only. Furthermore, the spherical aberration at intermediate focus yields a higher density of rays around the center area of the tertiary mirror, thereby setting the actual central obscuration. It can be shown that straylight requirements, added to the constraints on the maximum diameters of the tertiary mirror, set the available field of view and the central obstruction of the telescope. The

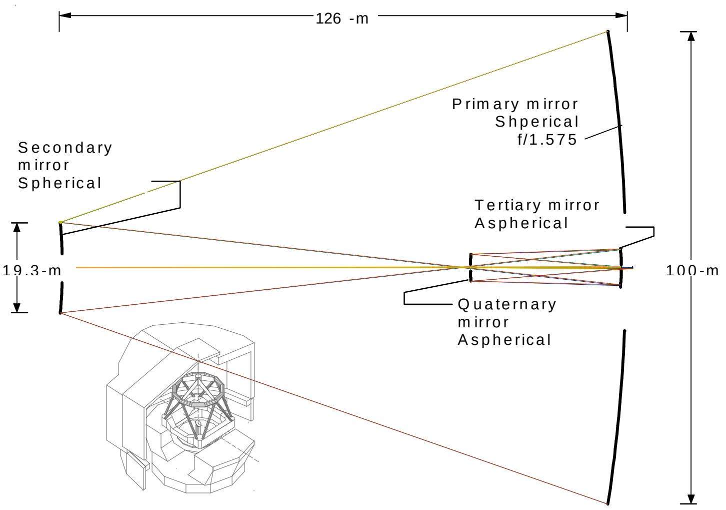


Figure 3 Optical layout

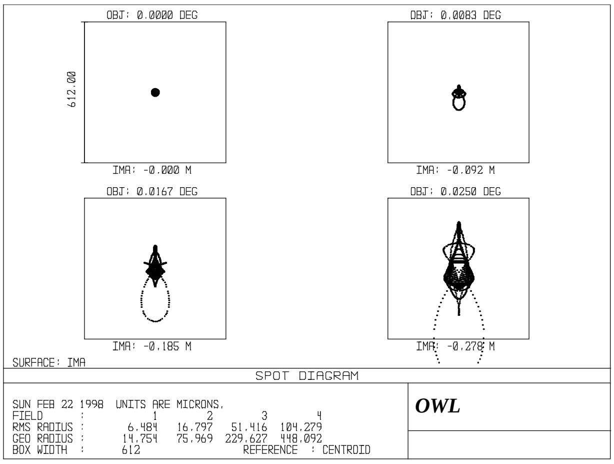
TELESCOPE OVERALL CHARACTERISTICS					
Primary mirror focal ratio				1.575	
Telescope focal ratio				6.36	
Unvignetted field of view				3 arc minutes	
Image scale				3.083 mm/arcsec	
Central obstruction				30%	
INDIVIDUAL MIRRORS DATA					
	SHAPE	Radius of Curv. (mm)	External Dia. (mm)	Center Hole (mm)	Type
M1	Spherical	315000.00	100000	~30000	Segmented
M2	Spherical	90000.00	19300	6500	Segmented
M3	Aspheric	56600.00	8270	960	Monolithic
M4	Aspheric	53420.80	5720	1100	Monolithic

Table 1

telescope overall characteristics and optical design data are listed in table 1.

It should be noted that a relaxation of the focal ratio of the primary mirror to f/1.75 would allow the tertiary mirror to be spherical. However, the subsequent savings would most likely not be sufficient to balance the effect of the longer telescope structure.

The optical quality is better than 0.1 arc second RMS for the geometrical image at 3 arc minutes total field of view (figure 4). In adaptive mode, diffraction-limited observations would be possible over a total field of view of about 20 arc seconds in the visible -a figure which would require a 40k×40k detector. Indeed the limitation of the science field is likely to come from the detector size and relay optics rather than from the optical design. The diffraction limited field of view becomes substantially larger in the infrared (table 2).



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SUN FEB 22 1998  UNITS ARE MICRONS.
FIELD       :        1        2        3        4
RMS RADIUS  :    6.484   16.797   51.416  104.279
GEO RADIUS  :   14.754   75.969  229.627  448.092
BOX WIDTH   :   612                REFERENCE  : CENTROID
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Figure 4. Spot-diagrams

The area outside the science field of view would serve essentially for telescope controls, including guiding, mirrors alignment, active deformations of the quaternary mirror, and phasing of the segments. A suitable methodology for segments phasing is to be identified; curvature sensing seems a promising solution[5]. In this respect, the experience of the *Keck*, *Gran Telescopio de Canarias* and *NGST* projects provides invaluable information.

As both primary and secondary mirrors are segmented, the target would be to phase sub-pupils within a specified field of view rather than phase the primary and secondary mirror independently. Detection of sub-pupils phase errors and possibly adaptive optics sensing on natural stars at intermediate focus, off-axis, is an option currently being addressed.

Field radius	0.5µm	1.0 µm	2.0 µm
axis	0.99	1.00	1.00
5 arcsec	0.96	0.99	1.00
10 arcsec	0.83	0.95	0.99
15 arcsec	0.55	0.86	0.96

Table 2 Strehl ratio vs. field radius and wavelength

Finally, it is worth mentioning that substantial decenters of the secondary mirror (a few cm) can be coped with by a suitable combination of tilts of the tertiary and quaternary mirrors, without depointing; alignment tolerances of the secondary mirror should thereby be greatly relaxed.

3. Optical fabrication

Two essential challenges underlie the fabrication of the optics of the 100-m OWL telescope: reasonable cost and lead-time for the primary mirror, feasibility for the highly aspheric quaternary mirror.

