Progress of the OWL 100-m Telescope Conceptual Design

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ABSTRACT

The European Southern Observatory is developing a concept of ground-based, 100-m class optical telescope, with segmented primary and secondary mirrors, integrated active optics and multi-conjugate adaptive optics capabilities. Preliminary analysis have confirmed feasibility of the major telescope components within a cost on the order of 1,000 million Euros and within a competitive time frame. The modular design allows progressive transition between integration and science operation, and the telescope would be able to deliver full resolution and unequalled collecting power 11 to 12 years after project funding. The concept owes much of its design characteristics to features of existing telescopes, namely the Hobby-Eberly for optical fabrication, the Keck for optical segmentation, and the VLT for active optics control. The only critical area in terms of needed development seems to be multi-conjugate adaptive optics, but its principles have recently been confirmed experimentally and rapid progress in the underlying technologies is taking place and benefits from consumer applications. Further studies are progressing, confirming initial estimates, and a baseline design is taking shape. The primary objective of those studies is to demonstrate feasibility within proven technologies, but provisions are made for likely technological progress allowing either cost reduction or performance improvement, or both.

Keywords: OWL, extremely large telescope, conceptual design, segmentation, active optics.

1. INTRODUCTION

The last two decades of the 20th century have seen the design and completion of a new generation of large telescopes with diameters on the order of 8 to 10-meter. To various degrees, concepts developed on this occasion have concentrated on feasibility of the optics, controlled optical performance, cost reduction, and have been quite successful in their endeavors.

The achievements of recent projects could hardly be summarized in a few lines, but we emphasize three major breakthroughs:

- Optical segmentation (Keck).
- Cost-effective optical and mechanical solutions (Hobby-Ebberly)
- Active optical control (NTT, VLT, Gemini and Subaru).

The lessons learned from these projects are, to some extent, already being implemented in a series of projects (e.g. GTC, SALT), but future concepts may quite naturally rely on a broad integration of positive features of each approach. Perhaps the most far-reaching innovations have been brought by the Keck, with virtually unlimited scalability of the telescope primary optics, and by the VLT, with highly reliable and performance-effective functionality (active optics, field stabilization). Scalability was traditionally limited by the difficulty to cast large, homogeneous glass substrates, and progress over the last century has been relatively slow. Indeed, even the relatively modest size increase achieved by the most recent telescopes with monolithic primary mirrors would have been impossible without innovative system approaches (e.g. active optics) which relaxed constraints on substrate fabrication.

Optical scalability having been solved, other limitations will inevitably apply. Taking only feasibility criteria into account, and modern telescopes being essentially actively controlled opto-mechanical systems, these new limitations may arise either in the area of structural design, control, or a combination of both. Our perception is that the fundamental limitations will be set by structural design, an area where predictability is far higher than with optical fabrication. However, it should be observed that, despite the fact that control technologies are rapidly evolving towards very complex systems, those technologies are also crucial when it comes to ensuring that performance requirements are efficiently and reliably met. Reliability will indeed be a major issue for extremely large telescopes, which will incorporate about one order of magnitude more active degrees of freedom (e.g. position actuators). In this respect, however, the Keck and VLT performances are encouraging. The 450 active force actuators currently in operation at the VLT (150 per telescope, and 3 telescopes completed at the time of redaction of this article), each activated an average of ~1,000 times per night, have proven to be highly reliable with a total of 7 uncritical failures, all attributed to electronic faults (infant mortality).

In view of the above, the European Southern Observatory has initiated a conceptual study for a 100-m class optical telescope[1,2], dubbed OWL for its keen night vision and for *OverWhelmingly Large*. Activities have progressively shifted from optical design and fabrication to structural design and opto-mechanical optimization. Although there is still major effort to be accomplished in order to come to a consolidated design, it appears already that the telescope is most likely feasible within currently available technologies and industrial capacity. Actually, the successive iterations of the opto-mechanical design indicate that OWL diameter is quite probably below the current feasibility limit for a steerable optical telescope, which we estimate to be in the 130-150 meter range.

Adaptive optics set aside, OWL's actual limitation seems to be cost, which we constrain to 1,000 million Euros, capital investment, including contingency. Such budget is within a scale comparable to that of space-based projects and spread over a longer time scale. Additionally, it can reasonably be argued that progress in ground-based telescopes is broadly beneficial in terms of cost and efficiency as it allows space-based projects to concentrate on and be optimized for specific applications which cannot be undertaken from the ground -because of physical rather than technological reasons.

It is obviously essential that the concept allows a competitive schedule, which we consider to be the case as the telescope could, according to tentative estimates, deliver unmatched resolution and collecting power well before full completion.

2. REQUIREMENTS

Provisional requirements have been derived from science objectives[2,3,4], and will only be outlined here. Those requirements may still evolve with the consolidation of the science case, but they are already sufficiently complete to allow conceptual design to proceed.