The current cost of primary mirrors of 8-10-m class telescopes is in the order of 0.5 MDM/m^2 and the production rate about 50 m^2 per year. Scaled to 100-m, these figures translate into 4,000 MDM and over a century. Hence a 100-m class telescope could not be realistically proposed unless the cost per m^2 and production rate could be improved by about an order of magnitude -a target already met by the Hobby-Ebberly project[6]. Serial production of identical segments (600 to 2000, depending on size) would bring the cost per unit area of the primary mirror down by a factor 4 to 5; the simple, spherical shape of segments should permit simpler, largely automated and cheaper processes, and thereby further gains in cost and lead-time. The proposed fabrication concepts aim at a lead-time in the range of 10-15 years for the optics, at a cost in the order of 500 Million DM -*a figure which could certainly be substantially reduced*, in view of the very conservative assumptions made herein.

Primary mirror segment geometry

Segment size would be essentially set by trade-off between five criteria: diffraction effects, cost, fabrication rate, acceptable number of degrees of freedom (incl. positioning and number of segments eigenmodes under active control) and substrate material. The trade-off would be between 2-m class passive[1] segments made in thermally stable materials or moderately active 4-m class mirror of NTT type with a larger selection of possible materials. Larger diameters would imply unacceptably high risks (handling and processes) and are not considered herein.

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[1] In this context, passive or active refers to shape control.

At this point we tentatively assume a segment size of 2.3-m, a dimension which has the advantage of permitting standard transportation means (10 to 15 blanks or mirrors per 40 ft container) -a feature which has far from negligible impact on cost. With the possible exception of optical fabrication by replication, the technologies referred to are scaleable up to 4-m.

The geometry of the mirror is illustrated in figure 5. The number of segments to be produced is in the order of 2000, hence a required production rate of about 1 segment every 1.3 days (continuous process, 10 years of 250 working days).

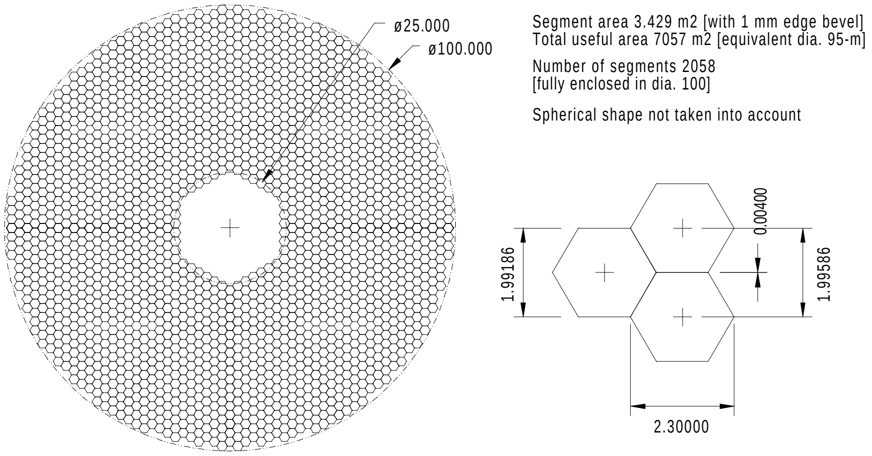

Figure 5 Layout of the primary mirror

In the following we shall take a very conservative approach and consider 150 mm thick, solid segments on 18-points whiffle-tree supports (assuming a mirror substrate having a stiffness comparable to that of glass-ceramics). A substantial reduction of thickness would certainly be possible and lead to a proportional reduction of cost and complexity.

Mirror blanks

Potential mirror substrates include SCHOTT Zerodur, Astro-Sital, Fused Silica, ULE, Silicon Carbide and Aluminum. Beryllium, siliconized SiC and SiC CVD would be ruled out for cost reasons. The thermal figures of merit of steel, pyrex and borosilicate glass are very unlikely to meet the requirements and these materials will not be considered further.

The selection of a suitable material would have to involve a number of performance- and production-related factors, two major ones being specific stiffness and thermal performance. Thermal aspects are reportedly a critical issue for a segmented mirror[7,8].The issue seems to be 3-folds:

1° inhomogeneities of the Coefficient of Thermal Expansion (CTE) between segments, leading to variable focus errors from segment to segment;

2° CTE inhomogeneities within individual segments, leading to higher spatial frequency errors than for a large monolithic mirror;

3° thermal gradients in the segments, which require the material to have a low ratio CTE / thermal conductivity

Nelson & al reported[7] about CTE homogeneity requirements in the 3×10^{-9} $^{o}K^{-1}$ range for the Keck segments and opted for Zerodur. Aluminum and Silicon Carbide should, at this point, not be ruled out. Silicon Carbide[2] panels with a simple lightweight structure might become, in view of the required quantities, a competitive solution. It is however not known, at this stage, whether this material has the potential to meet the thermal performance requirements.

SiC is the most attractive material in terms of mass. The process used by *Céramiques & Composites* is intrinsically fast - from pre-firing to cold blank in ~24 hrs. Hence there are reasonably good chances that a suitable production rate could be achieved. In view of the hardness of the material, particular attention would have to be paid in setting the process in a way to minimize machining/lapping after firing.

As of today the process is limited to up to ~40 mm thick plates, which would imply a simple structured design for the primary mirror segments. The current production facilities are limited to the ~1-m range, but REOSC is working with *Céramiques & Composites* to assess the feasibility of a 2- to 3-m class facility[9].