The highest priority requirement are understandably angular resolution, and sensitivity. Whereby in a seeing-limited regime the peak of the PSF is proportional to the square of the atmospheric turbulence and to the square of the telescope diameter[5], it becomes proportional to the fourth power of the telescope diameter in a diffraction-limited regime. Sensitivity is therefore not only a matter of throughput or collecting area, it is the result of a combination of high resolution and high throughput.

The requirements for OWL correspond to diffraction-limited resolution over a field of 30 arc seconds in the visible and 2 arc minutes in the infrared (λ~2 µm), with goals of 1 and 3 arc minutes, respectively. The telescope must be optimized for visible and near-infrared wave bands, although the high resolution still allows some competitive science applications in the thermal infrared[6]. Collecting power is set to ~6,000 m^2, with a goal of 7,000. The implied telescope diameter is 100-m.

The optical quality requirement is set to *Strehl Ratio > 20%* (goal ≥ 40%) at λ=500 nm and above, over the entire science field of view and after adaptive correction of atmospheric turbulence with a seeing angle of 0.5 arc seconds or better. We tentatively split this requirement into telescope and atmospheric contributions:

- Strehl Ratio associated with all error sources except atmospheric turbulence ≥ 50% (goal ≥ 70%);
- Strehl Ratio associated with the correction of atmospheric turbulence ≥ 40% (goal ≥ 60%).

It goes without saying that the field requirements imply multi-conjugate adaptive optics.

3. SYSTEM ASPECTS AND DESIGN CONSIDERATIONS

We consider that the essential function of the system is to reliably deliver a minimally disturbed -in terms of amplitude and phase- wavefront to the science detector, over a specified field of view. As disturbances inevitably occur -atmospheric turbulence, telescope optics, tracking, etc.-, those must be either minimized or corrected, or both.

In theory, correcting them all with a minimum number of integrated subsystems is an attractive option as it would likely be the most efficient way to preserve amplitude i.e. minimize the number of surfaces and losses. Actual disturbances -such as atmospheric turbulence and mirror decenters- having hugely different spatial and temporal spectra, this approach would however maximize constraints on each adaptive subsystem and thereby exacerbate feasibility, reliability and cost issues. For this reason, we prefer to achieve correction through distinct functions associated with well-defined subsystems and rule out, in particular, the option of adaptive correction at the level of the telescope main optical components.

It is quite logical to distinguish between atmospheric and telescope disturbances for their very different spatial and dynamic properties, the former being arguably the most difficult to compensate. Therefore, we incorporate into the telescope concept dedicated adaptive modules, to be designed and optimized for correction of atmospheric turbulence at specified wave bands, and we request that the telescope contribution to the wavefront error delivered to the adaptive module(s) be small with respect to the wavefront error associated with atmospheric turbulence. In brief, we request the telescope itself to be seeing-limited.

Taking into account the telescope size and some implied technology solutions (e.g. optical segmentation), we come to the unsurprising conclusion that the telescope itself should provide the following functions: phasing, field stabilization, and active optics, including active alignment. The case for field stabilization is very strong, as a "closed" co-rotating enclosure would be very costly and anyway inefficient in protecting the telescope from wind.

As pointed out in the introduction, we consider modern telescopes to be controlled opto-mechanical assemblies. The sheer size of OWL only emphasizes the need for a coherent system approach, with rational trade-off and compromises between different areas, e.g. optical and structural designs.

It is also essential that from the earliest stages the design incorporates integration, maintenance and operation considerations. Besides cost, the two essential reasons are construction schedule and operational reliability, the latter playing a critical role when it comes to telescope efficiency.

4. TELESCOPE OPTO-MECHANICS

4.1 OPTICS

A strongly dimensioning requirement is the total field of view, which must exceed the science field to provide objects for wavefront sensing. While active optics and guiding do not yield any particular problem, adaptive optics with natural guide stars (NGS) requires fairly bright objects and sky coverage is directly related to the field available for fast wavefront sensing. Laser guide star (LGS) solutions require smaller field. There is, however, ongoing debate[7,11] as to actual field requirements for NGS solutions, and at this point it would be premature to make any irreversible design decision. Hence, design is proceeding on the basis of the most conservative assumptions, which involve modest extrapolation of the performance of existing wavefront sensing technology[7,8] and implies the largest possible field of view.

The requirements applying to the optical design at technical focus i.e. prior to adaptive modules, are as follows:

- Diffraction-limited field of view larger than 30 arc seconds in the visible.
- Unvignetted field of view 2 arc min, goal 3 arc min (derived from the maximum required science field in the infrared).
- Technical field of view larger than 10 arc minutes, goal ~20 arc minutes.
- Optical quality in the technical field of view ~0.20 arc second RMS or better (seeing-limited).
- Linear field size of ~2-m to allow convenient design space for guiding and wavefront sensing.

In addition, the design should ideally provide for conveniently located surfaces for active optics and field stabilization - *conveniently located* being essentially meant for intermediate pupil images.