Assuming a simple structured design the overall mass of a SiC primary mirror would be in the ~1000 tons range. The product is in a too early development phase to make any sensible cost estimate. The raw material is fairly cheap, but this advantage would be balanced by the need for an additional Si or SiC coating[3] and for a lightweight structure. In addition,

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[2] e.g. SiC-100 by Céramiques & Composites; this is a one-phase material with the properties of pure SiC. The process starts with cold pressing of a SiC powder, mixed with a binding material (which will leak out upon firing). This substrate can be easily machined, than it is fired to ~1800 ºC. Shrinkage is about 14% but it is reportedly predictable to a sufficient accuracy to allow near-net shape blank manufacturing within ~0.2 to 0.5 mm of final dimensions. The substrate is however porous and requires a cladding prior to optical finishing (optical replication being a potential alternative).

[3] to cope with porosity; it is not clear today whether this coating could not be applied as a very thin layer *after polishing.*

any estimate would have to take into account the beneficial impact of the high stiffness of the material on the mirror cell and telescope structure designs.

With Zerodur or Astro-Sital, the overall mirror mass would be in the range of 3,000 t with 150-mm thick segments. In terms of raw material the required substrate production rate is within the reach of present technologies (Astro-Sital can reportedly be produced at a rate nearing 100 t per month).

The fabrication process for glass-ceramics is inherently "slow" because it requires slow thermal changes upon cooling, annealing and ceramization. However, tests made by SCHOTT within the framework of the VLT project show that direct ceramization after casting is possible for blanks up to the 4-m range. This should dramatically cut the overall duration of the process. In addition, the process could possibly be made continuous; figure 6 shows preliminary ideas on a possible production "line".

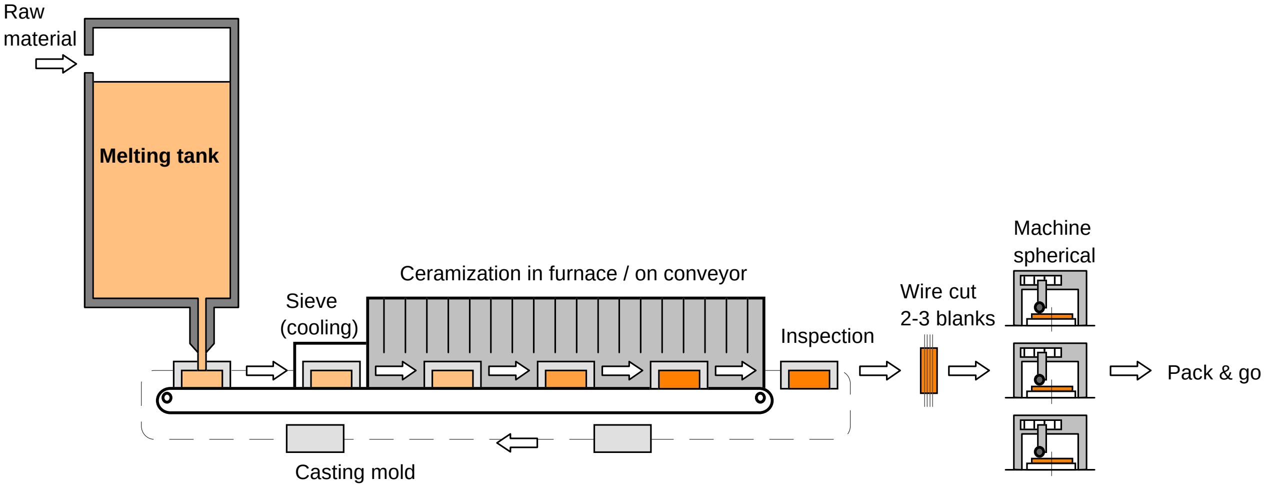

Figure 6 Zerodur segments production scheme

Assuming that one casting would lead to 3 useful blanks (hexagons 2.3-m diagonal, 15 cm thick), each cast would be approximately 9.2 t, 2.5-m diameter, 75 cm thick. The cast would be conveyed into a sieve where it would be cooled until solidification. Thereafter it would enter the ceramization furnace where it would be conveyed through areas having the temperature profile required for ceramization. After ceramization the cast would be inspected for inclusions and residual stresses, wire-cut into three hexagonal blanks, fixation holes would be drilled (if required by the design of the lateral support system), and the surfaces would be ground flat/spherical before packing. Depending on requirements, grinding of the flat surfaces (back, edges) could possibly be skipped.

In order to meet the required production rate of 1 blank per 1.3 days, and assuming a ceramization cycle of 90 days, the ceramization furnace would have to accommodate about 23 casts (for 3 blanks per cast) at any given time. Because of the low curvature, there are no concerns with respect to the grinding of the spherical surface. In this respect it must be pointed out that the improvements made by SCHOTT regarding the accuracy and smoothness of the VLT blanks would be a positive factor in reducing grinding time on the part of the optical manufacturer.

The limited lifetime of Zerodur melting tanks would probably require that the process be interrupted after 3-5 years for overhaul of the tank. The existing 8-m production facility could possibly be retrofitted, however to an extent essentially limited to the casting facility. Investments for a dedicated facility should be comparable to and possibly lower than the investments which were required to set up the VLT production facility. Prices for serial, standard quality and geometry Zerodur blanks (10 to 40 cm) is in the order of DM 130 per Kg. In view of the very large amount of substrates to be purchased, and provided that specifications do not differ substantially from standard quality, a cost reduction of 20 to 30% seems a reasonable assumption. With a 3,000 t overall mass, this leads to MDM 270-312 for the primary mirror blanks (segments in the 2 to 4-m range), plus investments for a suitable production facility. Thinner, 100-mm thick blanks, would bring the cost down to MDM 180-210.

Astro-Sital would lead to a price tag of MDM ~150-200 for the 150 mm thick mirror blanks. However, availability and prices over the next 20 years cannot be reasonably predicted.

Fabrication and testing of the primary mirror

Two fabrication processes, replication and conventional polishing on annular machines, seem promising for the production of a large number of identical segments.

Replication

In the late 80's a development program was run by CERGA/Observatoire de la Côte d'Azur under ESO contract, to validate the replication technology in the 1-m range (with the aim at applying this technique for the production of the VLT secondary mirrors). The program was successful[10] and the technology selected for the fabrication of the VLT M2, until problems unrelated to the replication made ESO decide to change contractor.

A replicated optical surface is obtained by molding a thin (about 0.1 mm) layer of resin onto the surface of a rigid substrate. The latter must be shaped down to a surface accuracy which is one or two orders of magnitude lower than the final specification to be met. The four steps are schematically represented in figure 7 (production of a convex mirror from a concave matrix). During preparation the polished mold, which has the exact negative shape of the final mirrors to be produced, is cleaned and vacuum coated with an un-molding layer and possibly with the coatings of the finished mirror, arranged in reverse order. The substrate is cleaned as well.

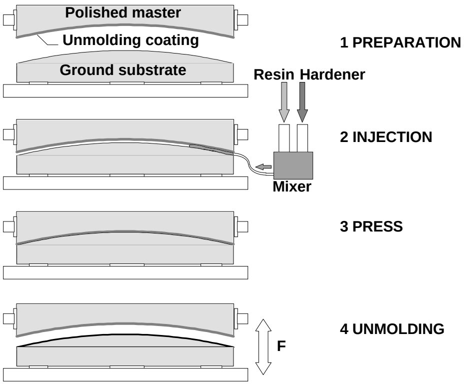

Figure 7 Optical replication

Prior to injection the epoxy resin and the hardener are mixed to a highly homogeneous blend. After injection the resin is pressed between the mold and the substrate. Hardening takes about two days at room temperature after which un-molding can take place. A post-curing thermal cycle is necessary to ensure a complete chemical reaction. In total the replication process of a 1-m class mirror takes about two weeks. The replicated mirror can easily be measured interferometrically against the master.

The effect of surface stresses over areas larger than ~1 m^2 would have to be carefully investigated; as of today it cannot be guaranteed that the process would be viable for 2-m class segments or larger -but the advantages of the technology are worth giving it a try.

The epoxy layer must be protected from humidity by 2-3 layers of e.g. SiO_2. The replicated surface is rather fragile as any scratch breaking through the protective coating will eventually permit humidity to reach the epoxy and distort the surface. For the same reasons the process requires extremely clean conditions because dust particles on the master or on the substrate impair the durability of the replica.

Cleaning and re-coating are possible according to the same procedures as the ones applied to conventionally polished surfaces; care must however be taken to prevent scratches upon cleaning. Long-term durability on glass-ceramics substrates has been evaluated through dry/humid thermal cycles and the results were found positive (except in the occurrence of damages to the protective coating).

The process allows superb reproducibility of the replicated surface, with master-replica differences down to the ~5 nm RMS range and virtually no degradation of surface roughness. Replication would undoubtedly provide -by far- the highest repeatability of curvature. In addition, the technique virtually eliminates edge effect.

Replication may offer an alternative to polishing, but not to the complete figuring process. The substrate must still be brought within a few microns of the final shape. This could possibly be achieved by lapping on a suitable annular machine (see *Polishing* below).

Polishing

Conventional polishing would become a viable solution only with machines having the capacity of processing simultaneously several mirrors.

An attractive solution would be to have the segments ground and polished on annular machines. The fabrication scheme is outlined in figure 8 (2-m class segments). Although primarily adapted to the production of flat surfaces, annular machines adapted to spherical surfaces have been successfully qualified for radii of curvature much lower than the one required here (~350-m). 8-m class machines would allow processing of batches of 5 segments. The first machine would serve for fine grinding, the second for rough polishing and the third for final polishing. Each segment would undergo about 20 actual days of figuring.

The process is known to provide an excellent repeatability of curvature, and with proper settings produces virtually no edge effect. The grinding and polishing cycles are run uninterrupted; segments nearing but not fulfilling the specification could be put on a *waiting list* for a shortened re-polishing cycle.

The quality of such machine results from an equilibrium between the wear of the conditioner and of the rotating table; hence the conditioner would have to be periodically adjusted in position to prevent a progressive drift in curvature. The option of an active conditioner, with feedback from segments acceptance test data, could be investigated.

With the arrangement shown figure 8 (1 grinding machine and 2 polishing machines, 8-m tables), the production rate would be about 5 mirror every 7 days. It is assumed that the polishing machines would have a sufficient rate of success in producing mirrors meeting the specifications. If not, computer-controlled machines or ion-beam figuring facilities would have to be built for fine correction of the segments shapes.

Segments would be optically tested against a silica, convex matrix. The rear side of the matrix would be convex, so as to reduce the length of the set-up. Preliminary calculations show that a 10- to 15-m long set-up (distance from interferometer to matrix) could be envisaged.