Several design solutions have been -and are still- explored. A trade-off between classical optical designs and solutions implying spherical primary and secondary mirrors is discussed elsewhere[12]; aspheric primary mirror solutions have, so far, been rejected in favor of spherical solutions as the former imply higher cost, higher constraints on structural design, and require a comparable number of surfaces (4-5 instead of 6) for comparable functionality. A spherical primary and aspheric secondary solution does not provide clear advantage either, as it requires the correction of a prohibitively large coma term.

The most advanced design is shown in figure 1; it is an evolution of a 6-mirror solution presented elsewhere[12,13] and resembles that of the Hobby-Ebberly and SALT telescopes. It could be described as a *bent primary focus* configuration. Mirror separation has been reduced from 120 to 95-m, and the design provides a well corrected 11.4 arc minutes field of view, with a geometrical image radius of 0.2 arc seconds RMS at the edge of the field. The diffraction-limited field of view in the visible is close to 3 arc minutes i.e. far larger than required. Focal ratio is 5.1 but will probably be increased to ~6.5 at the next iteration to relax constraints on the design and fabrication of the relay optics in the adaptive modules.

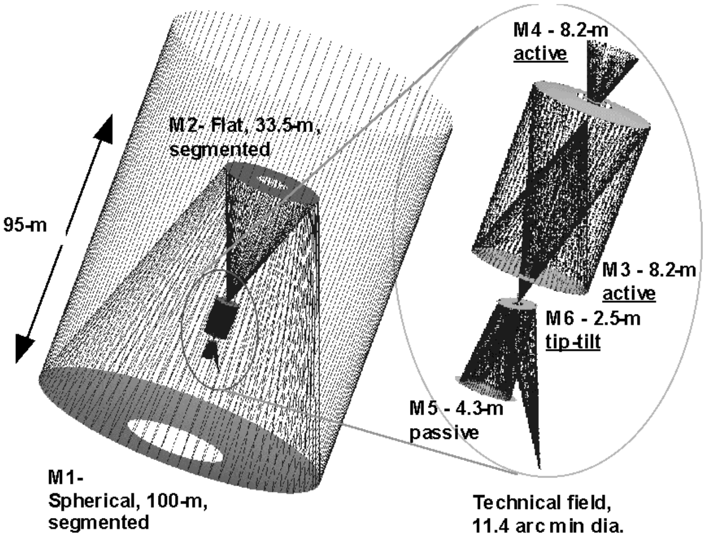

Figure 1. Layout of the optical design, 6-mirror solution

The design includes a 100-m spherical and a flat 34-m, segmented primary and secondary mirrors, respectively. Correction of spherical and field aberrations is provided by a 4-elements corrector, which includes two 8-m class active monolithic mirrors, a 4-m class passive and a 2.5-m flat tip-tilt mirror, located in a pupil and which can be rotated about the telescope axis to allow different focal stations. The dimensions of these two last mirrors can be substantially reduced if the total field of view is reduced.

The option of a large flat secondary mirror is somewhat counter-intuitive. Being flat, it does not provide any power nor aberration correction and being large, it adds mass at a location where mass is traditionally critical. In the present case, it should be observed that achieving high static and dynamic stability at the level of the secondary mirror will be extremely difficult. The advantage of a powered secondary mirror would be to reduce spherical aberration, at the cost of sensitivity (pointing, coma) to lateral decenters. The advantage of a flat secondary mirror is to eliminate the effect of lateral decenters. The influence of tilt is reduced as well, as a flat mirror does not yield angular magnification. Additionally, it is easier to produce a mechanical design minimizing secondary mirror tilt under varying gravity load than a design minimizing lateral decenter.

Sensitivity to corrector decenters is higher but remains within reasonable limits and the location of the corrector is evidently more favorable in respect of positional stability. Tolerance analysis shows[12] that internal metrology and a relatively uncritical actuation scheme would comply with the error budget. Decenters within the corrector are the most critical but again, the figures are such that internal metrology and simple actuation mechanisms should comply with the error budget.

The presence of two active mirrors leads to additional complexity but also added functionality. A minimum of 3 objects are required to differentiate the actual wavefront contributions of the two mirrors; as illustrated in figure 2, the differential between two wavefront measurements provides the differential of the out-of-pupil mirror along the separation of the guide stars. With subpupil diameters on the order of 2-m in the entrance pupil and integration times on the order of 20-30 seconds as in the VLT, availability of sources is not an issue.

The availability of two active mirrors allows for a more complete control of the actual prescription of the telescope. With a single active mirror, wavefront control is, in principle, achievable only at one single field position. A direct consequence of Schwarzschild's theorem[14] is that 2 active mirrors allow at least one third order field-dependent aberration term to become controllable.