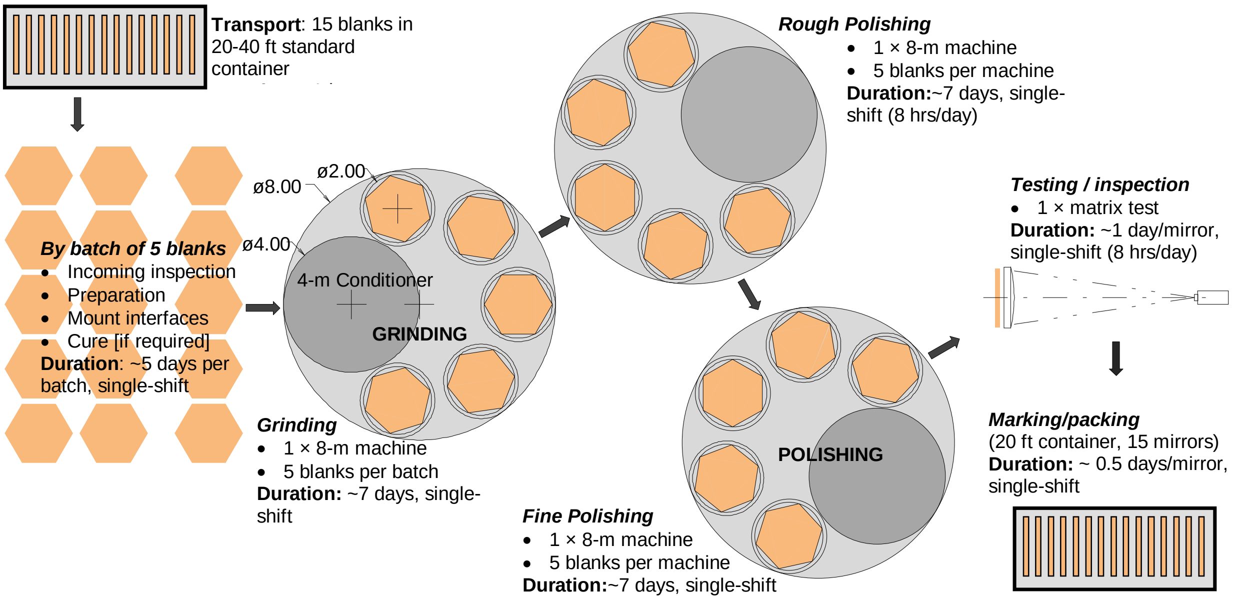

Figure 8 Optical figuring on annular polishing machines

Several preliminary cost estimates have been made for the optical fabrication of 2- to 4-m class segments, from blank delivery at the optical manufacturer’s site to finished segment delivery at an overseas observatory site, within a 9- to 12-years lead-time. The estimates range from 120 MDM for 2-m class segments to 180 MDM for 4-m class, a noticeable part of the difference being attributable to transport costs, which rise sharply if the segments do not fit into standard containers.

Hence a total cost in the range 390-490 MDM for the primary mirror optics, unmounted, including material (Zerodur). It shall be noted that this figure is fully in-line with the actual prices for the primary mirror optics of the Hobby-Eberly telescope[6].

Secondary mirror

The secondary mirror segments would be 400, 600 and 800-mm to match primary mirror segments of 2, 3, and 4-m respectively. Matching of the segmentation patterns of the primary and secondary mirrors can evidently be fulfilled for the on-axis beam only and the mismatch will increase in the field of view. With the proposed optical prescription, segments gap and bevels at the level of the secondary mirror shall be 1/5th of that at primary mirror level i.e. in the range of 1 mm or less. The segmentation patterns of the two mirrors would overlap up to about ±1.7 arc seconds field of view. Matching of 1 secondary mirror segment with groups of 7 or 19 primary mirror segments could be an alternative to reduce the effect of the field-dependent mismatch.

The potential candidates for substrate material and the possible optical fabrication processes are essentially the same as for the primary mirror segments. Table 3 gives the thickness of segments, mass and cost of Zerodur blanks on the basis of a conventional aspect ratio of 1:8 and a price of DM 105/Kg (assuming a cost-reduction of 20% due to quantity).

If segments are made of SiC plates, the total mass of the secondary mirror would decrease by 40% in the most conservative case. A more expensive but still reasonably simple structured design would allow a mass saving of 60-80%. All sizes considered are within the reach of current production facilities.

For polishing, 2-m class annular machines (1 for grinding, 2 for polishing) would accommodate about 10-11 segments of 400 mm and be sufficient to achieve the required production rate (in single shift). The price tag for polishing would be in the range of 20 MDM, assuming a production time of ~10 years. Hence the total cost of the secondary mirror, ex works, uncoated, would be in the 20-30 MDM range. The segments could most likely receive a durable dielectric coating, which would remove the need for periodic re-coating.

Segment size (mm)	400	600	800
Thickness (mm)	50	75	100
Segment mass (Kg)	15.9	53.7	127.2
Total secondary mirror mass (t)	~40	~60	~76
Total cost (blanks only, MDM)	~4	~6	~8

Table 3

A 3-points support system would probably be sufficient for 40-cm segments. 60 to 80-cm segments would most likely require 9-points support systems.

Tertiary and quaternary mirrors

The 8.3-m tertiary mirror is similar in size and aspherization to the current 8-m class mirrors, the only significant difference residing in the fairly high radius of curvature. The mirror could be figured according to the same process as the VLT or Gemini mirrors; optical testing at center of curvature through a null-lens would require a 50-m high test tower (to be compared to 30-m for VLT and Gemini). The mirror would be a thin, about 200 mm thick Zerodur monolith. Suitable blanks are readily available at Schott. The mirror would be supported by a 150 points support system, much alike the passive stage of the support of the VLT primary mirrors.

The figuring of the 5.6-m quaternary mirror probably represents the greatest technological challenge for the production of the optics of OWL. Figuring the steep aspheric shape seems out of question. Indeed, the slope deviation with respect to the best fitting sphere[4] is about 15 times that of the VLT primary mirrors. The solution explored so far is to bend the mirror and polish out the residuals.