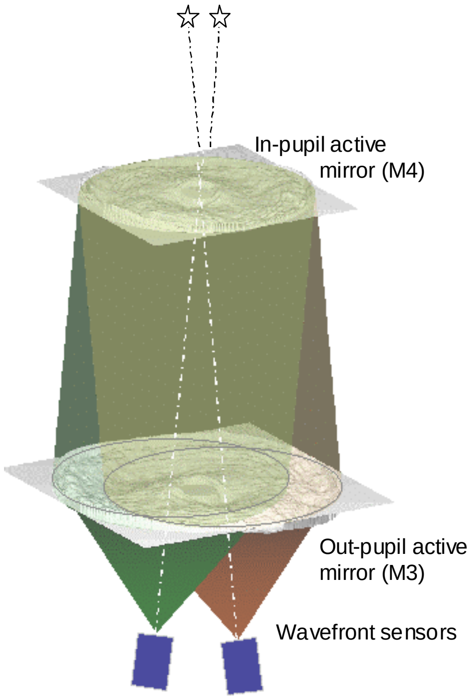

Figure 2. Active optics with 2 active mirrors

Optical fabrication aspects have been addressed[1,13], and there is strong evidence that production of the main optics, including substrates, is fully within the reach of current technology and would not require major facility investments[15,16,17]. Primary mirror segments size has been tentatively set to

2.3-m to allow cost-effective transport in standard containers. There are evident cost, fabrication and handling reasons to reduce segment size; on the other hand, a larger number of segments implies a proportionally larger number of degrees of freedom, hence a higher cost for the total number of actuators, a lower reliability, and possibly a lower phasing accuracy. A thorough trade-off is still to be made.

The current baseline relies on conventional mirror materials (e.g. Zerodur or fused Silica), which leads to a primary mirror mass on the order of 1,500-1,700 tons. An alternative that is given very serious consideration is Silicon Carbide which, in view of its exceptional specific stiffness, would allow major mass reduction. Priority being given to cost, the geometry of any lightweight structure must remain simple and adapted to mass production; the target for aerial density would be on the order of 50 to 80 Kg/m^2 (i.e. a total primary mirror mass of ~300-500 tons).

In terms of fabrication, the only area of concern is the quaternary mirror, which has an aspheric deviation of 9.5 mm with respect to best fitting sphere. The aspherization per se does not seem to be an issue with modern, computer-controlled optical figuring techniques. The optical test set-up envisioned so far requires this mirror to be tested against the tertiary mirror and through a fairly large null system[13].

Phasing is obviously a critical issue; the current budget allocation is 35 nm wavefront RMS for the combined contributions of the primary and secondary mirrors. Assuming equal allocation for tilt and piston, this budget translates into a piston error of no more than ±30 nm (mechanical surface) for each segment of each mirror. The current baseline approach is to rely on the same scheme as that successfully used with the Keck telescopes i.e. position sensors, combined with on-sky calibration techniques[18] and, possibly, complemented by day-time interferometric calibration of the flat secondary mirror phasing. We also identify a number of positive factors:

- Trade-off between tilt and piston contributions, the former being easier to control. A tightening of the tilt requirement and relaxation of the piston one will plausibly occur within the framework of further design iterations.
- Progress in position-sensing technologies (accuracy, reliability, cost, miniaturization) since the design of the Keck telescopes sensors.
- Progress of on-sky piston-sensing concepts[18,19,20].

4.2 ADAPTIVE OPTICS

Attaining diffraction-limited resolution over a field of view largely exceeding that allowed by conventional adaptive optics is a top priority requirement for OWL. Conservative estimates[8] indicate that multi-conjugate adaptive optics[9] (MCAO) should allow for a corrected field of view of at least 20 arc seconds in the visible, assuming a set of three adaptive mirrors conjugated to optimized altitudes.

In the visible, the implied characteristics of adaptive modules (about 500,000 active elements, a corresponding wavefront sampling and commensurate computing power) leaves no doubt as to the technological challenge. Novel ideas about wavefront sensing (e.g. pyramidic wavefront sensors) and spectacularly fast progress in cost-effective technologies which could potentially be applied to adaptive mirrors (MEMs), together with the strong pressure to achieve MCAO correction on existing 8-m class telescopes in a very near future, leaves room for cautious optimism.

Further discussions of adaptive optics aspects for OWL and extremely large telescopes are presented elsewhere[7,8,9,10,11]. Proposals for MCAO demonstrators or even functional instruments to be installed within a fairly short time frame on the VLT and Gemini, respectively, have been made. However promising such developments could be, it is impossible, at this stage, to make any substantiated statement as to their outcomes. Therefore, the telescope design incorporates the most conservative assumptions regarding the eventual technology solutions, which implies, in particular, large field of view for reasonable sky coverage with natural guide star. All attempts should also be made to avoid constraints on the design and correction range of the adaptive modules, which implies that the telescope be able to deliver seeing-limited performance comparable to that of existing large telescopes without the relying on adaptive correction.

4.3 MECHANICS

The current mechanical design is presented and analyzed elsewhere[21,22]; in the following we summarize key design characteristics.

Several mount solutions have been explored, including de-coupled geometries[23] based on fully separate structures for the primary and secondary mirrors. As was -to some extent- expected, the best compromise in terms of cost, performance, and feasibility in a broad sense (i.e. including assembly, integration and maintenance aspects) seems to be an alt-az concept. Figure 3 shows the evolution of the design of the telescope structure with the reduction of the primary-secondary mirrors separation.

As in the case of the main optics, the mechanical design relies heavily on standardized modules and parts, allowing cost reduction factors which are normally not attainable with classical telescope designs. Manufactured or pre-assembled parts are constrained to having dimensions compatible with cost-effective transport in standard 40 ft containers. It should be pointed out that, in view of the structure dimensions, the standardization does not necessarily impair performance. Particular attention is given to assembly and integration constraints as well as to suitability for maintenance.

The all-steel structure shown in figure 3 has a moving mass on the order of 13,500 tons (including mirrors) and does not rely on advanced materials, except for a limited number of carbon-fiber cables at the level of the secondary mirror units. This mass figure corresponds to a 20% gain with respect to the former design iteration[23]. Iso-static and hyper-static configurations are being evaluated, the former yielding lower dynamic performance and the latter, slightly higher mass, complexity, and cost. First locked rotor frequency is 1.5 Hz for the iso-static and 2.4 Hz for the hyper-static configurations, respectively. Static deformations require the decenters of the secondary mirror and of the corrector to be compensated, but the relevant tolerances, which are set to guarantee that the on-sky correction loop by active optics can be closed, are not particularly stringent[12].

Preliminary stress analysis shows that the design would exceed the acceptable safety limits of seismically active sites such as Paranal -which could arguably be considered as a worst case. There is reasonable confidence that further design improvements could remove such concern, but the actual cost implications are yet to be assessed.

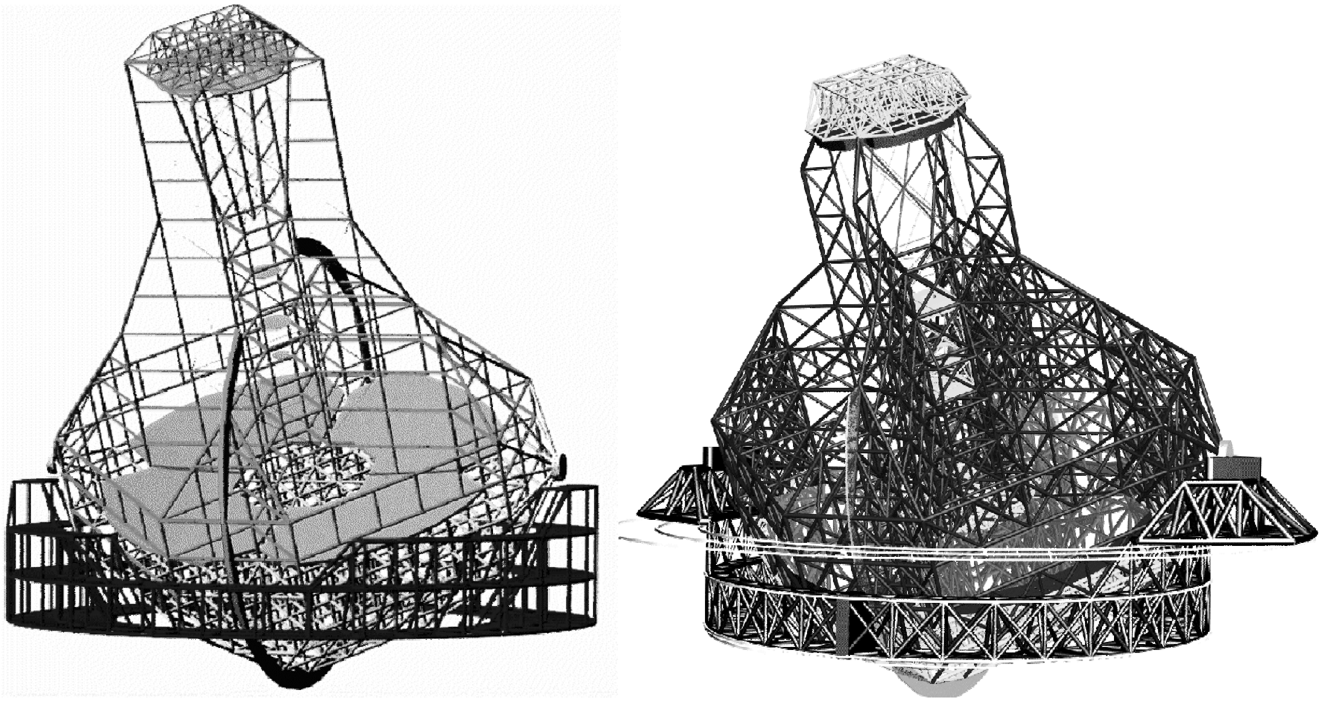

Figure 3. Progress of opto-mechanical design (left: mirror separation 120-m; right: mirror separation 95-m).
The left view does not include full details.

There is no provision for a co-rotating enclosure, the advantage of which being anyway dubious in view of the enormous opening such enclosure would have. Protection against adverse environmental conditions and excessive day-time heating would be ensured by a sliding hangar, whose dimensions may be unusual in astronomy but actually comparable to or lower than those of large movable enclosures built for a variety of applications[22]. Air conditioning would lead to prohibitive costs and is not foreseen; open air operation and unobstructed air circulation within beams and nodes seem sufficient to guarantee that the structure reaches thermal equilibrium within an acceptably short time. In this respect, it should be noted that OWL structure is, in proportion to size, more than an order of magnitude less massive than that of the VLT.