With the VLT, active change of the aspheric shape must be performed when the optical configuration is changed from Nasmyth to Cassegrain. The change of optical configuration requires the correction of about 20 μm of spherical aberration (wavefront) and is achieved by refocusing and applying a force distribution whose peak is about 400 N. The correction is achieved within an accuracy in the order of 1%, the limiting factor being essentially the discrete number of support rings. If the quaternary mirror of OWL were of the same material, had the same flexibility as the VLT primary mirrors and a comparable support system, the force required to achieve the aspheric shape would therefore be in the range of 160,000 N.

We propose to reduce this figure by increasing the flexibility and densifying the support system. Assuming a design of the support pads comparable to that of the VLT primary mirrors, taking into account thermal stresses in the bonded connection over the thermal range -10 to +25 °C, and assuming an acceptable level of local stresses of 5 Mpa, we come to a maximum acceptable force of about 7,000 N. With 350 support points on 9 rings, we come up with a thickness of 27 mm (Zerodur mirror), with residuals in the order of 12 μm RMS (mechanical surface). Because of the requirement to generate a specific deformation of the mirror, the geometry of the support system could possibly be optimized with a view to reducing the peak force and improve the accuracy of the deformation. The radial thickness profile might also be optimized along the same lines.

Control of the first eigenmode (astigmatism) rather than accuracy of aspheric bending would be the dimensioning factor for the force accuracy. With a flexibility 10 times that of the VLT primary mirror, the force setting accuracy would have to be in the 0.01 N range. This requirement could be relaxed to about 0.1 N for the polishing support system.

In a first step, the mirror would be find-ground to the best fitting spherical shape. At that point, the residual deformation would be polished out; potentially suitable figuring technologies include either active tools[11], membrane polishing[12], or computer-controlled polishing[13]. During figuring the mirror would be passively supported i.e. bending forces would be

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[4] The best fitting sphere being defined herein as the sphere having the minimum gradient (slope) deviation with respect to the desired shape

applied for testing only, the mirror being thereupon supported on the same force field as the one to be applied in the telescope.

Testing of the highly aspheric surface in a time-efficient manner compatible with production constraints is another serious challenge. Two suitable options (not reproduced herein) have been identified so far; the first one is similar in its principle to the option proposed for the 25-m telescope[14] and has the advantage to ensure that the quaternary mirror is controlled with the tertiary mirror in the exact configuration to be used in the telescope. The corrector system would be made of a 1-m silica lens and a fast, 1.4-m diameter, diamond-turned aspheric mirror. The second option is much more compact but requires reconstruction from sub-pupils measurements, and the manufacturing of one or two 8-m class spherical mirrors and of an aspheric, 1.8-m diamond turned mirror.

In view of the risks involved and the development needed to come up with a viable solution, the cost of the quaternary mirror cannot, at this point, be reliably estimated. Assuming that a single facility is built for the production of the tertiary and quaternary mirrors, a cost in the 70 MDM range for the two mirrors seems a plausible guess.

4. Adaptive optics

Gain and requirements

We have already said that diffraction limited resolution is mandatory for this concept. It doubles the gain in limiting magnitude for unresolved objects, and provides a gain of 100 (near infrared) to up to 500 (visible) in angular resolution. It is well known that adaptive optics is better suited to large telescopes, for the following reasons :

- the collected energy increases as the square of the telescope diameter D and the angular resolution increases as the telescope diameter; therefore, at a fixed Strehl ratio (i.e. fixed phase error), the energy concentration increases as D^4,
- the sensitivity to noise depends only upon the number of photons per spatial r_o and temporal τ_o cells of the turbulence, therefore is independent of the telescope diameter,
- the overall isoplanatic angle θ_o over which a given image quality is achieved, is basically independent of the telescope diameter, whereas the resolution increases as D. Therefore, the total resolution points in a compensated field increases as D^2 .

This scaling assumes a fixed ratio between r_o and the distance between two compensation points (actuators), and a fixed compensation rate. Is that a problem? What does that imply ? We have identified two types of issues, technological issues and fundamental limitations. Table 4 presents the requirements of an adaptive optics system that would provide good Strehl ratio Sr ≈ 50% at visible wavelength and consequently almost perfect correction in the red and the near infrared (Sr > 90%). We also assume a site with excellent seeing (average $r_o \approx 25$ cm and $\tau_o > 5$ ms).

Number of actuators	200000
Bandwidth	100 Hz
Number of LGS	≈10

Table 4: OWL Adaptive Optics requirements

Challenges

Mirror : The overall phase excursion expected on a 100 meter baseline is approximately 70 microns PV, tip-tilt removed. Including an outer scale of 50 meters, given by most authors[15, 16], leads to phase excursions of 30 microns PV (tip-tilt removed). This is not far from what is currently feasible (typically 10-20 microns, scaleable) with, for instance, piezostack mirrors. The idea would be to use a two (or three) stage compensation, consisting of a first mirror (e.g. piezostack) correcting the large amplitude, low spatial frequency modes, which means large stroke capabilities. A 50x50 actuator mirror, with a pupil size of 500 mm diameter, should allow to achieve the stroke requirements using the current technology. The second stage would consist in a device with a large number of degrees of freedom (actuator in the large sense, see table), small stroke requirements (typically below 5 microns with the above example of a 2000 actuator first stage corrector) and bandwidth requirements comparable to what is currently available (a few hundred hertz). Potential candidates for this are MEMS (micro-electromechanical systems) which already achieve stroke of the order of one micron and are scaleable to very large number of control points, or high density deformable mirrors as proposed for the NGST[3]. The advances of technology in this field make the availability of adequate components in the mid term highly probable.