Open-air operation is evidently a major issue with respect to tracking and, as mentioned before, full protection from the effect of wind is not a realistic option. Hence the need for field stabilization. The latter is provided by a 2.5-m class flat mirror located in a pupil image, and there is reasonable confidence that a bandwith of 5-7 Hz could be achieved with available mirror technology. There are, however, limitations to field stabilization as it introduces tilt of the image plane (unless additional surfaces are incorporated to cope with this effect), and every attempt is made to reduce dynamic pointing errors. The effect of image tilt could, in principle, be taken care of in the adaptive modules, but we prefer to avoid additional constraints on these modules. The current design would comply with the error budget up to a wind speed on the order of 4 m/s, without constraints on the adaptive modules. A preliminary assessment of the telescope dynamic properties and drives control parameters indicates that there is room for substantial improvement with respect to amplitudes. It should also be noted that active and passive damping systems have not yet been incorporated into the design.

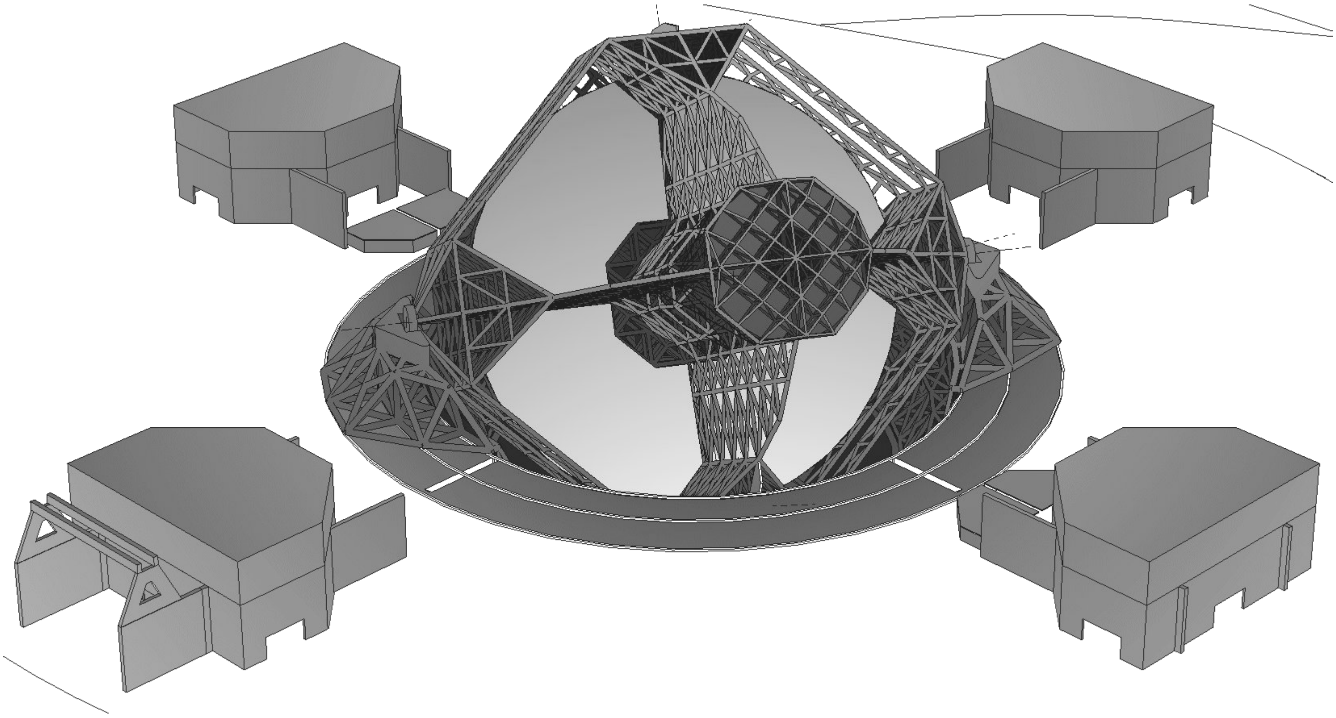

Figure 4. Telescope pointing at 60^o from zenith, layout of the facilities (sliding enclosure not shown)

The benefits of a lighter primary mirror (Silicon Carbide) has been briefly assessed for the iso-static design. Dynamic performance remains basically unchanged, but the lighter mirror allows for very substantial mass savings in the structure (several thousands tons). This is mainly caused by the better balancing of the Tube structure which, in case of the Zerodur option, is made difficult by the high mass of the primary mirror.

The kinematics of the structure is comparable to that of the VLT telescopes: 3 minutes for 90º elevation range, 12 minutes for 360º azimuth range, maximum centrifugal acceleration not exceeding 0.1 g at any location of the structure, and 1 degree zenithal blind angle. The number of motor segments would be on the order of 200 for elevation and 400 for azimuth. These figures are based on VLT technology and appear very conservative.