Wavefront sensor : Already to date, phase derivative sensors could be used (Shack-Hartmann or shearing interferometers). The major issue here lies in the detector and the computers. Rates of 2 Gpixel/s are typical, which must be read out and processed. This is almost within reach of current detectors with full use of parallel output capabilities to achieve noiseless detection. Concerning computing power, the requirements are only a factor 300 to 400 above what is currently done for 8 m class AO. The emergence of extremely fast computers (optical or quantum computers) strengthen by the past progress in computing power during the last decades - factor 2 every 1.5 year- is very encouraging.

Laser guide stars : The major issue here is the cone effect, whose magnitude is such that it prevents the use of a single guide star if good correction has to be achieved even in the NIR on such a large telescope. This problem is more of a fundamental nature. However, several solutions have already been proposed, the most encouraging being merging[17] and tomography[18]. They still have to be demonstrated but do not present insurmountable theoretical nor implementation problems. Tomography would require a few stars (4-10), independently of the telescope diameter, and is therefore the most attractive solution for our purpose. The power requirement per star only depends upon the wavelength at which one wants to compensate, so is comparable to what is aimed for in current LGS experiments, that is 10 to 20 W. As an alternative to laser guide stars, and in view of the extremely large aperture, the field available for tomography becomes sufficiently large to provide adequate sky coverage using solely bright natural guide stars[19].

The full aperture gain one can benefit from in the tip-tilt sensing on natural guide star lead to limiting magnitude for the tip-tilt guide star of at least m_v= 23 to 24. This, combined to the isoplanatic limitation lead to a full sky coverage at 2.2 microns. To get full sky coverage at shorter wavelengths is possible if one uses multi-conjugate adaptive optics to enlarge the compensated field of view, which is a natural by-product of tomography and the use of a multi-stage AO system as we consider here.

Adaptive optics is a key component of the 100-m OWL concept. In summary, if the problem of turbulence tomography is assumed solved, there is no fundamental limitation for AO going on such large telescopes, where the gain in angular resolution and detectivity can be huge. The technology for wavefront correctors, detectors and computers is not yet fully mature, but fast progress are being made that should make such high order systems possible in the horizon of 2010-2015. Rough estimate of the cost should be in the order of 100 MDM.

5. Mechanical structure, drives and bearing system

The mechanical structure

To investigate the OWL's mechanical feasibility, we have considered an alt-az structure with a altitude range of 30° to 90°, full azimuthal rotation. The concept foresees direct drives and tachometer, direct mounted encoder, motorized cable wraps, and hydrostatic bearing system on all axes.

The altitude structure (the "tube")

The tube is designed using the *rocking chair* concept, which is found practical for these dimensions and masses. To the classical concept a lateral containment has been added to avoid lateral rocking of the tube out of the altitude plane.

The primary mirror is divided into four sectors about 90° wide, separated by four gaps 4m wide, and is supported on a half cylindrical cell based on a square modular structure, well suited for mass production and easy to assemble.

The four triangular truss structures which will hold the secondary, tertiary and quaternary mirrors are composed of two main tubes of 4 m diameter connected by beams to provide stiffness in the plane of the triangular structure. They have shown to be critical for the dynamic behavior of the telescope.

Figures 9 and 10 show models of possible configurations with first eigenfrequencies in the range of 1.6 Hz for the tube and 1.4 Hz for the entire movable structures. This value is obtained using a conventional and cheap material like steel. Better behavior could be obtained using composite materials (carbon fiber) or titanium alloy to decrease the mass of the structures which hold the secondary mirror unit.

We plan to study active means of controlling the dynamic behavior which may be localized on the structure itself, or be similar to the ESO VLT M2 field stabilization system, in order obtain good tracking performance at higher wind speed. We may envisage to protect the telescope from direct wind with fixed steel wind screens placed around the construction.

The lower part of the tube, the cell, is also built as trusses structure, and stiffness will be traded off against mass. The relative compactness and the favorable aspect ratio will favor the transmission of the control torque. The journals for the "altitude" hydrostatic bearing and the seats for the permanent magnets of the motors are placed in the bottom side of the "cell". The motor and the hydrostatic support is regularly distributed on the cell to provide support of the structure and to distribute the control torque most evenly.

The azimuth structure (the "fork")

The fork is the structure that supports the tube and provides the capability to turn around the azimuthal, axis. It is divided into two parts with precisely defined functions:

- the lower part (flat) is the structural part: takes the load, transfers the reaction of the altitude control torque to the foundations and transfer to the tube the azimuth drives torque.

- The upper part is mainly used to stabilize laterally the tube.

The simple shape is well suited to be built in concrete. The use of such a material can also allow to use water hydrostatic bearing system, as in the case of large rotating building like a stadium. It would be also possible to use a solution with an upper part made in steel and a lower part in concrete which would allow a lighter structure.

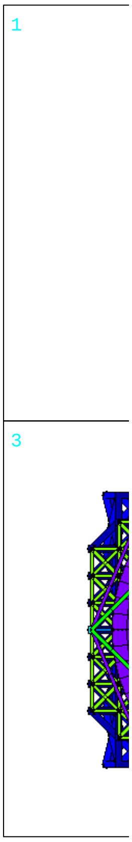

Figure 9

The drives and the hydrostatic bearing system

The segmented linear motors already used for the VLT find here their natural and best use due to the large diameters of the axes. The maximum acceleration should be kept within 0.1°/s^2 so to limit centrifugal effects at the outer diameter. For the same reason the maximum speed should be set around 0.1°/s.