The telescope can point towards horizon, which allows to reduce the dimensions of the sliding enclosure and facilitates maintenance of the secondary mirror unit and extraction of the corrector unit along the axis of the telescope. Mirror covers are foreseen; they would consist of four quadrants sliding into the structure when the telescope is pointing towards zenith. One of these covers would be equipped with segments handling systems and in-situ cleaning facilities allowing periodic cleaning of the primary mirror. Figure 4 show the telescope pointing towards 60^o zenithal distance, mirror covers retracted. The sliding enclosure is not figured.

5. COST AND SCHEDULE

The current schedule calls for a completion of phase A, including demonstration of the principle of multi-conjugate adaptive optics on the VLT, by 2003. As ambitious as such objective may seem, it should be recalled that the design of the OWL observatory relies extensively on proven technologies, bar adaptive optics -an approach which has also been adopted for the CELT program. In this respect, it should be pointed out that technology development for long-lead items (primary mirrors) played a determinant role with the current generation of 8-10-m class telescopes. These specific, highly time-consuming technology developments being largely unnecessary for extremely large telescopes such as CELT and OWL, tighter scheduling may become possible.

Once project go-ahead would be granted, schedule to technical first light is essentially driven by the construction and integration of the structure. The schedule shown in figure 5 assumes that final design of the telescope structure could be completed within 2 years after project go-ahead, and that its fabrication, assembly and integration could be completed within 5-6 years after final design. It is evidently conceivable that the final design of the structure occurs ahead of the final design of less time-critical subsystems. Full completion of the enclosure, which is close to the critical path, may occur after completion of the structure, provided that a suitable solution is found to complete the structure integration with the telescope pointing horizontal. An iteration of the enclosure and structure possible schedules is needed to come to a clearer plan.

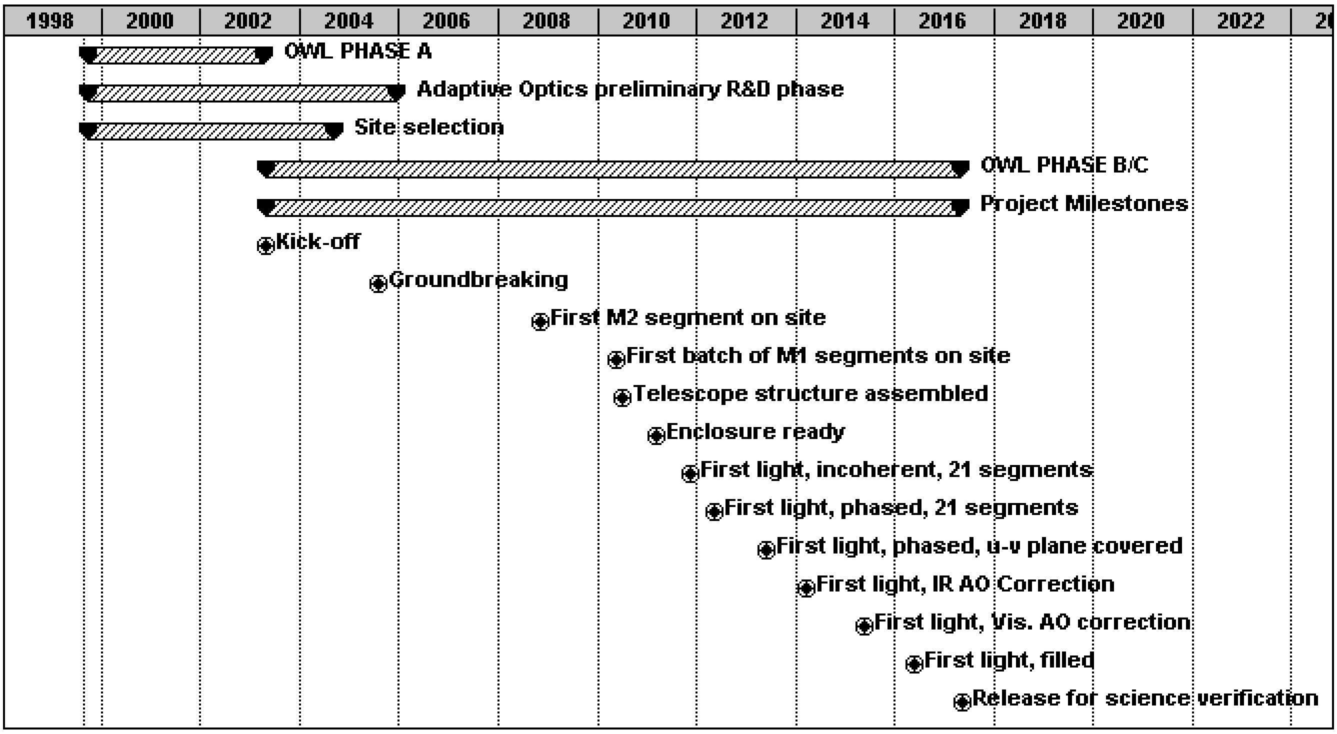

Figure 5. OWL tentative schedule (technical considerations only).