The price trend of the permanent magnets and windings material is decreasing, and all the advantages of mass production are available. Due to the large inertia and the high stiffness required also hydraulic cylinders can be taken into consideration, especially to actuate the altitude axis.

The hydrostatic bearing system is based on the classic solution which uses oil as fluid. We consider worthwhile valuable to study the possibility to use water, where the materials allow, and also magnetic bearings. The latter are extremely stiff and would have the advantage not to have fluids circulating on the structure. This advantage is to be traded off against the power consumption.

At this early point, we believe that a first eigenfrequency of 1.6 Hz can already be considered a fairly good result, leading to a telescope which can reach a 0.5 Hz position loop bandwidth, allowing a good tracking performance in low wind speed condition (3 to 5 m/s). We will, however, continue to investigate other solutions, including but not limited to active ones, to improve the dynamic performance of the structure.

Time schedule and approximate cost

The dimension of such a concept in terms of electro-mechanical construction and design is not unusual in the modern industry world. Oil platforms and large rotating stadiums are almost routine work.

On the basis of these preliminary considerations, the estimated time required to complete a viable conceptual design would be in the range of 3 years; detailed design and prototyping would require another 3 years. Taking into account that erection could most likely start before the end of the fabrication phase (assumed to be in the range of 5 years), our preliminary estimates are that an additional 9 years would be required for the mechanical structure, bearings and drives to enter into operation.

Cost estimates made on the basis of steel structures, hydrostatic bearings, linear drives and conventional encoder solutions lead to a figure in the 275 MDM range. This figure would increase by about 80 MDM if composite or titanium alloys are required at selected points in the structure, and by another 60 MDM with a mixed fork structure (steel + concrete). Civil construction, installations, mirror protection, transport and assembly would possibly be in the range of 215 MDM.

The cost of mirrors support systems is, at this point, fairly difficult to estimate. Scaling up the support system of the VLT primary mirrors on the basis of the number of degrees of freedom, taking into account the modular design inherent to the segmented solution and the large quantity of identical items to be produced, a figure of 200 MDM could be a plausible guess.

Figure 10 Alternative design for the telescope “tube” (mirror cell not shown)

6. Conclusions

Extremely large telescopes in the 100-m range would have such unprecedented scientific effectiveness that their construction would constitute a milestone comparable to that of the invention of the telescope itself, and provide a truly revolutionary insight into the universe (figure 11). The modular concept and fabrication scheme of the 100-m OWL concept would allow major discoveries to occur even before completion, as progressive filling of the aperture would allow dedicated instruments to be built and already operated at an early stage, in parallel to the fabrication and integration of mirror segments, and with unprecedented resolution and sensitivity.

Preliminary assessments show that such breakthrough might very well become possible within the next decade. Current optical fabrication processes and active control of optical shapes seem already very close to meeting the requirements underlying the fabrication of the optics; promising if not inevitable developments in the area of adaptive optics as well as control of segmented mirrors may very well lead to the same conclusions within a few years. A substantial effort is still to be put into mechanical design if the structure is to meet stiffness requirements in open loop; it should be pointed out, however, that the figures derived so far are almost completely non-optimized and design concepts only constitute starting points.

Preliminary estimates lead to figures in the range of 10 to 15 years for fabrication, with a possible start of science operation within 9 years after start of fabrication, at a limited -but unequaled- potential which would ramp up to 100% within 15 years, and to a likely cost of 1 billion $ (the estimated cost for the telescope optics, adaptive optics, and structures presented herein amounting to about 0.75 billion $). It should be pointed out that this figure derives from generally pessimistic if not over-conservative assumptions -cf. the thickness of the primary mirror segments, about double of Keck’s.

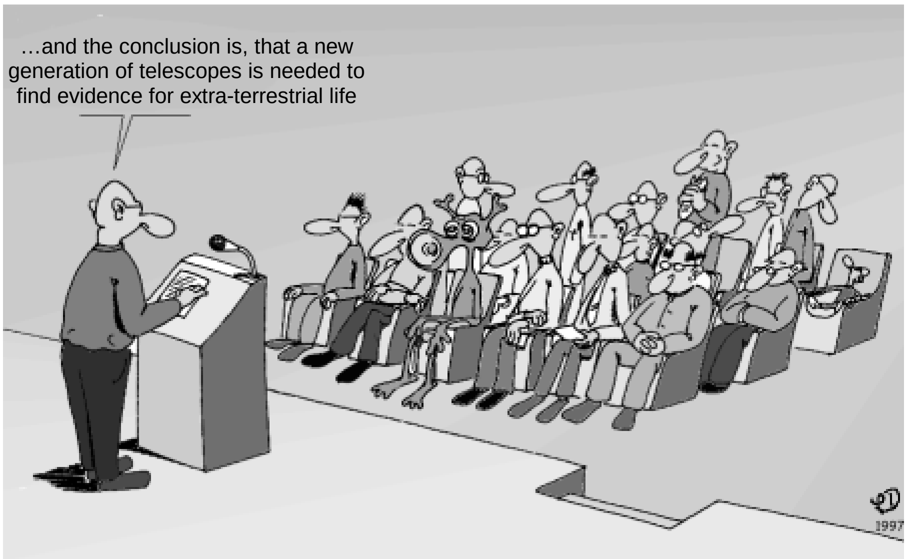

Figure 11 On the purpose of OWL

At this point, the authors conclude that the question which forms the title of the present article has a positive answer.

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