Once the structure is ready to accept primary and secondary mirror segments, integration "rate" can be tuned by duplicating optical integration lines. First light could plausibly occur within 8-9 years after project funding; allowing for ~2.5 years integration and verification of the IR adaptive module(s) and ~3.5 years for integration and verification of the visible adaptive module(s), the telescope could already deliver science data in the IR and in the visible within 10.5-11.5 and 11.5-12.5 years after project go-ahead, with unmatched resolution and collecting power. There are, indeed, strong incentives to design and build a first generation of instruments that would take benefit of the telescope unequalled potential before full completion. Full science operation would start approximately within 14 years after project funding.

1	OPTICS	347	
1.1	Primary mirror unit		266.7
1.2	Secondary mirror unit		27.0
1.3	M3 unit		14.4
1.4	M4 unit		23.9
1.5	M5 unit		5.3
1.6	M6 unit		10.1
2	ADAPTIVE OPTICS	47	
2.1	Prototyping		2.0
2.2	Visible AO module		30.0
2.3	IR AO module		15.0
3	MECHANICS	229	
3.1	Azimuth ring		14.8
3.2	Tube		36.7
3.3	Rocking chair		3.0
3.4	Azimuth tracks		50.8
3.5	Cable wraps		3.0
3.6	Bearings		30.0
3.7	Drives		20.0
3.8	Mirror shields		15.0
3.9	Adapters		6.0
3.A	Erection		50.0
4	CONTROL SYSTEMS	17	
4.1	Telescope Control System		5.0
4.2	M1 Control System		8.0
4.3	M2 Control System		2.0
4.4	Active optics Control System		2.0
5	CIVIL WORKS	220	
5.1	Enclosure		40.4
5.2	Technical facilities		35.0
5.3	Site infrastructure		25.0
5.4	Concrete		120.0
5	INSTRUMENTATION	45	
TOTAL WITHOUT CONTINGENCY		906	
CONTINGENCY	10%	94	
FIXED TOTAL		1000	

Table 1. OWL cost estimate, in million Euros (capital investment).

A preliminary cost model has been assembled and, to some extent, consolidated. The total capital investment remains within the target maximum of 1,000 million Euros, including contingency. It should be pointed out, however, that some of the most determinant cost positions correspond to subsystems involving mass production (primary optics, structure), an area traditionally *terra incognata* to telescope designers. The full implication of mass-production of the primary optics, of actuators and sensors, and of the structure may be underestimated. The cost estimate presented here (table 1) should therefore be consolidated by industrial studies, which are planned. Our perception is that current estimates are probably conservative.

Progress of the design has led to a reduction of former estimates[2] in the area of optics (including supports) and mechanics, mainly as a result of mass reduction. The allocation for civil works has been increased but design optimization, still to be started, should arguably lead to lower figures. The estimate shown in table 1 assumes Zerodur primary and secondary mirrors (at 80 Euros / Kg). Silica or Astro-Sitall would probably lead to lower estimates (yielding to an increase of contingency to 12 or 14%, respectively).

6. CONCLUSIONS

Progress of the conceptual design of the OWL telescope does not reveal any obvious show-stopper. Underlying the feasibility of a 100-m class telescope is the fact that traditional scalability issues, such as the feasibility of the optics, have shifted to entirely new areas, namely mechanics and control. These last are evidently more predictable, and their limitations inevitably exceed those so far applying to conventional telescope design -a size increase by a factor 2 per generation.

The sheer size of reflecting optics and structures permitted by optical segmentation, active optics, field stabilization, and suitable mechanical design, respectively, calls for novel approach towards opto-mechanical design. Design options, in particular, must be assessed at system level and evaluated in proper relation to angular resolution and total throughput.

The current design incorporates all functions required to deliver a minimally disturbed wavefront over the science field, prior to adaptive correction.

Adaptive optics is evidently the most critical aspect of any Extremely Large Telescope concept. OWL design can accommodate for conservative assumptions as to the future field and quality requirements that will be implied by adaptive optics.

There is strong indication that a competitive schedule is possible; the critical path is set by the mechanics, and, in contrast to the situation which prevailed at the time the last generation of 8- to 10-m class telescopes was designed, long-lead items such as the main optics do not require time-consuming technology developments. Whereby achieving technical first light within 8-9 years after project go-ahead would be a challenging objective, flexibility in the subsequent integration phases should allow a start of partial science operation at full resolution within 11 and 12 years in the infrared and in the visible, respectively.

ACKNOWLEDGEMENTS

The concept presented in this article is the result of the work of several people. The authors wish to thank, in particular, Bernard Delabre, Enzo Brunetto, Marco Quattri, Franz Koch, Norbert Hubin, Miska le Louarn and Elise Viard for their valuable input. We also thank Jerry Nelson for his positive -and stimulating- criticism.

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